Adaptable load-bearing timber structures

Using a scenario based design methodology

Master thesis research

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MSc in Architecture, Urbanism and Building Sciences (Building Technology)
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How can the life span of mid-rise buildings be extended by developing an adaptable hardwood timber structure through scenario based design?

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Abstract

Keywords: Design for adaptability, Hardwood, Circular design qualities, Glulam, LVL

The life span of buildings is currently largely determined by economic motives. This often results in a large number of vacant buildings, or unsubstantiated demolition. Since the building industry has the most significant consumption of natural resources compared to other industries worldwide, it is important that the ecological motive gets prioritized more. A strategy to minimize the use of new materials and prevent demolition is to adapt existing buildings to new functional requirements. Current existing buildings are most often not built with the intention to be adapted in the future, making adaptation activities not feasible. Structures that are intented for future adaptation, are mostly focused on complete deconstruction, while most functional changes only require small adaptations. The aim of this research is to develop a framework for the design of adaptable load-bearing structures, focused on adapting individual building components to extend the functional life span of a building. Since there is a level of uncertainty related to the future life span of a building, a scenario based design method is used to formulate different design scenarios to which an adaptable structure should comply. The framework consists of five design domains: material, structural layout, kit-of-parts, building layers and construction process. These domains are explored parallelly on the aspect of adaptation and are evaluated using circular design qualities. The design proposal addresses a structural principle that consists of a primary and secondary connection, in which the secondary connection is used during an adaptation process. The adaptable structural system performs better on the circular design qualities when compared to existing circular systems, mainly on the independency and compatibility. However, the adaptability performance of a building is not solely reliant on the load-bearing structure. This principle only works when the other building layers are also designed with adaptability in mind. This research contributes to the building industry research field by providing a well-rounded overview of factors where adaptability could be implemented into the design process and rethinking the approach to handling the life span of a building.

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I would also like to extend my gratitude to my mentors, whose guidance and knowledge have been extremely valuable throughout this research process. I am truly appreciative for their insights, constructive feedback and encouragement.

I am excited about my future endeavors in the next phase of my life in which I plan to use the knowledge and skills that I have gained through this education to make a meaningful contribution to the environmental impact of the building industry.

Contents

Chapter 1

Defining research structure

1.1 Problem statement

Unsubstantiated demolition I Vacancy I Resource depletion

Main problem: The lifespan of buildings is unnecessarily cut short.

Buildings are objects made from different layers and parts, each with a different life span. Parts can be maintained, or the whole building can be renovated to improve physical and functional aspects and extend the life span. As long as buildings are perceived as useful, their life span could be prolonged endlessly (Gruis, Visscher, & Kleinhans, 2006). When buildings are no longer seen as valuable in their current state, there are four types of actions that can be undertaken: consolidation, adaptation, demolition and redevelopment, and conversion. Most often owners choose to consolidate and either leave the building vacant or sell it, or the building is demolished (Wilkinson, Remøy, & Langston, 2014).

Sub problem: Unsubstantiated demolition

Demolition and redevelopment is a building strategy, focused on ending the life span of an existing building and replacing it with a new building (Gruis, Visscher, & Kleinhans, 2006). The quality of the building and public health used to be the main determining factors in deciding whether a the life span of a building should be extended or ended. More recently, functional and economic aspect tend to dominate the decision (Thomsen & van der Flier, 2008). Ideally, sustainability would be a major factor in the decision making process. For example, a demolition and redevelopment approach requires much more building materials and produces more waste compared to other approaches like adaptation or renovation, resulting in a higher environmental impact. When a buildings is adapted, almost 60 percent less building materials are used than during redevelopment. Similarly, with adaptation, 80 percent less waste is configured than with demolition (Itard & Klunder, 2007).

Compared to its neighboring countries, the Netherlands has a much higher demolition rate. The amount of buildings demolished also grew steadily in the Netherlands, with an increase of 60 percent in 7 years (Thomsen & van der Flier, 2008).

Sub problem: The rising relative amount of vacancy within the existing building stock.

Vacancy rates in the building stock have been increasing globally since the 2008 global financial crisis. This has specifically been an issue for offices and other commercial spaces. Still, new office buildings are realized, leaving the existing stock vacant or obsolete. A small percentage of vacancy in a building market is healthy. Around 4 to 5 percent of vacancy is needed to serve as a buffer zone, for users to move around from one place to another without requiring new construction (van Zutphen et al., 2015). However, at the end of 2012, 15 percent of the office spaces were vacant in the Netherlands (Wilkinson, Remøy, & Langston, 2014).

A building becomes obsolete when the technical, functional or economic life of the building is deemed as not viable (Wilkinson, Remøy, & Langston, 2014).

Obsolescence and vacancy in the existing building stock can cause social and economic issues. When a building is obsolete, it is more prone to vandalism, break-ins and illegal occupancy. Another indirect social issue is the negative image that a vacant building translates to its surroundings. An economic issue is the lack of income for owners when a building is vacant (Remøy & van der Voordt, 2007). Although owners of properties are often not inclined to improve vacancy issues, because they pay less for a vacant building than when they would actively renovate or adapt the building, due to high building costs and complex projects (van Zutphen et al., 2015).

Sub problem: Environmental impact related to material use in the built environment.

The emission of greenhouse gases (GHG), like CO_2, CH_4 and N_2O, is one of the most influential causes of negative global environmental harm, the main issue being global warming. These emissions result from human activities like burning fossil fuels, deforestation and land use changes. Other harmful environmental impacts as a result from human activities worth considering are ozone depletion, water consumption, toxicity, eutrophication of lakes and rivers and resource depletion (Khasreen, Banfill, & Menzies, 2009).

The biggest contributor to the emission of greenhouse gases and other harmful environmental impacts is the building industry, responsible for 50 percent of the global CO2 emissions (Khasreen, Banfill, & Menzies, 2009). These emissions happen throughout the whole life cycle of realizing and maintaining buildings. For example, harvesting materials from destinations far from the building site, require a well-developed infrastructure and longer transportation, resulting in emissions indirectly related to material extraction during the transportation phase (Icibaci, 2019).

Another large environmental issue, next to the emission of greenhouse gases, is the consumption of materials and energy. The natural resources extracted for construction of buildings and infrastructure constitute the most significant consumption of all economic sectors. The consumption of material and energy resources has increased tenfold over the past hundred years, while the human population increased fourfold (Icibaci, 2019). The building sector consumes 3 billion tons of raw materials annually, which is 40 percent of all materials entering the global economy (Khasreen, Banfill, & Menzies, 2009; Akadiri, Chinyio, & Olomolaiye, 2012).

The need for responsible material consumption and production is directly related to the triple planetary crises: climate change, biodiversity loss and pollution (United Nations, n.d.-a). Additionally, the building industry currently uses almost exclusively finite resources, the relative amount of bio-based resources in The Netherlands being only 2 percent (Wageningen University & Research, 2022). If the building industry will continue this type of material use behavior, resources will become depleted.

The awareness of climate change is happening globally and calls to action are established officially, for example in the Paris Agreement. The Paris agreement is a legally binding international treaty on climate change, involving 196 parties. It was enforced since November 2016. The goal is to limit global warming and achieve a climate neutral world by 2050. It requires participation of all parties and industries (United Nations, n.d.-b). Therefore, it is important to develop solutions that minimize the greenhouse gases emitted and natural resources exploited in the field of building development, considering the high environmental impact made by this industry.

1.2 Objectives

Extend life span I Adaptable structure I Local materials I Dutch industry

From the problem statement can be concluded that there needs to be a behavioral shift in the decision making about extending or ending the life span of a building, using sustainability as a main guiding theme. To aid reaching this goal, the main objective of this research will be **to extend the life span of buildings by designing an adaptable structure using locally sourced, bio-based materials, making use of a scenario based design methodology.**

The main objective can be divided into sub-objectives:

Prevent the premature demolition of buildings and high vacancy percentages in the future

Currently, demolition and redevelopment and consolidation are the most appealing life span approaches for property owners, mainly due to economic reasons. Adaptation often accounts for additional building costs and complex projects, that owners are not inclined to take on. By involving design for adaptation into the initial design process of a building structure, adaptation could become a more attractive building strategy than demolition and redevelopment or consolidation.

Design an adaptable load bearing structure

During the initial design of a building, the future scenarios are not definitive. By designing an adaptable load-bearing structure, that can adapt to fit different future scenarios, the life span of the building can be extended further. This process optimizes the value of the embodied energy and the quality of the original building in a sustainable way.

Minimize the impact of material use in the building industry

To further strengthen the sustainability perspective of this research, the material use of the adaptable structure should also have a minimal environmental impact. Firstly, for this project a bio-based and renewable material is used, which is timber. Secondly, this material is chosen based on the local availability, to minimize the impact of transport. The local region chosen for this research is the Netherlands. In the Netherlands, there is currently a shift happening in the availability of wood species from softwood to hardwood. To optimally use this future stock, the thesis is specifically centered around designing with hardwood.

Design a solution applicable to the Dutch building industry

Since the materials are harvested and produced locally, the eventual product should also be applicable to the Dutch building industry. This means the adaptable structure are designed based on probable Dutch scenarios.

1.3 Research questions

Main question I Sub-questions

The main research question answered through this research is:

How can the life span of mid-rise buildings be extended by developing an adaptable hardwood timber structure through scenario based design?

The main question is answered by answering a sequence of sub-questions, being:

- What is the current availability of circular building systems and what are they lacking in terms of adaptability?
- What are the technical characteristics of hardwood timber and what hardwood product is most suitable for an adaptable structure?
- What does an adaptable structural layout look like and how can that be realized using hardwood?
- How would a connection work with which you are able to disconnect individual building components?
- How do other building layers influence the adaptability of the load-bearing structure?
- What are critical limitations during the transition process of the structure and how does this influence the design?

1.4 Methodology

Scenario based design

Humans are dynamic beings, that are influenced by and grow with their surroundings, while buildings are perceived as machines with no spirit and with limited opportunity for change (Lüley, Pifko, & Špaček, 2019). Instead of being seen as a static object, buildings should be treated as dynamic as well: they adapt, grow, develop and change in response to their environment. Thus, buildings should be created in a systematic, but flexible manner, in which scenarios form building blocks to create different possible time sequences in which the building changes (Eilouti, 2018). Since the aim of this research is to develop an adaptable timber structure, a scenario based design (SBD) methodology is qualified to guide in developing flexible solutions.

What is scenario based design?

Rosson and Carroll (2009) define the concept of scenario based design in their research as "a family of techniques in which the use of a future system is concretely described at an early point in the development process". This methodology is focused on mapping various possible configurations and predicting their potentials, performances, weaknesses, strengths and opportunities, eventually guiding the further development of a system that fulfills the goal of the project (Eilouti, 2018; Rosson & Carroll, 2009).

Scenarios are the main ingredients within the SBD approach. In general, a scenario can be defined as a concrete yet flexible design proposal, functioning as a tool for a designer to evaluate and refine their design. A scenario description may be rough, so the details can be easily changed throughout the process (Rosson & Carroll, 2009). Within the scope of architectural design, a scenario is defined by Eilouti (2018) as "a dynamic slice of the future life cycle of a building which entails a description of settings, operations, as well as users and their actions and interactions with their internal and external environments". Because scenarios map the future life span of a building, it is a suitable approach for an adaptable design, which will change throughout its life span.

There are different types of scenarios, used in different design briefs. For this research, the ten strategies from the R-strategy ladder from Potting et al. (2017) are used as possible scenarios. For each R-strategy, various sub-scenarios are described. A sub-scenario is an activity where a certain R-strategy is applied to adapt a building structure and extend the life span of a building. This 'activity sub-scenario' does not focus on one static setting, but on the transition from the current situation to a new one (Eilouti, 2018).

Steps in scenario based design

Using the scenario based design methodology is the process of understanding three different types of context: current, designed and altered (Lüley, Pifko, & Špaček, 2019). Therefore, this research using the SBD methodology consists of three phases connected to the context types, respectively: analysis, design and evaluation.

Analysis phase
The analysis phase begins by conducting a contemporary image of the current practice in the field of building technology, specifically focused on adaptable design and timber structures. By analyzing the current situation, a deep understanding of the available opportunities, complex problems and existing knowledge gap is

created. The analysis of current practice is done through relevant literature on a circular economy and case studies. The scenarios and sub-scenarios are defined next, using the R-strategies as mentioned before. To translate the scenarios into a detailed design brief, they are further explained through circular design qualities. These qualities act as an evaluation system.

Before the design phase commences, existing circular structural systems are analyzed using the evaluation system, to gain insight into the knowledge gap and the availability on the current market.

Design phase
The goal of the design phase is to create a detailed design proposal of an adaptable timber structure, able to seamlessly transition from one situation to another. The design phase is structured using five design domains: material, structural layout, kit-of-parts, building layers and construction process. Each domain provides background information, as well as various design options and a recommendation for the most optimal adaptable design. Each domain is concluded by a detailed design proposal based on the recommendation. A design proposal is developed by using computational tools and more conventional design tools, like sketching. The five domains are explored parallelly and iteratively.

Evaluation phase
Familiarity and human cognition might appear as an issue when using SBD, as designers overestimate the relevance of aspects that are familiar to them personally. They might unconsciously optimize their idea for the scenario in which the actors or context is most recognizable to them (Rosson & Carroll, 2009). To avoid this, it is important to work with a structured evaluation matrix, analyzing the positive and negative consequences of certain interventions. In this matrix, the design characteristics of the design proposal are evaluated against the predefined required circular design qualities and their criteria. Every proposal that results from the design phase is evaluated using this method. Like mentioned before, the evaluation results of the previous design proposal create refined input for the next in an iterative feedback loop.

Results
Eventually, when a design proposal meets the required criteria, the technical details and development of the vision are crystallized, and the five domains are combined into one final design proposal. Additionally, a summative evaluation is written in which potential further research topics and remarks on the results are summarized.

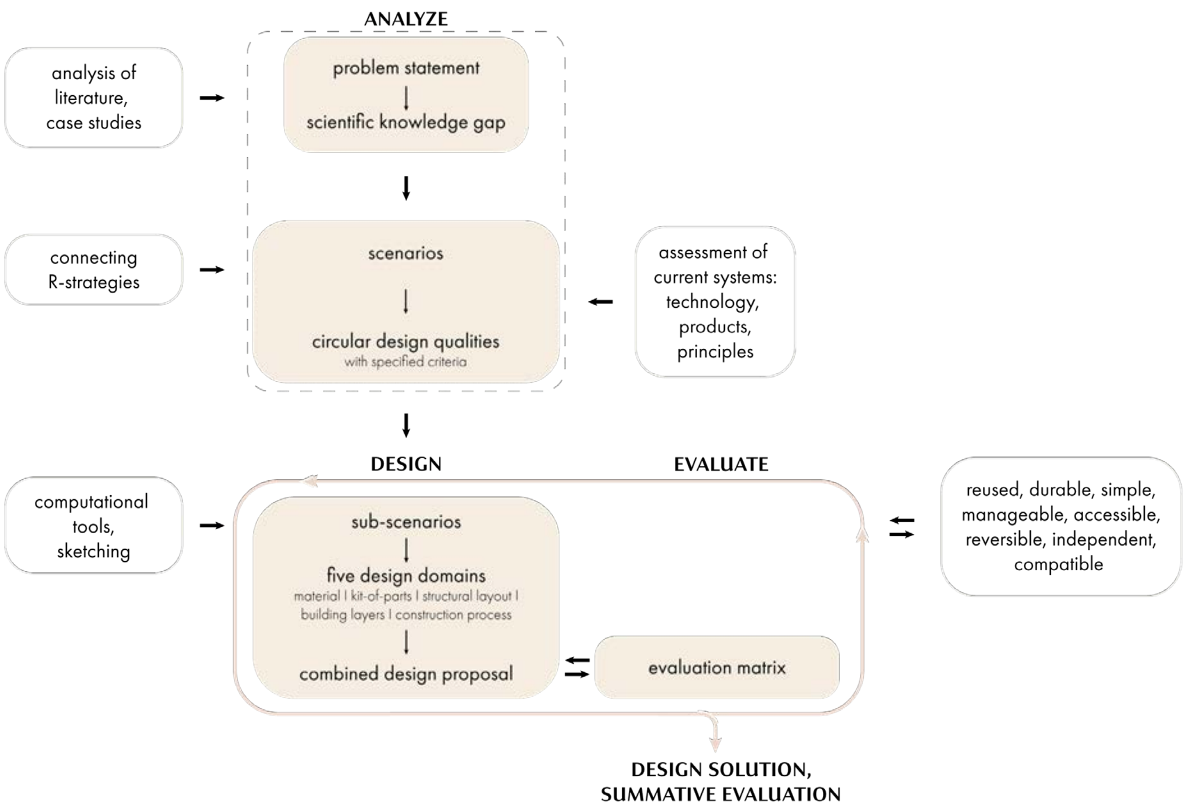


Fig. 1.1 Scenario based design methodology based on Rosson and Carroll (2002, 2009); Eilouti (2018)

1.5 Scope and design domains

Material I Structural layout I Kit-of-parts I Building layers I Construction process

The main objective of the thesis as mentioned before is: **extending the life span of mid-rise buildings by developing an adaptable hardwood timber structure.** A scope is formulated to clarify the focus of the thesis project and the design proposal. In chapter 3.3, the evaluation method to check the design proposal is defined stating the exact parameters of the evaluation criteria.

The main assignment of this thesis is to develop a structural hardwood system for mid-rise buildings, that allows for easy adaptation. The structural system has to contain the load-bearing components of a building, meaning the timber skeleton, the lateral stability components and the floor system. The other building layers will be discussed but not specifically designed. The most important criterion to complete this assignment is that all parts of the structure can be handled independently.

The design proposal is tailored for the mid-rise building typology. For this research, that means that the structure can be established using solely timber components without a concrete or steel core. The structural layout is adjusted for building programs that require a mid-rise building.

A set of five design domains guide a well-rounded design process. The five domains are explored parallel to each other and findings from one domain are used to continue the design process in another domain. Design explorations can also fall within the scope of multiple domains simultaneously.

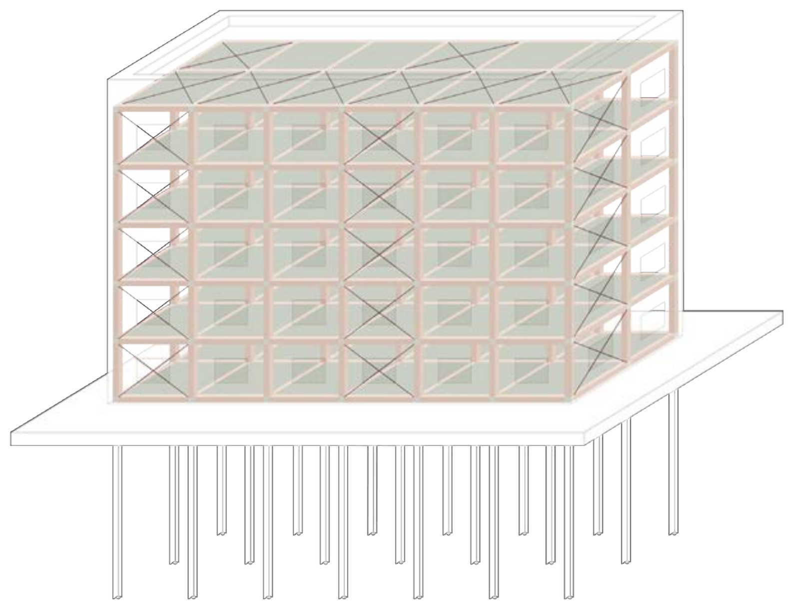
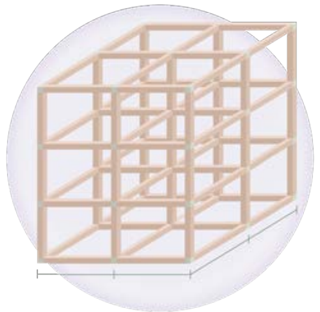


Fig. 1.2 By author, Scope definition related to building layers

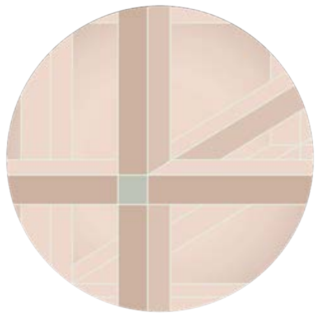
Material

The chosen material for this design project is hardwood timber. This design domain contains all explorations related to the properties of hardwood and hardwood products. The material is analyzed on its workability and a specific hardwood timber product is chosen to start developing an adaptable structure with.



Structural layout

The purpose of an adaptable structural system is to eventually construct an entire building. This design domain focuses on working with different grids and testing their influence on the design of the components. The dimensioning of the components is determined and a matrix to determine the vertical loads is developed using computational tools.



Kit-of-parts

The adaptable hardwood structure consists of a number of components, which can be assembled to form a complete structure and can be disassembled as individual parts. This domain explores the configuration of the connection and the possible design of the components. The kit-of-parts contains all necessary parts to be able to develop an adaptable hardwood timber structure for a mid-rise building. The aim of this domain is to integrate as few unique parts as possible and keep the system simple.

Building layers

This thesis research focuses on the load-bearing structure of a building. However, other shearing layers are directly or indirectly related to the structure. The influence of that relation on the design of the load-bearing structure is explored within this design domain.

Construction process

An adaptable structure has to be constructed initially, but also has the ability to be partially deconstructed during its life span. This domain explores these processes and how to optimize the structure to execute the adaptation activities with a low threshold. The transportability of the individual parts within the mid-rise building and on the road are explored.

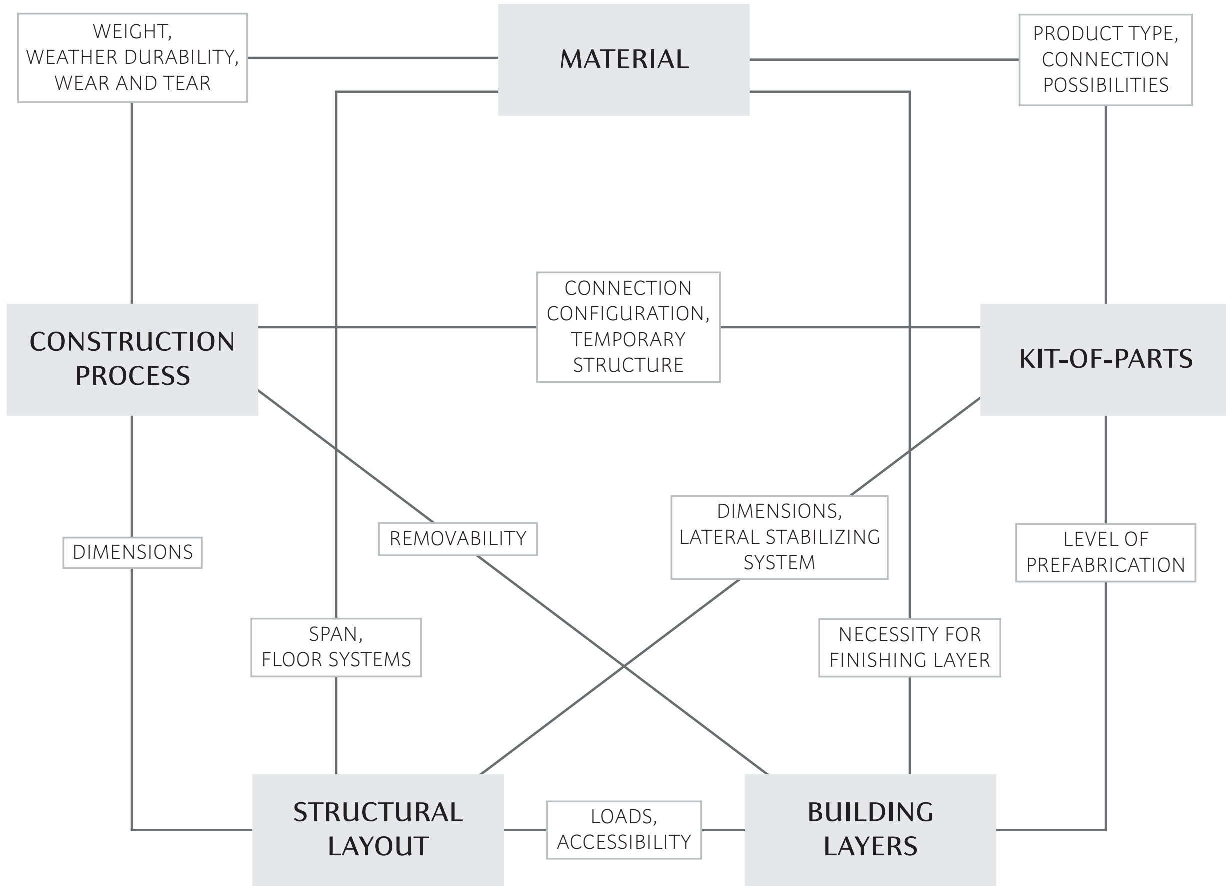


Fig. 1.3 By author, Overlap between design domains

Altogether, these five design domains are combined into a comprehensive design proposal for an adaptable structural system using hardwood, highlighting the main technical concerns in developing such a system. As previously highlighted, aspects of the design can fall within the scope of multiple domains simultaneously. These aspects are illustrated in figure 1.3. For the readability of this report, the overlapping aspects are discussed within one of the domains.

Some other design aspects could be viewed as important for the subject of this thesis, such as the connection of other building layers onto the load-bearing structure, the harvesting process and source of the hardwood, recycling of old building parts and materials, and other concerns like moisture and fire safety, but fall outside the scope. These aspects are discussed briefly in the reflection, however.

1.6 Glossary

Adaptable structures I Adaptation I Building component I Building life span I Mid-rise buildings I Transformation I Scenario

Some of the terms used throughout the research have an ambiguous definition. A short glossary establishes the definitions of some of the commonly used terms in relation to the context of the thesis research.

Adaptable structures
Structures that are designed with the intention of easy execution of adaptive activities throughout the life span of the building. The building structure can be defined as the load-bearing structure of a building, separate from the facade, installations or other building layers, including the floor and lateral stability components.

Adaptation
The process to adjust something to different conditions or uses, or to meet different situations (Cambridge University Press, n.d.-a). Within the scope of this research, the 'something' that is adapted is the building structure, with the aim to actively extend the life span of a building. Adaptation can be exercised through maintenance, technical innovation or change of function.

Building component
A component is a part of a building, which is manufactured as one independent element. Components can be assembled with other components to form a more complex building item (Designing buildings, 2022). Examples of building components are: columns, beams and floor slabs.

Building life span
After the initial phases, like the initiative, briefing, design, and construction of a building, the life span of a building begins. During the life span, use and operation phases alternate with adaptation activities. The life span of a building has to be assessed throughout for various reasons: the technical or functional characteristics do not meet the requirements of users or owners anymore, or the costs of the building exceed the benefits. In these cases there are two possibilities; major adaptation activities to continue the life span, or to terminate the life span and demolish the building (Wilkinson, Remøy, & Langston, 2014).

Mid-rise buildings
Mid-rise buildings in the Netherlands are defined by the TU Delft as being a minimum of three to a maximum of six storeys (TU Delft OpenCourseWare, 2016). Furthermore, the prevailing building height using a timber post-and-beam system is also approximately six storeys, without using a concrete or steel core (Centrum Hout, 2021).

Transformation
Transformation is a specific type of adaptation activity. Activities connected to transformation occur when the function of a building changes. The building structure, layout, facade and other elements are transformed to properly house the new function.

Scenario
Scenarios are used to describe the dynamics of a building throughout the life span. They represent situations of how a building could function, grow or change and how users can interact with that specific situation. Scenarios are used and analyzed to translate activities into functional and technical undertakings and solutions (Eilouti, 2018).

PART I

Research and analysis

Chapter 2

Review of literature and case studies

2.1 Circular economy

R-strategies I Butterfly diagram I Bio-based materials

Circular economy

Our current economy is based on a linear mindset: materials are extracted from the Earth, products are made and eventually discarded as waste. A circular economy is an economic model with the aim of efficient use of resources. This is achieved by minimizing waste, retaining the value of products and materials for as long as possible, reducing the use of primary resources, and forming closed loops of products, parts and materials (Morseletto, 2020). The Butterfly diagram developed by the Ellen MacArthur Foundation (n.d.) is one of the first visualizations of how a circular economy would work. The diagram is divided into a technical cycle and a biological cycle. In the technical cycle, the products and materials circulate by using so-called 'R-strategies', extending their life cycles this way. In the biological cycle, the biodegradable materials form a regenerative loop with nature, by returning their nutrients to the Earth (Ellen MacArthur Foundation, n.d.).

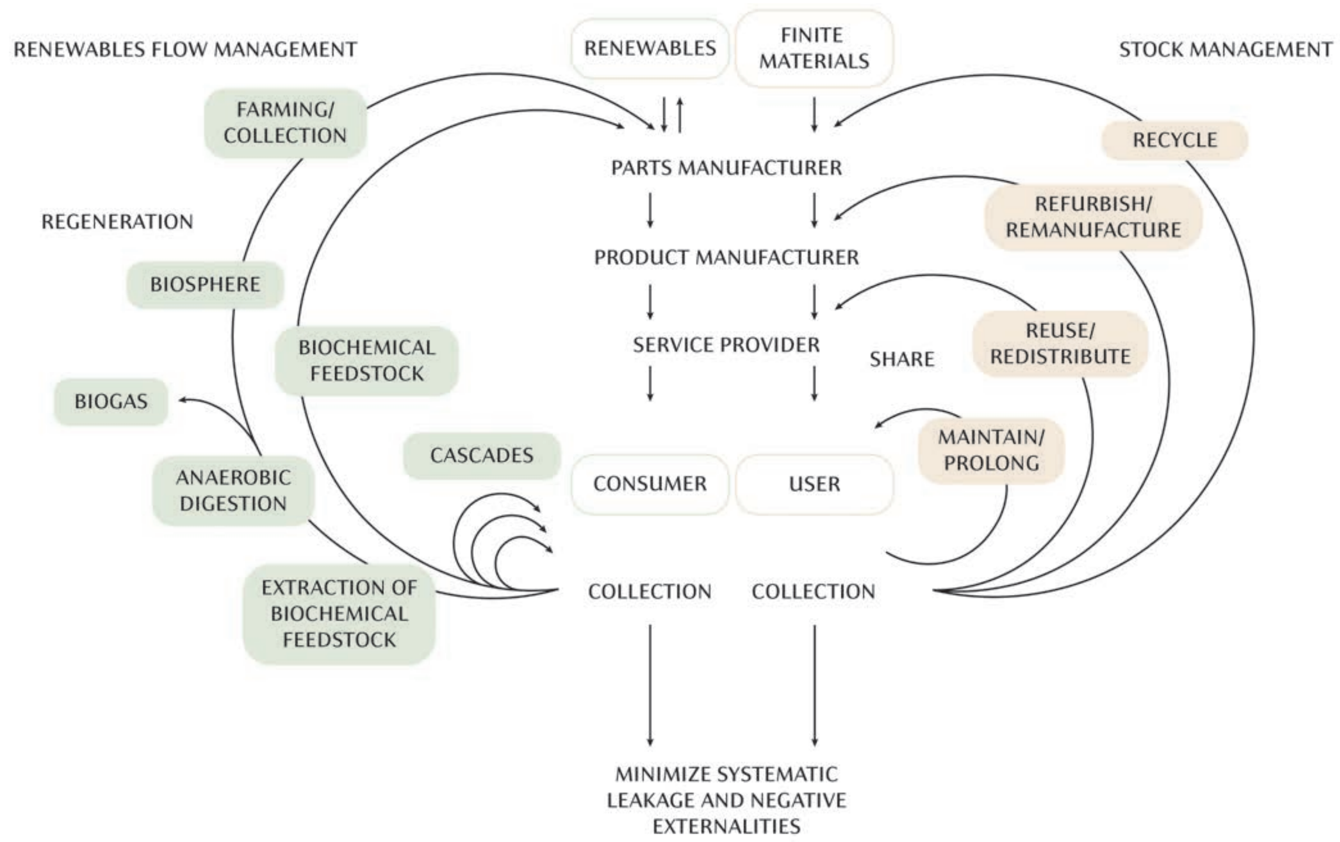


Fig. 2.1 Ellen MacArthur Foundation (n.d.) Butterfly diagram

Since the concept of a circular economy has become more defined, there has been some criticism on the Butterfly diagram. By dividing the material cycle into a biological and technical wing, it seems like there is a perfect regenerative natural environment without waste production, coexisting with an isolated system in which people use and produce technical products which are eventually wasted (Velenturf et al., 2019).

Velenturf et al. (2019) propose a different distinction, between natural and industrial materials. Industrial materials in the context of a circular economy are natural materials that are transformed into products, engineered in such a way that they can be reintegrated as natural materials into the uncontrolled biophysical environment at the end of their life, without negative environmental consequences, as visualized in figure 2.2 (Velenturf et al., 2019). In their research, Velenturf et al. (2019) describe natural materials as materials present in the wider biophysical environment, uncontrolled by people. Natural materials can be both of natural or engineered origin and processes including natural materials do not cause any environmental harm.

Fig. 2.2 Based on Velenturf et al. (2019) Natural and industrial materials

Bio-based materials

An example of natural materials are bio-based materials. Bio-based materials are substances that come from renewable sources from nature. Examples of bio-based products are: hemp, flax, mycelium, cork, bamboo and timber (M. Yadav & Agarwal, 2021). In contrast to materials made from fossil fuels, bio-based materials come from resources that are able to regenerate themselves. Additionally, bio-based materials are recyclable, more often than not. Whereas fossil fuels most often cannot be recovered or recycled and inevitably produce waste. As one of the aims of a circular economy is to minimize waste production and aim for efficient use of resources, it is important to minimize the use of fossil fuel based materials and switch to bio-based materials.

An additional benefit of bio-based materials is the fact that they are able to store the embodied carbon during existence of the material. This means that when bio-based materials are used to construct buildings that have a long life span, the CO_2 can be stored for decades before release. With fossil fuels, the CO_2 is immediately emitted during production (M. Yadav & Agarwal, 2021).

R-strategies

The Ellen MacArthur scheme mainly focuses on the extension of the life span of products and materials, but there are actually more R-strategies that should be applied beforehand, centered around smarter production use and manufacture. Potting, Hekkert, Worrell and Hanemaaijer (2017) have formulated a list of ten circular strategies, building on the original R-strategies listed in the butterfly diagram, organized in order of circular impact, shown in figure 2.3. A higher level of circular impact means that the material or product remains in the loop for a longer duration, and that it can be applied again after discarding, preferably retaining as much of their original value. R8 recycling and R9 recovery carry an extremely low circular yield. These two strategies can only be applied after the functional life span of the material or product has ended (Morseletto, 2020).

Smarter product use and manufacture	R0	Refuse
	R1	Rethink
	R2	Reduce
Extend life span of product and its parts	R3	Reuse
	R4	Repair
	R5	Refurbish
	R6	Remanufacture
	R7	Repurpose
Useful application of materials	R8	Recycle
	R9	Recovery

Fig. 2.3 Potting, Hekkert, Worrell, & Hanemaaijer (2017) Circularity strategies within the production chain

R0 Refuse
The purpose of a potential product can also be fulfilled without using the actual product. In this case the product does not have to be realized at all, it becomes redundant in this specific case (Mast, Von Unruh, & Irrek, 2022).

R1 Rethink
A product type is used with a higher intensity by different actors, without more individual products being produced (Mast et al., 2022). Rethinking strategies are sharing a product, or developing a multi-functional product, for example (Morseletto, 2020).

R2 Reduce
A reducing strategy is focused on the reduction of natural resource extraction (Morseletto, 2020). Whereas a rethinking strategy uses the product more intensively without changing the product, improves a reducing strategy the efficiency of the product, resulting in a lower required amount of production of said product (Mast et al., 2022).

R3 Reuse
A product is reused when the product remains in an unchanged state, but with a change in ownership (Mast et al., 2022). A reused product retains its original function.

R4 Repair
By repairing a product, it returns from a defective state to its original state and function (Mast et al., 2022). On a building scale, repair can be compared with maintenance.

R5 Refurbish
Similar to repair, refurbishing a product means it is transformed from a defective to a functioning state. Additionally, the product is brought up to the quality of the current state of the art (Mast et al., 2022).

R6 Remanufacture
During a remanufacturing process, components of an old product are used to complete new products with the same function (Mast et al., 2022). The remanufactured product must have the same quality as a newly manufactured product (Morseletto, 2020).

R7 Repurpose
A repurpose strategy focuses on taking components from an old product and constructing an entirely different product with it (Mast et al., 2022). Repurpose differs from other strategies, because the original products and parts acquire a different function then before.

R8 Recycle
Recycling strategies are executed when the existing product or component do not have any further functional potential. The raw materials are recovered and used to produce new products and components (Mast et al., 2022). Recycled materials can maintain the same quality as the original material (high-grade), or decrease in quality (low-grade) (Morseletto, 2020).

R9 Recovery
A final option in handling products and components without functional potential or recycling possibilities, is to recover the energy embodied in the material (Mast et al., 2022). Recovery has the lowest circular yield of all ten strategies, but due to the affordability of the strategy, it is still highly competitive with the other R-strategies (Morseletto, 2020).

R-strategies in the context of a timber structure

The definitions of the R-strategies are not specifically targeted towards the design process of buildings and structures. The ten strategies can be placed into the life cycle of a building as shown in figure 2.4. The most influential strategies, from R0 to R2, happen during the design phase of the building and the building components. The engineer and architect can decide where the amount of materials could be limited and how a structure could be prepared for the implementation of other R-strategies throughout the life span of the building. R3 Reuse is applied when the ownership of a building changes. Strategy R4 until R7 happen during the use phase of the building. By applying the R-strategies during the use phase, the life span of the building is extended. Strategies R8 and R9 focus on the useful application of the building materials, when there is no further potential in applying the more circular impactful R-strategies. Recycled materials can be used to redevelop building products and components for a new construction project. In case recycling is not possible, the embodied energy of the material is recovered through incineration.

Conclusion

A circular economy is an economic model in which the main goals are related to transforming linear material streams into circular loops with minimal waste streams. To minimize waste streams, it is important that the type of materials used for producing products can be reintegrated as natural materials at the end of their life, bearing no negative environmental consequences. Bio-based materials are a type of natural materials, with many benefits that correspond with the goals of a circular economy. They are often times recyclable, they regenerate and store embodied carbon.

Although there are many benefits attached to the use of bio-based materials, for a successful circular economy, the R-strategies need to be applied to the product as well since one of the fundamentals of a circular economy is the minimization of natural resource extraction. R-strategies higher on the ladder, like refuse and rethink, have a higher circular yield than R-strategies at the bottom of the ladder, like recycle and recover. Thus, to maximize the impact of a circular design, it is important to aim for the highest possible R-strategy on the ladder.

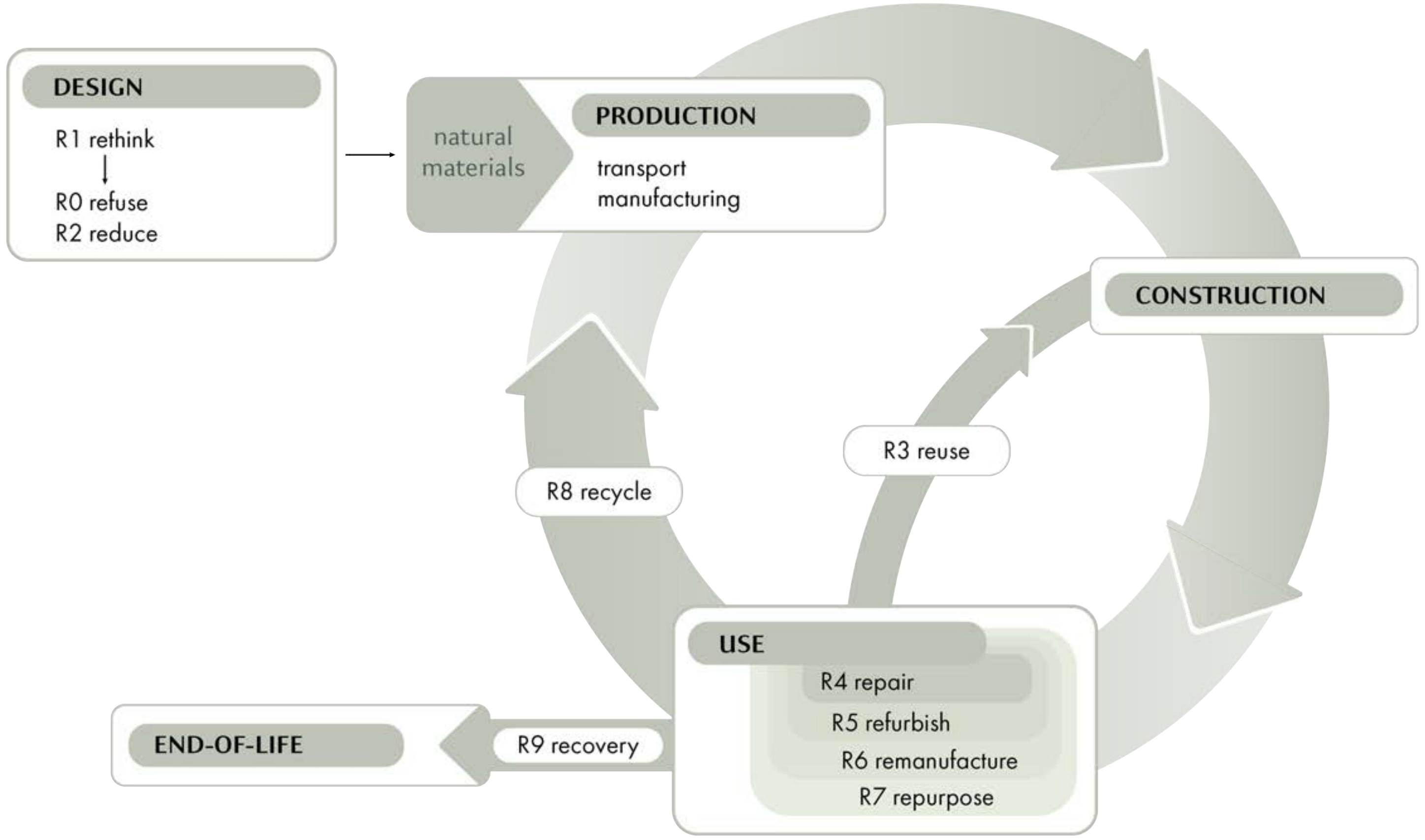


Fig. 2.4 By author, R-strategies placed in the life cycle of a building

2.2 Dealing with the life span of a building

Demolition I Vacancy I Adaptation

Different approaches

Buildings have a certain life span. When the performance capacity of the building decreases below the accepted level of the users, friction occurs (Thomsen & van der Flier, 2009). At this point, a decision has to be made on how to continue the further life span of the building. There are different approaches on how to handle the further life span of a property. The life span can be prolonged by changing the accepted performance level of the users, by improving management or changing the target group (Thomsen & van der Flier, 2009). Alternatively, the life span can be actively extended through technical innovation or change of function, passively extended by leaving the building vacant, or actively ended by demolition or material mining (Thomsen & van der Flier, 2009). After demolition, complete redevelopment of new buildings can take place. In table 2.A, these different approaches are categorized into active or passive approaches, that either extend or end the life span of a building. Most often, building owners either opt for consolidation and wait for more optimal conditions to present themselves, by leaving the building vacant, searching for a new target group or selling the property, or they choose demolish the building and redevelop a new building (Wilkinson, Remøy, & Langston, 2014).

To be able to make a shift in the decision making of life span approach, from demolition and vacancy to adaptation, a clear image of the boundaries and opportunities of each approach is required.

Why are buildings currently often demolished?

In the Dutch building industry, demolition is a common approach applied for urban renewal projects. The decision to choose demolition and redevelopment as a development approach, heavily relies on economic factors, since it is a more appealing investment than

	ACTIVE	PASSIVE
EXTENDED	building: ▪ improved maintenance management ▪ technical innovation ▪ change of function user: ▪ change of functional expectations ▪ change of target group	building: ▪ vacancy
ENDED	building: ▪ demolition ▪ material mining	building ▪ external factors (e.g. natural disasters)

Table 2.A Based on Thomsen & van der Flier (2009) Different approaches in dealing with the lifespan of buildings categorized

approaches like adaptation or renovation (Bullen & Love, 2011). In their research, Bullen and Love (2011) explain that the percentage of buildings actually requiring demolition is estimated to be 0,5-1% of the complete building stock, while the remaining properties have an additional 30 to 50 years life span. There is a correlation between the life span of buildings and the demolition rate. Older buildings are more likely to be demolished. Although, this relation is not linear and does not account for the large amount of relatively young, post-war buildings demolished (Thomsen & van der Flier, 2009).

There are situations in which demolition is the best qualified approach. When the expected life span of the adapted building is less than a newly developed alternative, demolition could be a good choice (Bullen & Love, 2011). Another benefit advocating for demolition and redevelopment is the complete freedom of design when developing a new building on a clean slate.

Why should we be adapting buildings?

There are several benefits connected to adaptation. Like mentioned before, an adaptable building approach provides a sustainable perspective. On one hand ecologically, because building materials are reused and saved. On the other hand, adaptation is also beneficial in creating a sustainable urban morphological structure. By retaining the structure of an urban area, the existing definition of space is maintained and the historical value of the location increases (Remøy & van der Voordt, 2007). Furthermore, adaptation also saves construction time, carrying additional economic benefits (Remøy & van der Voordt, 2007).

Why are buildings not often adapted currently?

As described before, demolition is often a more economically interesting investment for developers than adaptation. To make adaptation projects more appealing, they should be economically feasible. This can be done by adding a commercial program to a function like housing or offices (Remøy & van der Voordt, 2007). Furthermore, there often is a lack in sufficient communication tools when working with existing buildings. The building could not correspond with the original drawings, or drawings could not even be available at all (Remøy & van der Voordt, 2007). Other barriers associated with an adaptable development approach are: perceived increased maintenance costs, meeting the building regulations and lack of knowledge about the state of the existing building (Bullen & Love, 2011). Finally, buildings need to meet certain quality requirements in order for adaptation to be feasible. The existing stock in the Netherlands is not built with adaptation in mind, and do not meet the needs to make renovations possible (Itard & Klunder, 2007). Itard & Klunder (2007) constructed research in which they analyzed different approaches when dealing with the life span of a building and compared them on their environmental impact. The research shows that the average quantity of materials embodied in demolition and new construction is almost 60% more than in adaptation. In the Netherlands, the waste produced by construction and demolition is one of the most significant waste streams in the country, containing approximately 24 megatons in volume (Icibaci, 2019). Adaptation has been found to be a more environmentally efficient approach than demolition and rebuilding, although this strategy is only possible if the existing stock has a certain degree of flexibility, which is currently often lacking (Itard & Klunder, 2007).

Conclusions

Demolition and redevelopment is the most common approach because it is an attractive economic investment. It is the approach with the highest environmental impact, however, and often not necessary. There are benefits connected to demolition and redevelopment, like the complete freedom of design of a new dwelling.
One of the benefits associated with adaptation is the low environmental impact, due to using less building materials and producing less waste. Additionally, adapting a building ensures the maintenance of an urban morphological structure and increases the historical value of a property.

An adaptable approach could become more feasible, if new buildings are developed with future adaptation in mind. Hypothetically, this could further decrease the construction time and costs, making an adaptive approach more economically attractive.

2.3 Case studies transformation

15 case studies I Selection criteria I Findings

Transformation is a type of adaptation activity, during which the function of a building is transformed, from offices to housing for example. A different function often requires a different floor plan, facade etc. This makes transformation an adaptation activity that requires a lot of the design interventions that the development of an adaptable structural system should be able to solve. Current transformed buildings were almost never prepared for adaptive interventions on this scale. An inventory of the positive and negative qualities of a project in regards to its adaptability potential is made by looking at case studies of transformed buildings.

15 case studies of transformed buildings are studied to gather the qualities of existing buildings that eased the transformation process, or complicated it. Four of those case studies are presented on the next two pages, the other case studies can be found in appendix I.

Selection criteria

To select the case studies to study the transformation of buildings, certain selection criteria are predetermined:

The most important and obvious criterion is that the buildings have to be initially built to house one function, and have later been transformed to house another function.

The scope of this research project is on mid-rise buildings. Since the analysis of case studies is done early in the research process, the definition of mid-rise is not yet clearly defined. The selected buildings have between three and eight storeys. There are some exceptions of buildings with more or less building layers, technically falling out of the case study scope. These buildings are maintained in the final overview however, because it is also interesting to see if there is a difference in the process of transformation in other building heights.

All case studies are buildings located in the Netherlands. This helps to gain insight on the current existing building industry in the area that is also the scope for the design proposal for an adaptable structure.

There is no limitation in the structural material of the case studies, since it is interesting to see how specific materials ease or limit the process of transformation.

Findings

From the case studies, the following conclusions are drawn:

- A lack of information about the existing building makes transformation more complicated, because it is not clear what type of structure you are working with and if reinforcements are necessary.
- Floors are often the limiting factor in making changes. Most projects are constructed with concrete floors, which are hard to make new shafts into. Or the existing floors were too thin and could not easily be reinforced.
- Transformation is more feasible when stairs and elevator shafts can be reused, or when the structural grid is suitable for multiple functions. This is mostly the case with post-and-beam structures.

Wilkinson, Remøy, & Langston (2014)

Wilhelmina Staete

Architect: Rappange & Partners
Year transformation: 2007
Original - new function: offices - residential
Floors: 5
Structural material: concrete

Factors easing adaptation
Adaptive column structure with suitable dimensions, stair could be reused

Herbestemming.nl, (n.d.-b)

Oude Postkantoor

Architect: Van de Looi Van Aken Architecten
Year transformation: 2010
Original - new function: postoffice - residential, commercial
Floors: 3
Structural material: masonry, with timber additions

Factors easing adaptation
Existing structure suited new function. Monumental status nudged conversion
Factors complicating adaptation
Lack of information about existing structure limited adaptation options

Herbestemming.nl, (n.d.-a)

Bassein

Architect: SARCH architecten Krommenie
Year transformation: 2020
Original - new function: factory - residential
Floors: 5
Structural material: steel

Factors easing adaptation
Existing structure did not have to be adapted
Factors complicating adaptation
Legal processes made the adaptation process more difficult

architectenbureau cepezed (n.d.)

Park Hoog Oostduin

Architect: Cepezed
Year transformation: 2019
Original - new function: offices - residential
Floors: 17
Structural material: concrete, with steel additions

Factors easing adaptation
Existing structure and foundation could be reused, reducing costs and complexity

2.4 Case studies flexible buildings

15 case studies I Selection criteria I Findings

Design for flexibility, design for disassembly and design for adaptability are upcoming strategies in the building industry. These design strategies have in common that their goal is to design a building with future adaptability activities in mind. This way, executing an adaptive activity has less impact on the complete building, results in less material waste, costs less time and thus less money.

Through 7 case studies on flexible buildings, information is gathered on the circular design strategies behind these particular projects, which form an inspiration for the design proposal of this thesis. Four of the case studies are highlighted on the next two pages, a summary of all case studies can be found in appendix II.

Selection criteria

The case studies on flexible buildings are selected on two main criteria:

The load-bearing structure has to be made from timber, because that is the aimed for material for the final design proposal. For this stage, there is no distinction made between hardwood and softwood timber, because the principle of timber structures is similar between the two material types. Also, the availability of case studies only using hardwood is too limited to conduct a well-rounded case study.

The selected projects are all presented as being circular projects on their website or other publication material.

Findings

The main findings gained from analyzing these case studies are centered around the knowledge gap of adaptable design. All case studies are adaptable on a complete building scale, meaning that the complete building can be deconstructed and potentially be reconstructed somewhere else.

Gebouw XX in Delft was designed with the idea to be a temporary building, for the duration of the life span of the materials, and to be easily deconstructed after. It turned out that the life span of materials was actually much longer than anticipated, so the building was never deconstructed. This case study shows the unpredictability of what could happen during the life span of a building, invigorating the scenario based design principle that is used for this research project.

Another remarkable finding is that most projects promoted as circular buildings, have a post-and-beam structure. The reason given by most developers is the flexible floor plan this structural type provides.

The Natural Pavilion (2022)

The Natural Pavilion

Architect: Circlewood and DP6
Year: 2022
Function: Offices and meeting space
Floors: 3
Area: 1.000 m²

Circular design aspects

Design approach: Parametric design
Structural type: Houtkern modules
Timber product: CLT

"Liander Westpoort" (n.d.)

Liander Westpoort

Architect: De Zwarte Hond
Year: 2023
Function: Offices, education, workshop, storage
Floors: 8
Area: 21.000 m²

Circular design aspects

Design approach: Design for flexibility, scalability and modularity
Structural type: Post-and-beam
Timber product: Glulam

Redactie ArchitectuurNL (2019)

Gebouw XX

Architect: XX architecten
Year: 1999
Function: Offices
Floors: 2
Area: 2.100 m²

Circular design aspects

Design approach: Design for disassembly
Structural type: Post-and-beam
Timber product: LVL

Östermalmshallen padel (n.d.)

Östermalmshallen padel

Architect: Tengbom
Year: 2022
Function: Market hall transitioned into sports hall
Floors: 2
Area: 2.000 m²

Circular design aspects

Design approach: Design for disassembly
Structural type: Grid structure
Timber product: LVL

Chapter 3
Design criteria

3.1 Circular design qualities

Evaluation tool I Building scale I Component scale

To create a design proposal for a circular building component or building structure, it is helpful to define some qualities to which the design proposal needs to comply, focused on circularity. With a higher amount of circular qualities met, it is easier to reuse, repurpose or apply another R-strategy to a building component or building structure. Cambier et al. (2019) constructed 16 circular design qualities, which can be used to evaluate a circular design proposal.

The 16 circular design qualities are:
Reused, recycled, renewable, biodegradable, safe and healthy, pure, robust, simple, manageable, accessible, reversible, independent, compatible, versatile, varied, location and site.

A complete description of all 16 circular design qualities, as well as the advantages of meeting the specific quality in a design and the actions that could be taken to achieve that goal are listed in the appendix III. Circularity design projects can have various different types of focuses. Not all of the qualities are as relevant for realizing an adaptable structural system. The R-strategies are used to select the qualities that are relevant for the scope of this thesis.

The R-strategies focused on extending the life span of a building are noted in table 3.A. This excludes R0 Refuse, R1 Rethink and R2 Reduce, because those strategies are inherent to this research project, as the existing use and distribution of materials is rethought. R8 Recycle and R9 Recovery are also excluded, since they have the lowest circular yield. For R3 to R7, the circular design qualities that are important to be met in order to execute a strategy are matched to said strategy.

This process is repeated on two scales: on a building scale, where the building is perceived as the product, or the component scale, focused on specific elements within a building structure.

This thesis is centered around developing a structural system, in which components can be treated individually to extend the life span of the entire building. Hence why the circular design qualities related to R-strategies on a component scale are selected and used as an evaluation method during the design phase. The eight selected circular design qualities are listed in table 3.B.

Conclusion

For the design of a structural system, it is helpful to define some qualities focused on a circular design on a building component scale. By relating the qualities to the previously described R-strategies, a set of eight circular design qualities is selected, which are used as an evaluation method during the design phase. The eight selected circular design qualities are: reused, durable, simple, manageable, accessible, reversible, independent and compatible.

R-STRATEGY	DESCRIPTION BUILDING SCALE	REQUIRED CIRCULAR DESIGN QUALITIES	DESCRIPTION PRODUCT SCALE	REQUIRED CIRCULAR DESIGN QUALITIES
R3 REUSE	Change in ownership of existing building, with the same function *e.g. social housing apartment building becomes owner-occupied housing*		-	
R4 REPAIR	Repair or maintain the building so it can be used to house its original function *e.g. Maintain fire protective finish of the entire structure*		Repair, replace or maintain a defective part so it can be used with its original function *e.g. Replace a rotten timber beam*	
R5 REFURBISH	Restore an old building and bring it up to date, by complying to the new building regulations *e.g. Adjust ceiling height building*		Restore an old product and bring it up to date. Improve the looks and possibly the functionality *e.g. Reinforce an existing beam*	
R6 REMANUFACTURE	Rebuild a building at a different location in the same configuration *e.g. Building is transported from city A to city B*		Use an old building component in a new structure, fulfilling the same function *e.g. Beam stays beam but in another building*	
R7 REPURPOSE	Change the function of an existing building, adapting the structure accordingly *e.g. Offices become apartments*		Use an old building component in a new structure, fulfilling a different function *e.g. Beam becomes column in another building*	

Table 3.A By author, R-strategies on building and component scale with their according circular design qualities

	CIRCULAR QUALITY	DESCRIPTION	ADVANTAGES	ACTIONS
	REUSED	Use building components or elements that are already present at the building site or that are sourced elsewhere	Reuse extends the life span of a product and prevents consumption of new resources	Set up a catalog of the components inside a building with a clear description
	DURABLE	Use components that can easily withstand the wear and tear of use and reuse	Robust products have a longer lifespan, making them attractive for future reuse	Use materials that age naturally and require limited maintenance
	SIMPLE	Integrate simple and clear solutions instead of complex ones	Simple solutions are easier to understand and adapt	Limit the amount of different components and connections. Apply repeating patterns and standard dimensions
	MANAGEABLE	Design building components that are easy to handle and to move	Manageable components make adaptation easier and increase the feasibility	Apply components that can be lifted by a max. of two people with minimal mechanic aid. Minimize dimensions for easy transport
	ACCESSIBLE	Integrate components in a way that they can be reached and recuperated without damage	Accessibility makes repair, replacement and adaptation more effective	Design a visible connection and tolerances around the connections to allow for movement
	REVERSIBLE	Integrate connections that can be demounted without damaging other components	Reversible connection allow for selective deconstruction and recuperating individual components	Prevent building components to be connected permanently
	INDEPENDENT	Combine components while they remain structurally and functionally autonomous	The independency of a single component allows for selective deconstruction.	Analyze which components require replacement and repair most often, check if the connection allows removing them
	COMPATIBLE	Use building components that are interchangeable and can be combined with each other	Compatible components can be reused in more parts of a structure, making replacement easier	Design a building according to a module strategy, using reoccurring dimensions

Table 3.B Based on Cambier et al. (2019) Summary table of eight selected circular design qualities

3.2 Sub-scenarios

Complexity I Necessity

The scope of the thesis research focuses on the R-strategies on a component scale, to eventually be able to develop a design proposal for a structural system that complies to the eight selected circular design qualities related to these R-strategies. The R-strategies as described in Table 3.A can be translated into different actions, or 'sub-scenarios'. A number of sub-scenarios are placed into a diagram illustrated in figure 3.1, where the complexity of the sub-scenario is plotted against the necessity of a certain problem being solved. The sub-scenarios are placed into the diagram based on the examined case studies and literature on comparable cases, but ultimately on hypothetical insights. The placement of the sub-scenarios could be revised in another study and result in a different outcome of the eventual design proposal.

The formulated sub-scenarios are based on events in which an adaptive activity has to be performed involving a building component, such as a column, a beam, the connection node, or a floor element. Not all possible sub-scenarios have the same priority in being performed easily, as some are more necessary to be possible than others. Additionally, certain adaptation sub-scenarios are more complex to realize than others. One could hypothesize that when the most complex sub-scenarios are solved, the knowledge gained could be used to make the adaptation activities from the less complex sub-scenarios possible. The terms complex and necessary are both quite ambiguous. For both, a definition for how the terms are perceived within this research is provided. Eventually, the focus throughout the advancement of the thesis is on the sub-scenarios that are most complex and most necessary.

Complex

The Cambridge University Press (n.d.-a) defines the term complex as: Something involving a lot of different but related parts, making the concept difficult to understand and or solve. The sub-scenarios that hypothetically involve the most additional building layers or other components are perceived as more complex and are placed higher in the diagram.

Necessary

The term necessary is defined as: Needed in order to achieve a particular result (Cambridge University Press, n.d.-b). In the case of the sub-scenarios in the diagram, the activities described are needed to adapt the building in order to extend its life span. For example, the sub-scenario 'beam on two points is transformed into cantilever beam' is needed when the anticipated result is to attach balconies to an existing structure. A sub-scenario can be related to multiple results. The likelihood of these results being needed is evaluated based on the transformation case study complications as well as current and future trends in the built environment. The sub-scenarios are placed within the diagram accordingly.

The sub-scenarios that are explored during the design phase are those present in the upper right quadrant of the diagram, making them both necessary and complex. In figure 3.1, there are five sub-scenarios present in this region. An additional sub-scenario, 'defective column is replaced', is added to the selection, since it is closely related to the pre-selected sub-scenario; 'defective beam is replaced'.

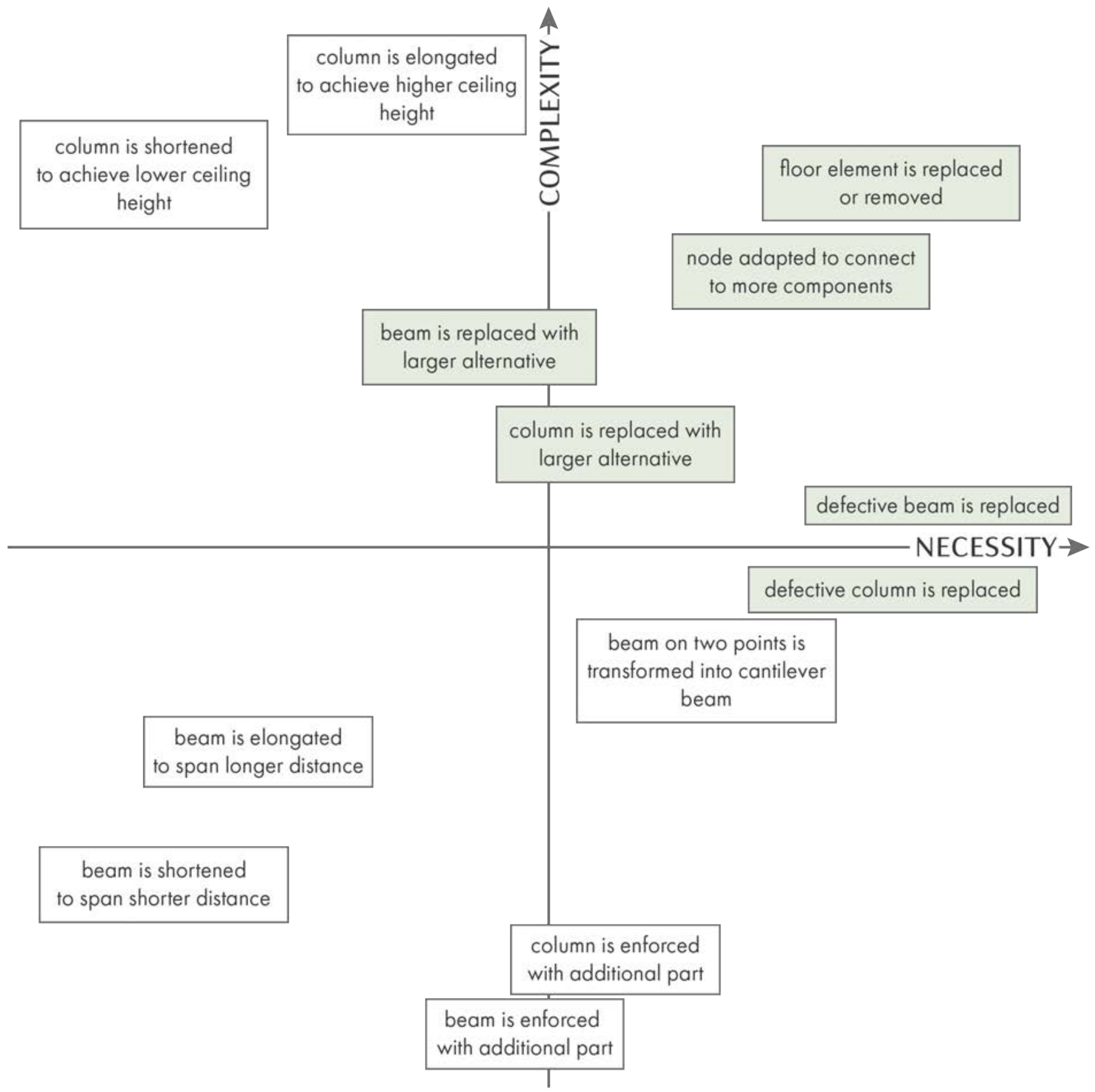


Fig. 3.1 By author, Sub-scenarios rated on complexity and necessity

Design possibilities

When the selected sub-scenarios are feasible by the design of an adaptable structural system, there are multiple design possibilities that can be performed. These are illustrated in figure 3.2. The possibilities can be divided into different categories. First, the general shape of the building is adapted. For example, additional storeys can be added to a building by connecting more components, like columns and beams, to existing connection nodes. Second, a building can be enriched with accessories. An example is creating a mezzanine, by removing floor elements in an existing building. The last category of design possibilities is 'program'. When an apartment building is adapted into an office building, different load requirements might come into play. The possibility to replace the existing columns with larger columns, that can carry a heavier load, makes this adaptation process more feasible.

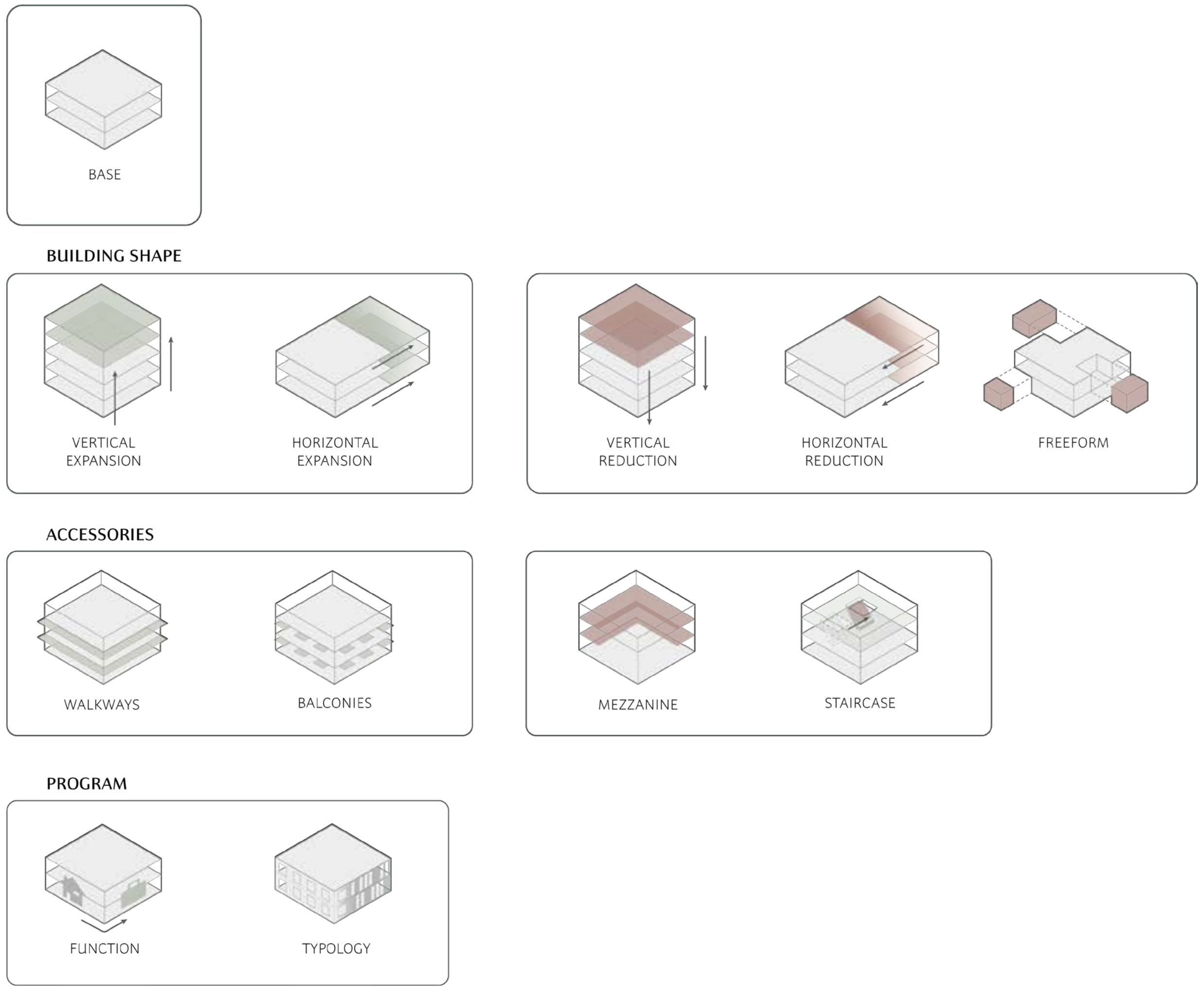


Fig. 3.2 By author, Possible design results made feasible by performing sub-scenarios

3.3 Evaluation method

Circular design qualities

The six complex and necessary sub-scenarios highlighted in figure 3.1 are grouped into four:

- Node adapted to connect to more components
- Floor element is replaced or removed
- Beam is replaced
- Column is replaced

These sub-scenarios all have in common that they require **a connection system, with the ability to connect and disconnect building components with varying dimensions onto**.

The circular design qualities paired with the R-strategies on a component scale from table 3.B act as an evaluation tool for the development of an adaptable structural system made from hardwood, that is able to achieve the results from the chosen sub-scenarios. These eight circular design qualities are further defined using concrete criteria, that will help evaluate if a design is indeed circular on a component scale for the chosen sub-scenarios.

The five design domains, as described in chapter 1.5, are used to group the list of criteria. This categorization helps a designer to prioritize certain criteria while working on a specific design domain when developing a circular structural system.

The final evaluation method is a list of the eight selected circular design criteria and their criteria as shown in table 3.C.

Example:
A designer wants to create a circular structural system and starts by developing the structural layout of the building. The designer takes the complementary design criteria from this design domain, as listed in table 3.C:

- *Standard dimensions*
- *Repeating patterns*
- *Small dimensions*

For this research, all design domains are explored parallelly and the design proposals from each domain are combined into one cohesive design proposal eventually.

	Reusable
	Catalog of building components
	Standard dimensions
	Standard connection system
	Repeating patterns
	Limited use of adhesives or plasters
	Durable
	Long life span material
	Surface treatment
	Additional building layers covering the structure
	Minimal amount of holes in components
	Simple
	Minimal unique parts
	Costs little time to construct
	Minimal steps in assembly
	Minimal experience or training needed
	Repeating patterns
	Standard dimensions
	Manageable
	Small dimensions
	Light weight
	Minimal mechanic aid needed
	Minimal amount of people needed
	Accessible
	Minimal additional building layers covering the structure/connection node
	Additional building layers are removable
	Visible connection system
	More tolerance around components and connection node
	Reversible
	Connection node can be demounted
	Independent
	Components are individually connected
	Little disturbance of other components when handling one component
	Compatible
	Multi-functionality of single component
	Standard connection system
	Standard dimensions
	Repeating patterns

MATERIAL
KIT-OF-PARTS
STRUCTURAL LAYOUT
BUILDING LAYERS
CONSTRUCTION PROCESS

Table 3.C By author, Selected circular design qualities and their criteria, categorized into design domains

Chapter 4

Existing systems

4.1 Circular building systems

Houtkern I Knoopwerk I Circle house I LVL dovetail I Structurez

The reason for doing an extensive analysis on existing building systems that claim to have circular qualities is threefold. Firstly, by analyzing various systems that are already realized and available on the current market, the knowledge gap of what is missing on the field of circular and adaptable structures is established. This way, the design proposal can fill that gap. Secondly, for the analysis of existing systems, the same evaluation method will be used as for the evaluation of the design proposal. By using the method on existing systems, the evaluation method can be tested and the results of the design proposal can be easily compared to those of the analyses. Lastly, by using the same evaluation method on both the existing systems as the design proposal, they can be compared and a conclusion can be drawn on how well the design proposal fills the gap for an adaptable structural system on the current market.

An exploded axonometry is made of the main connection of each system to analyze them. Next to that, information about the system is gathered through the websites of the suppliers and by contact via email. An elaborate analysis of each individual system can be found in appendix IV and V. In this chapter, a summary of a description of the systems, the evaluation of the adaptivity potential of the systems and main findings are presented.

5 circular building systems

Houtkern
The Houtkern structural system is a timber 3D module based system suitable for the realization of housing, schools, offices and more. The modules are prefabricated off site and assembled on the construction site, which shortens the construction time. The system is claimed to be demountable. Up to five storeys can be built purely with timber, if more storeys are desired, a steel core is used (Noordereng Groep, 2022).

Knoopwerk
Knoopwerk is promoted as a circular and modular timber structural system. The unique quality of this system is the 'click and play' connection principle, that works by connecting timber elements through steel attachments (Knoopwerk, n.d.).

Circle House
Circle house is a housing project, where a like-named structural principle is used to construct 60 social housing units. Circle house structures are made from concrete, not timber. The system analyzed in this chapter is the post-and-beam version, which is promoted as a flexible solution (Gxn & Assets, 2018).

LVL Dovetail
This hardwood timber system is used in an office building project for Augsburg software company. A skeleton structure is made through unique timber on timber dovetail connections that can be demounted (Merz, Niemann, & Torno, 2021).

Structurez
Structurez is a timber prefabricated post-and-beam system based on Japanese joinery principles. The connections are established by steel connector hooks without additional fasteners. The structure can be demounted and reused.

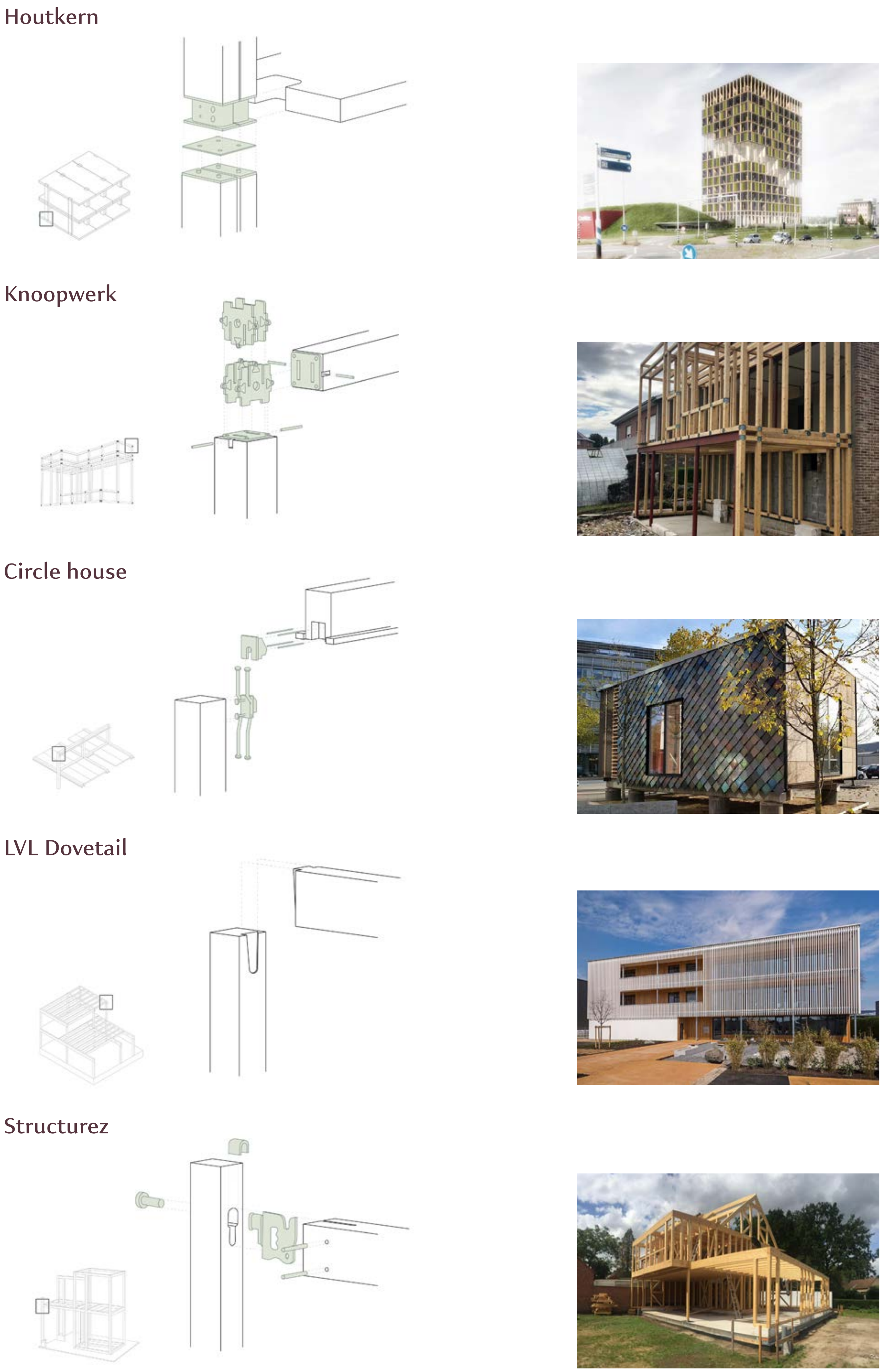


Fig. 4.1 By author, based on Noordereng Groep (2022); Knoopwerk (n.d.); Gxn & Assets (2018); Merz, Niemann, & Torno (2021); WoodInc (2021), circular systems axonometries

4.2 Evaluation

Circular design qualities I Spiderweb diagrams I Findings I Further research

The five circular building systems are evaluated using the circular design qualities that were formulated in chapter 3.3. Each circular design quality covers a few more concrete criteria which the systems are evaluated on. The systems are evaluated using a rating system from 1 to 5 points. A better circular performance is scored with a higher amount of points and vice versa. The results of the evaluation are presented in table 4.A. The argumentation behind the point distribution can be found in appendix V. This argumentation is based on information provided by the suppliers of the regarded building system on their websites, or through email correspondence, as well as a comparison between the circular performance of all evaluated systems. Different systems can be rated with the same amount of points for a certain criterion, if the circular performance is comparable.

The results of the evaluation are presented in spiderweb diagrams in figures 4.2 to 4.6. Each evaluated system has its own diagram in which the eight circular design qualities are placed in the outer corners of the diagram. The average scores of each circular quality are placed into the diagram. The closer the average to the edge of the spiderweb, the higher the score and the better circular performance on that particular quality.

This overview of all five evaluated systems allows for the determination of the knowledge gap about adaptable design on the current market, within the limits of the considered systems.

Houtkern
This building method has the lowest rating on the circular design qualities of all analyzed systems. The fact that the Houtkern system consists of three dimensional modules instead of individual building components negatively influences the rating. The independency is compromised due to the stacking principle of the system. Other than that, the modules are much heavier than individual components, making them more difficult to manage.

Knoopwerk
The Knoopwerk system performs best on compatibility and manageability. The connection node of this system is consistent throughout the whole structure, as well as the sections of the timber components. This makes the parts deployable for multiple structural layouts. The components of the Knoopwerk system are light-weight and have small dimensions, which results in minimal need for mechanic aid during construction. On the other circular design qualities, this system performs average.

Circle House
This system obtains the highest score in reusability and reversibility, although it has to be noted that all systems perform above average on reversibility. The standard dimensions and repeating patterns of this building system result in a high score in reusability. The standard modules that are created can be reused to configure different building layouts. The lowest rated quality is the accessibility. This mainly due to the fact that the connection is not visible and thus not accessible in the finished state of the building.

LVL Dovetail
The hardwood material that is used to construct the LVL Dovetail connection improves the durability of the system. The material is protected with a surface treatment and the components are minimally impacted by any holes. On the other hand, this system is rated lowest on its independency. The building components

	Houtkern	Knoopwerk	Circle House	LVL Dovetail	Structurez
Reusable					
Catalog of building components	1	1	5	1	4
Standard dimensions	3	5	4	2	1
Standard connection system	3	5	3	4	1
Repeating patterns	3	2	5	4	1
Limited use of adhesives or plasters	3	3	5	3	3
Durable					
Long life span material	2	2	5	4	2
Surface treatment	3	4	3	5	3
Additional building layers covering the structure	2	2	2	2	2
Minimal amount of holes in components	1	4	2	5	3
Simple					
Minimal unique parts	5	2	4	3	1
Costs little time to construct	1	5	3	2	4
Minimal steps in assembly	1	3	2	5	3
Minimal experience or training needed	1	4	1	3	5
Repeating patterns	3	2	5	4	1
Standard dimensions	3	5	4	2	1
Manageable					
Small dimensions	1	5	3	2	4
Light weight	3	5	1	2	4
Minimal mechanic aid needed	1	5	3	3	5
Minimal amount of people needed	1	5	3	3	5
Accessible					
Minimal additional building layers covering the structure/connection node	3	3	3	3	3
Additional building layers are removable	3	3	3	3	3
Visible connection system	1	5	1	1	4
More tolerance around components and connection node	1	2	2	2	2
Reversible					
Connection node can be demounted	4	4	5	4	5
Independent					
Components are individually connected	1	3	4	2	5
Little disturbance of other components when handling one component	1	2	3	1	3
Compatible					
Multi-functionality of single component	4	5	1	1	1
Standard connection system	3	5	3	4	1
Standard dimensions	3	5	4	2	1
Repeating patterns	3	2	5	4	1

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Table 4.A By author, Analyzed systems rated on their performance on the selected circular design qualities and their criteria

are stacked on one another, making is difficult to maneuver an individual component without influencing other components.

Structurez
Similar to the Knoopwerk system, the Structurez system is established by timber components with small cross-sections and standard steel connection anchors, that can also be demounted. This positively influences the rating on manageability and reversibility. The difference between Knoopwerk and Structurez is the low compatibility of the Structurez system. The components of this system are specifically designed and produced to construct one project. This means that there are no standard dimensions or repeating patterns and that the building components are not multi-functional.

General findings

All five systems have a high rating on their reversibility. The connection nodes of these systems can all be demounted. Although most of the connections can only be demounted when the whole structure is disassembled.

It is difficult to rate the building systems on the criteria that are part of the building layers domain. This is because the structural systems are not limited to be combined with only one set of standard building layers, like cladding or finishing. This makes the circular performance on these aspects variable.

The systems that consist of individual components perform better on the eight circular design qualities than the Houtkern method, which consists of three dimensional modules.

Knowledge gap

The individual management of components is what is missing amongst the analyzed systems. The Knoopwerk and Structurez systems both show potential of adaptability. But where the Knoopwerk system performs well on manageability and compatibility, it lacks on independency. Structurez performs better on independency but lacks in compatibility. A better balance between these qualities improves the adaptability potential of the structural system.

Further research

A factor that is not considered during the evaluation is the potential hierarchy amongst the listed criteria. Some of the criteria are probably more influential on the adaptability of a building system than others. Within this evaluation method they are all perceived with the same importance. Additionally, the criteria listed in table 4.A are not all possible circular criteria. Through further future research, the evaluation table could be expanded to include more criteria and the criteria could be weighed on their importance.

Five circular building systems are regarded for this evaluation. Naturally, there are more systems currently available. By selecting five different systems, a widespread coverage of the available systems types is attempted. These five systems do not cover the entire scope of circular systems, however. Through further research, more systems with different characteristics could be analyzed to complete a more refined image of the current market and define the knowledge gap more specifically.

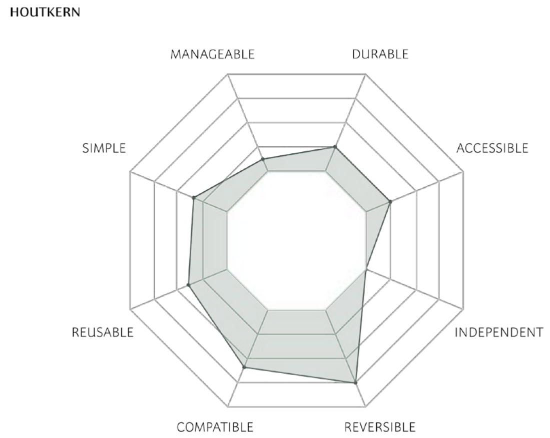

Fig. 4.2 By author, Houtkern system analyzed on circular design qualities

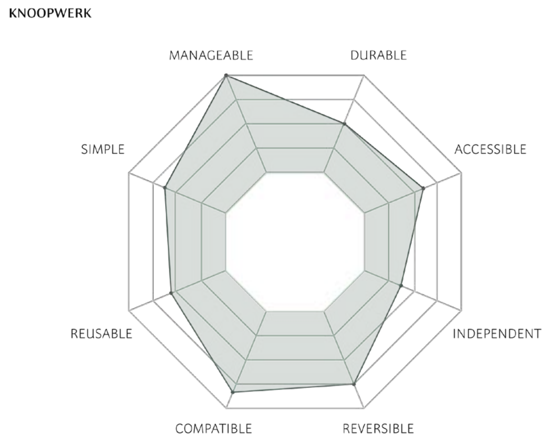

Fig. 4.3 By author, Knoopwerk system analyzed on circular design qualities

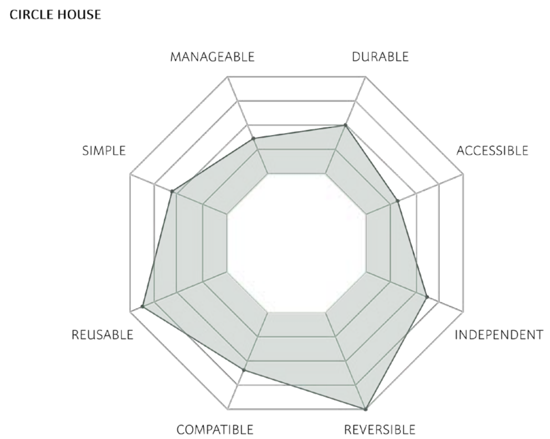

Fig. 4.4 By author, Circle house system analyzed on circular design qualities

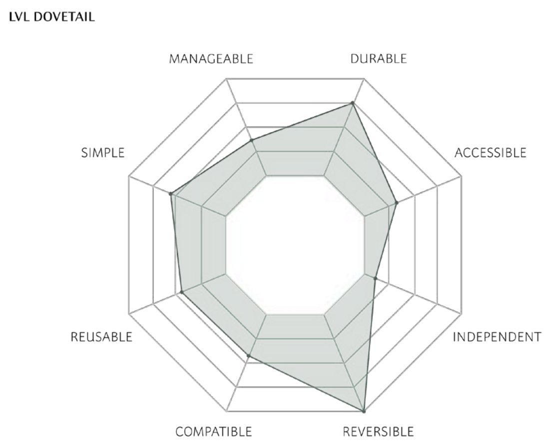

Fig. 4.5 By author, LVL dovetail system analyzed on circular design qualities

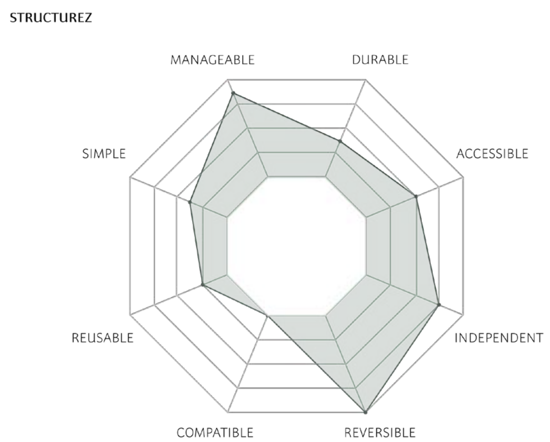

Fig. 4.6 By author, Structurez system analyzed on circular design qualities

PART II

Design and evaluation

Chapter 5

Design proposal

5.1 Structure part II

Design domains

Chapter 1.5 introduced the five design domains as a method to analyze circular systems on each domain distinctively, to be able to get a clear overview of how each aspect of the system performed on adaptability. The second part of the report uses the design domains once again for the design process of an adaptable structural system. Each domain has a separate chapter. Each chapter applies the same structure:

The front page contains a list of all the criteria from the evaluation table related to that specific domain. This serves as a reminder of the most important aspects for that domain and acts as an evaluation tool at the end of the chapter.

First, the chapter starts with some background information about the domain in relation to the theme of adaptability.

Then, different options are presented that are currently available on the market in relation to the domain.

After that, a recommendation is done on how one of the presented options can be selected from an adaptability point of view. One of the presented options is chosen to be used in the final part of the chapter: the design proposal.

The design proposal aims to present the design of an adaptable structural system, based on the described principles from that specific chapter.

Although the design domains are discussed separately, there is no chronological order in how the domains should be read or used. The design proposal is developed using all design domains parallelly, because each domain has overlap with all of the other domains, as chapter 1.5 discussed.

Before the design domains chapters begin, a summary of the complete design familiarizes the reader with the design proposal first. This makes it easier to remember the design domains in relation to each other while reading about one specific domain.

5.2 Overview of design proposal

Material I Structural layout I Kit-of-parts I Building layers I Construction process

The following design proposal can be seen as an example of how the developed circular principles can be further developed into a concrete proposal. This means that the same adaptability principle can create a completely different structural system, using different building products, dimensions etcetera.

Material
The building components are made from a hardwood product, specifically beech glulam made from lvl, from the supplier Pollmeier. This material choice improves the durability of the structure, but makes the components harder to manage due to the heavy weight.

Structural layout
The grid dimensions of the system consists of rows of columns with a distance of 7,2-2,4-7,2 meter, repeated every 6 meters. The repeating patterns and standard dimensions mainly improve the simplicity and the compatibility of the components.

Kit-of-parts
The kit-of-parts consists of seven components: beams and columns of various sizes, the primary connection components and the floor elements. The connection principle is based on a primary connection that is used during initial construction and a secondary connection that is used during adaptation of the structure. The connection layout is specifically designed so that building components can be moved out of their original place without disrupting other building components. The fasteners makes the connections demountable, enabling for partial or complete reversibility. The system improves the independency because all components connect individually to the connection node.


Fig. 5.1 By author, Exterior render


Fig. 5.2 By author, Interior render

Building layers
The building layers are independent of the load-bearing structure and each other. The floor consists of a box floor with on top a concrete slab that is mechanically connected. The facade is placed in front of the structure instead of in line with the structure, to maintain the accessibility to the secondary connection. The hardwood does not require an interior finish, but can be applied for aesthetic purposes. In this case, the finish needs to be applied with a dry connection, to maintain the demountability of the system. Finally, the installations are situated underneath the floor system. The secondary attachment component of the kit-of-parts can be altered in height to accommodate the necessary installations underneath the floor, should a suspended ceiling be prefered. This way, the secondary connection remains accessible without having to remove the suspended ceiling and installations beforehand.

Construction process
During the execution of sub-scenarios, temporary support structures are needed to take on the loads of the removed building component. Different temporary structures are required depending on which scenarios is performed. When replacing a beam, for example, falsework is placed under the neighboring floor elements until a new beam is installed. Because the connection design is fairly straight-forward, the construction requires minimal time and steps, improving the simplicity and independency of the system. The material choice of hardwood has a negative influence on the manageability however, since the material is heavy and requires mechanic aid and more construction workers.

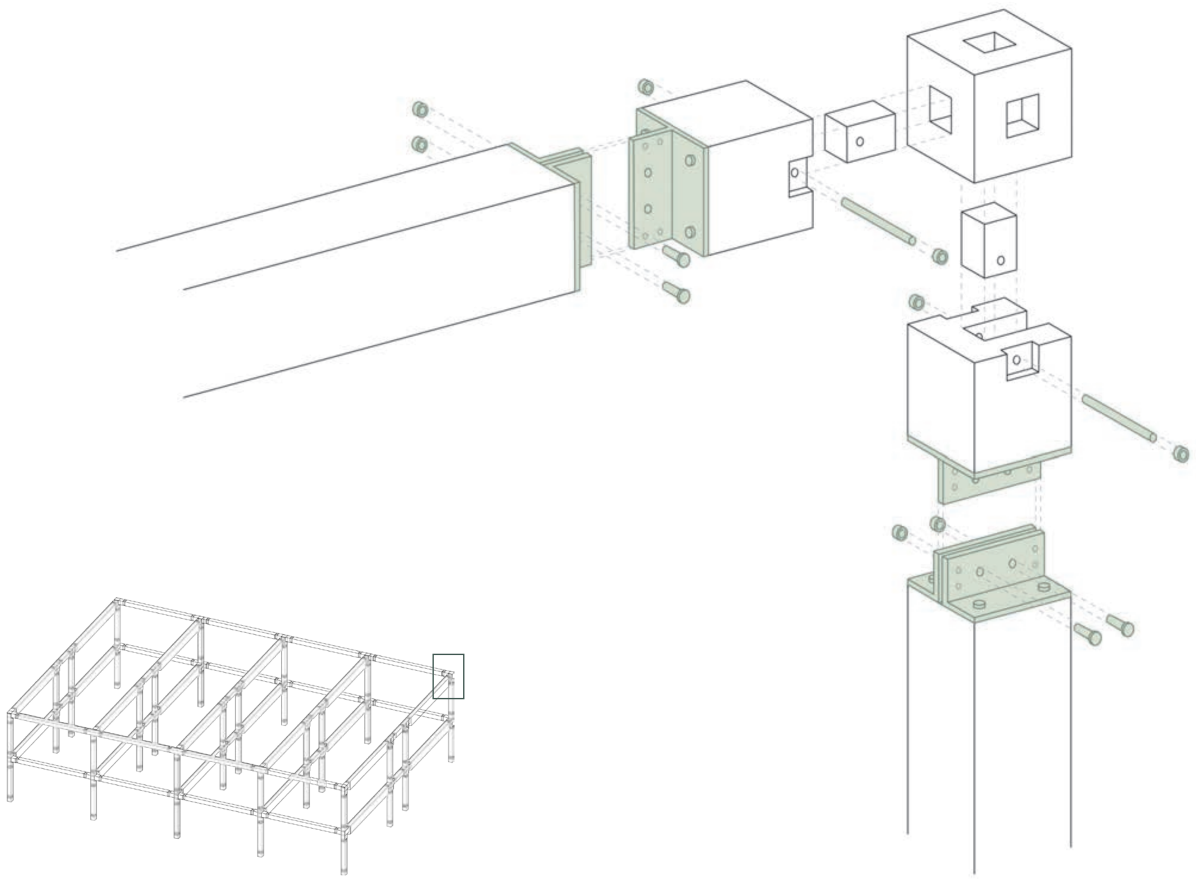
Fig. 5.3 By author, Exploded axonometry design proposal

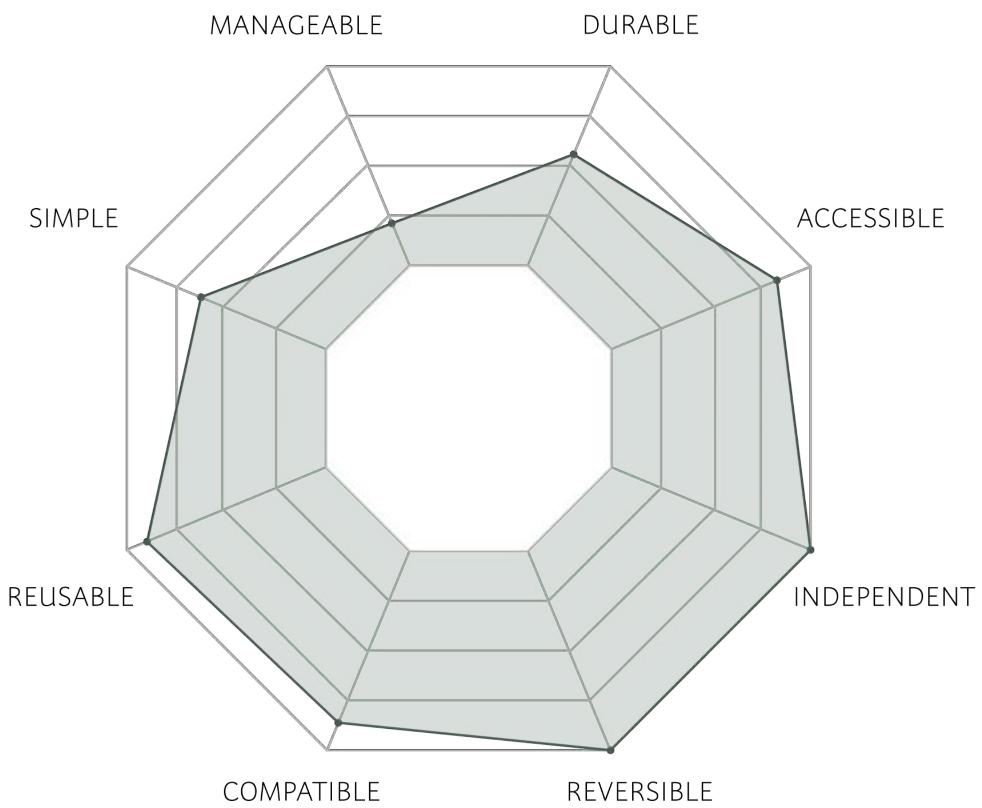

Fig. 5.4 By author, design proposal analyzed on circular design qualities

	Adaptable system
Reusable	
Catalog of building components	5
Standard dimensions	5
Standard connection system	5
Repeating patterns	5
Limited use of adhesives or plasters	3
Durable	
Long life span material	4
Surface treatment	5
Additional building layers covering the structure	2
Minimal amount of holes in components	2
Simple	
Minimal unique parts	4
Costs little time to construct	4
Minimal steps in assembly	2
Minimal experience or training needed	1
Repeating patterns	5
Standard dimensions	5
Manageable	
Small dimensions	2
Light weight	2
Minimal mechanic aid needed	1
Minimal amount of people needed	2
Accessible	
Minimal additional building layers covering the structure/connection node	4
Additional building layers are removable	4
Visible connection system	5
More tolerance around components and connection node	4
Reversible	
Connection node can be demounted	5
Independent	
Components are individually connected	5
Little disturbance of other components when handling one component	5
Compatible	
Multi-functionality of single component	3
Standard connection system	5
Standard dimensions	5
Repeating patterns	5

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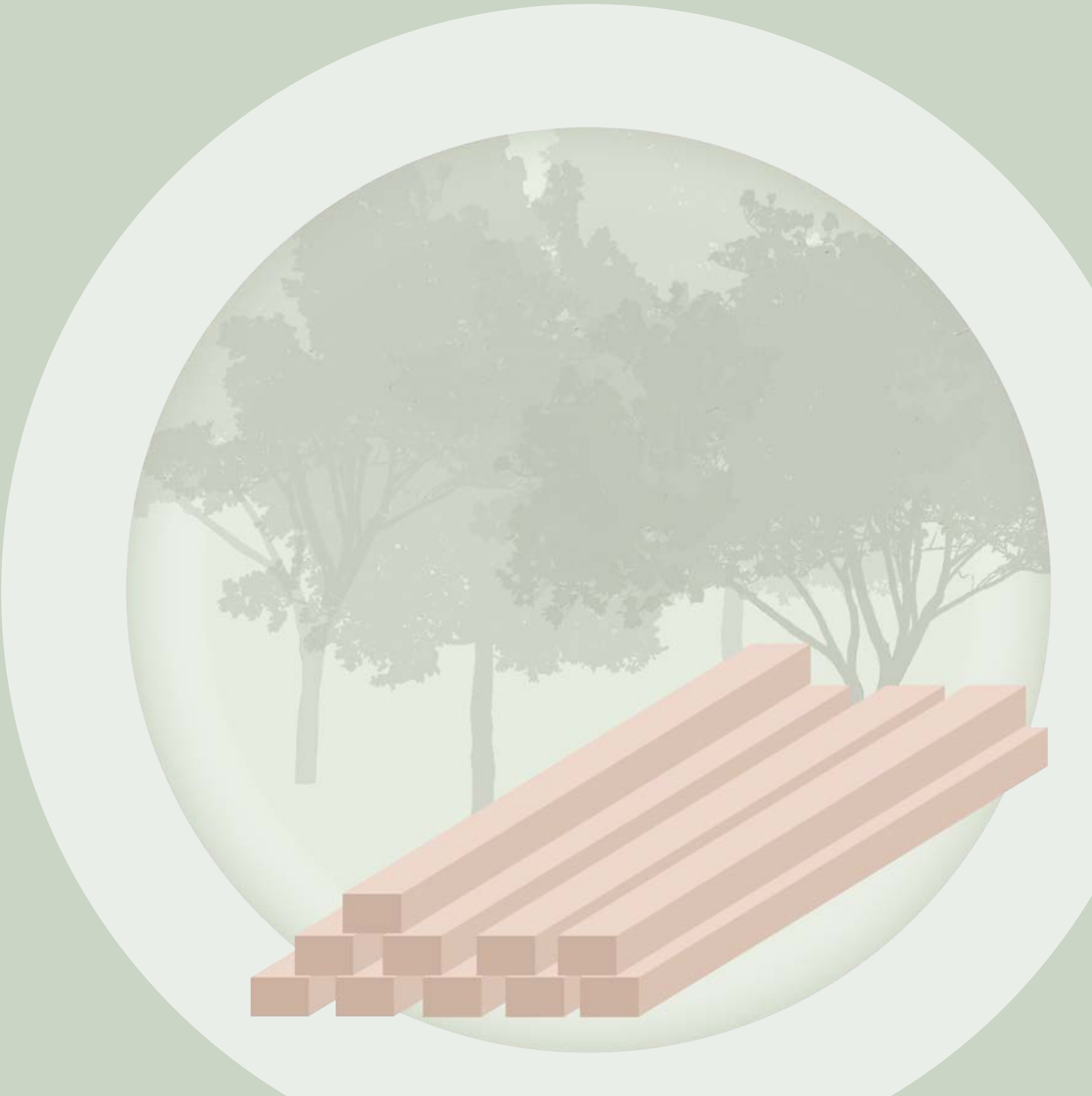
Table 5.A By author. The design proposal rated on its performance on the selected circular design qualities and their criteria

Chapter 6

Material

Design criteria

- Long life span material
- Surface treatment
- Light weight
- Limited use of adhesives or plasters



6.1 Background information

Forestry I Dutch tree species I Hardwood

Thousands of years ago, North and Central Europa were covered in trees for more than two-thirds of the total area. When agriculture commenced 6.000 years ago, requiring a lot of area to produce crops and maintain livestock, the majority of those forests were cut down (Kraaijvanger, 2018). In the Netherlands, reforestation started from the 1850s. Initially, only coniferous tree species were planted because the soil had become unsuitable for the native deciduous tree species of the area and coniferous trees were a desired building material. Eventually, deciduous trees began to erect from the soil and forests started to rejuvenate. Forest management organizations figured out that thinning forests would result in a continuous stream of timber material, and also had additional benefits like an increase of biodiversity and lower maintenance costs. Cutting down complete forests became a thing of the past (Natuurvolgend bosbeheer, 2021). Currently, approximately 10 percent of the total land coverage of the Netherlands consists of forests. This is roughly about 360.000 acres. This number has been increasing over the past few years, because more trees are added than harvested (AVIH, n.d.). From this stock of trees, 1.2 million cubic meters of wood is harvested each year currently, but most of the wood that is needed for the production industry is imported from Scandinavia and

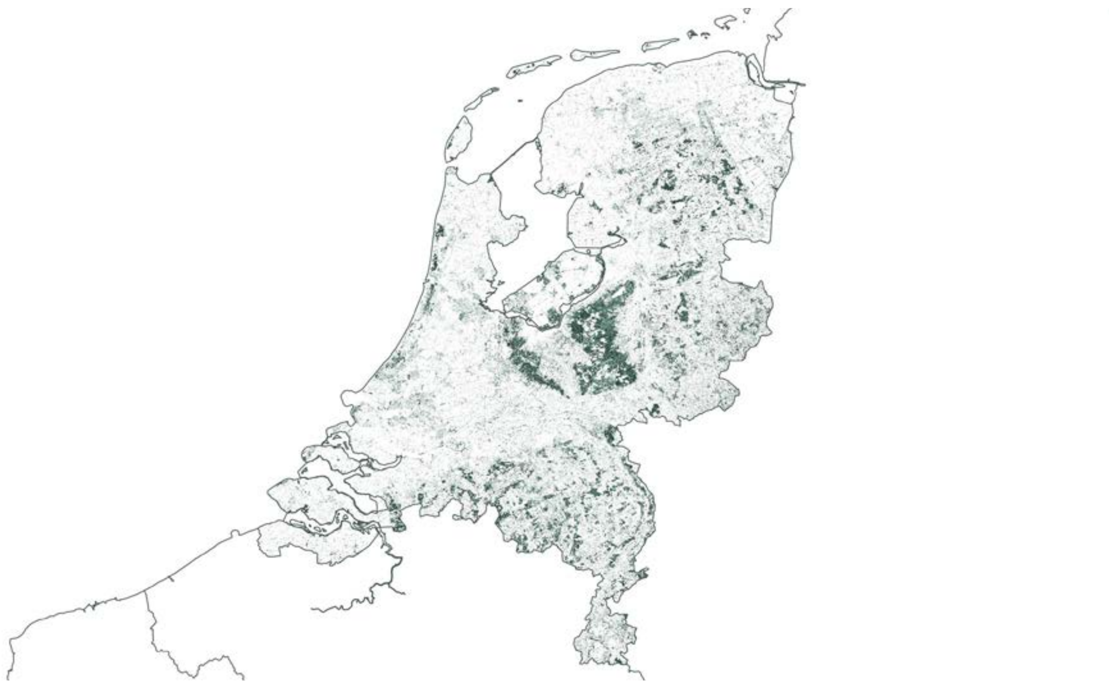


Fig. 6.1 Atlas leefomgeving (2022) 'Bomenkaart' Map showing trees in the Netherlands

Middle Europe (AVIH, n.d.). The Dutch forests are slowly maturing; they are becoming more dense, with a good mixture of different species (Schelhaas & Clerkx, 2015). As the amount of trees in the Netherlands is increasing, there is a high potential to harvest more trees and import less. The most common tree species in Dutch forests are the Scots pine (33%), Oak (18%), Douglas (6%), Larch (6%), Poplar (6%), Birch (6%), Spruce (4%) and Beech (4%). The current ratio between deciduous and coniferous trees is 45 to 55 respectively. This ratio will change however, because more deciduous tree species are planted, with the exception of Poplar. Additionally, the coniferous species which are harvested, are not rejuvenated enough to maintain the stock (AVIH, n.d.).

The vast majority of the wood harvested for industrial purposes is coniferous, being 66 percent. Of the 34 percent deciduous trees harvested, almost half consists of Poplar trees. Since the amount of poplar trees and coniferous trees is declining, and the other trees species are increasing in number, there is a potential and need to harvest more of the other deciduous species and learn how to utilize their potential as a building material (Probos, 2019).

Deciduous tree specie characteristics[1]

- Oak

Height: 18-30m, max. 45m
Diameter: 1,2-1,8m
Durability class: 2 (durable)

- Poplar

Height: 18-35m
Diameter: 0,9-1,2m
Durability class: 5 (not durable)

- Birch

Height: 18-21m
Diameter: 0,5-1,0m
Durability class: 5 (not durable)

- Beech

Height: 30-45m
Diameter: 1-1,5m
Durability class: 5 (not durable)

Of these deciduous tree species, oak and beech are the most commonly used for structural purposes. For the other species, a European technical assessment or a general construction technique permit is required (Merz, Niemann, & Torno, 2021).

[1] (Centrum hout, n.d.)

Fig. 6.2 GROEN! natuurlijk (n.d.) Oak tree

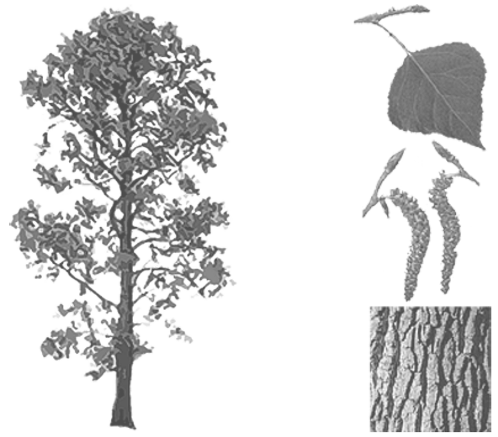


Fig. 6.3 GROEN! natuurlijk, (n.d.) Poplar tree

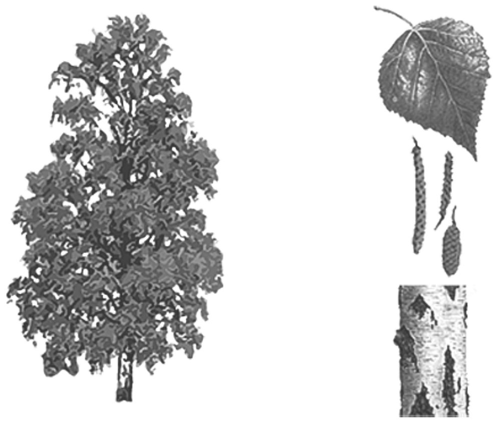


Fig. 6.4 GROEN! natuurlijk (n.d.) Birch tree

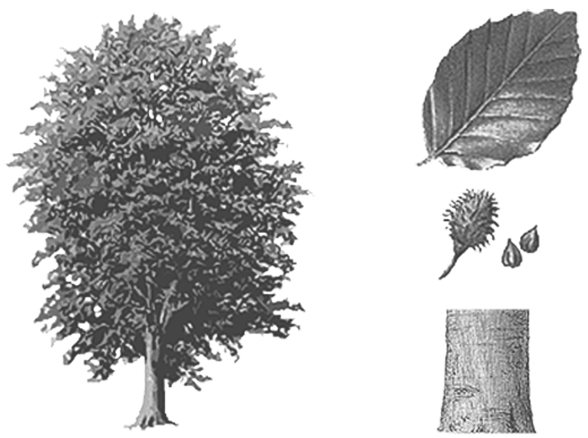


Fig. 6.5 GROEN! natuurlijk (n.d.) Beech tree

Softwood and hardwood

Wood that is obtained from deciduous trees is called hardwood and wood harvested from coniferous trees is called softwood. The prefixes 'hard' and 'soft' are not related to the actual properties of the wood, as hardwood is often softer than the average softwood (Ramage et al., 2017).

The speed of growth of a tree influences the density of the wood in the trunk. The trunk of a tree consists of sapwood, the water conducting tissue, and heartwood, which is what sapwood becomes after the tissue has died and the wood cells have become hollow. Each year, a tree produces an annual ring in which the environmental circumstances of the tree can be recognized. In figure 6.6, a singular annual ring is illustrated for both softwood and hardwood. For both wood types, rapid growth during spring results in large cells with thinner walls, whereas the colder months result in more densely packed, smaller cells (Ramage et al., 2017). There are large cellular differences between softwood and hardwood. Softwood predominantly consist of tracheids. Their function is to conduct water through the trunk and provide structural support. In hardwood, there are two different types of cells: fibers and vessels. The fibers provide the structural support and make up 50 percent of the trunk, while the vessels transport water and make up approximately 30 percent of the wood. The remaining part is made up by rays: radially positioned parenchymal cells that carry substances like resin (Ramage et al., 2017). The sections in figure 6.6 show that hardwood has larger vessels, which vary in size amongst the different seasons, while the softwood has a more uniform appearance, with tracheids that also vary in size through the seasons, but less drastically.

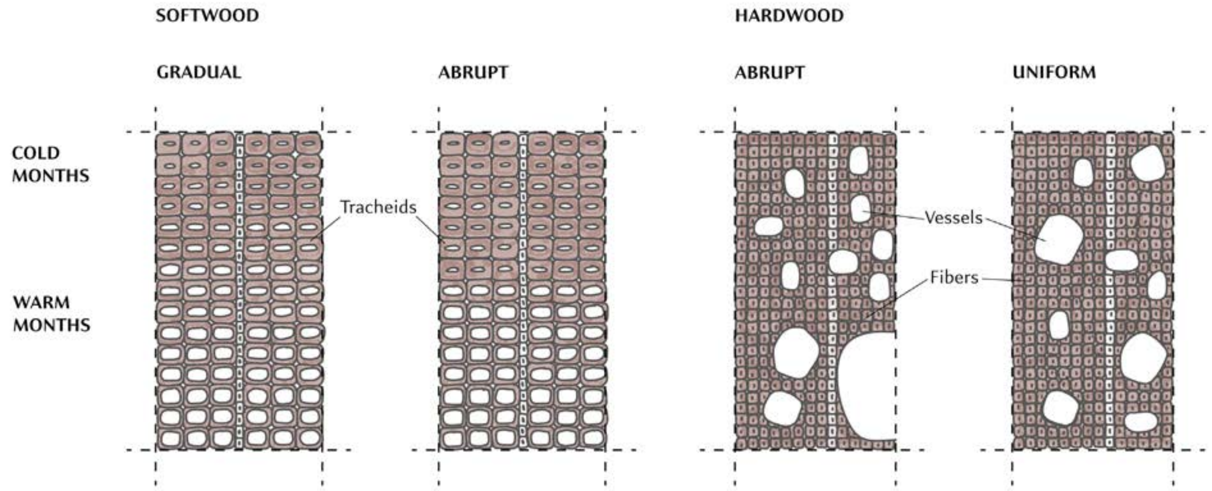


Fig. 6.6 Based on Ramage et al. (2017) Cellular structure of softwood and hardwood, showing one annual growth ring

6.2 Options

Hardwood products

Current commonly produced softwood building products are limited by their strength performance and their cross-sectional stiffness (Merz, Niemann, & Torno, 2021). Hardwood alternatives perform significantly better on both aspects and create opportunities to build higher, more complex timber buildings. The type of hardwood product determines the dimensions of a structural layout and components in a kit-of-parts. There are six different commonly used hardwood products on the current market:

Sawn lumber / solid wood

Sawn lumber, or solid wood, is produced by sawing or shaving roundwood along the length of the trunk and has at least a 6 mm thickness. Sawn lumber can be categorized into squared timbers, planks and boards. The finger joint is a connection type in which one piece of solid wood is connected to another by a serrated edge that causes longitudinal friction and allows to form longer units (Merz, Niemann, & Torno, 2021).
The availability and variety of sawn lumber is highly dependent on the dimensions of the obtainable roundwood.

Glued laminated timber (Glulam)

Glued laminated timber is produced by gluing layers of dimensional timber to one another, with their grains running parallel. Hardwood glulam can be homogeneous, when all the layers are made of the same hardwood specie, or hybrid, which is a combination of softwood and hardwood. In case of a hybrid glulam product, the outer layers are generally made of hardwood, because they carry the highest strength (Merz, Niemann, & Torno, 2021).
The layers of wood are connected by surface gluing them to one another, using a bonding agent.

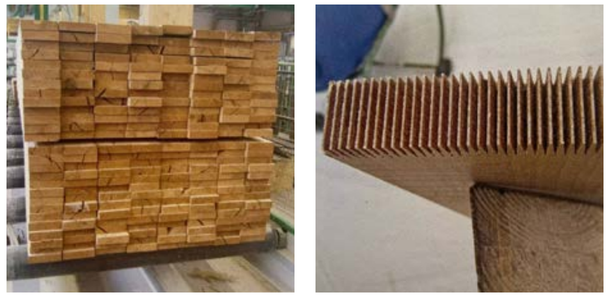


Fig. 6.7 Merz, Niemann, & Torno (2021) sawn lumber (left) and finger joint (right)

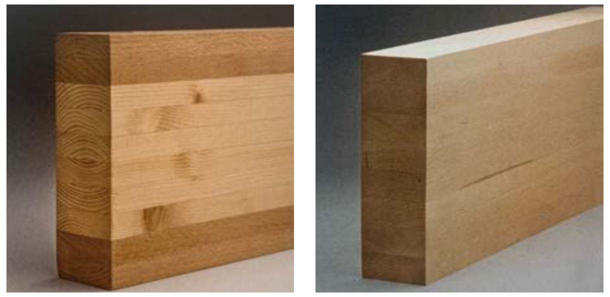


Fig. 6.8 Merz, Niemann, & Torno (2021) hybrid glulam (left) and beech glulam (right)

Laminated veneer lumber (LVL)

Laminated veneer lumber is produced by gluing layers of veneer together. These layers are most often arranged with their grains in the same direction, but some products also contain occasional layers that are oriented transverse. These transverse layers make up 15 to 30 percent of the complete cross-section. The layers of veneer have a thickness of 3 mm (Merz, Niemann, & Torno, 2021).
The layers of veneer are obtained by shaving thin layers of the circumference of the trunks of the trees. This makes this product less dependent on the dimensions of the available tree stock.

Oriented strand board (OSB)

Like structural plywood, oriented strand board is made by combining chips of wood. OSB is made up by several layers of wood strands, bonded by an adhesive. The fibers in the outer layers of an OSB panel are oriented parallel to the length of the panel. The fibers of the inner layers are arranged randomly, or perpendicular to the fibers of the outer layers. The minimal thickness of a structural oriented strand board is 8 mm (Merz, Niemann, & Torno, 2021).

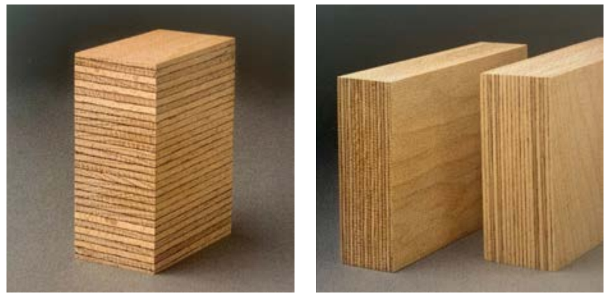


Fig. 6.9 Merz, Niemann, & Torno (2021) Beech LVL with transverse layering (left) and edgewise vertical layering (right)

Fig. 6.11 Merz, Niemann, & Torno (2021) Poplar OSB panel

Structural plywood

Structural plywood is made by joining chips of wood of varying sized together using a bonding agent. This product does not maintain the original wood fiber structure (Merz, Niemann, & Torno, 2021).
Plywood consists of multiple veneer layers, which are organized with the direction of the fibers perpendicular to the previous layer. The thickness of the veneer layers is generally between 1.5 and 3 mm. The configuration contains an odd number of layers and the outer layers have the same fiber orientation and treatment to prevent warping. The minimal thickness of a plywood panel is 6 mm (Merz, Niemann, & Torno, 2021).

Cross-laminated timber (CLT)

Cross laminated timber is a timber product that consists of layers of wood that have been glued together perpendicularly. CLT is most often produced with an uneven number of layers: 3, 5 or 7. An additional layer is added when the outer layer is visible and a more aesthetic looking wood specie is preferred, making the number of layers even. Cross laminated timber is produced in sheets with varying dimensions, depending on the limitations of the production machinery of the supplier. In contrast to LVL and Glulam, CLT is not used in a post-and-beam system, but as a panel system in which the CLT walls are load bearing (Joost de Vree, n.d.).

Fig. 6.10 Merz, Niemann, & Torno (2021) beech plywood

Fig. 6.12 Woodteq (n.d.) CLT panels

6.3 Recommendation

Glulam I LVL I Glulam from LVL

The previously mentioned hardwood product types can be grouped into three categories: solid wood for a post-and-beam system, glued products for a post-and-beam system and glued panels. Glued products are optimal to achieve the highest potential of a hardwood material, because the growth related reductions in stiffness and strength that sometimes occur in certain sections can be eliminated and a product with homogeneous properties is created (Merz, Niemann, & Torno, 2021).

When developing an adaptable building system, flexibility in the floor plan is required. A post-and-beam structure provides more flexibility than a panel structure, because the interior walls are not part of the load-bearing structure and carry less implications when moving them.

Based on these two reasons, a glue laminated beam product is used for the further development of the design proposal. Additionally, because of the high strength properties of laminated hardwood in comparison to solid lumber, it requires less material to achieve the same performance. A glue laminated beam product is either a Glulam product, LVL, or a combination of the two, since Glulam can also be made from laminated veneer lumber. In table 6.A, the properties of a Glulam from LVL beam from Pollmeier are provided. The properties of other Glulam and LVL products can be found in appendix VI, documented in the same way.

Product type	Glulam from LVL
Manufacturer/permit holder	Pollmeier Furnierwerkstoffe GmbH
Product	BauBuche GL75 beam
Wood species	Beech
Beam	
Construction	-
Height [mm]	80-600
Width [mm]	50-300
Length [m]	≤18
Laminates	
Thickness [mm]	40 ± 3
Width [mm]	50-300
Cross section [mm^2]	-
Length [mm]	-
Minimum number	3
Strength [N/mm^2]	
Bending $f_{m,k}$	75
Tensile parallel $f_{t,o,k}$	60
Tensile orthogonal $f_{t,90,k}$	0,6
Compressive parallel $f_{c,0,k}$	49,5
Compressive orthogonal $f_{c,90,k}$	12,3
Shear $f_{v,k}$	4,5
Stiffness [N/mm^2]	
$E_{0,mean}$	16.800
G_{mean}	850
Density [kg/m^3]	
ρ_k	730

Table 6.A Austrian institute of Construction Engineering (2021) Properties oak glulam product

6.4 Design proposal

Lamination layers I Cross-sections I Evaluation

Different hardwood timber products lend themselves for different structural configurations and layouts. The product used for the development of the final design proposal is based on the dimensions of the structural layout, which will be further elaborated on in the next chapter. For other design project with different grids, the preferred hardwood product might differ.

For the span of 7.200 mm, a cross-section of 600x300 is needed. This section consists of a lamination of 15 layers, each being 40 mm thick. For the column, the required cross-section is 300x300 mm for a ceiling height of 3.000 mm. This cross-section is also recommended for a beam component of both 3.000 mm and 2.400 mm long. For a beam with those spans, a cross-section of 300x300 is actually a little bit over-dimensioned. It improves the compatibility of the total system and makes mass-production of the components easier, however.

LENGTH [MM]	BEAM/COLUMN
7.200	600x300
3.000	300x300
2.400	300x300

Table 6.B Sections and laminations of beams and columns

Evaluation

Long life span material **4**

The life span of a baubuche GL75 beam component is advertised as being a minimum of 50 years. This life span is sufficient for an adaptable system, since the elements can be replaced when reaching their end of life (Austrian institute of Construction Engineering, 2021).

Surface treatment **5**

A protective coating protects the baubuche GL75 product for damage by moisture during transport and installation (Austrian institute of Construction Engineering, 2021).

Light weight **2**

Hardwood has a higher density than commonly used softwood timber, but a lower density than concrete and steel.

Limited use of adhesives or plasters **3**

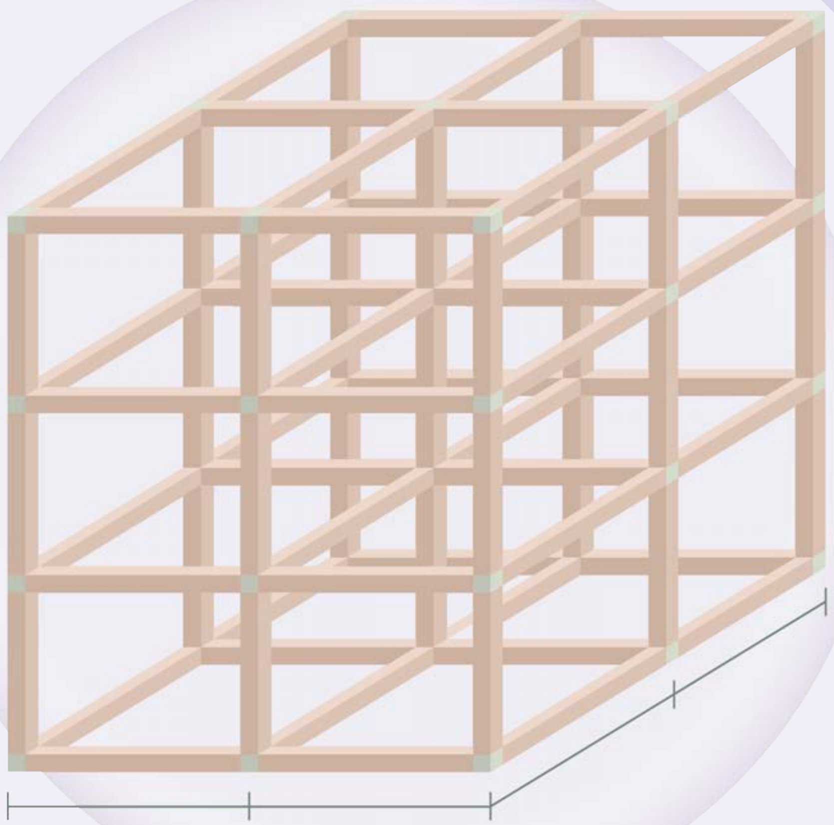
There are no adhesives or plasters used for making the connection. On the other hand, most of the timber components are made from laminated timber products, which are made by gluing layers of timber together with an adhesive. This could make eventual recycling of the components more complex even though the components will be reused several times before being recycled.

Chapter 7

Structural layout

Design criteria

- Standard dimensions
- Repeating patterns
- Small dimensions



7.1 Background information

Grid dimensions I Timber floors I Loads I Lateral stability components

Grid dimensions

Most building floor plans make use of a floor plan grid. This grid structures the plans into sections with standard dimensions, which are often times used for similar building functions, to accommodate the standard floor plan layout of that specific function.

One of the design potentials that could be realized by developing an adaptable structural system is to transform the function of a building, or accommodate multiple functions within the same structure simultaneously. An overarching building grid should be determined that can easily house all desired different building functions, like housing, offices, meeting spaces and shops.

Using this overarching building grid, the dimensions of the kit-of-parts components are defined. Besides this particular grid, the building components from the kit-of-parts can be used to generate other structural layouts. This way, the design freedom and flexibility of the designer is minimally limited.

Flexibility of a post-and-beam system

In a post-and-beam structure, vertical and horizontal components carry the loads of a building. These components are beams and columns. Because all the loads are carried through these slender components, it eliminates the need for load-bearing walls within the floor plan of the building. This results in little limitations in how the floor plan of a post-and-beam building is arranged, making it more flexible and suitable for housing different functions, as is required for an adaptable structural system.

Lateral stability components

Lateral stability components are part of the load-bearing structure and have the function to resist seismic, wind and gravity loads. There are many different types of stability components, but generally they can be grouped into three categories: shear walls, moment resisting frames and braced frames. A stability component provides stiffness to the structure, preventing it to distort.

Floors

Like the post-and-beam system, the floor also has to comply to certain criteria in order for it to be suitable for an adaptable system. Apart from the criteria that were determined prior, there are some additional qualities that ideally an adaptable floor system would have to match the adaptable post-and-beam system:

- A floor component can be removed
- A floor component can be replaced
- It can house functions that require a structure that can carry a minimum of 5 kN/m²
- It does not need a permanent finishing layer, or the finishing layer can be easily removed
- It can limit sound transmission between different storeys
- The connection between floor and beam can be demounted
- The floor components have to be able to span the maximum span length of the structural layout

Loads

There are different vertical load cases to consider when dimensioning a structure. The first load case is the weight of the building component itself. The second load case is the weight of the other structural components resting on the calculated building component. The final load case is determined by the function of the building of which the building component is part. NEN-EN 1991-1-1+C1/+NB: Eurocode 1 defines the functional loads on structures in buildings.

CLASS OF LOADED AREA		q [kN/m²]
Class A	housing	
floors		1,75
stairs		2,0
balconies		2,5
Class B	offices	
offices		2,5
Class C	meeting spaces	
spaces with tables or permanent seating		4,0
large open spaces, physical activities or large crowds		5,0
Class D	shopping	
retail, department stores or supermarkets		4,0

Fig. 7.1 By author, Different load cases

Table. 7.A NEN-EN 1991-1-1+C1/+NB: Eurocode 1 Functional load cases

7.2 Options

Floor system I Lateral stability

Different floor systems

The presented floor options are compatible with a timber structure, show circular potential and are currently often used.

Dowel laminated timber
These panels consist of solid layers of wood that are joined using dowel fasteners, instead of an adhesive. Originally steel nails were used, but due to the difference in material properties, they disrupt subsequent working. Instead, timber dowels are used. The dowel laminated boards are load-bearing, but not stiff. To provide stiffness, they are nailed to a suitable wood-based panel. Openings are difficult to realize in this floor type (Kaufmann, Krötsch, & Winter, 2018).

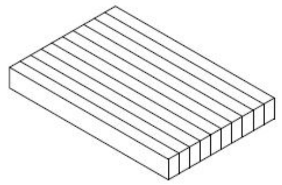


Fig. 7.2 Kaufmann, Krötsch, and Winter (2018) Dowel laminated

Cross laminated timber
CLT panels consist of layers of wood arranged perpendicularly which are glued together to form one large panel. This gives the panels great lateral stability properties. The load-bearing direction is parallel to the direction of the top layer. This floor type can be cantilevered in two directions (Kaufmann et al., 2018).

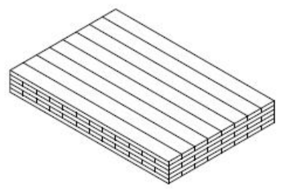


Fig. 7.3 Kaufmann, Krötsch, and Winter (2018) Beam floor

Box floors
This floor type is based of beam floors, but are a more prefabricated, light-weight alternative. Box floors are ideal to use in structures with medium to large spans. They consist out of ribs in the primary span direction, edge beams on either end, and panels on the top and bottom to close the box. Openings are realized in box floors similarly to beam floors. Box floors have a great stiffness and can be used for lateral stability. This floor type can cantilever in two directions (Kaufmann et al., 2018).

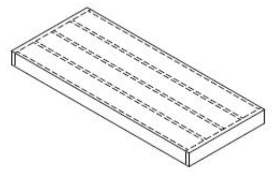


Fig. 7.4 Kaufmann, Krötsch, and Winter (2018) Box floor

Beam floors
This floor type is made up by beams that span the primary direction and panels on top to form the floor. This floor type has been used for centuries. Beam floors are either prefabricated components, or assembled on site with individual beams and panels. Openings can be easily realized in this floor type, by introducing secondary beams (Kaufmann et al., 2018).

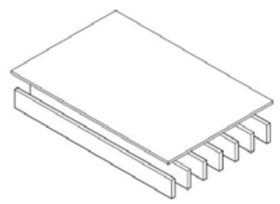


Fig. 7.5 Kaufmann, Krötsch, and Winter (2018) CLT floor

Laminated veneer lumber
LVL is made from layers of wood veneer that are glued together. The difference between CLT and LVL is that in LVL the layers are much thinner. Also, most layers are positioned parallel, with some positioned perpendicularly. The panels are load-bearing and also function as lateral stability components. This floor type can cantilever in two directions.

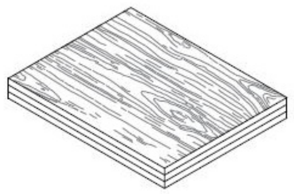


Fig. 7.6 Kaufmann, Krötsch, and Winter (2018) LVL floor

Concrete top layer
Other than the structural and lateral performance of a floor, there are other requirements that a floor system has to comply to, like sound proofing and fire safety. A timber floor requires additional mass to account for these requirements. This mass cannot be provides by just using timber. Concrete slabs have a higher density than timber and are placed on top of the timber floor system (Kaufmann et al., 2018).

Different lateral stability components

Shear walls
The term 'shear wall' is not completely accurate for the function it is fulfilling, since a wall subjected to a lateral force is mainly deflected by the occurring moment and there is often minimal shear distortion. Shear walls have to be applied both in the transverse and longitudinal direction of the building to obtain stability. A shear wall functions optimally if there are no substantial window or door openings present in the slab. Ideally, multiple shear walls are connected, because their combined stiffness exceeds the summation of their individual contribution to the stiffness of a building structure. Shear walls can be connected through beams or slabs.

Moment resisting frames
Moment resisting frames provide stability from within the connection node between beams and columns. This means that there is no need for obstruction within the structural layout and they allow for an open and flexible floor plan (Stamatopoulos, Malo, & Vilguts, 2022).

There are two types of fasteners that create moment connections in timber structures: inclined self-tapping screws and glued-in rods, parallel or perpendicular to the grain. An alternative could be to use rods with wood-screw threads, which are pre-installed into the timber members (Stamatopoulos et al., 2022).

Braced frames
A braced frame provides lateral stability by using a diagonal ductile brace spanning from the connection node of the frame to another point within the same plane. These braces are made from steel rods, timber, or a combination of steel and timber.

7.3 Recommendation

Grid dimensions I Floor system I Stability component

Dimensions of the grid

Damen (2009) conducted research in their Master thesis about multi-functional grids. A multi-functional grid is a floor plan layout that can accommodate different functions throughout its life span. The recommendation of a multi-functional grid for an adaptable structure is based on this research.

The following functions are initially considered for the development of a multi-functional grid: parking, shops, offices and housing.

The determining factors for the dimensions of the standard grid are the maximum depth of a space from a window, which is 7,50 meters with a ceiling height of 2,60 meters, and the commonly used dimensions for specific functions, like a parking spot and apartment spaces.

Damen (2009) concludes in their thesis that the most optimal width for a multi-functional building is 16,80 meters, divided into grid dimensions of 7,20 m-2,40 m-7,20 m. The optimal grid dimension for the length of a building is 6,00 meters, which can be repeated to fit the required program. The positioning of columns within a structural floor plan with these dimensions is extremely limited by the parking function, as confirmed by Damen (2009). For the further development of this design proposal for an adaptable structural system, the parking function is left out of consideration. Further research could be done on incorporating this function into the scope, which will probably result in a different structural layout.

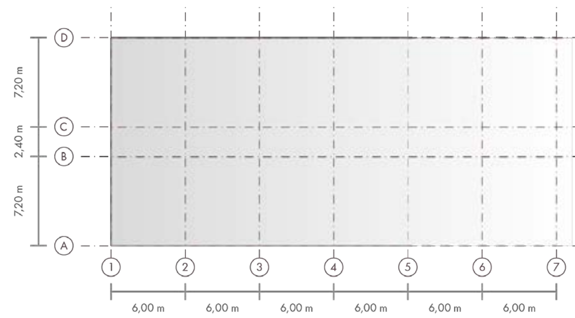


Fig. 7.7 Damen (2009) Recommended grid dimensions multi-functional building

Chapter 6 discusses the properties of different hardwood building products. A timber product that is able to span the dimensions of the grid has to be selected to be able to design with the multi-functional grid. Table 7.A shows the properties of the Baubuche GL75 beam by Pollmeier, including the maximum length of parts that can be produced. Appendix VI provides the lengths of other similar products. For the GL75 beam, the maximum length that can be produced is 18 meters. Since the largest span of the proposed grid is 7,2 meters, is the GL75 suitable for this structure. Of course, there are other available hardwood beam products that can also span this distance.

Floor system

A flexible floor system is preferred for an adaptable structure. From the previously listed options, the floors that can cantilever in two directions fit an adaptable structure best, because they can be easily supported by temporary structures when their linear support beam is being replaced (see chapter 10: construction process). Those options are: Laminated veneer lumber, Cross laminated timber and box floors. Since openings can be made easily in the box floor, which is another positive aspect in regards to adaptability, this is the floor type that is used for the further development of the design proposal.

While the addition of a concrete slab is necessary for the extra mass, it is not a bio-based material and strictly does not match the ideal circular economy philosophy. Instead of pouring the concrete on site, the concrete can also be applied by a prefabricated concrete slab. This allows for the application of R-strategies nonetheless.

Lateral stability component

The recommendation of a lateral stability component type is based on the contribution to the adaptability of a building structure. This chapter explains how the use of a post-and-beam system results in a flexible floor plan, because there are no permanent load-bearing walls that limit the layout of the space. Similarly, shearing walls create obstructions in the open floor plan or in the facade, making the process of adapting or expanding the building more complex.

Both moment resisting frames and braced frames have flexible qualities. Although bracing components are also placed in the wall plane of a structure, they are easier to move than a shear wall. A moment connection leaves the load-bearing frames completely empty and minimally obstructs the floor plan. Creating a moment resisting connection in timber means that the connection has to be dimensioned larger, to gain the necessary friction area needed for this type of connection. This is not very common to do for mid-rise buildings with a relatively small span and ceiling height.

Conclusively, for the design proposal of an adaptable system, braced frames will be used.

7.4 Design proposal

FEA I Evaluation

Finite Element Analysis

To check the performance of the proposed hardwood timber product in the proposed grid dimensions, a Finite Element Analysis (FEA) is used. The analysis structure is created in grasshopper, using the Karamba 3D plug-in. The most important aspect about creating the analysis structure is not to check if this specific grid structure complies with the maximum deformation and buckling requirements, but to provide a structure in which different structural layouts can be checked. The structure of the grasshopper model can be found in appendix IX. The beam cross-sections, materials and load cases can be changed by using parameters. An excel sheet determines the required load cases and dimensions as input data for the computational model. Appendix VII and VIII show the structure of the excel sheet.

The model uses the multi-functional grid dimensions developed by Damen (2009) and the hardwood product properties of the Baubuche GL75 product.

Load cases

The load case tested in the FEA consists of three parts. First, the weight of the regarded beam or column itself. This is based on the properties supplied by the manufacturer of the Baubuche GL75 products. Second, the weight of the structural components resting on the regarded beam or column are calculated. This entails the floor elements resting directly on the beam, but also the building components of other floors. In this case, a column on the ground floor is analyzed, carrying the load of four more storeys and the roof. Lastly, the imposed load is applied depending on the function of the building. The maximum imposed load of the regarded functions is 5 kN/m². For the analysis, the maximum imposed load is considered so that the components are dimensioned for every possible function. This way they do not have to be replaced if a building project is adapted to house a different function.

Results

The Unity Checks of the calculations and the computational model show that with a cross-section of 300x300 mm a column is able to withstand buckling and deformation for the maximum load-case. The beam requires a cross-section of 600x300 mm to be able to span the largest span of the proposed structural layout, which is 7.2 meters.

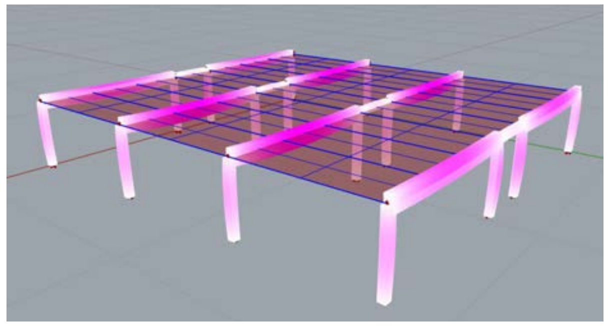


Fig. 7.8 By author, Deformation beams and columns Rhino

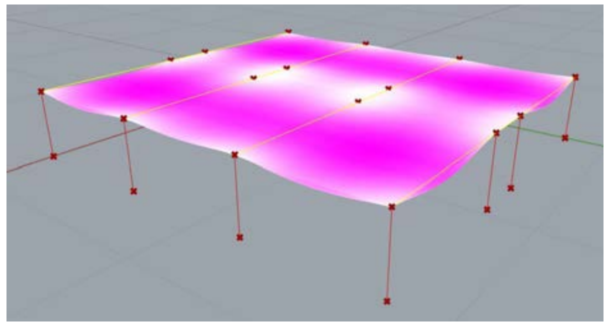


Fig. 7.9 By author, Deformation floors Rhino

Evaluation

Standard dimensions **5**

The proposed structural layout is based on a Master thesis study by Damen (2009) on the most suitable grid dimensions for a multi-functional building. The grid consists of a row of columns with spans of 7,2 - 2,4 - 7,2 meters, which repeats every 6 meters.

Repeating patterns **5**

In line with the previous criterion, the structural layout consists of a repetition of the same column rows every 6 meters.

Small dimensions **2**

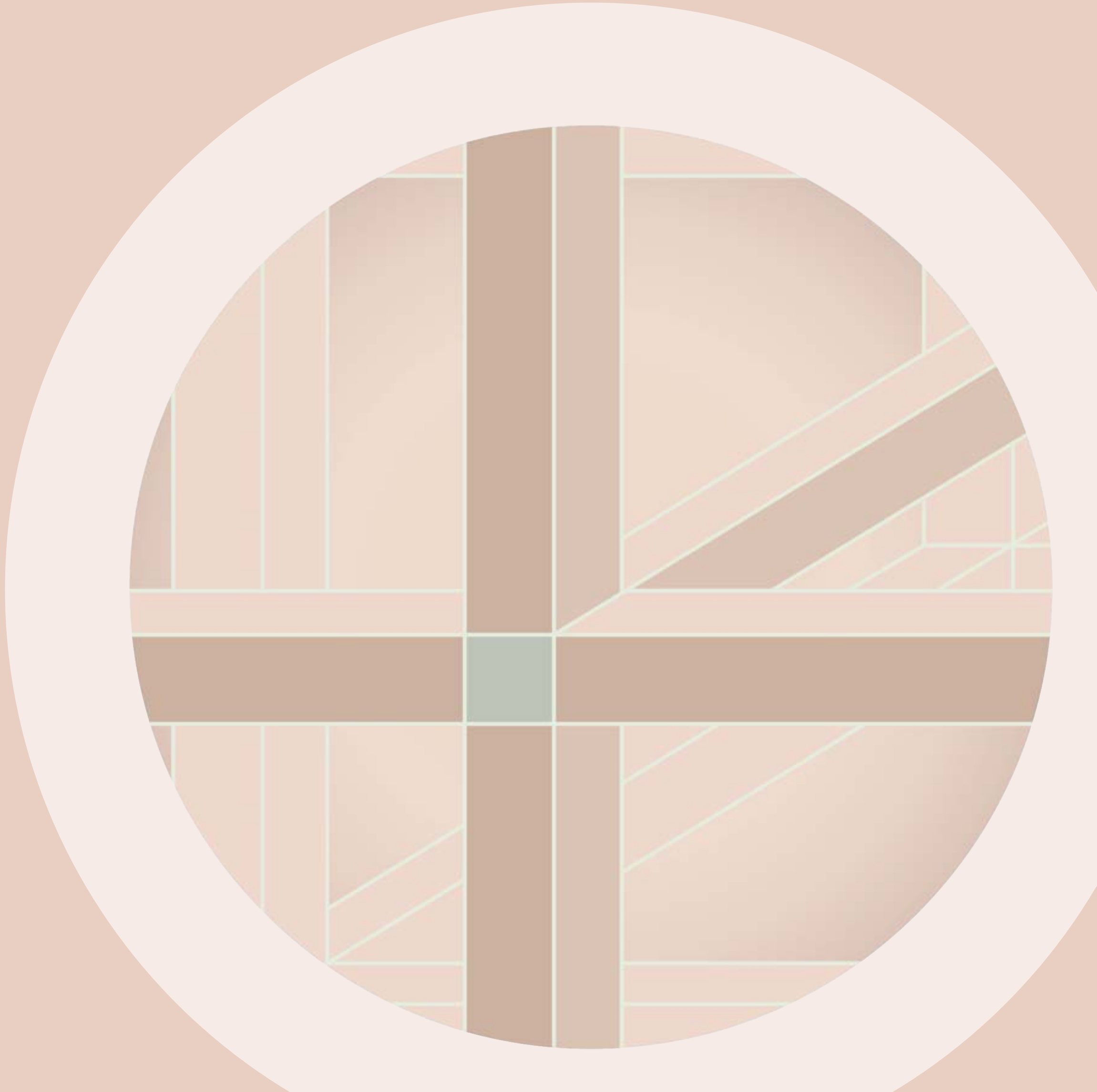
The largest dimension of the grid is 7,2 meters. Standard hardwood products can be used to span this dimension. The structural layout could hypothetically also be composed using only the 2,4 meter span, resulting in smaller parts and smaller dimensions. This would not benefit the multi-functionality of the grid and would not get the most out of the material properties of hardwood, however.

Chapter 8

Kit-of-parts

Design criteria

- Standard connection system
- Minimal unique parts
- Minimal amount of holes in components
- Connection node can be demounted
- Components are individually connected
- Multi-functionality of single component



8.1 Background information

Hardwood connections I Levels of prefabrication

Hardwood connections

Connections in hardwood products show much promise when compared to a softwood alternative. Due to their higher density and strength, hardwood products can transfer greater forces within smaller places (Merz, Niemann, & Torno, 2021). In general, almost all the same connection types can be used in hardwood structures as in softwood structures. Since hardwood is a material with a higher density than softwood, it is necessary to pre-drill holes in order to apply fasteners and create a connection. Consequently, this excludes fasteners like clamps, thin nails and toothed-plates for creating a hardwood connection (Merz, Niemann, & Torno, 2021).

Kit-of-parts

An adaptable structural system should be applicable for many different programs and project envelopes, whilst also maintaining low development costs for a higher feasibility. This need for customized products for a reasonable price and quality is solved by the concept of mass customization. This means that a mass-produced set of products can be used in various ways, to create a customized design. In the construction industry, this concept of a collection of pre-designed building components that can be assembled in a variety of ways to create a building is called a kit-of-parts (Cao, Bucher, Hall, & Lessing, 2021).

Typically, a kit-of-parts includes architectural, structural and installation elements. Because this thesis focuses on developing a structural system, the architectural elements, like a facade or interior walls, and the installations elements are not regarded. A structural kit-of-parts includes the load-bearing structure: beams, columns, floors and lateral stability components.

A successful kit-of-parts contains optimized structural members and joints that fit different structural requirements and can be combined to create multiple different structural layouts (Brütting, Senatore, & Fivet, 2021).

Levels of prefabrication

A kit-of-parts can consist of individual building components and/or pre-designed and assembled component groups. To explain what this means, figure 8.1 shows different levels of prefabrication within a kit-of-parts. A 1D component is an individual component, like a column or a beam. A 2D component consists of multiple 1D components, which are connected before being transported to the building site to form a framework in one plane. A 3D component, or module, is a component group that exists in multiple planes. All different levels of prefabrication can be part of a circular structure. Although 3D systems have shown to be less independent and accessible compared to a 1D system, as chapter 4 concluded through system analyses. For this reason, the design proposal of the kit-of-parts only considers individual building components.

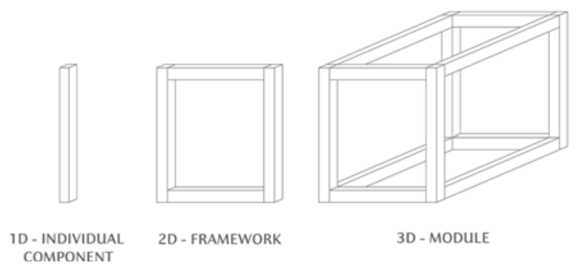


Fig. 8.1 By author, Different levels of prefabrication

8.2 Options

Connection typologies I Mechanical connection I Joinery

The most complex part of a kit-of-parts is the connection node. Existing timber connection principles can be categorized into groups and help determine the knowledge and market gap or give inspiration for an adaptable connection design.

The considered connection types are defined based on modern timber connection systems. Hereby the connection types requiring outdated production techniques, are lacking adequate fire resistance, or show no potential for adaptable design are eliminated.

Connection types

There are two main categories of timber connections that can be distinguished: mechanical connections and joinery. A mechanical connection is a timber connection made using an additional secondary material. A joinery connection is a connection purely configured with wood. This is also called carpentry. Within these two main categories, many different types of connections are differentiated.

Dowel
One of the most common timber connection types is a dowel connection. A dowel connection is made up by two wooden members, connected by a penetrating pin-shaped component made from a secondary material like a metal or plastic. Doweled connections can be made using nails or screws, for example. The type of dowel used depends on the requirements of the structure, like the transferred loads, environmental conditions and exposure to moisture (Engineering center, 2015).

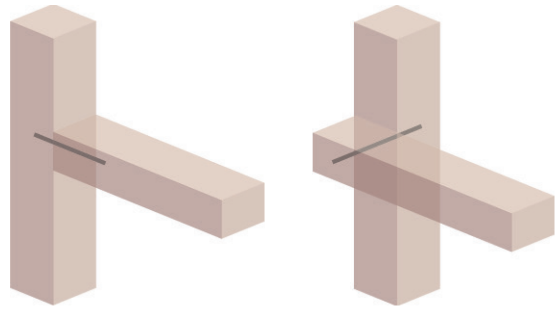


Fig. 8.2 By author, Dowel

2D external sheets
The second mechanical connection type is 2D external sheets, meaning that two timber components are connected by a flat sheet of a secondary material, that is applied on the outside of the connection node. An example of this connection type is a timber rivet connection. Timber rivets are high-strength steel nails, driven through a steel plate into the timber member. Due to the multiple nails, the load is evenly distributed along the entire connection node, making this connection type appropriate for structures that require greater ductility and resilience (Engineering center, 2015). Another example of this connection type is connector plates with integrated teeth.

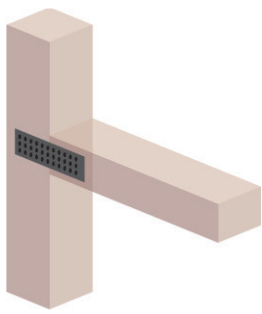


Fig. 8.3 By author, 2D external sheets

Shear connectors
Shear connectors, like rings and shear plates, are usually applied in structures that require a heavier load transfer. The principle of this connection type relies on the transmission of loads through the bearing and shear resistance properties of the wood (Engineering center, 2015). This connection type is either visible or concealed within the node.

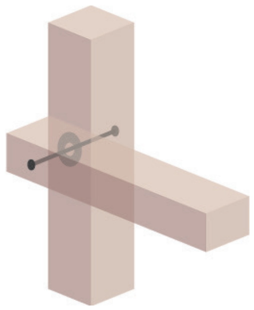


Fig. 8.4 By author, Shear connectors

3D integrated components
3D integrated components are connection components made from a secondary material, like a metal or plastic, in a three dimensional shape by attaching multiple sheets together or bending the material. The component is integrated into the connection node by making a cut into the timber member where the connection component slides in.

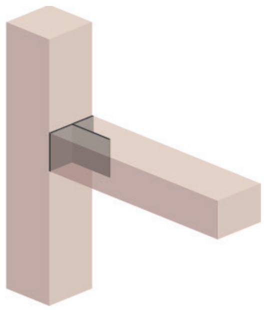


Fig. 8.5 By author, 3D integrated components

3D external framing anchors
3D external framing anchors are similar to 3D integrated components, except these are applied on the outside of the connection node and are thus visible when the structure is complete.

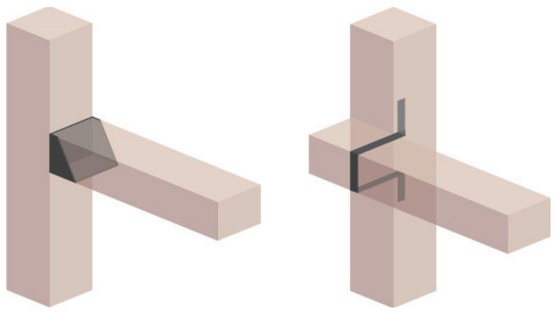


Fig. 8.6 By author, 3D external framing anchors

Secondary material nodes
A secondary material node is a connection type where the timber members are not directly connected to each other. The node is entirely made from a secondary material like a metal or plastic. The timber members are often provided with a prefabricated connector element, that connects to the connection node. The secondary material remains visible in the final structure.

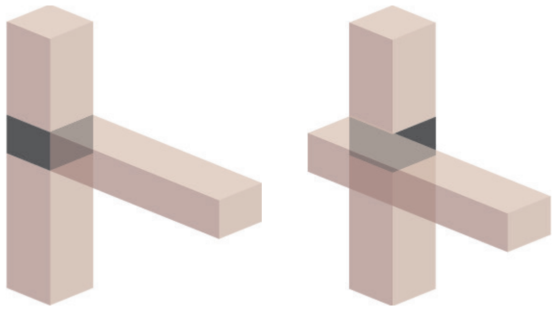


Fig. 8.7 By author, Secondary material node

Joinery
Whereas all the mechanical joints are made from straight cut timber members with additional components made from a secondary material, a joinery connection is established by cutting the timber members in a way that they have notches, holes and tongues, enabling them to interlock with each other (Engineering center, 2015). An additional dowel or other component made from a secondary material can be used to keep the joinery connection in place. Joinery connections are not commonly used in multi-story buildings, due to the higher level of craftsmanship required than with mechanical connections. However, with the introduction of CNC technology, timber joinery has become more feasible. The benefit of a connection made completely from timber is the uniformity in material properties (Engineering center, 2015).

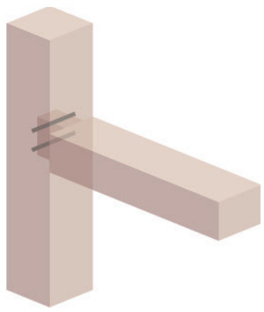


Fig. 8.8 By author, Joinery

8.3 Recommendation

Adaptable connection typology I Limitations (de)construction

Direction limitations

Once a structure is built completely, building components are positioned in direct relation to other building components. A minimally invasive adaptability process requires that only the necessary building components for the desired result have to be moved, without influencing other components. To be able to do this, the connection should facilitate the motion direction needed to move a building component out of its original place, without influencing other building components.

Figure 8.9 to 8.13 explain this concept, by illustrating in which direction specific components can freely move in order to realize the predetermined sub-scenarios.

Beam is replaced
A beam is positioned between two columns and a floor element lies on top of it. Section A-A' illustrates how the floor elements are on top and sideways of the beam section. The consequence is that a beam can only be moved downwards during a sub-scenario in which the beam is moved.

Column is replaced
A column is positioned on top of a floor and carries another floor or roof on top of itself. This means that the range of motion is limited upwards and downwards. A column can be moved out of its original place by moving it sideways. However, when a connected beam or floor element has a height larger than the connection node, as illustrated in section C-C', the column cannot move in that direction. This means that a column in an adaptable structure using this principle can never have four neighboring components with a height larger than the connection node.

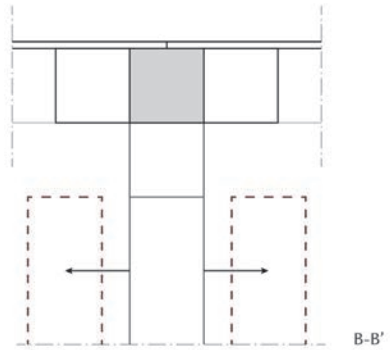


Fig. 8.10 By author, Direction limitation column section B-B'

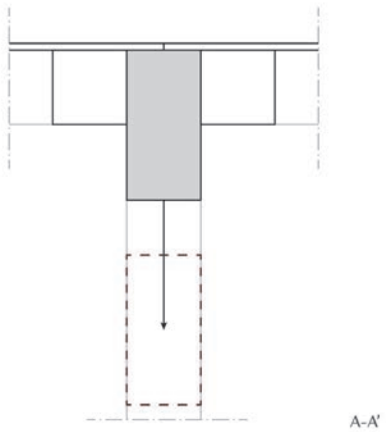


Fig. 8.9 By author, Direction limitation beam section A-A'

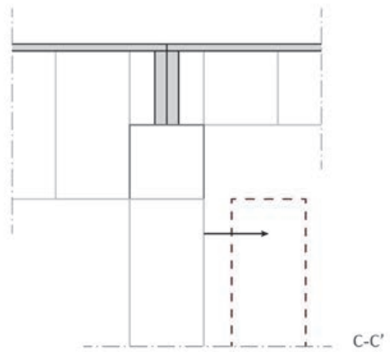


Fig. 8.11 By author, Direction limitation column section C-C'

Floor element is replaced or removed
A floor element lays on top of beams as demonstrated in sections D-D′ and E-E′. This means that a floor element cannot be moved downwards. It also is situated between other floor elements sideways, limiting movement in those directions. The only direction a floor element can be moved towards without impacting other components is upwards.

Node adapted to connect to more components
To connect a new component to an existing connection node, no other building components of the load-bearing structure are influenced. However, other building layers need to be removed in order to access the connection node. This relation is explained in chapter 9: Building layers.

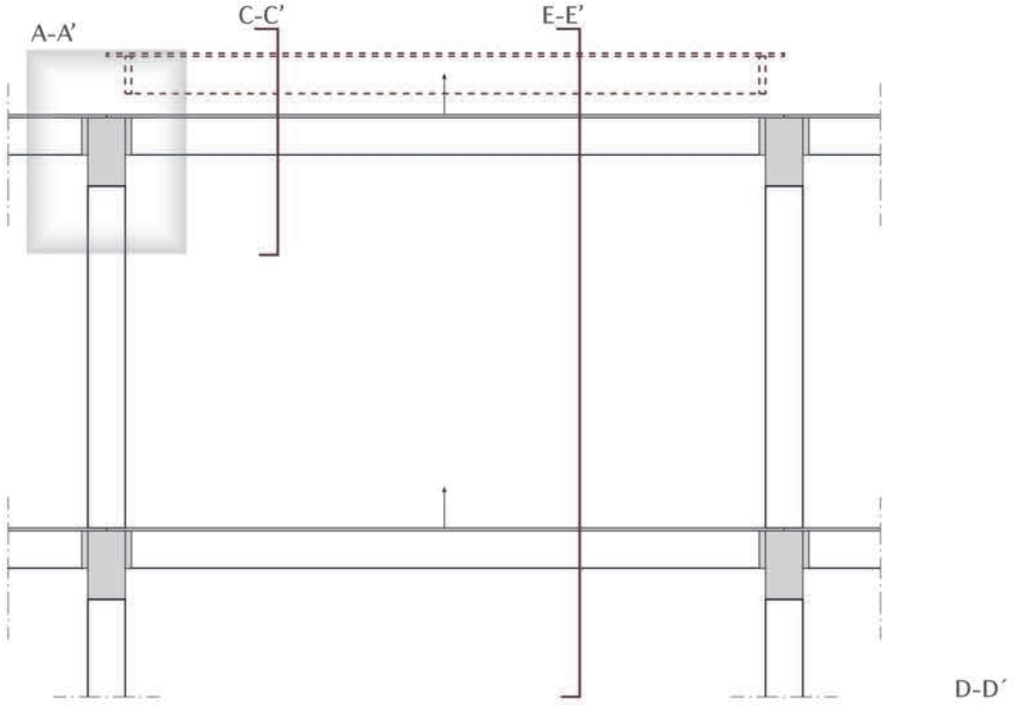


Fig. 8.12 By author, Direction limitation floor element section D-D′

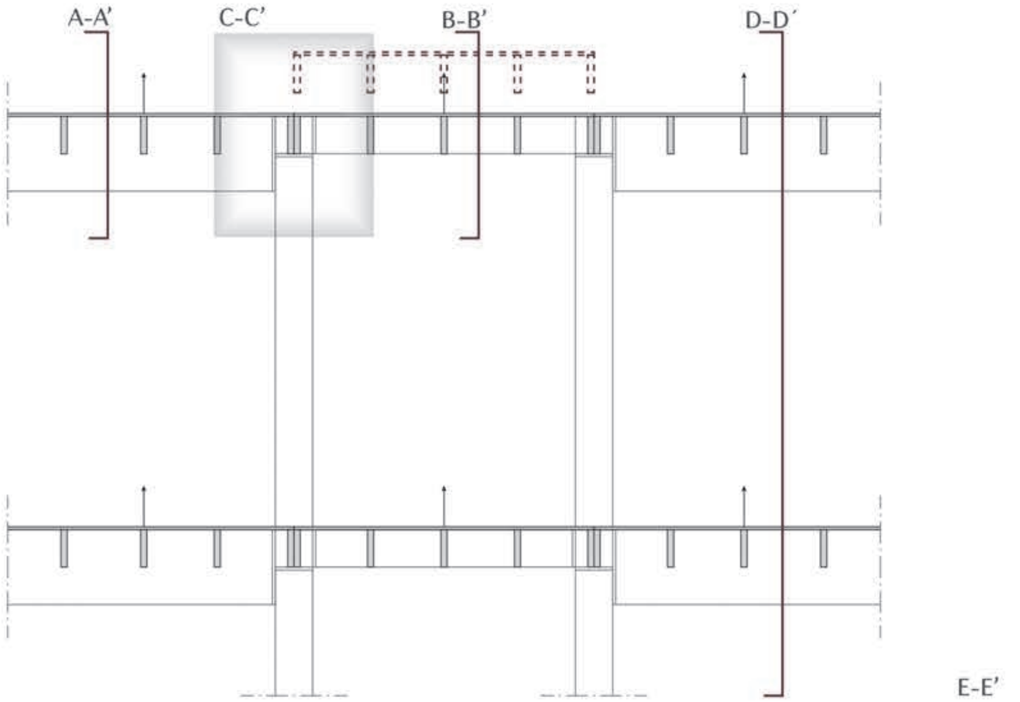


Fig. 8.13 By author, Direction limitation floor element section E-E′

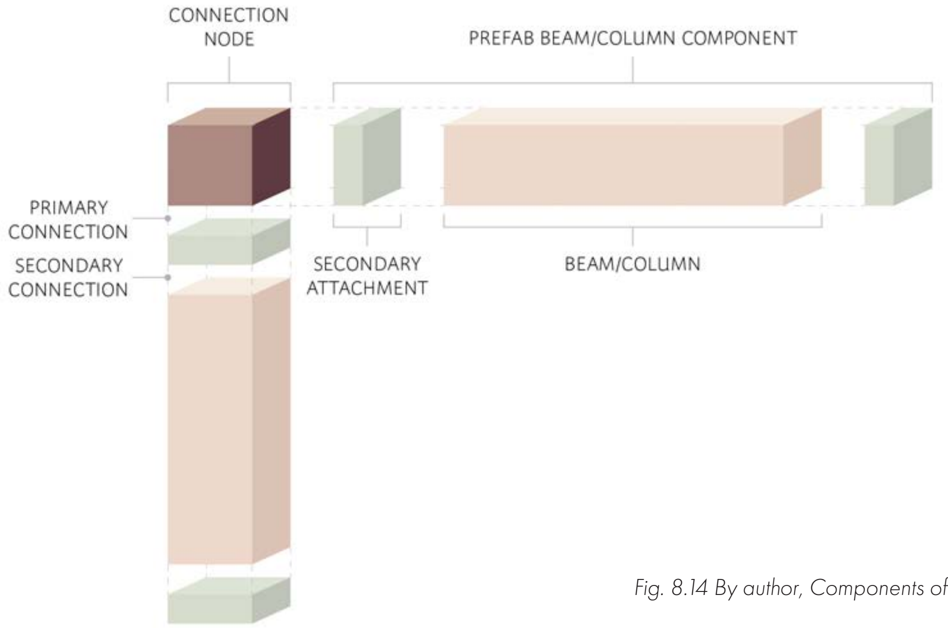


Fig. 8.14 By author, Components of adaptable connection principle

Secondary connection principle

The individual maneuvering of components as necessary for the feasibility of the selected sub-scenarios, requires a range of motion that is not easy to realize with existing connection principles. Table 8.A provides an overview of the before mentioned connection principles, along side a new principle: secondary connection. This secondary connection principle makes it possible to move individual building components during the life span of for adaptation purposes, while maintaining the building speed during the initial construction.

Different from the existing connection principles, this adaptable connection principle consists of two connections. One primary connection, used during the initial installment of the building structure, and a secondary connection, which is used during adaptation activities during the life span of the building.

The connection entails a connection node and a prefabricated oblong component, like a beam or a column. The prefabricated component is made up of the timber element, which is the beam or column itself, and the secondary attachment element. Figure 8.14 shows the components of the connection principle.

Six prefab components can be connected to each connection node, one in each orthogonal direction, see figure 8.15.

The primary and secondary connection both require a different set of qualities to fulfill their role in a well functioning adaptable structural system. Most important for the primary connection is the manageability and simplicity of the initial construction process, when the complete building is constructed. This connection stays put during most of the life span of the building, unless substantial changes are made to the floor plan of the building. The secondary connection is used during the execution of the sub-scenarios more frequently throughout the life span of the building. It has to allow for the freedom in motion that the sub-scenarios require. When a beam or column needs to be replaced, the secondary attachment remains connected to the connection node and the timber parts of the oblong component is removed, as illustrated in figure 8.16. In case the secondary connection is also defective, it is removed after, see figure 8.17.

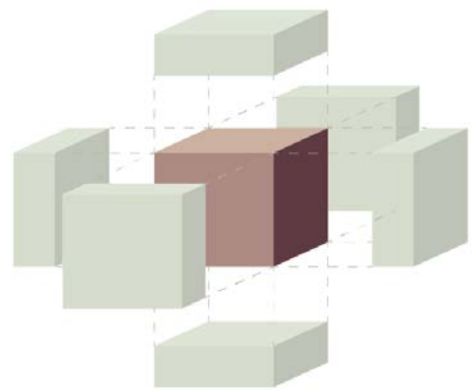


Fig. 8.15 By author, Connection directions connection node

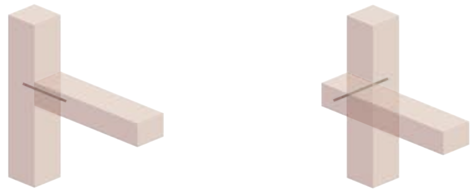
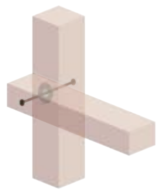
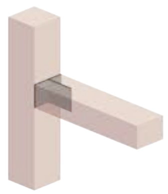
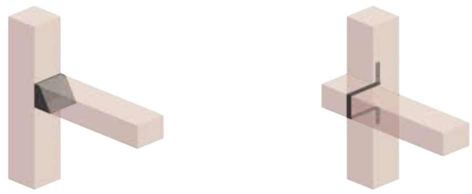
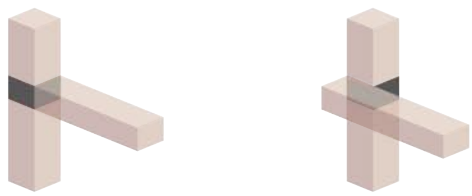
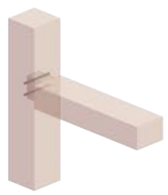
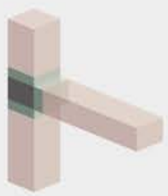
	CONNECTION TYPES
DOWEL	
2D EXTERNAL SHEETS	
SHEAR CONNECTORS	
3D INTEGRATED COMPONENTS	
3D EXTERNAL FRAMING ANCHORS	
SECONDARY MATERIAL NODES	
JOINERY	
SECONDARY CONNECTION	

Table 8.A By author, Adaptable connection principle added to existing timber connection principles

Fig. 8.16 By author, Repair of replacement of beam component

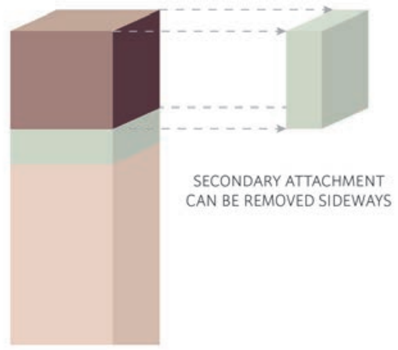


Fig. 8.17 By author, Repair of secondary attachment

Hardwood connection

The standard timber connection principles from table 8.A configure the primary and secondary connection of the new connection principle.

Dowel connection
The most standard connection type when using hardwood is a dowel fastener. Holes for the fasteners have to be pre-drilled when used in combination with hardwood, a material that has a high density (Merz, Niemann, & Torno, 2021).

2D external sheets
Steel plate connectors can be used on hardwood, as long as the holes are pre-drilled.

3D integrated components
In this connection category, glued-in threaded rods show the most promising results (Merz, Niemann, & Torno, 2021).

Joinery
The high transverse compression strength of hardwood allows for creating joinery connection with minimal contact area (Merz, Niemann, & Torno, 2021). This means the beam or column in which the connection socket is shaped, is less weakened than in softwood.

For the purpose of an adaptable structural system it is important that connections can be repeatedly demounted and remounted. If a fastener has to be removed and re-inserted from the hardwood, it could damage the material and deform the hole, making it complex to reuse the same hole for a new connection and thus limiting the life span of the component. Therefor, in the adaptable connection principle the fasteners that are put directly into the timber are there permanently as part of the prefabricated component. The adaptable connection is demounted through an external connection.

The primary connection that is used during the initial installment of the structure does not need this restriction, because it will only be mounted once during the construction phase.

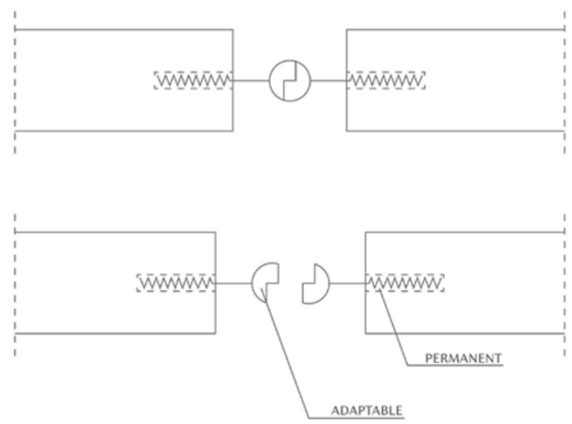


Fig. 8.18 By author, Permanent internal connection, adaptable external connection

8.4 Design proposal

Adaptable connection I Kit-of-parts I Evaluation

Detailed connection design

The design proposal for the kit-of-parts builds on the recommended connection principle, containing the primary and secondary connection, in more detail. Figure 8.22 illustrates the different parts and figure 8.19 to 8.21 provide technical details.

Connection node
The connection node is made of a hardwood timber block of 300x300x300 mm, with recesses on all six sides where a beam or column can be attached to.

Primary connection
The primary connection between the prefabricated beam or column and the connection node is established through a dowel connection. On the side where a column or beam will be attached, a hardwood timber block of 150x100x100 mm is pushed into the recess of the connection node. Then, the prefab beam or column is hung onto this connection piece. Both the prefab beam or column and the connection piece have holes that line up, through which a steel dowel is put to lock the primary connection. This connection is only used for the initial construction of the building, or when big changes are made to the structural layout.

Secondary connection
The secondary connection is made between the secondary attachment and the beam or column. This connection is already established before the components are transported to the site, resulting in a prefab building component. The secondary connection is demounted when the beam or column has to be moved individually. The secondary connection is a steel on steel connection. The steel connectors attach to the timber through bolts. The vertical slender parts of the connection make it possible to move the beam downwards without disrupting other components. Similarly, the column can be moved sideways when the steel on steel connection is demounted.

Varying beam heights
Figure 8.21 illustrates what a connection between a beam with a height of 600 mm and the connection node with a height of 300 mm would look like. The secondary attachment remains 300 mm, to create enough tolerance to still be able to move all the components with minimal disruption.

Lateral stability component
The lateral stability components are also attached to the secondary connection. In the steel connectors, additional holes are created to which an extra piece can be attached. Since the connection of the lateral stability element limits the move-ability of the column, the lateral stability component has to be disconnected first, before the secondary connection can be demounted. This connection is illustrated in figure 8.20 and 8.21.

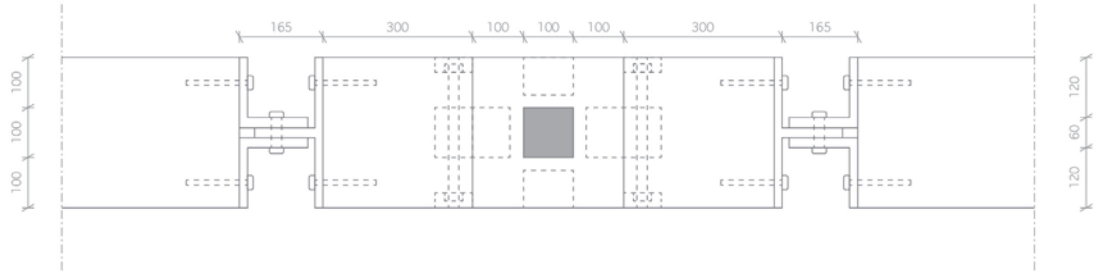


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Fig. 8.19 By author, Connection details adaptable structural system; top view

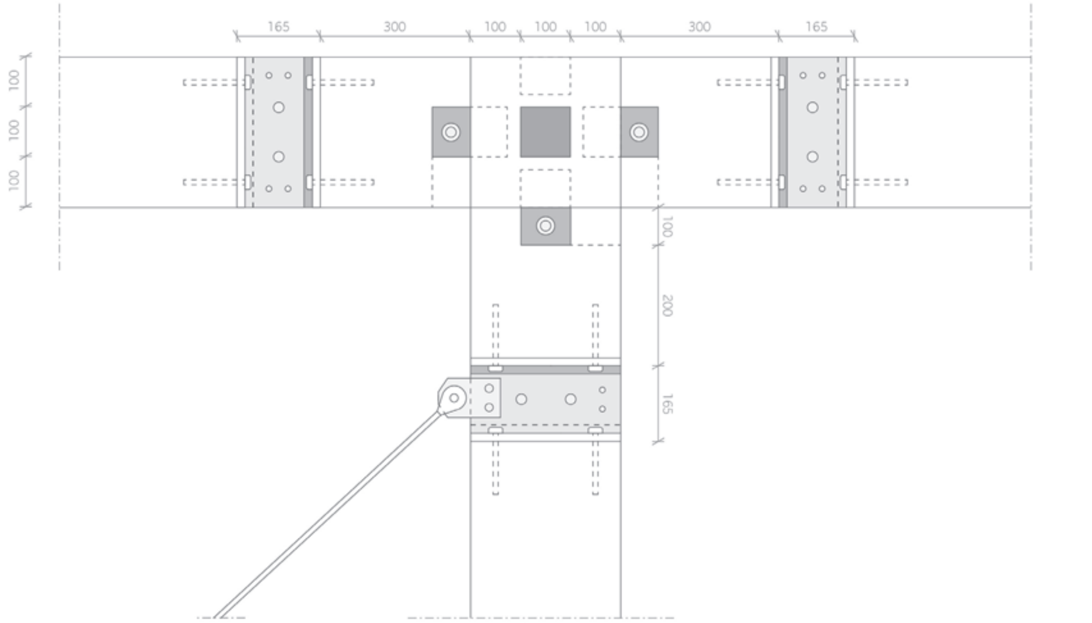

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Fig. 8.20 By author, Connection details adaptable structural system; front view 300 mm beam

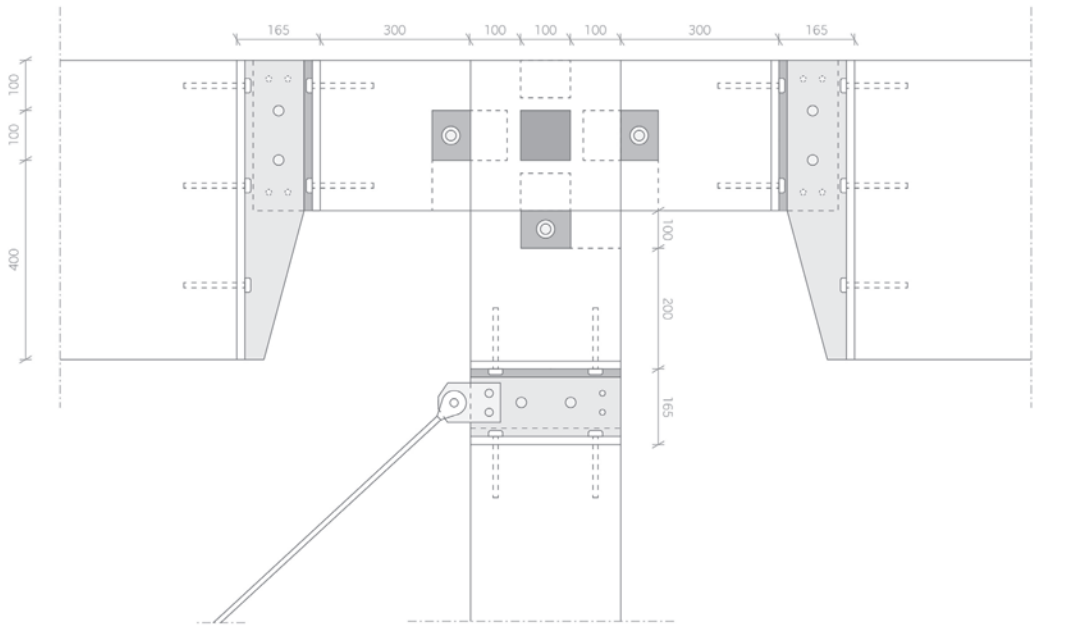

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Fig. 8.21 By author, Connection details adaptable structural system; front view 600 mm beam

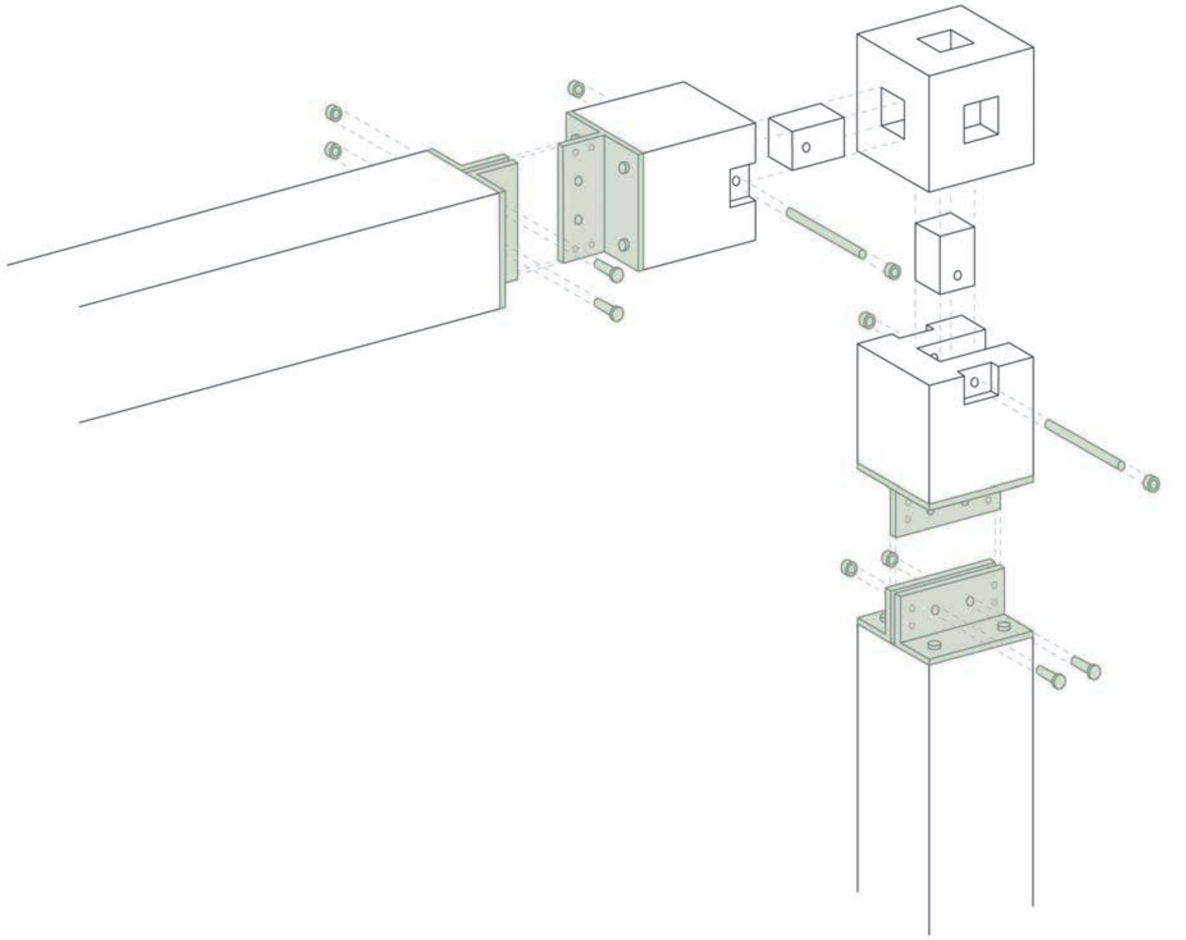

Fig. 8.22 By author, Exploded axonometry adaptable structural system

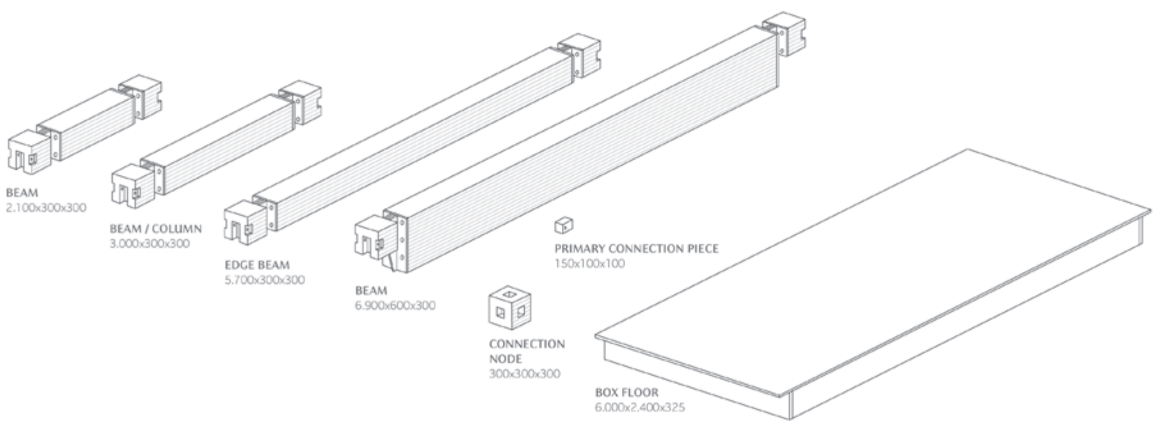

Fig. 8.23 By author, Kit-of-parts adaptable structural system

Complete kit-of-parts

A kit-of-parts of seven components, excluding the lateral stability elements, is able to construct a full load-bearing structure for the proposed multi-functional grid. Figure 8.23 shows all the parts. The kit-of-parts contains four prefabricated oblong timber components, each with different dimensions to account for different spans in the grid. For this design proposal the dimensions were determined, but in theory, all spans and cross-section could be used within this structural system, as long as they have the secondary connection piece attached to the ends of the timber. Furthermore, the kit contains two pieces that make up the primary connection of the system: a connection node and a primary connection piece. These are also made of laminated hardwood timber. Finally, the floor system is integrated into the kit-of-parts. As described in the recommendation, a box floor system would be suitable for an adaptable structural system. In this kit, the floor components have a width of 2.400 mm, so they fit within the multi-functional grid well, and a span of 6.000 mm.

Evaluation

Standard connection system **5**
The design proposal for this kit-of-parts contains two different connections, a primary and secondary connection, that are both integrated into one standard connection system. This design proposal focuses on the connection between columns and beams. The connection of columns and the foundation could possibly require a different connection, but that could be a variation on the same principle.

Minimal amount of holes in components **2**
The primary connection is established by a timber on timber connection and locked in by a steel fastener. This connection requires holes in components. The primary connection will only be utilized during the initial construction, so the fastener does not have to be moved in and out of the holes repeatedly. The secondary connection is made by a steel on steel connection. The steel connection pieces are attached by bolts to the hardwood timber elements, also requiring holes. The bolts in the hardwood are not moved during the adaptation process, however.

Connection node can be demounted **5**
Both the primary and the secondary connection node can be demounted, because they are created by fasteners that can be repeatedly screwed on and off the connection node. Demounting the primary connection will result in a larger intervention, since it is not accessible in the finished state of the building structure. Although access to primary connection is only necessary when the building is completely demounted or when big structural changes are made to the structural layout of a building.

Components are individually connected **5**
Every beam and column has a secondary connection attachment to either end that creates a prefabricated component. The attachment enables the individual maneuvering of beams and columns, without disrupting the other components of the structure. Even the lateral stability elements can be mounted and demounted without influencing other components.

Minimal unique parts **4**
The kit-of-parts consists of seven unique components. Four of those components are beams/columns that are based on the same principle of a hardwood timber element, with two prefab connection attachments on either ends.

Multi-functionality of single component **3**
The aim of the kit-of-parts is that the beam and columns can be used interchangeably while using the same component. In theory this is possible because all the components make use of the same connection. In practice, there are different cross-sections needed for a column or a beam of the same length. So for the multi-functionality to function optimally, some components would have to be over-dimensioned. For the kit-of-parts of this design proposal, some components have been slightly over-dimensioned to allow for multi-functional use.

Chapter 9

Building layers

Design criteria

- Additional building layers covering the structure (durability)
- Minimal additional building layers covering the structure/connection node (accessibility)
- Additional building layers are removable
- Visible connection system

9.1 Background information

Shearing layers I Life span

Shearing layers

Frank Duffy, the original theorist on change rate in buildings, describes buildings as something consisting of multiple layers, each with a varying life span. Duffy distinguishes four layers: shell, services, scenery and set (Brand, 1994). Stewart Brand revises these layers and defines six instead:

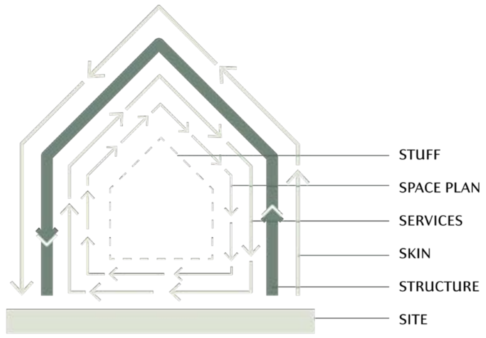

Fig. 9.1 Brand (1994) Shearing layers of change

Site - the geographical setting with an eternal life span;

Structure - The foundation and load-bearing elements, which have a theoretical life span of between 30 and 300 years;

Skin - The exterior facade, which is acknowledged a life span of 20 years, mostly because facades are adapted to keep up with current trends;

Services - This layer entails all the wiring, plumbing and other technical systems, with a life span of 7 to 15 years;

Space plan - The interior layout including walls, ceilings, floors and doors. This layout can be changed every 3 years in commercial spaces, to 30 years in residential spaces;

Stuff - All things that can be freely moved without too many implications, like furniture, lamps, appliances. While the life span of the product might be longer, their position in the space might change daily to monthly (Brand, 1994).

The longevity of a building is largely determined by the replaceability of the service layer and how well the other layers adapt to this change (Brand, 1994). It is important to grant good access to the service installations. Furthermore, the stuff and the space plan layer, being most visible to the users of the building, are adapted most frequently due to boredom of the current layout (Brand, 1994). The building layers are dependent on each other. There is no changing the space plan, without impacting the structure and vice versa. The layers with a quick pace tear up the layers with a slow changing pace and the slow layers block the adaptive flow of the quick layers the other way around (Brand, 1994). Brand (1994) states: 'An adaptive building has to allow slippage between the differently-paced systems of Site, Structure, Skin, Services, Space plan and Stuff'.

An adaptable building layer design is one where the layers are not embedded in one another. Currently, the potential theoretical life span of a building layer is not completed, because the layers are dependent on one another. When a layer is inaccessible or complicated to replace, complete buildings are sometimes demolished, while the other building layers have not fulfilled their duration yet.

9.2 Options

Finishing layers floor I Layer configurations I Prefabrication

Finishing layers floor

Timber floors generally require a concrete top layer to improve the structural performance, and the sound proofing and fire safety properties by increasing the mass of the floor slab. The additional mass also reduces any unwanted vibrations within the building (Kaufmann, Krötsch, & Winter, 2018). To act as one floor element, the concrete slab and the timber floor have to be connected through a rigid, shear-resistant connection. Traditionally, a layer of concrete is poured onto the timber floor on site. This goes against the principles of an adaptable design, because the layers cannot be easily deconstructed this way as all floor elements are attached to each other. There are also mechanical connection options available, through which a prefabricated concrete slab is attached to the timber floor. The connection can be established through dovetail joints, screws, or steel plates as can be seen in figure 9.2 (Kaufmann, Krötsch, & Winter, 2018).

Facade

A facade is the outer shell of a building, realizing a stable and controlled interior environment. A facade often consists of the following components: carrier, finish, insulator and supplementary (Deniz & Doğan, 2014). Sometimes one layer can fulfill the function of multiple components. A facade is placed either in front or in line with the load-bearing structure.

Prefabrication

Chapter 8 Kit-of-parts, explains how a structural system can be produced in different levels of prefabrication. With minimal prefabrication, the system consists of separate building components that are assembled on site. With a high level of prefabrication, the system is produced in three dimensional modules, which require minimal labor on the construction site. Similarly, the other building layers can be prefabricated or separately installed on site. For example, a facade can be prefabricated into panels which include the insulation, finishing layers, cladding, etcetera, or these layers can be applied separately. Like mentioned before, an adaptable building layer design is one where the layers are not embedded in one another. So with both prefabrication and on site labor, the different layers have to be demountable, to be able to access every individual layer up to the load-bearing timber structure.

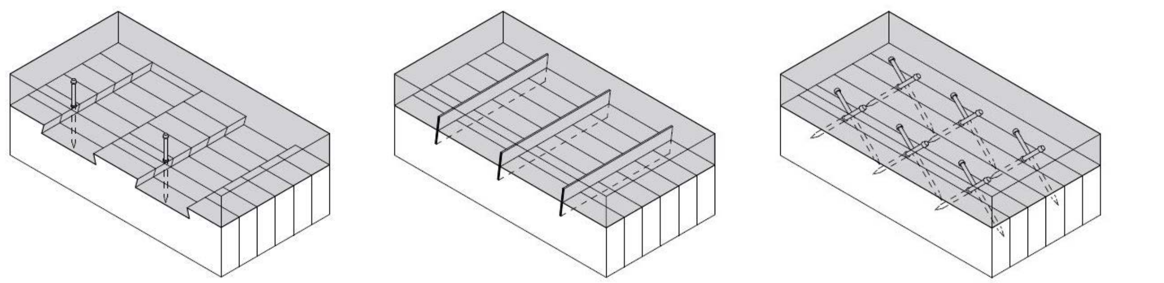

Fig. 9.2 Kaufman, Krötsch & Winter (2018) Mechanically connected concrete timber floors

9.3 Recommendation

Skin I Services I Space plan

Skin

For an adaptable external wall, it is important that each layer executes only one function and that the individual layers can be demounted independently and easily (Deniz & Doğan, 2014). This also benefits the recycling process at the end of life.

The adaptable connection of the system relies on tolerance in line with the plane of the facade. Anything placed inside the load-bearing frame obstructs the adaptability of the system. To maintain the accessibility to the connection node and the movement of individual components, the facade is placed in front of the structure.

Services

The service layer consists of the installations present in the building, for example the ventilation, water pipes and electricity. Commonly, the installation infrastructure is placed underneath the ceiling. The installations can be incorporated into the floor system, hidden by a lowered ceiling, or kept in sight. For an adaptable system it is best if all layers are independent of other layers and can be maneuvered individually. The incorporation of installations into the floor system is therefor not a recommended adaptable option. The installations would be wired through multiple floor elements, indirectly connecting them and compromising the individuality of the structure.

Space plan

In an adaptable building, the floor plan should be able to change to fit different programs. There are already various flexible interior wall systems available on the current market, for example the flexible office wall system by NxtWall. As opposed to the placement of the facade in front of the structure, the interior walls connect to the structure in line with the frame. If the load-bearing structure is adapted, the interior walls probably also require a different position and have to be (re) moved anyway. After removal, access to the structural connection is available again.

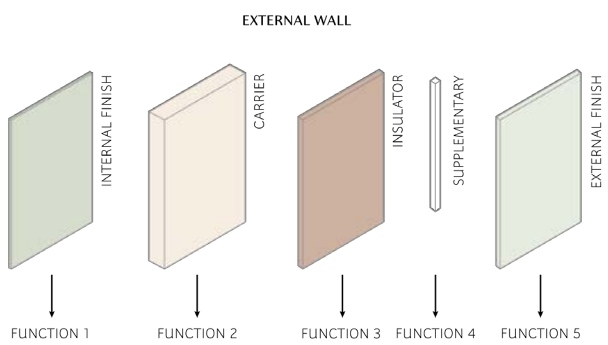

Fig. 9.3 Deniz & Doğan (2014) External wall layers

Fig. 9.4 NxtWall (2018) Flexible office wall system

9.4 Design proposal

Floor system I Facade connection I Interior finish I Evaluation

Figure 9.5 and 9.6 present a detail of a vertical section where the floor lays on top of the structure and the facade is connected to the structure based on the proposed independency principle of different building layers.

Floor system

A concrete slab is attached on top of the timber box floor system. The prefabricated slab is attached through mechanical dowel connections, ensuring the demountability of the floor system. The box floor is filled with insulation material for acoustic and thermal purpose.

Facade connection

The facade connects directly to the connection node. This way, the columns and beams coming of the node can still be moved. It is important that there is no overlap between different external wall panels, because panels should be able to be removed individually if needed. The gap between the two external wall panels is closed with an additional finishing plate.

The specific configuration of the external wall - see figure 9.3 - is not determined because it does not fit into the scope of this research.

Interior finish

The hardwood used for the structure does not require an interior finish layer for protection purposes. An interior finish can be applied for aesthetic purpose, but it has to be attached through a dry connection, so that it can be removed if necessary for adaptation activities.

In case no finishing layer is applied, the steel connectors are also unprotected. This potential issue is further touched upon in chapter 11.

Installations

The installations are hung underneath the floor system. A suspended ceiling can be added until 300 mm underneath the floor, to maintain accessibility to the secondary connection of the load-bearing structure. If larger installations are required for the function of the building, a larger secondary attachment component could be applied to increase the suspended ceiling height.

Evaluation

Additional building layers covering the structure (durability) **2**
Additional finishing layers are possible but not required.

Minimal additional building layers covering the structure/connection node (accessibility) **4**
Additional finishing layers are possible but not required. The secondary connection is not obstructed by the facade, floor or installations.

Additional building layers are removable **4**
All other building layers, facade, floor, are installed with a mechanical connection that can be demounted.

Visible connection system **5**
The secondary connection is visible during the finished state of the building and accessible for adaptation activities.

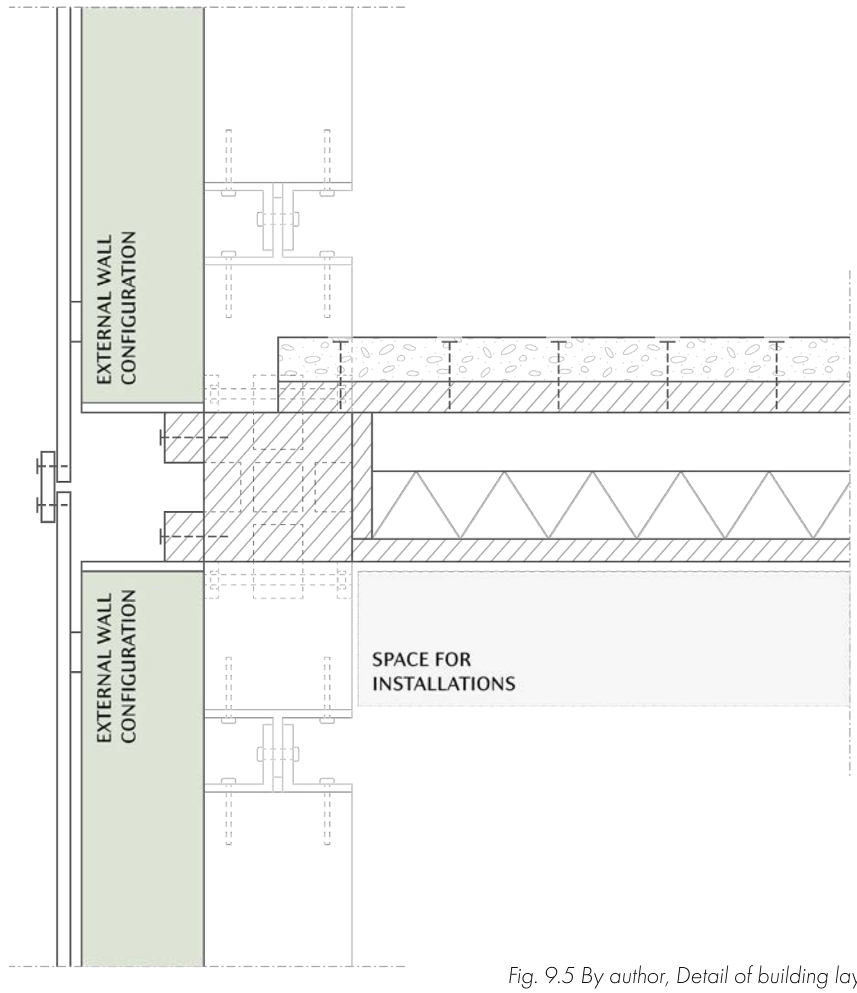

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Fig. 9.5 By author, Detail of building layers to bearing structure

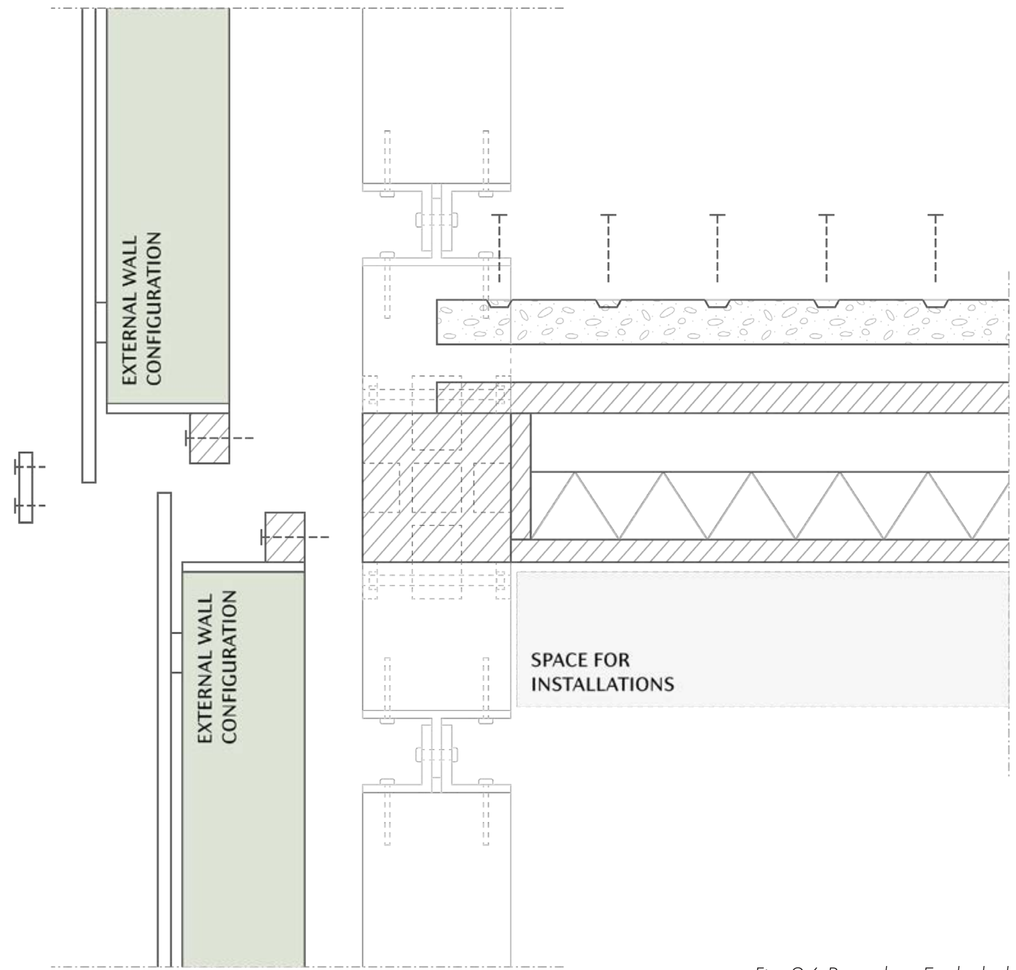

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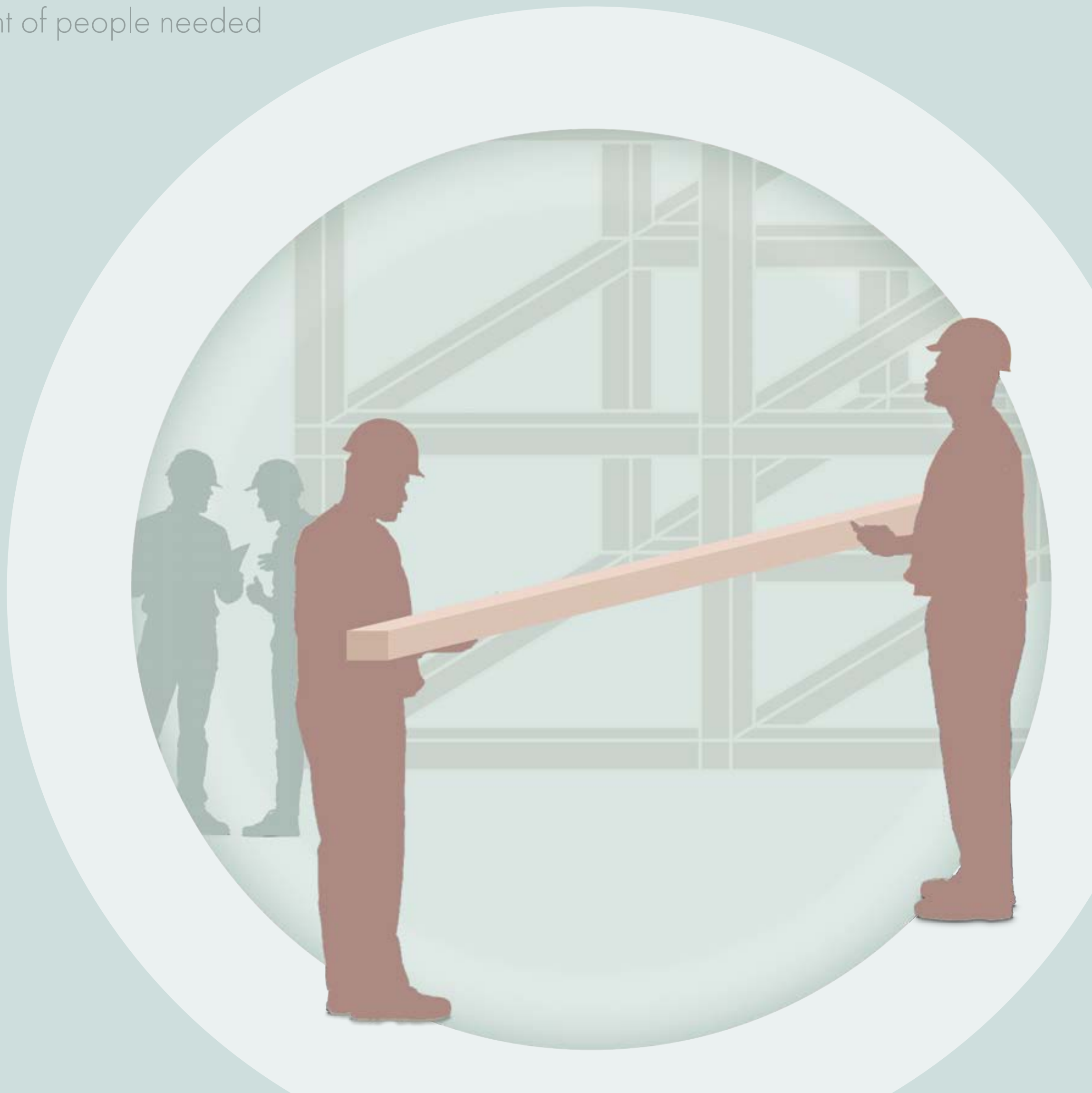
Fig. 9.6 By author, Exploded detail of building layers

Chapter 10

Construction process

Design criteria

- More tolerance around components and connection node
- Little disturbance of other components when handling one component
- Minimal steps in assembly
- Catalog of building components
- Costs little time to construct
- Minimal experience or training needed
- Minimal mechanic aid needed
- Minimal amount of people needed



10.1 Background information

Temporary structures I Limitations builders I Durability of wood

Temporary structures

Temporary structures stabilize a structure during a construction process and assure the safety of construction workers. They can be completely dismantled when the permanent structure is self-supporting and stable, or the temporary structure is part of the final result.

There are different types of temporary structures, each serving a different purpose:

- Temporary structures that help with the accessibility of the construction project for construction workers, like scaffolding, ramps, runways and platforms;
- Temporary support and stability structures, like falsework, shoring, bracing and guying;
- Molds, like concrete formwork;
- Site protection structures, like sidewalk bridges, fall protection boards and nets (Ratay, 2004).

The temporary structures focused on for the design proposal of an adaptable structural system are those assisting with the support and stability of the main structure, while one of the sub-scenarios is executed.

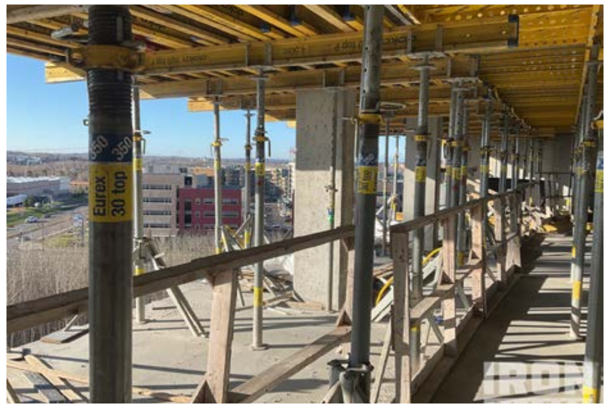


Fig. 10.1 Iron Planet (n.d.) Falsework temporary structure

Weight limitations builders

In the Netherlands, there are no legal limitations about the working circumstances of the builders on site apart from the general consensus that a construction site should be a safe place to work.

Generally, the maximum weight allowed to be lifted by singular employees is 23 kilograms and objects heavier than 50 kilograms have to be moved using machinery (Ministerie van Sociale Zaken en Werkgelegenheid, 2018).

Durability of wood

After wood for a timber construction is cut, the water present in the material starts to evaporate. Moisture in wood is categorized into two groups: free water in the cell cavities and bound water held in the cell walls. When all the free water is evaporated, the wood reaches a stable saturation point of 30 percent on average (Wang, 2016). However, when external factors are extremely humid and the wood is exposed to condensed water for a longer period of time, this balance can be disrupted.

It is highly important to prevent wood being exposed to moisture, to prevent durability issues during construction and throughout the service life of the timber component. Decay caused by moisture can seriously affect the strength of a timber structural component. Moisture issues are particularly challenging with hardwood materials. Especially when using beech, since this wood specie has a significantly stronger shrinkage and swelling response in comparison to softwoods.

The factors carrying risk of decreasing the durability of the material as formulated by are:

- Construction weather conditions;
- Wetting potential of the wood materials/built-up assemblies;
- Drying ability of the wood material/built-up assemblies;
- Durability related risks after wetting and insufficiently rapid drying;
- Appearance deterioration risks of exposed wood members and finishing materials;
- Location of the assembly in the building and associated impacts on exposure and drying (Wang, 2016, p. 3).

There are certain measures that can be taken to minimize the risk of decay:

- Using prefabrication as much as possible to reduce on-sit exposure time;
- Scheduling framing and enclosure in a drier season, whenever possible;
- Coordinating material delivery for just-in-time installation to reduce on-site exposure time;
- Keeping materials away from ground by placing them on dunnage with sufficient clearance to permit airflow under the packages;
- Storing materials in well-ventilated shelters;
- End-sealing exposed grains of wood members, such as by using a water repellent or a primer;
- Using wraps and tarps to prevent rain ingress during storage and construction (Wang, 2016, p. 23).

To improve the durability of the hardwood building components, they are impregnated by a resin, which prevents water from penetrating the material. Keeping the moisture content in the wood on a constant low level ensures that mold cannot grow and that the wood deforms less (Merz, Niemann, & Torno, 2021).

Production methods

The current production tools and methods in the timber industry are all optimized for the production of softwood. The use of these production tools on hardwood has proven to be unsuccessful and resulting in greater material waste, what goes against the principles and goals of a circular economy as previously discussed. If or when hardwood products will be applied in the building industry on a greater scale, new production tools and techniques have to be developed.

10.2 Options

Sub-scenarios step-by-step

There are four types of sub-scenarios that each require a different construction process. A list of steps describes the steps necessary to execute the sub-scenario, specifically focused on the potential necessity of a temporary structure during the adaptation process.

Node adapted to connect to more components

- Locate concerning node
- Remove additional building layers where new component will be attached
- **Install temporary structure if necessary**

Option 1:

- Mount secondary attachment to node
- Mount beam/column to secondary attachment

Option 2:

- Mount secondary connection of prefab component

- **Remove potential temporary structure**
- Re-install additional building layers

Beam is replaced

- Locate concerning beam
- Remove additional building layers
- **Install temporary structure**
- Demount secondary connection
- Remove beam out of its original place
- Position new beam in place
- Remount secondary connection
- **Remove temporary structure**
- Re-install additional building layers

Floor element is replaced or removed

- Locate concerning floor element
- Remove additional building layers
- Remove floor element

Option 1:

- Position new floor element
- Re-install additional building layers

Option 2:

- Install building layers to finish new configuration

Column is replaced

- Locate concerning column
- Remove additional building layers
- **Install temporary structure**
- Demount secondary connection
- Remove column out of its original place
- Position new column in place
- Remount secondary connection
- **Remove temporary structure**
- Re-install additional building layers

10.3 Recommendation

Supported parts per scenario

Node adapted to connect to more components
Since there is no building component removed but only added in this sub-scenario, there is no need for a temporary structure. Unless it is a large scale project where additional storeys are added, for example. In that case, the temporary structures that are also used during the initial construction process are necessary.

Floor element is replaced or removed
Since the floor element is not load-bearing in this structural layout, there is no need for temporary support, unless there are multiple floor elements, beams and columns removed to create an atrium for example. Then, additional support is needed until the floor above is enforced to span the atrium distance.

Beam is replaced
When a beam is removed, the floor elements that were laying on top of that beam require temporary support until the new beam is installed.

Column is replaced
Since loads of a building are transfered through the columns to the foundation, it is important to account for enough support to temporarily account for these loads. For safety, multiple posts are placed underneath the beams that connect to the connection node of the regarded column.

10.4 Design proposal

Replacing a beam I Evaluation

Replacing a beam with temporary falsework

This chapter previously describes the different options for temporary structures, of which falsework is recommended for the execution of the chosen sub-scenarios. For the four sub-scenarios a list of steps is provided. In the following diagrams, those steps combined with the recommended temporary structure are illustrated for the following sub-scenario: Replacing a beam.

Step 1
The beam that has to be replaced is located and the additional building layers are removed locally. In this case that would be the ceiling finish and possible installations.

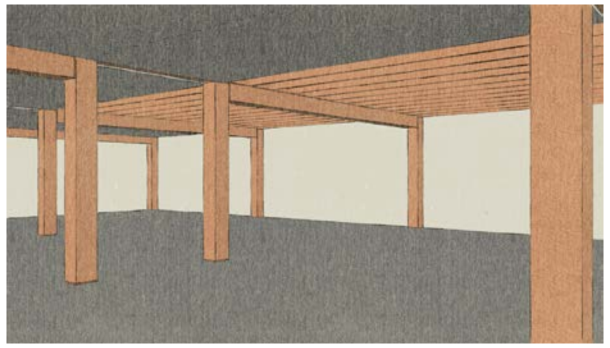


Fig. 10.2 By author. Ceiling finishing layers removed

Step 2
The falsework is installed. Two sets of falsework are used to temporarily carry the forces that the beam would have carried normally. Additionally, it keeps the floor elements in place that were originally positioned on the beam. The falsework consists of a beam, which is supported by several small columns. The two falsework installations are placed at a distance from the beam that has to be replaced, in order to keep enough space for the construction workers to work and maneuver the beam.

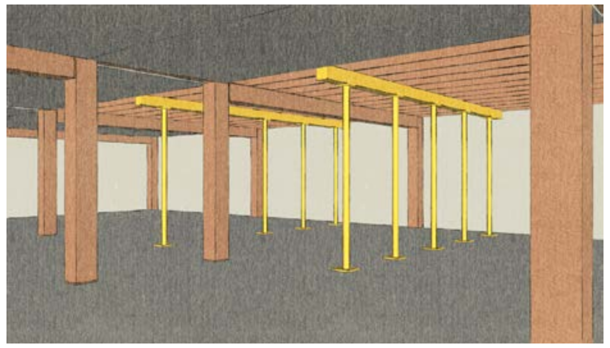


Fig. 10.3 By author. Falsework installed

Step 3
After installing the falsework, the secondary connection of the beam can be disconnected and the beam can be lowered out of place. Chapter 8 Kit-of-parts explains what the movement limitations are for each building component. The beam can only be moved downwards without influencing surrounding components.

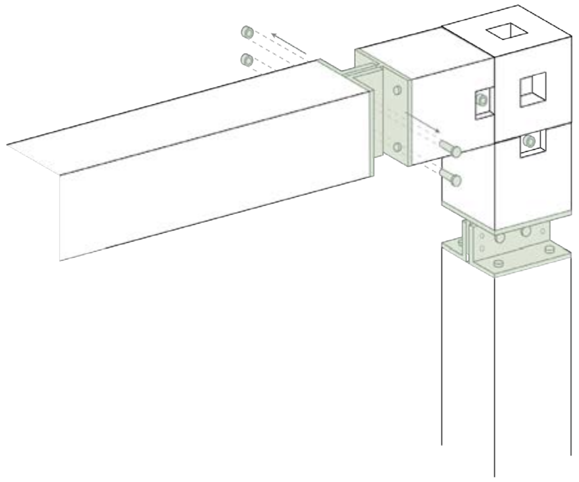


Fig. 10.4 By author. Secondary connection demounted

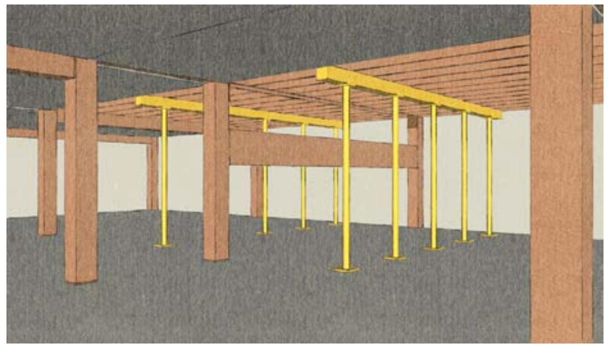


Fig. 10.5 By author. Beam moved out of original place

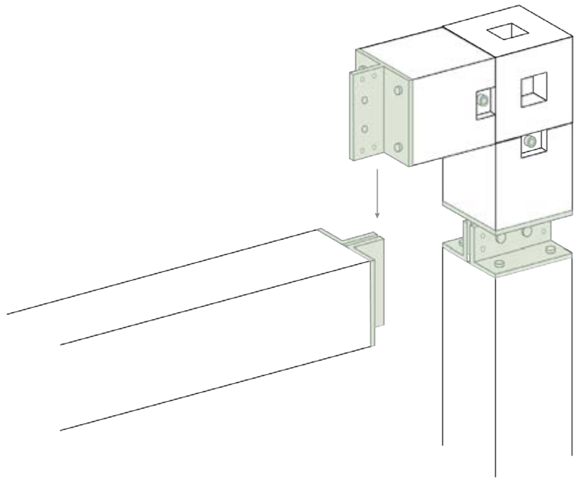


Fig. 10.6 By author. Beam lowered out of original position

Step 4
When the original beam is moved out of its original space, you are left with an empty void with two secondary attachment components, to which a new beam can be connected. To do that, the previously explained steps have to be executed in reverse.

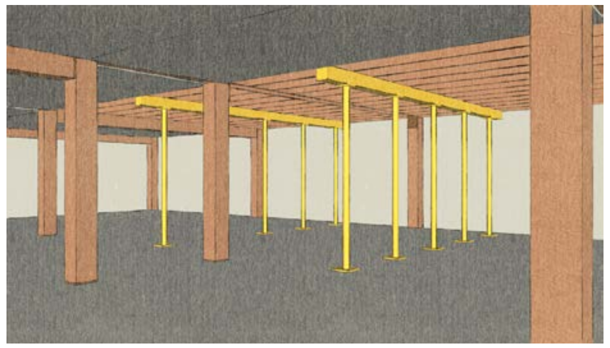


Fig. 10.7 By author. Empty void ready for new beam component

Evaluation

More tolerance around components and connection node **4**
The tolerance around the connection node and other components is facilitated both by the connection design, as well as the placement of the temporary support structure. The secondary connection node has a length of 300 mm, creating the same amount of tolerance around the node to manipulate the connected components. The temporary structure has to be placed at a certain distance from the -to be adapted- component, in order to create enough space for the construction workers to work comfortably and install the mechanic equipment to move the component.

Little disturbance of other components when handling one component **5**
It depends on which sub-scenario is being executed, but in general the connection principle is mainly developed around the idea that individual components could be moved without disturbing other components. For example, when replacing a beam, only the finishing layers have to be temporarily removed to access the beam. The other structural components can remain in their spot.

Minimal steps in assembly **2**
Related to the previous criterion, both the initial construction and adaptation process are simple. Both connections are dismounted by loosening one or two bolts, resulting in minimal steps.

Catalog of building components **5**
Keeping a catalog of the used building components in a building has not been explicitly mentioned before, but since the kit-of-parts consists of a small number of unique parts, it is relatively easy to keep track of which components are present in a building structure and what their properties are for future adaptation processes.

Costs little time to construct **4**
The initial construction process is executed by hanging the beams between rows of columns and securing the connection with a pin fastener. This process is relatively simple and should cost little time to construct. During the adaptation process, there is minimal intervention of other components needed.

Minimal experience or training needed **1**
Although the connections are innovative, they are based on established timber connection principles. On the other hand, Handling individual components within an existing building is not common practice currently, this might require additional training. Lastly, for the production of the prefab timber components training in working with hardwood is necessary.

Minimal mechanic aid needed **1**
Hardwood is a heavy material. In the construction process example given in this chapter, a beam needs to be lowered from the ceiling. This cannot be done without mechanic aid. After, the beam will need to be transported out of the building. This can also not be done without mechanic aid.

Minimal amount of people needed **2**
This evaluation point is difficult to draw a conclusion on, because estimating the amount of people needed is a theoretical guess. For the adaptation process, there are fewer people needed than for the initial construction, since that is a larger scale intervention.

Chapter 11

Non-circular criteria

11.1 Moisture

Moisture in wood I Uncovered steel

Moisture in wood

Wood is a material that is able to release and absorb moisture at equilibrium with its surroundings. The benefit of this property is that it takes a lot of water before the moisture level in the material is high enough to risk the growth of mold, which can harm the structural integrity of the timber component. The downside of the ability to balance the moisture content with the surrounding environment, is that the varying moisture level can lead to the expansion, shrinkage and warpage of wood.

Wood only shrinks or expands if the moisture contents are below the fiber saturation point for a longer period of time. The fiber saturation point is reached when all the wood fibers are fully saturated with water at about 28% moisture, but the material stabilizes at 8-14% moisture in an indoor environment. If the wood has a moisture level higher than the fiber saturation point for a longer duration, that is when the growth of mold happens (Steffen, 2000).

To prevent the build-up of water in the structure it is crucial to install a vapor barrier in the external wall configuration and provide ventilation and drainage for any moisture that does enter the structure to be eliminated easily and quickly.

Uncovered steel

The secondary connection of the adaptable system is made from steel connection anchors. In the final state of the building, these steel connections are uncovered if no additional finishing layer is applied. There are potential issues that can occur when untreated steel is uncovered, especially when it is in direct contact with wood. Steel is susceptible to corrosion and rust if it is exposed to moisture and oxygen. Corrosion is the process of oxidation due to the presence of moisture and oxygen on the surface of the metal. Wood can act a source of moisture for this process (Umney, 1992).

Over time, the structural integrity of the steel connection anchor can be weakened and pose safety hazards. Another negative consequence is the decrease in appearance quality of the material (Umney, 1992).

There a certain precautions that can be taken to prevent the corrosion of steel. In the detailing of the connection node a few things have to be taken into account. There should be no corners in the connection where moisture or debris can get trapped. Furthermore, crevices should be avoided. If there are any crevices in the final design, they should be sealed. Finally, enough drainage and ventilation should be assured to prevent lingering of moisture on the steel. After the connection has been detailed for minimal risk on corrosion, a coating is applied. This can be a paint coating or a metallic coating (SteelConstruction.info, n.d.).

Another solution for this particular research is to rethink the design of the secondary connection and develop a connection without a secondary metal material, or a steel connection in which the steel is not exposed in the final structure.

11.2 Fire safety

Regulations I Steel connections

Regulations timber buildings

In the Netherlands, regulations about the fire safety of structures are formulated in the Building Decree 2012 (Bouwbesluit 2012). Timber structures also have to comply to the regulations in the Building Decree 2012. The regulations describe measures to prevent the spread of fire, early warning of fire and means of escape. The latter two relate to installations like smoke detectors and fire alarms and the general layout of the grid respectively. There are also measures specifically focused on the material of the structure, in this case timber.

When a timber structure catches fire, the outer layer of the wood burns into a protective charcoal layer. A complicating factor when using laminated timber products is the effect of heat on the glue layer in between lamination layers. If the layer of glue, to which the protective charcoal layer is attached, fails, the protection falls off and fresh wood is exposed. This then burns into a new charcoal layer. With every bit of the wood burnt, the structural integrity of the timber is compromised. To account for this, the timber elements are over-dimensioned with roughly 50 mm. Other possible precautions are fire proof plating to cover the structure, or installing a sprinkler system.

Steel connections

The fire safety of a complete structure is highly dependent on the performance of the connections. The strength of steel reduces by elevated temperatures. The Dutch Building Decree from 2012 states that the structure should be able to remain its structural integrity for 30 minutes, allowing for users to use escape routes out of the building (Rijksoverheid, 2012).

Steel connections can be protected against fire with various methods. With boards, a case can be build around the steel connection. Otherwise, the connection can be protected with a cementitious spray. This can influence the adaptability, however, since the bolts of the connection lose their demountability (SteelConstruction.info, n.d.-b).

When protecting the timber and steel connections with gypsum board, the connection between gypsum board and load-bearing structure has to be demountable and independent, to maintain easy accessibility to individual building components and the secondary connection.

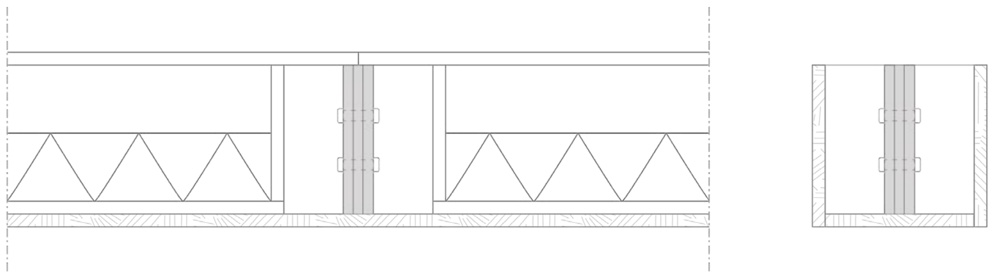


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Fig. 11.1 By author, Gypsum board fire protection

11.3 Producibility

Complex timber components

Elongating laminated components

The length of a singular timber plank depends on the available tree stock and the length of a tree. Often, the required length to span the distance of the structural layout is larger than the available wood. For the beam and column components a finger joint technique is used to make longer spans of the glulam material. This is done by creating a zigzag patterns on the ends of the timber components, which is then interlocked with another zigzag edge and fixed by friction and a glue bond. After, the lamination of the layers is established.

Complex timber components

In the adaptable connection, there are two components with a complex three dimensional shape, shown in figure 11.2. These components are made of hardwood timber and have various notches that create the desired joinery connection of the primary connection. To produce components like these, a CNC machine can be used. A CNC machine can precisely make compelx recesses, roundings and notches into wood, based on a preset calculated milling path using a rotating tool (mill). This method has a high precision and ensures that the joinery connection fits well. It also eliminates the need for highly trained carpenters(CNC-STEP GmbH & Co. KG, 2021).

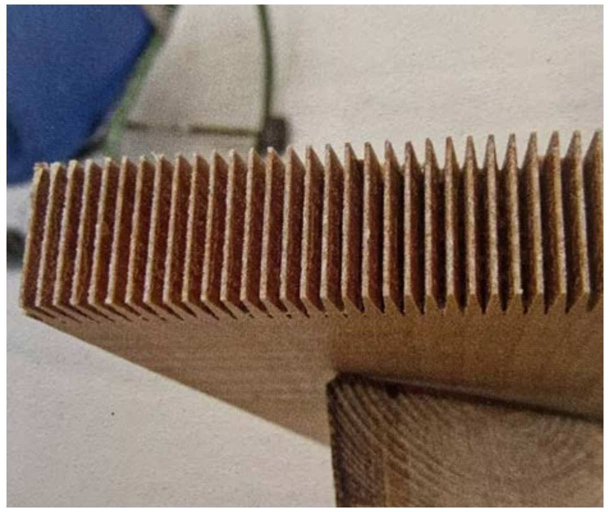

Fig. 11.2 Merz, Niemann, & Torno (2021) finger joint

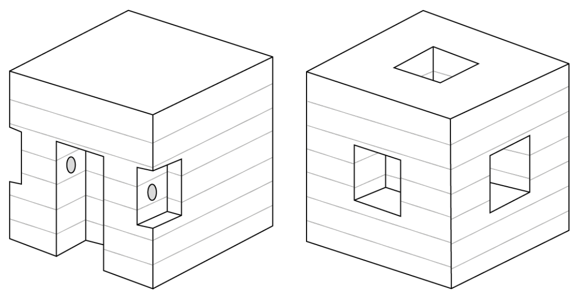

Fig. 11.3 By author, Complex 3D kit-of-parts components

Chapter 12

Case study

12.1 Case study description

Scenarios I Sub-scenarios I Euregon office building I Design domains

Chapter 6 to 10 discuss the five design domains which together form a design proposal for an adaptable structural system. Theoretically, the system of the design proposal can be used to execute changes to the building so that it keeps up with changing functional and technical requirements. Because it is impossible to predict the exact occurrences during the life span of a building, scenarios are used to account for different time sequences in which the building changes.
A scenario is the description of a dynamic slice of the future life cycle of a building which entails a description of the users, their actions, the motives behind the actions and consequences for the building design. In this case the focus is on the consequence for the load-bearing structure. The adaptations that need to be made to the structure because of the scenario are expressed by sub-scenarios. The sub-scenarios that are designed for within the scope of the thesis are as follows:

- Floor element is replaced or removed
- Node adapted to connect to more components
- Beam is replaced with larger alternative
- Column is replaced with larger alternative
- Defective beam is replaced
- Defective column is replaced

Chapter 3.2 further explains the selection and formulation process of these sub-scenarios.

Case study

To further evaluate the feasibility of the design proposal, the structural principle is tested through a case study. Within the case study, the possible life span of a building is described. During the life span, there are two scenarios that occur for which the structure of the building has to be adapted. The first scenario is one where the program of the building changes from an office building to an apartment building. To accommodate a different function in the same building, a few structural changes have to be made: balconies are added to the north facade, an elevator shaft is added, the staircase is moved. The second scenario describes a situation in which the end of life of some of the building components has been reached. To extend the life span of the structure, the defective components are replaced with new components.

These two different scenarios are chosen because one of them exemplifies a scenario in which the owner of a building voluntarily decides to adapt the building to fit the current market better and thus expands the life span, and the other is a scenario in which adaptation is required because the life span of a building component has ended.

Fig. 12.1 Pollmeier (2023) Euregon AG office building

Euregon office building

For the case study an existing project is used. It concerns the Euregon office building in Augsburg, Germany, designed by Lattke Architekten. This building has been built with a hardwood timber construction, not specifically developed to be adapted throughout the future. In order to test the design proposal in the case study, a few changes are made to the building project. For these changes, a balance between maintaining the original design of the building and the integration of the design proposal is attempted. For each domain is described which changes are made or are not made:

Material
The original project was already constructed with a hardwood product. The same Baubuche GL75 product by Pollmeier was used for the design proposal. This means that the same material properties are valid for both the design proposal and the case study project and no changes have to be made.

Structural layout
For the case study the original structural layout of the project is assumed. The building consists of a grid with two chambers of 5.10 meters on either side of a 2.40 meter wide corridor.

Kit-of-parts
The kit-of-parts of the design proposal is applied to the case study project. Instead of the dovetail connection, the adaptable secondary connection principle is considered. The cross-sections of the components maintain the same dimensions as in the original project. The columns are 200 x 200 mm, the beams spanning 5.10 have a cross-section of 200x400 mm and the beams spanning 2.40 meters have a cross-section of 200x200 mm. Consequentially, the connection node is 200x200x200 mm and the secondary attachment is as well.

Building layers
The locations of the building layers in the case study correspond with the design proposal. The location of the facade in the case study project is in front of the load-bearing structure, for example. The exact configuration of the external wall layer remains like the original project, since it is not part of the scope. The floor system is adapted to the proposed box floor system with mechanically connected prefab concrete.

Construction process
The construction process depends on what sub-scenarios are executed. The aim of the design proposal remains: to handle the building components individually. During the adaptation process, temporary structures are applied where necessary.

To summarize, the structural principle as developed in the design proposal with the secondary connection principle and box floor system, is applied to the grid structure of the case study project. The building layers of the original project remain to preserve the architectural design. The construction process depends on the occurring scenarios.

In the case study, the life span of the building is followed from initial construction to 50 years into the future. 50 years is chosen for the case study because the estimated life span of the Baubuche GL75 building product is 50 years, provided that the product is subject to appropriate installation, use and maintenance (Austrian institute of Construction Engineering, 2021). During the life span, two different scenarios present themselves that require adaptation of the building. The technical and practical implications of the scenarios in combination with the design proposal are considered and the limitations and opportunities of the adaptable principle are defined. In the scenario description, the building is described as being initially built with the adaptable structural principle. The scenarios described are not based on actual events, but describe a possible life sequence of the building, as if it were initially built with the adaptable structure from the design proposal.

Scenario 0

2016 – Completion of the office building
The construction process of an office building in Augsburg, Germany is complete. The software company Euregon AG moves into the building. The floorplans of the three storey building consist of multiple office spaces, meeting rooms that can be converted into bigger seminar rooms, a lounge, toilets, and a corridor in the middle of the floor plan that connects all the spaces. A loggia is positioned across the entire length of the south facade.

The office building is constructed with an adaptable timber building system. This means that future changing functional requirements can be facilitated easily.

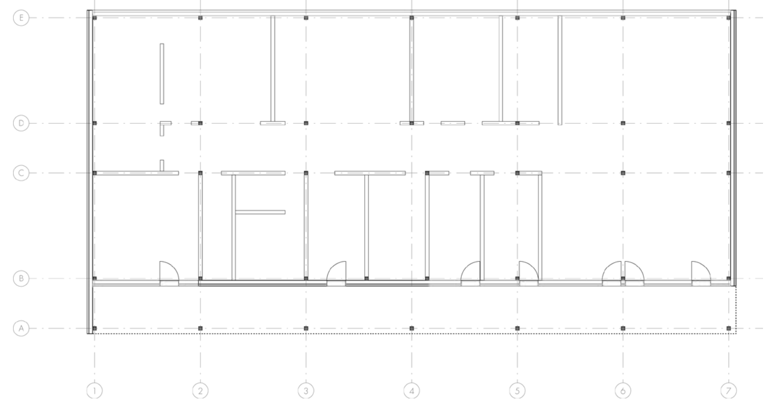
Fig. 12.2 Second floor Euregon building 2016

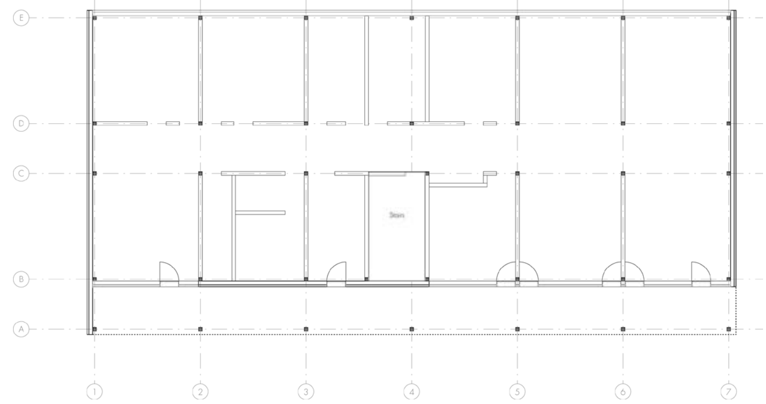
Fig. 12.3 First floor Euregon building 2016

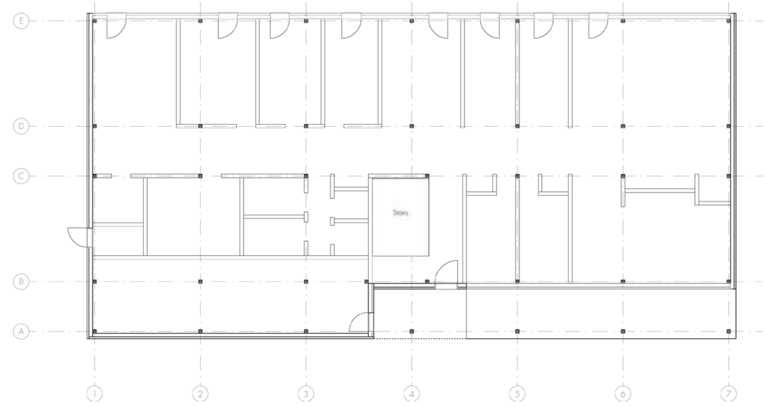
Fig. 12.4 Ground floor Euregon building 2016

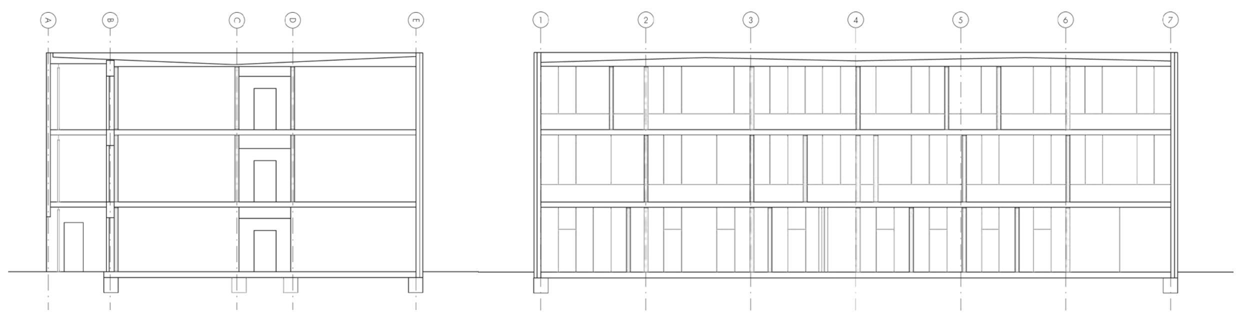
Fig. 12.5 Sections Euregon building 2016

12.2 Scenario 1 - 2036

Transformation I Stakeholders I Technical challenges

It is the year 2036, 20 years after the completion of the office building. Euregon AG has outgrown the space of the office building and moves to a larger building elsewhere. The property is sold to an investor that plans to transform the office building into an apartment building. The need for housing is in fact much higher than the need for office space at this moment. The investor notices that the general layout of the current building has much potential for apartment floor plans, but a few large adaptations have to be performed to make the building completely suitable.

Instead of the small entrance that the building has now, the investor decides to move the entrance and staircase to the corner of the building where there is more space. The extra space enables the addition of an elevator shaft, which presence is preferable in an apartment building. The irregular position of the columns surrounding the previous entrance are moved back into the grid, to maximize the efficiency of the floor plans of the apartments.

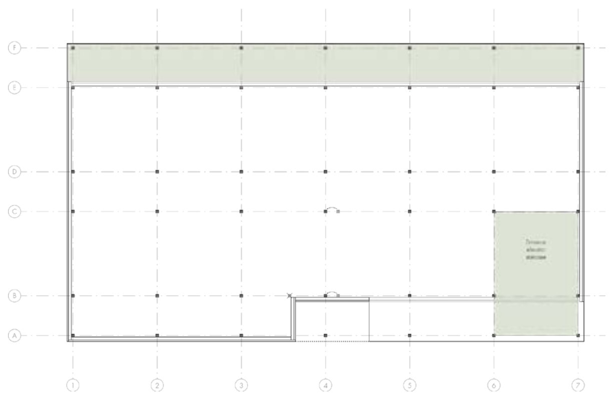

Fig. 12.6 Ground floor Euregon building 2036

Other than that, there is currently only a loggia on the south facade, but an outdoor space is preferred for all apartments. Another loggia is added to the north facade of the building.

Stakeholder analysis

For any building or renovation project there are various stakeholders involved. The added aspect of adaptation might require additional contributions or knowledge from the stakeholders. Figure 12.7 provides an overview of the stakeholders involved during the transformation of an office building to an apartment building and their relation to each other. Also, a description of the stakeholders' responsibility in general and in regards to the adaptation aspect is provided.

Property developer/owner
This is the instigator of the transformation process and the one who owns the property. The property developer hires the architect, engineers, and contractors to execute the design and construction of the transformation. The property developer has an external or intrinsic motivation to adapt an existing building instead of investing in a new development project. It is the task of the property developer to maintain the preset transformation goals throughout the project.

Architects and engineers
These two stakeholders work closely together to look at the existing plans of the building and redesign the building's layout, plumbing, electrical, and of course any changes to the structural system. They are hired by the property developer and work closely together with the contractors. Both the architects and the engineers have to be familiar with the adaptable structural system and know its limitations and opportunities. If the system is applied on a large scale on a lot of building projects, a group of architects and engineers could specialize in designing with this building system.

Contractors and subcontractors
These stakeholders are responsible for the execution of the construction process and perform the specifications outlined by the architects and engineers. Because the structure is made with a specific kit-of-parts, the building materials are sourced directly from the supplier of the adaptable building system. The contractors working with the system need to know how the connections work and how to manage the building components. Then there is the additional niche of working with a hardwood material, which requires some expertise. Since the building components are prefabricated of site and no material manipulation has to be performed during construction, the needed expertise is limited to protecting the material to moisture and maneuvering the components.

Supplier
This is the provider of the kit-of-parts to the contractors. The supplier could also be the developer and manufacturer of the adaptable structural system. Since the transformation is done with a specific system and not with standard products, the supplier also functions as potential guidance for the design team should there be information required about the system.

Government agencies
The provide legal and regulatory oversight to ensure that the transformed building conforms to building codes, laws and other regulations. They also generally provide permits and inspections to ensure that the building is safe for the tenants to utilize. There are different building codes for renovated buildings than newly developed buildings, so the building is checked according to those.

Financial institutions
The adaptation of a building is currently mostly done when a building has a monumental status, or out of sustainability considerations. Since the economic feasibility of adaptation is lower than with demolition and redevelopment, the financial institutions might be more apprehensive, unless they are driven by the same motivation as the project developer. The financial institutions provide financing for the transformation process. They might require regular progress reports and ensure that the transformation meets certain financial metrics.

Tenants
These are the end-users of the transformed building. Their needs and requirements are considered during the design process by the architects and engineers. The property developer communicate these needs on behalf of the tenants.

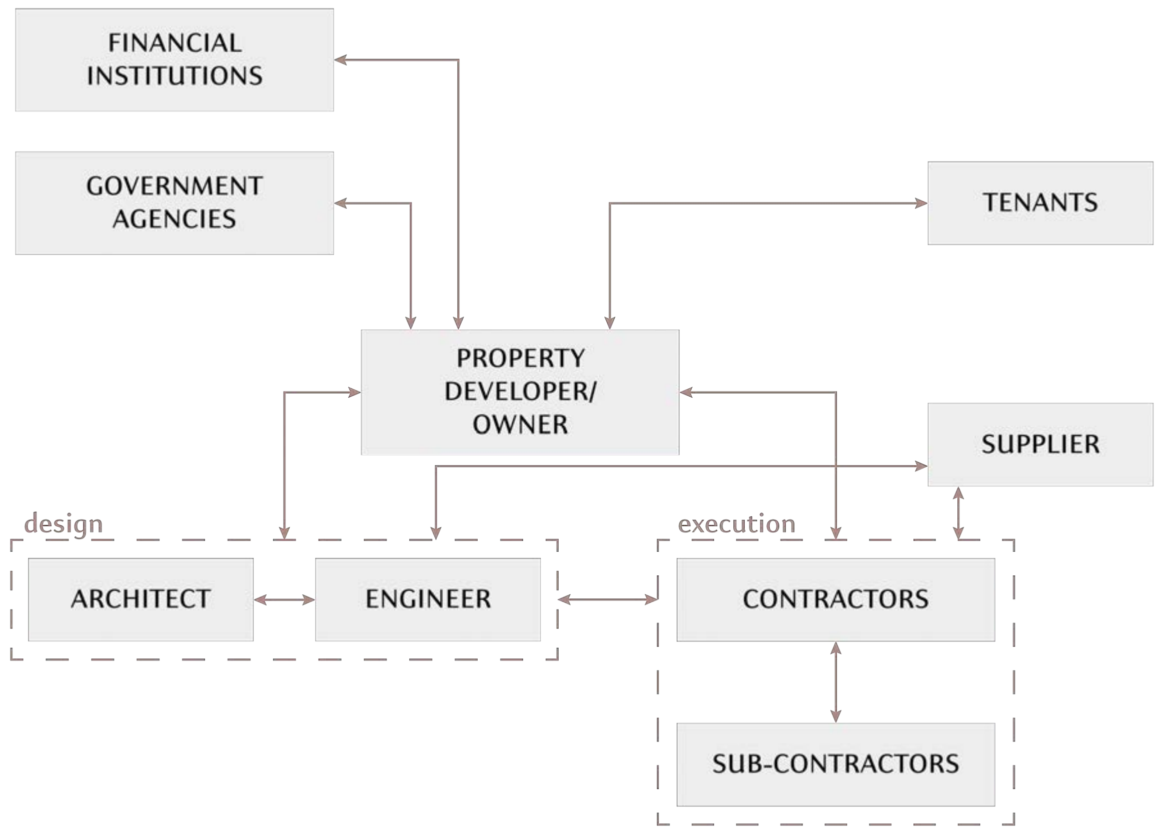

Fig. 12.7 Stakeholder diagram transformation process

Process description and potential challenges

The transformation of the office building consists of a number of adaptations to the building, like the scenario describes. Each adaptation activity involves a sequence of steps to come to the desired result. Throughout the process, technical or social challenges can occur. Those challenges are described in this chapter and hereby the shortcomings of the adaptable system in a hypothetical scenario are evaluated.

Changing program of the building

- The current space layout is designed to fit office activities. Even though the structural layout is suitable for both functions, other building layers have to be adapted to fit the new program. The interior walls have to be removed and the installations have to be adapted as well.

Attaching balconies to the north facade

- Additional concrete foundation blocks are needed to support the columns of the balconies. Since the columns are placed outside the pre-existing grid of the building, the location of the additional concrete foundation blocks is easily accessible. A hole is dug and precast concrete blocks are installed.
- The facade of the office building is a shell around the load-bearing structure. To be able to access the connection nodes of the adaptable structure, all building layers up to this point have to be stripped. Depending on the configuration and the adaptability level of the facade system, this could mean that the entire facade has to be demounted and remounted after the balconies are attached. This results in an extensive process even though the structure is designed for a minimally invasive adaptation process. The least adaptable and flexible building layer creates a bottleneck for the entire adaptation process.
- After the connection nodes are made accessible, the structure for the balconies is attached. The columns in the existing facade need to carry an additional load of the balconies in comparison to the 2016 scenario. A bigger load case requires a larger cross-section to transfer the loads. Either the columns have to be over-dimensioned in advance during the initial design process of the building, or they have to be replaced with columns that have a larger cross-section during the execution of this scenario.
- After the load-bearing structure of the balconies is complete, the other building layers are restored.

Moving staircase

- The existing stairs have to be demounted and moved out of the building. This leaves and empty void.
- The scenario describes how a few columns are placed outside the structural grid in the original situation to accommodate the staircase. The columns could be moved to a location in the structural grid, making it easier to develop floor plans for the apartments. The consequence of moving columns is also needing to replace the floor elements that span from one column to another, since the span changes. Also, depending on how far the columns are moved from their original position, new foundation points have to be added. This is more complex to execute when compared to adding foundation blocks for the balconies, because the columns are located inside an existing building and the site in difficult to access.
- To create a shaft at the new location of the staircase, floor elements have to be removed. The floor element is lifted from the structure and moved out of the building. This activity requires access through the facade that is large enough to fit a floor element.
- When the shaft is created, the new staircase and elevator are installed.

12.3 Scenario 2 - 2066

Replacement I Stakeholders I Technical challenges

It has been 50 years since the completion of the original office building. Since the adaptation 30 years ago, people have been living in the transformed apartment building.

Because of a leakage in one of the apartments, two beams carrying the first floor have been damaged by moisture and started rotting. The inhabitant contacts the owner of the building about the moisture damage. The two beams are replaced by new building components.

Since the expected life span of the timber building components is 50 years, the other components are also checked on their state. Other than the two rotting beams, the components still look good and remain functional. Regular checks are planned in the future and components are replaced when needed. The life span of individual components is carefully cataloged, so the owner of the building knows exactly which beams and columns have been replaced and how old every component is.

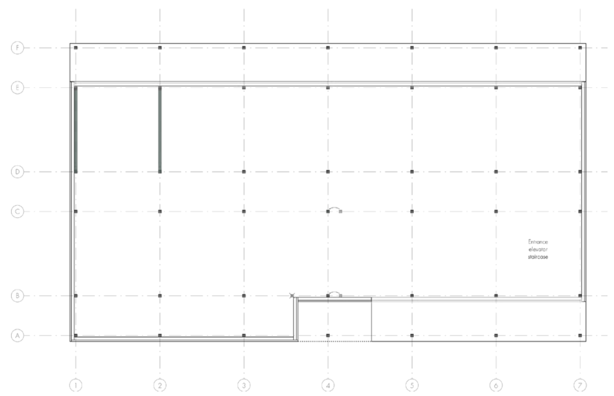

Fig. 12.8 Ground floor Euregon building 2036

Stakeholder analysis

The stakeholders involved in this scenario of replacing two beams is for the biggest part comparable to the stakeholder explanations in the previous scenario. The difference is the nature of the project. Whereas the transformation of an office building into an apartment building is more a design project for which technical knowledge is required, this scenario concerns a technical problem that has to be solved. A short description for some of the stakeholders explains their role in this scenario.

Tenants

In this scenario, the tenants already live in the building and are influenced by the adaptation process. The beams are located in the apartment on the ground floor. The tenants living in this apartment have to move out during the replacement of the beams. One of the beams is located in frame with the house separating wall with their neighbor. Since this wall has to be temporarily be removed to access the load-bearing structure, the neighbor is also influenced by the adaptation process and has to spend time elsewhere during the construction process. This also applies to the upstairs neighbors of the regarded apartment. Even though the floor elements are supported by temporary structures, For safety, these tenants are probably also asked to spend time somewhere else.

Engineers

The engineers are involved in the adaptation process to assess the structural integrity of the building and ensure that the replacement beams are correctly installed. They work together with the contractors for a smooth adaptation process.

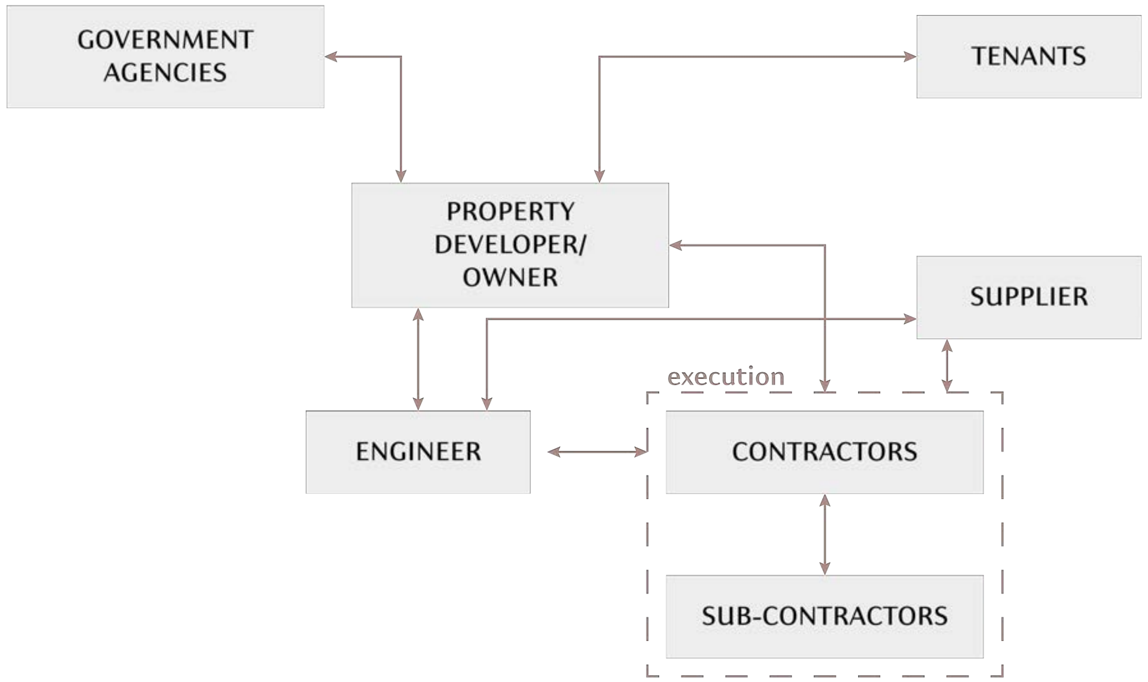

Fig. 12.9 Stakeholder diagram repair process

Process description and potential shortcomings

Replacing two defective beams

- To be able to work on the defective beams, enough space has to be created to work and handle the components. The tenants living in the concerning apartments have to move their belongings temporarily.
- One of the beams is located by the facade, but because the facade is placed in front of the load-bearing structure, the beam is accessible without difficulties. The other beam is located in line with an interior wall that separates two apartments. The interior wall is temporarily removed. This requires an interior wall system that is demountable.
- To support the floor elements, temporary structures are installed. They are placed on either side of the beam, or in case of the facade beam only on the interior side. The defective beams are not replaced simultaneously, since that would mean that one row of floor elements is completely supported by just temporary structures.
- To prepare the beam to be lowered out of place, a machine is positioned underneath the beam. The beam is too heavy to be lifted by the construction workers. The infrastructure of the building has to accommodate for the machine to be easily moved to the desired location.
- After the secondary connection is demounted, the beam is lowered by the machine and lifted out of the building, also with mechanic aid. There needs to be an access point in the facade through which the beams are lifted out of the building. This should be present in all apartments, should adaptable activities need to be performed there.

12.4 Findings

Potential shortcomings I Threshold

Potential shortcomings

Changing the positioning of columns in a structural layout can result in the need of additional foundation supports, depending on how much the new location differs from the initial position of the column. Likewise, when the building is expanded, for example by adding balconies, new foundation points are needed to support the building. Adding new foundation point around the existing grid is easier than adding new points inside the existing building. This issue is not specifically related to the adaptable structural system, but will occur with every structural system during an adaptation process.

The same goes for the changing load case when expanding a building. The columns on the border of the existing structure, that connect to the addition, need to carry an additional load compared to what they were originally dimensioned for. This issue will occur regardless of the adaptability level of the structure. However, this issue could be solved relatively easy with the adaptable structural principle, since the secondary connection allows for the replacement of columns with an alternative that has a larger cross-section.

In general, the adaptability level of a building is dependent on all building layers. Even though the structural system has a high level of adaptability, if the facade is not adaptable, this slows down the entire adaptation process and lowers the feasibility of the project. Scenario 2 describes a situation where two defective beams have to be replaced. One of the beams is located in line with an interior wall. If the interior wall system is adaptable, it can be temporarily demounted and access to the load-bearing structure is granted. Otherwise, the interior wall has to be demolished, creating material waste and a more extensive adaptation process.

During an adaptation process, it is crucial to be able to move the components inside the building and maneuver them from the inside to the outside and vice versa, like the floor elements in scenario 1 and the defective beams in scenario 2. This means that the structural grid and the facade have to be designed with this requirement in mind.

Scenario conclusions

Scenario 1 concerns a large scale adaptation process in which a building is transformed from an office building to an apartment building, requiring multiple changes to the building. Expanding the structure with balconies could be a feasible intervention due to the adaptable system as long as the facade is aligned with the adaptability level of the structure. The interventions inside the building require a more complex process, where multiple components have to be moved in and out of the building. Maneuvering the components is relatively easy in this case, because the interior walls are removed prior because a new floor plan is required for the new function. So there are less obstacles in the way of moving the components.

Scenario 2 describes a maintenance process in which two defective beams need to be replaced. The execution of this scenario is feasible with the adaptable structural system, because the secondary connection allows for a fast construction process. The feasibility is increased when the interior wall is also part of an adaptable -or at least- demountable system. A complicating factor is the fact that tenants are living in the building in this scenario.

Chapter 13

Conclusion and reflection

13.1 Conclusion

Scenario based design I Adaptable design I Hardwood I Further research

Problem statement and a circular economy

The life span of building is unnecessarily cut short by demolition and redevelopment approaches. This approach of building development is unsustainable and has a high impact on the environment. Instead, alternative options like adaptation can be more sustainable and result in less material consumption and waste. It is crucial for the building industry to adopt responsible material consumption and production practices meet the goals of the Paris agreement and to address the triple planetary crises; climate change, biodiversity loss and pollution. Additionally, addressing the rising relative amount of vacancy in the existing building stock by increasing the adaptation of buildings can mitigate social and economic issues.

To address the environmental challenges that arise from the current linear economy model, a circular economy model is needed. In this economy model minimal waste production, extension of the life span of products and materials, and reduction of primary resource use is pursued. Alongside the integration of a circular economy, the use of bio-based materials instead of fossil fuel based materials can significantly reduce the environmental impact of the building industry and store embodied carbon.

Although the adaptation of buildings is a more sustainable approach that provides ecological and social benefits, the barriers surrounding adaptation have to be addressed in order to increase the feasibility of the approach. This includes perceived high maintenance costs, meeting the required building regulations, lack of knowledge about the existing building and the quality of the existing structure.

Methodology

The technical and functional requirements will change during the life span of a building. It is important to treat buildings as dynamic entities that adapt and change in response to their environment, instead of static objects like currently is done. This requires a shift in the design method used during the initial design process of a building. The scenario based design methodology is an effective method for developing flexible and adaptable building solutions. Since the exact course of the life span of a building is unpredictable, by considering various potential scenarios, architects and engineers can create a design that can be easily reconfigured to meet changing needs.

Adaptable design

An adaptable design is primarily one where the connections are reversible and the components can be handled independently. But other qualities like the simplicity of the structural concept and the manageability, will all lower the threshold of adapting a building structure.

Adaptability is not a black and white concept, but rather a spectrum on which a system can have a higher or lower level of adaptability. Each building and situation have unique constraints and requirements, for which a higher or lower level of adaptability suffices.

Design proposal

The main research question answered in this thesis is:

How can the life span of mid-rise buildings be extended by developing an adaptable hardwood timber structure through scenario based design?

The adaptation of buildings eliminates the need for demolition and redevelopment, resulting in less material consumption and waste. Since adaptation is currently a less feasible approach and less economic attractive investment than demolition and redevelopment, the goal of this research was to investigate if the integration of an adaptable load-bearing structure does indeed lower the threshold for adapting an existing building and thereby extend its life span. Important factors in lowering the threshold and increasing the feasibility of adaptation is mitigating the anticipated boundaries of this approach that are mainly focused on the extensive construction process, lack of information about the existing building and economic factors.

From the iterative design and evaluation process in which an adaptable structural system is developed, can be concluded that this system is suitable for local interventions without disrupting an entire building and its occupants, due to the individuality of the building components.

The kit-of-parts provides a defined set of building components, of which the properties are known. In case a structure is transformed to house a different function with a different load-case, the presence of information about a structure makes adaptation more feasible, since the limitations and opportunities of the structure are clear and it is known which columns and beams have to be replaced with larger alternatives.

During development process of the design proposal, the load-bearing structure was observed as an isolated building layer. Through a case study, conclusions can be drawn about the potential shortcomings of this adaptable system when put in context with the other building layers in realistic scenarios. The adaptability level of a building is dependent on the adaptability potential of all different building layers. If the facade is not designed with adaptability in mind, the load-bearing structure also becomes less accessible and therefore less adaptable.

Furthermore, the implementation of an adaptable structural system does not eliminate all potential issues that would occur with adaptation of a non-adaptable structure. Two examples are the changing load-case when expanding a building and the need for additional foundation points when changing the structural layout.

The adaptability of the load-bearing structure is highly dependent on the adaptability of the other building layers. Therefor, it is useful if the design processes of all building layers happen simultaneously and are coordinated. The downside of having a set of standard adaptable building layer systems is the lack of variety to design with. The fact that the adaptable structural system is only compatible with a specific set of building layers could limit the creative freedom of the architect, depending on how extensive the standard set of building layers is.

Material

Hardwood is a bio-based material, which contributes to the aspirations of the circular economy model. Other than that, the choice for hardwood as a building material in an adaptable structural principle has no particular benefits for the adaptability performance of the structure. The unique characteristics of hardwood are the long distances it can span with relatively slender components and the minimal surface contact in joinery connections. Both are not optimally utilized in the design proposal of this thesis. The connection of the proposal could be rethought to integrate a joinery connection with little contact area.

Further research

Further research topics could be to evaluate the environmental impact of the design system, to check if the impact of the building industry would indeed be lowered by implementing an adaptable design approach. Furthermore, the economic feasibility of implementing an adaptable structure can be analyzed. The economic feasibility is the main factor that results in a high or low threshold for adopting an adaptable approach. In theory, accounting for future adaptation in the initial design phase will limit maintenance costs in the future by minimizing material costs and construction time. Also, future studies could explore the impact of different materials and construction methods on the adaptability and circularity of the structural system. Finally, the social acceptance of the proposed design can be investigated.

13.2 Reflection

Graduation process I Societal impact

Graduation process

The objective of my graduation project is to design a proposal for an adaptable hardwood timber structure, focused on the individuality of the building components. The process of the graduation started focused on designing on specific solution, but evolved into the design of a framework in which the necessary tools are provided for other engineers and designers to develop their own adaptable timber structures. To exemplify how the framework could be utilized, one design proposal was created showing a detailed hardwood timber structure design in which all building components can be individually moved.

The approach used for this graduation project was a scenario based design methodology. This means that situations that could occur are used as small design envelopes, to which the design proposal should comply. In my case, the scenarios were structural activities that would result in the adaptation of an existing building. For example, a beam would have to be replaced. Because there is a certain level of uncertainty attached to the future life span of a building, using scenarios helps with developing a design proposal that is prepared for different possible occurring situations. In hindsight, the scenario based design method was effective in the sense that I was not focused on solving one specific problem, or creating one specific solution, but rather to create a framework that could be used and adapted for varying scenarios. Of course, there are more scenarios possible than I have accounted and designed for. Implementing more scenarios would inevitably influence the final design proposal.

Using the scenario based design method was not implemented successfully from the start of my graduation process. At the beginning of the graduation, the main feedback from my mentors was that I was focusing on a subject that was too broad, which would limit the depth of my research and final results. Taking this feedback, I defined my scope in more detail. From that point, I only focused on the material hardwood, the manipulation of individual building components in a post-and-beam structure and on mid-rise buildings.

Other feedback I got from my mentors during the research process was that there would not be one correct solution to design an adaptable structure. Instead of developing one solution, providing a framework and showing how that can be used to design a structural principle would be better. I translated this feedback into my work by trying to clearly explain what the current market already offers on the aspect of circular structures. Next, I explained how certain choices will influence the adaptability of a structure. From the presented options, I used one to develop my own design proposal and presented that as one of the many possibilities on what to create with the offered information.

What I have learned most from my graduation process is how a design, specifically a structural design, exists of many different facets, working together to form one cohesive concept. The choices made on one domain will influence the possibilities and limitations of another domain, repeatedly in an iterative loop. Furthermore, I learned that a good understanding of the existing research field is important before a new contribution can be made.

Graduation topic in relation to the master

When doing the master Architecture, Urbanism and Building Sciences, blending knowledges and skills from different fields within the built environment is key. A combination of design, technology and social aspects can result in innovative sustainable development. This, I think, has been achieved while doing this master thesis project by taking a social and environmental problem and designing a technical solution in order to take a step in solving the problem.

The development of adaptable structures is a mean to achieving the goal of using less raw materials and reducing the environmental impact of the building industry. This relates to the main emphasis of the Building Technology track: designing innovative and sustainable building components. The relation between architecture and engineering is an important aspect of this master track. I feel like this relation has been established by explaining how an adaptable structure can create architectural opportunities, instead of limiting the design freedom, which is always a concern with mass-customized products.

Within the Building Technology track, my research topic was part of the Sustainable Structures theme. The aim of the topic was to design a structure that can change over time, accounting for probable future scenarios that can happen during the life span of the building. This scenarios based design approach fits within the theme of sustainable structures, because by designing a building for future adaptability in different scenarios, the threshold of actually performing adaptability activities becomes lower and the chances of extending the life span of the building will be higher. This prevents unnecessary demolition and production of waste materials, which will eventually aid in lowering the environmental impact of the building industry.

Research

Approach

Like previously explained, I implemented a scenario based design methodology as the main research structure of my graduation project. The scenarios were structural activities that would cause adaptation of an existing structure. This methodology was mainly useful in establishing design criteria to which the design proposal had to comply. Furthermore, the scenarios functioned as a guide to not develop one specific solution, but rather a framework accounting for all desired scenarios.

During the design phase of my graduation process, I felt like I needed more structure in my process, because the design of a structural principle can be quite broad and intimidating. Hence why is divided the second part of my thesis into five design domains: material, structural layout, kit-of-parts, building layers and construction process. For each domain, I started by gathering background information and presenting the currently available knowledge, products or methods. Using that research, I chose the presented option with the most adaptability potential for my design. If existing options were not yet suitable for the requirements I had for an adaptable structure, I changed certain aspects.

I would estimate my method of working; with scenarios and the design domains, as valuable and organized. If someone else would be interested in adaptable structures, but only a specific aspect of the design, they could source only that specific domain and be supplied with the required background information and design implications.

Results

The results of my graduation project serve as a framework for designing adaptable timber structures. It provides an overview of all aspects of the design and how certain choices can influence the adaptability potential of the structure. Since this project is a collection of research on a broad topic, it lends for further in depth academic research on specific parts.

Most of the analysis and evaluation done during my research was based on case studies and personal insights. While the projects results are substantiated by results of other scientific research or realized building projects, this makes the results sometimes ambiguous and subjective. Another designer or engineer could look at the same information and draw slightly different conclusions. This makes the transferability of the results complex. However, the reasoning behind certain choices has always been clearly described, so decisions can always be traced back to the source of reasoning.

SWOT of the method

Strengths – Using scenarios to develop a design proposal prevents limiting the focus to only one future possibility of what could happen during the life span of a building structure.

Weaknesses – The broad focus can also be a weakness, because it can distract from the final aim of the research. The possible scenarios to analyze are endless, so a selection of scenarios is necessary to able to continue to next phases of developing the design.

Opportunities – Creating a adaptable structure design principle means that other engineers of designers can take the same information and create and entirely different design proposal with it. Additionally, there are numerous other scenarios that were not considered within the scope of this thesis. This creates opportunities to explore more scenarios in another research project on this topic.

Threats – The research approach used is quite theoretical. The practical aspects and implications of the final design proposal are mentioned, but not tested. By performing experiments to test the proposal in reality, the design could be further evaluated and adapted accordingly.

Societal impact

Architectural freedom against sustainability

For the development of an adaptable structural system, the philosophy of mass customization was used. This means that a set of standard components is supplied to the designers, which can be combined in different configurations to design the structural layout of a building with. The issue with working with a mass customized system, is that it limits some of the design freedom of the architect working with the system. There has to be a balance between obtaining the sustainability goals, which means creating a multi-functional, easy to adapt design, and providing the freedom to let architects perform their jobs, which is to design interesting and distinguishable architecture. There is no clear guideline on when that balance is achieved. I dealt with this dilemma by developing a kit-of-parts, containing building components with different dimensions, that can be combined to create different grids and architectural designs. The more unique components are added to the kit-of-parts, the more different designs are possible resulting in more design freedom. The multi-functionality and simplicity of the structural principle will decrease, however, negatively influencing the adaptability and sustainability potential of the concept.

Feasibility

There are certain aspects of the project that improve the feasibility of the concept, but there are also some complicating factors and missing information that lower the feasibility. For example, for the design proposal of the kit-of-parts, hardwood products from existing suppliers are used. These are products that have been tested and are already used for building timber structures. However, these products have not been used in combination with my adaptable connection principle. This principle has not been tested and is purely hypothetical. Another aspects that complicate the feasibility is the fact that hardwood is a material that is currently not widely used. The machinery and production methods are not up to scale to produce a system like this yet, especially on a mass-production scale that would make the economic costs feasible.

A feasible aspect is the fact that the core of the project is a theoretical framework for other engineers and designers to design their own an adaptable structure. To use this framework to develop other solutions than the design proposal of the graduation project is a very feasible use of the graduation results.

Sustainability

The contribution of this research project contributes to sustainable development in twofold. Firstly, the material studied and used for the project is hardwood timber. This is a biobased material, preventing the use of fossil fuels. Hardwood is harvested from deciduous tree species, which are native to the scope area: The Netherlands. This means that less importation of wood should be needed in the future, if hardwood construction becomes a more obvious choice in The Netherlands. Less transport means a lower environmental impact. Secondly, the concept of the project is focused on adaptable buildings. The aim of using an adaptable building structure is to prevent unnecessary demolition and extend the functional life span of existing buildings. This decreases the amount of waste produced by the building industry and the amount of new materials needed for the development of new buildings.

In case of economic sustainability, the aim is that adapting a building is lower in costs than demolition and redevelopment. In order to achieve that goal, the adaptation process needs to be quick, require little machinery and manpower, and little materials. These were all aspects taken into consideration during the design process of the proposal. Hardwood products are not widely produced currently and new machinery and production methods are needed in order to produce them on a large scale. This will be a costly investment and until hardwood is a commonly used material, the economic feasibility is low.

The building industry

The adaptability of buildings will affect the built environment in the sense that urban development projects will need to be approached differently. Currently, architectural projects are often first approached from the design perspective and later in the process the structural type is selected based on what fits the architectural design best. To successfully use an adaptable system, the structural type should be the starting point of a design process. Using the available kit-of-parts, the building grid can be determined and the architectural design should be centered around that.

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Chapter 14

Appendices

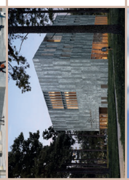
Appendix I - Case studies transformation

	PROJECT NAME	ARCHITECT transformation	YEAR original	YEAR transformation	FLOORS	STRUCTURAL MATERIAL	IMAGE	FUNCTION original	FUNCTION transformed	FACTORS easing transformation	FACTORS complicating transformation
1	Reitemakersrijge 13	Beauvast	1980	unk.	5	steel		offices	residential, commercial		Location in city centre complicated adaptation activity
2	Granida	Kandelaars architecten	1958	2005	5	concrete		offices	residential		Lack of information about the structure
3	De Stadhouder	Herms van den Berg	1974	2005	7	concrete (with timber top ups)		offices	residential	Higher revenues than with demolition and redevelopment	
4	Lodewijk State	Martini Architekten	1954	1999	3	steel		offices	residential		Thin floors limited the amount of extra weight that could be added
5	Oude Postkantoor	Van de Looi Van Aken Architecten	1908	2010	3	masonry (with timber taddition)		postoffice	residential, commercial	Existing structure suited new function. Monumental status nudged conversion	Lack of information about existing structure limited adaptation options
6	Lactaria Stevensbeek	Van de Looi Van Aken Architecten	1911	2023	2	timber		farm, monastery	residential, healthcare	Not many structural changes were needed	
7	Westplantsoen	Karina Benraad Architecture office	1980	1999	4	concrete and steel		offices	residential	Column grid of 1.8 meters. Floors could easily be removed	
8	Bassein	SARCH architecten Krommenie	1897	2020	5	steel		factory	residential	Existing structure did not have to be adapted	Legal processes made the adaptation process more difficult

Appendix I - Case studies transformation

	PROJECT NAME	ARCHITECT transformation	YEAR original	YEAR transformation	FLOORS	STRUCTURAL MATERIAL	IMAGE	FUNCTION original	FUNCTION transformed	FACTORS easing transformation	FACTORS complicating transformation
9	Wilhelmina Staete	Rappange & Partners	1969	2007	5	concrete		offices	residential	Adaptive column structure with suitable dimensions, stair could be reused	
10	Residence de Deel	G. Stuwe and C.P. van den Bliek	1959	1999	3	concrete		offices	residential		Existing concrete floor had to be thickened to be able to carry the new weight
11	Twentec building	A12 Architects	1965	2002	12	concrete		offices	residential		The structure presented unforeseen challenges and balconies could not be added because of the floor type
12	Eendrachtskade	Scheffer van der Wal Stichting In	1980	2004	7	concrete		offices	residential		Making shafts in the concrete floors was problematic
13	Park Hoog Oostduin	Cepezed	1968	2019	17	concrete (with steel additions)		offices	residential	Existing structure and foundation could be reused, reducing costs and complexity	
14	Puntegale	De Jong Bokstijn Architecten	1946	1999	6	concrete (with timber additions)		offices	residential	Sturdy structure and large dimensions made housing feasible	
15	Westerlaan Tower	Ector Hoogstad Architecten	1966	2012	20	concrete (with steel additions)		offices	residential	Sturdy structure and reuse possibilities of the stairs and elevators shafts made conversion feasible	

Appendix II - Case studies flexible buildings

	PROJECT NAME	ARCHITECT	YEAR	FUNCTION	FLOORS	AREA	IMAGE	DESIGN APPROACH	STRUCTURAL TYPE	TIMBER PRODUCT
1	The natural pavilion	Circlewood and DP6	2022	offices and meeting space	3	1.000		parametric design	houtkern modules	CLT
2	Liander Westpoort	De Zwarte Hond	2023	offices, education, workshop, storage	8	21.000		design for flexibility, scalability and modularity	post-and-beam	glulam
3	Gebouw XX	XX architecten	1999	offices	2	2.100		design for disassembly	post-and-beam	LVL
4	Östermalmshallen padel	Tengbom	2022	market hall into sports hall	2	2.000		design for disassembly	grid structure	LVL
5	Circl	De architecten Cie. bv	2016	Bank office and meeting space	3	3.350		material passport, urban mining, design for disassembly	post-and-beam	glulam
6	A circular cube	Powerhouse company	TBD	University building	4	5.000		design for disassembly	post-and-beam	CLT
7	Bouwdeel D	cepezed	2012	Offices	4	800		flexible floorplan, design for disassembly, kit-of-parts	post-and-beam	Steel and LVL

Appendix III - Circular design qualities

CIRCULAR QUALITY	DESCRIPTION	ADVANTAGES	ACTIONS
REUSED	Use building components or elements that are already present at the building site or that are sourced elsewhere	Reuse extends the life span of a product and prevents consumption of new resources	Set up a catalog of the components inside a building with a clear description
RECYCLED	Use building components that are made from waste materials	Decreases the need for new resources and the amount of waste produced	Set a preliminary goal for the amount of recycled products used in a building project
RENEWED	Use building materials that are renewable and can continuously be produced through sustainable farming and forestry	Some resources are infinite due to natural restorage	Filter materials on sustainability labels stating the reconfiguration of the harvested source
COMPOSTABLE	Use materials that can be biologically degraded into natural waste streams	Biodegradable materials do not convert to waste at the end of life, but can be degraded into water, CO2 or biomass	Select materials that are known to be biodegraded correctly
SAFE AND HEALTHY	Use components that do not harm the environment or humans while using, reusing or recycling them	Safe and healthy materials are often recyclable or reusable	Check if a certain materials complies with the regulations on environmental and human toxicity
PURE	Preferably use components consisting of a single material instead of multiple	Pure components require a less complex recycling or composting process, making the process more money and time efficient	Use untreated materials. And check when the use of a composite is inevitable, if the materials can be taken apart easily
DURABLE	Use components that can easily withstand the wear and tear of use and reuse	Robust products have a longer lifespan, making them attractive for future reuse	Use materials that age naturally and require limited maintenance
SIMPLE	Integrate simple and clear solutions instead of complex ones	Simple solutions are easier to understand and adapt	Limit the amount of different components and connections. Apply repeating patterns and standard dimensions
MANAGEABLE	Design building components that are easy to handle and to move	Manageable components make adaptation easier and increase the feasibility	Apply components that can be lifted by a max. of two people with minimal mechanic aid. Minimize dimensions for easy transport
ACCESSIBLE	Integrate components in a way that they can be reached and recuperated without damage	Accessibility makes repair, replacement and adaptation more effective	Design a visible connection and tolerances around the connections to allow for movement
REVERSIBLE	Integrate connections that can be demounted without damaging other components	Reversible connection allow for selective deconstruction and recuperating individual components	Prevent building components to be connected permanently
INDEPENDENT	Combine components while they remain structurally and functionally autonomous	The independency of a single component allows for selective deconstruction.	Analyze which components require replacement and repair most often, check if the connection allows removing them
COMPATIBLE	Use building components that are interchangeable and can be combined with each other	Compatible components can be reused in more parts of a structure, making replacement easier	Design a building according to a module strategy, using reoccurring dimensions
MULTI-PURPOSE	Design buildings and spaces that can morph to changing requirements without adaptation	Versatility prevents the vacancy of buildings and eliminates unnecessary renovation	Create an open floorplan structure with mobile components
VARIED	Introduce diversity instead of one uniform solution	A divers area allows users to move buildings instead of requiring unnecessary renovation	Introduce multiple user scenarios within one project, to appeal to a wide audience
LOCATION AND SITE	Recognize and develop the qualities of a location responsibly	Buildings on attractive building sites have a larger potential to be maintained and redeveloped in the future	Situate buildings on a site that is easily accessible through the existing infrastructure

Table 12.A Cambier et al. (2019) Overview of circular design qualities

Appendix IV - Existing systems

Houtkern

Module version

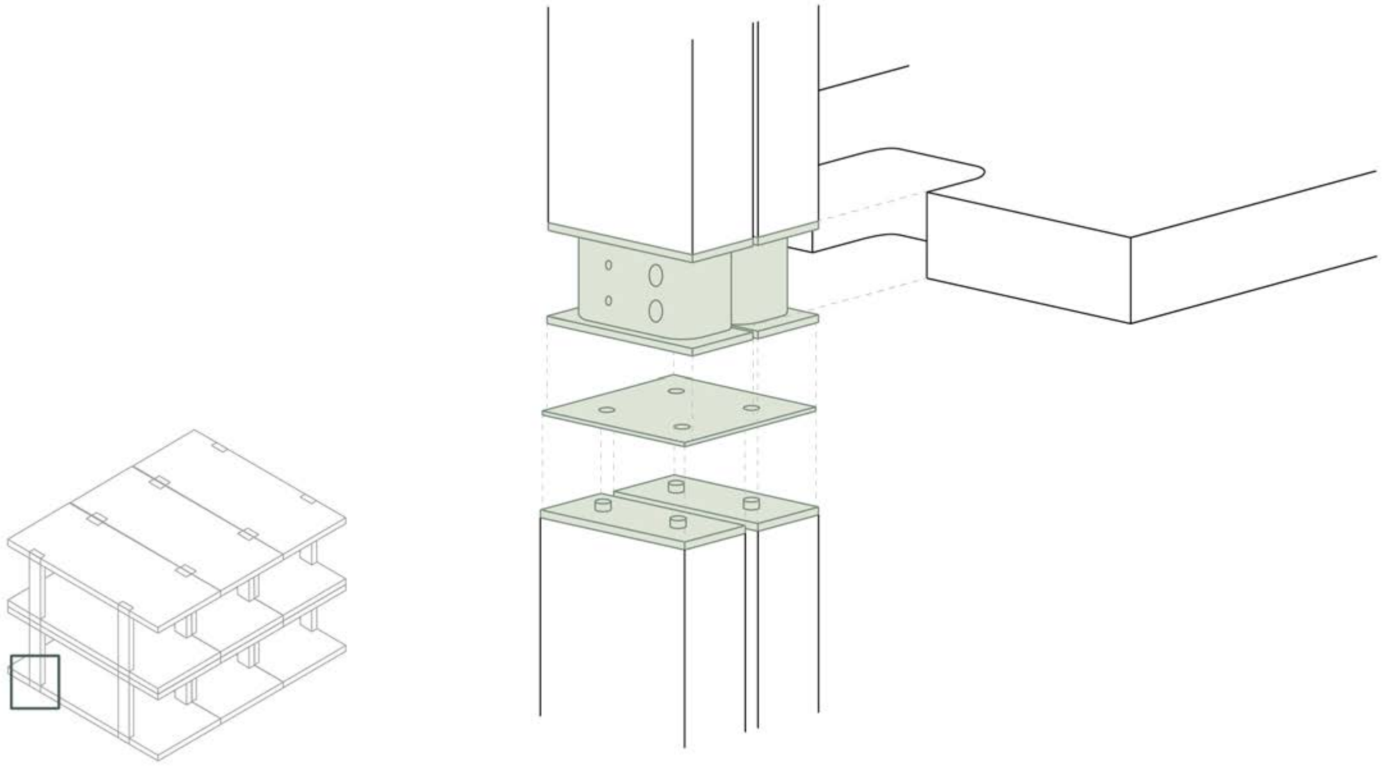


Fig. 12.1 By author, based on Noordereng Groep (2022), axonometry building system

Unique qualities:
Fast building speed
Lightweight transport

Dimensions building parts:
Width 3-3,5 meters
Length between 7-13 meters

Maximum building height:
5 building layers using just timber
80 meters using a steel core

Demounting process:
Destacking modules from top to bottom

Material:
Softwood timber

Product:
CLT

Fig. 12.2 Noordereng Groep (2022) exterior building

Fig. 12.3 Noordereng Groep (2022) Interior building layers

Appendix IV - Existing systems

Circular aspects

The circular design qualities that Houtkern is performing best on are simplicity and reversibility.
All analyzed systems perform well on the reversibility aspect. The Houtkern system is reversible, because the connections to connect individual components are demountable, as well as the connections that connect the modules in the eventual building together. This allows for the opportunity to decide whether the building can be reused in the existing modules, or in separate components.

The Houtkern system can be described as simple, because of the minimal unique parts it entails. The structural system consists of column and floor components, with complementary wall to make different desired layouts for the interior space. Because most of the construction process is done off-site, the eventual building construction consists of relatively few steps and costs minimal time. Another factor adding to the simplicity of the Houtkern system is the standard dimensions and repeating patterns used for the modules. Although the modules can be combined in various ways to create different interior spaces, the dimensions of the base of the module stay the same throughout.

Non-circular aspects

The two circular design qualities that the Houtkern module system is performing least on are manageability and independency.

Other than the other analyzed systems, Houtkern is a module system. Meaning that the 3D modules are prepared of-site and assembled on site. This causes a low rating on the aspect of manageability. The modules are much heavier and larger than individual 1D components and there is mechanic aid needed in order to lift the modules in place on site. The prefabrication process of making the modules themselves however, is feasible to do with minimal mechanic aid and people.

The independency of the individual components within the Houtkern system is not rated highly. First the components are connected to each other. A beam to a floor component for example. Then, on site, the modules are connected as well. This makes the opportunity to handle an individual component lower. Furthermore, moving individual modules out of the complete structure is not possible due to the interconnection.

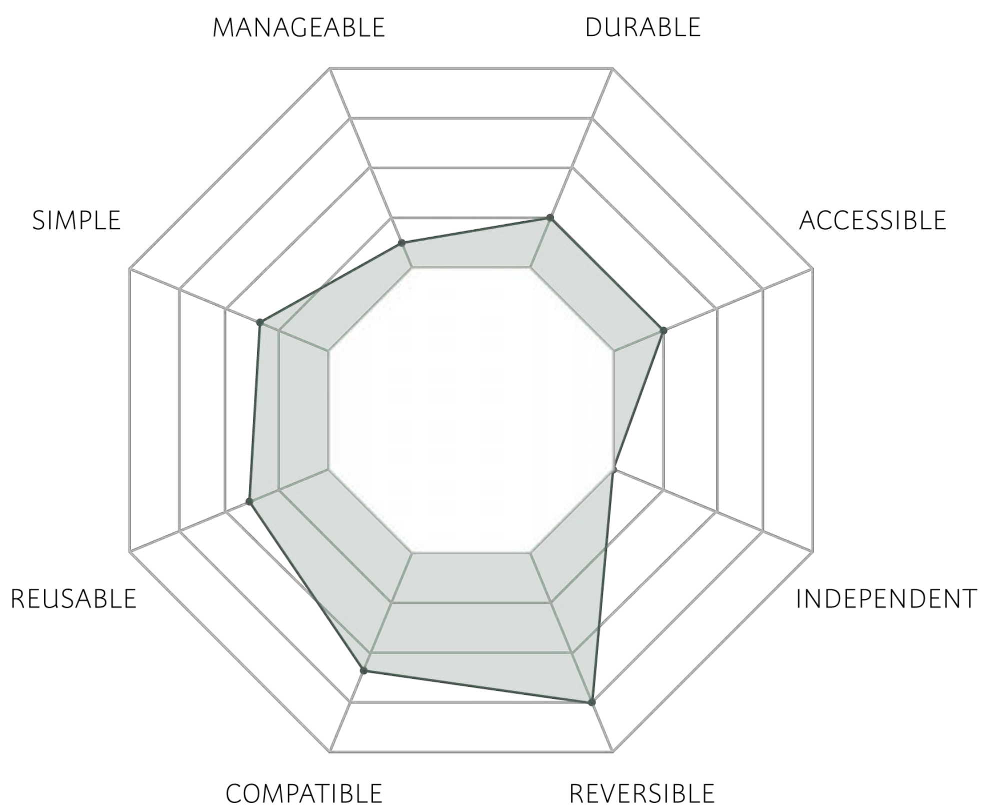


Fig. 12.4 By author, Houtkern system analyzed on circular design qualities

Appendix IV - Existing systems

Knoopwerk

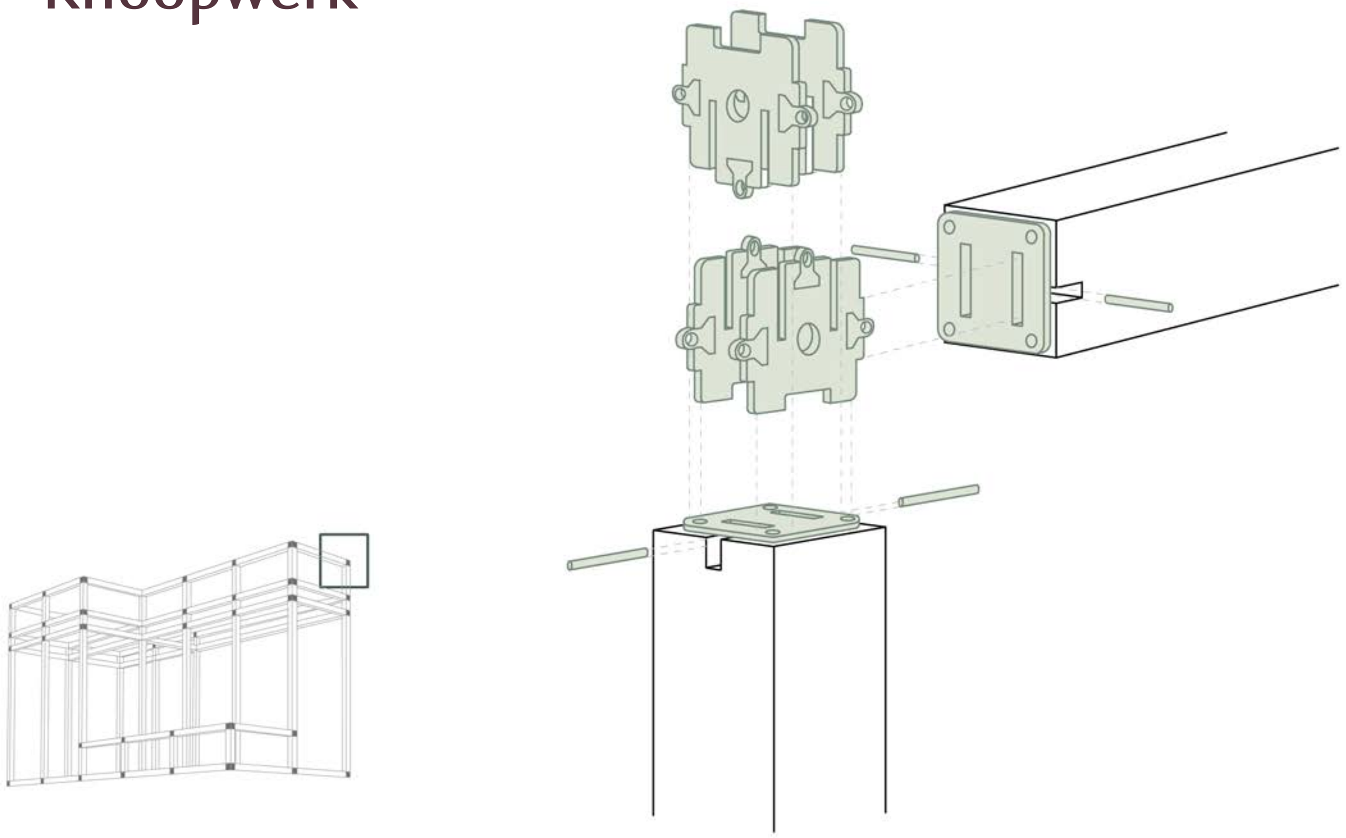


Fig. 12.5 By author, based on Knoopwerk (n.d.), axonometry building system

Unique qualities:
Reusable without recycling in a different design
Minimal unique components suitable for various designs

Dimensions building parts:
Connection cube is 90x90 mm
Section wood is 90x90 mm

Maximum building height:
Unknown to author

Demounting process:
Inverse to the mounting process, using a specifically design demounting pin

Material:
Softwood timber

Product:
Glulam

Fig. 12.6 Knoopwerk (n.d.) exterior building

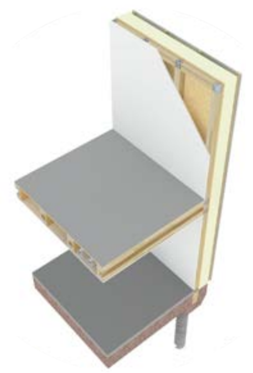


Fig. 12.7 Knoopwerk (n.d.) Building layers

Appendix IV - Existing systems

Circular aspects

The circular design qualities on which the Knoopwerk system is rated most circular are manageability and reversibility, as well as accessibility.
In contrast to the other analyzed systems, the Knoopwerk system consists of relatively small components. The longitudinal elements have a small section. This is possible because of the framework layout of the system. The small dimensions make the parts easy to handle and minimize the weight. This allows for the use of minimal mechanic aid.
The Knoopwerk connection node is completely reversible. Four flat metal components slide into each other in two directions and are then connected to the timber components. In the same way, the connection node can be demounted as well.
The Knoopwerk production company provides the option to combine a facade layering configuration, which is especially tailored for their building system. The interior finish is realized without using any adhesive or plaster, which makes removing the finishing layer to access the bearing structure possible. A non-accessible aspect of the system is the fact that the components can only be moved in certain directions, being limited by the connection node lay-out and the lack of tolerance around the connection node.

Non-circular aspects

The Knoopwerk system is rated high on the majority of the selected circular design qualities. The circular design qualities on which it is performing less are the reusability and the durability.

This system is available in all different lengths possible, within the possible span range. This means that it is more difficult the take a component from an existing building, for which the building kit was specifically developed, and build another building with it, without copying the exact structure.

Softwood is used for this building system, which is less durable than hardwood.

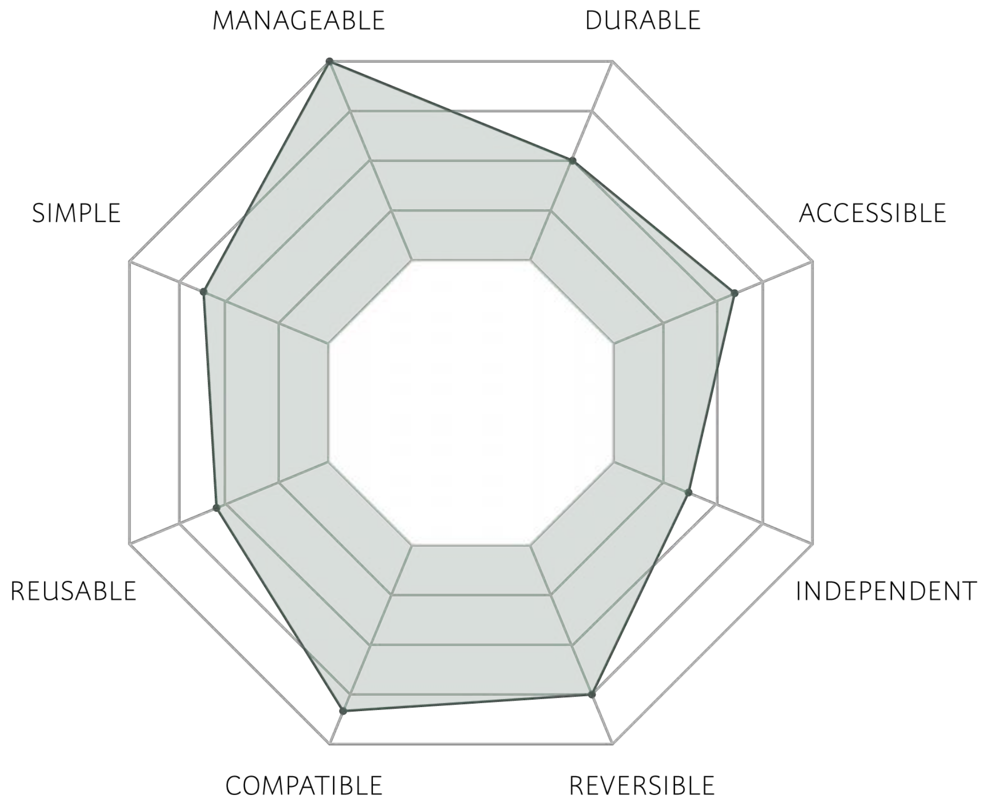


Fig. 12.8 By author, Knoopwerk system analyzed on circular design qualities

Appendix IV - Existing systems

Circle house

Post-and-beam version

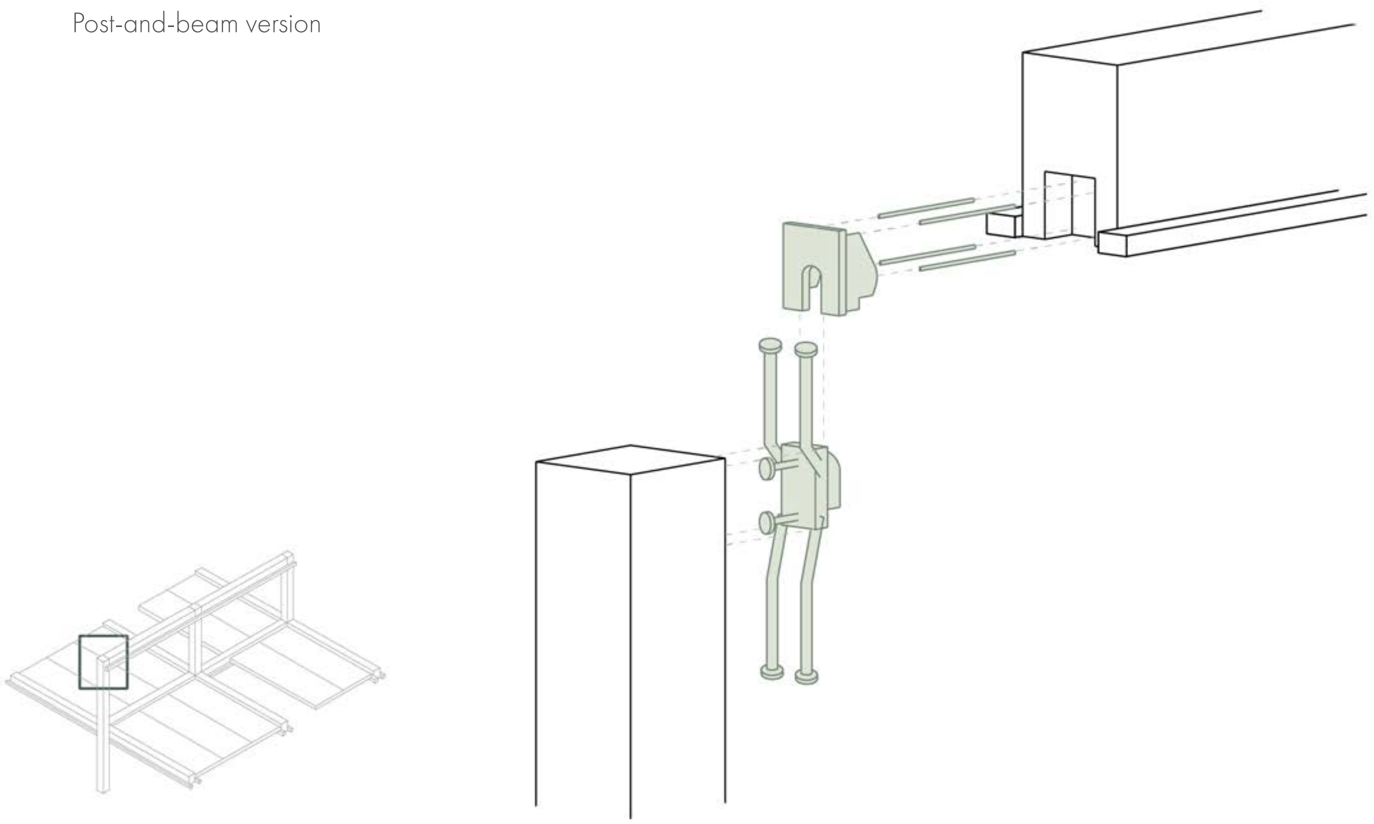


Fig. 12.9 By author, based on Gxn & Assets (2018), axonometry building system

Unique qualities:
Different versions of the same structural principle depending on the requirements

Dimensions building parts:
Unknown to the author, beams estimated to be between 3-6 meters

Maximum building height:
Unknown to the author

Demounting process:
Floor elements are removed, mechanical connection is demounted

Material:
Concrete

Product:
Prefabricated concrete

Fig. 12.10 Gxn & Assets (2018) exterior building

Fig. 12.11 Gxn & Assets (2018) Interior building layers

Appendix IV - Existing systems

Circular aspects

The Circle House building system is rated as most circular on the reusability and reversibility circular design qualities.

The components used in a Circle House building structure are all coded and labeled. This improves the reusability potential of the structure, because the characteristics of the component can be administrated in a catalog, providing all necessary information for the assembly of a new structure. Moreover, the system consists of components with standard dimensions, creating repeating patterns that can configure various building types.

The connection of the Circle House system consists of metal connection components, connecting the concrete elements. The system in itself is completely reversible, because there is no adhesive involved and the metal connectors can be demounted.

Non-circular aspects

The circular potential on a component scale of the circle wood system heavily dependent on the choice of material. Instead of timber, concrete is used for this system. The circular design qualities most negatively rated are durability and manageability.

The durability rating for this system cannot be compared with the other systems, since the material is different and consequentially the criteria for durability do not align with the properties of concrete. Concrete is actually a very durable material and requires little maintenance.

The manageability of the Circle House system is also dependent on the material choice. Concrete is much heavier than wood, making the components impossible to lift without mechanic aid. Additionally, this system involves components with relatively large dimensions.

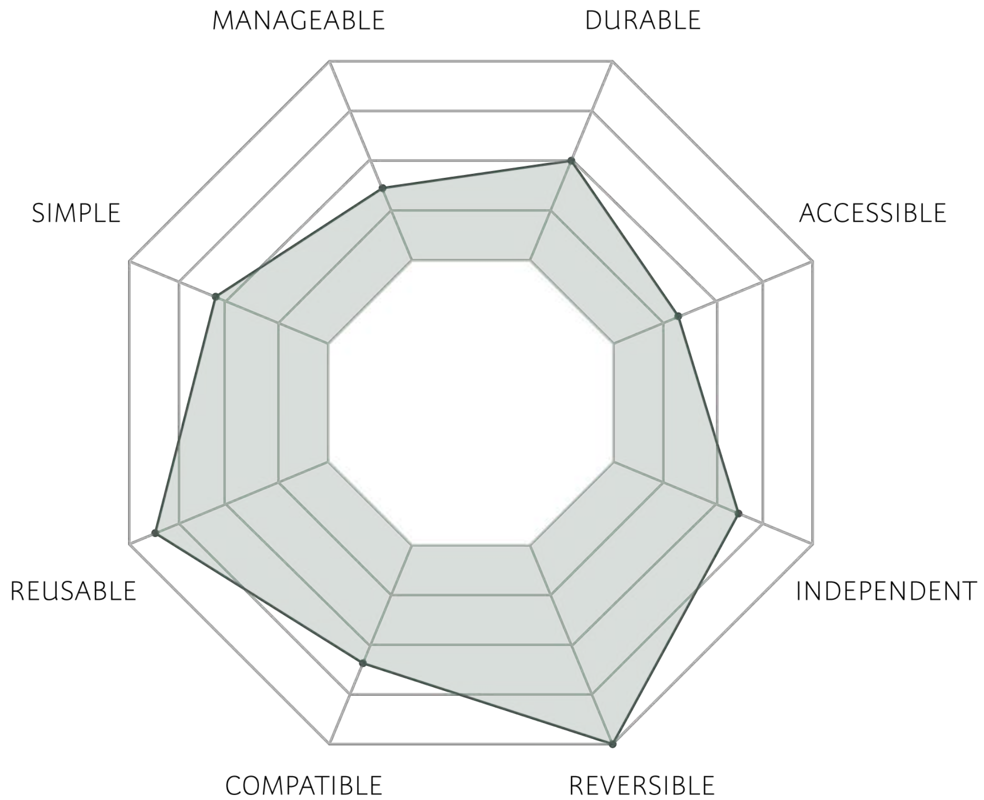


Fig. 12.12 By author, Circle house system analyzed on circular design qualities

Appendix IV - Existing systems

LVL Dovetail

Euregon AG, Augsburg

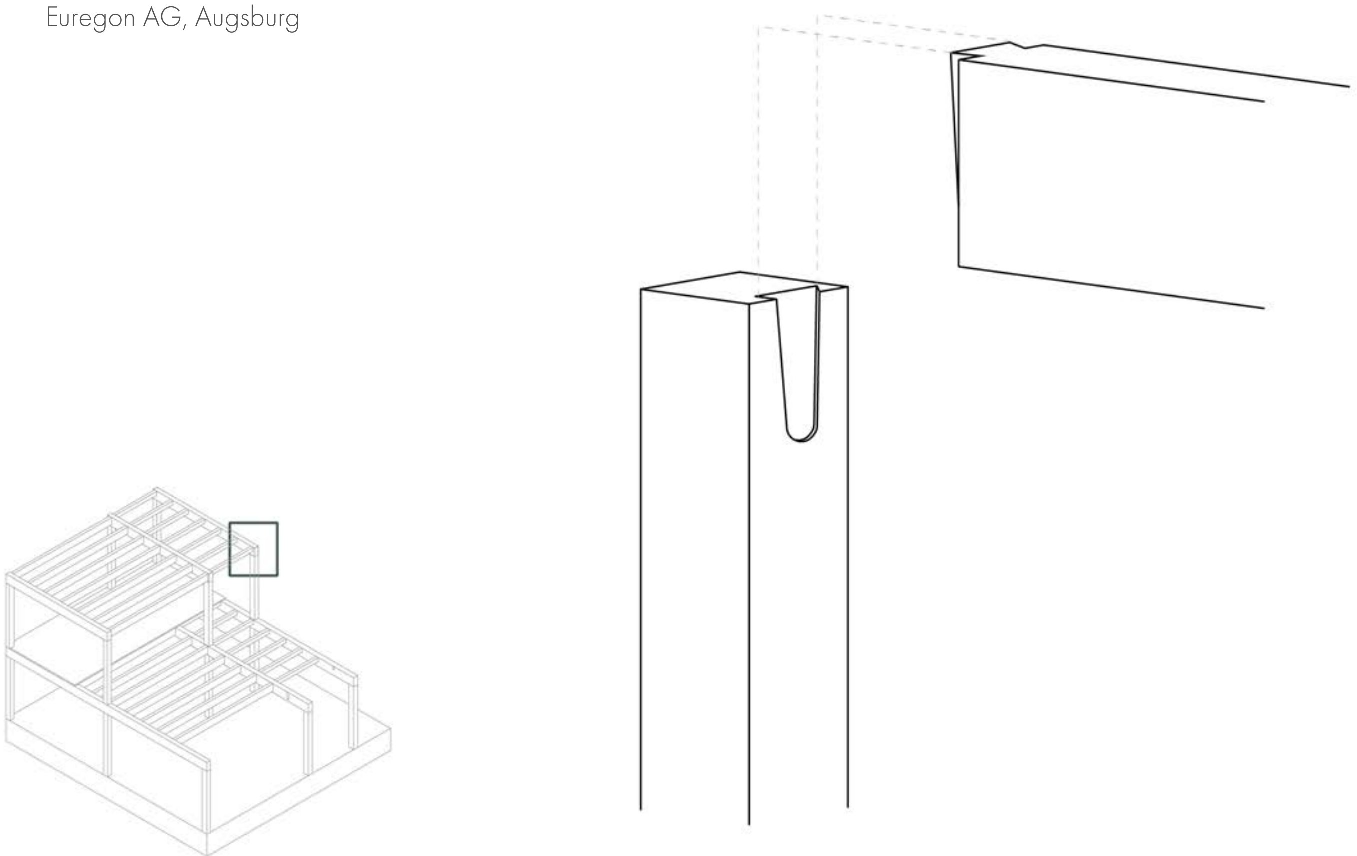


Fig. 12.13 By author, based on Merz, Niemann, & Torno (2021), axonometry building system

Unique qualities:
Minimal surface area in connection without additional fasteners

Dimensions building parts:
Primary beams: 200x400x5100 mm
Columns: 200x200xceiling height
Secondary beams: 120x320x5100 mm

Maximum building height:
Unknown to author

Demounting process:
Complete building disassembly, working from top to bottom

Material:
Hardwood timber

Product:
LVL

Fig. 12.14 Pollmeier (2023) exterior building

Fig. 12.15 Pollmeier (2023) Interior building layers

Appendix IV - Existing systems

Circular aspects

The circular design qualities which are scored highest for the LVL dovetail connection are durability and reversibility.

The high durability is mostly due to the hardwood material used for this system. Next to that, there are minimal holes made in the timber components, making the elements robust. Lastly, there was a surface coating applied to the elements, to protect them against external damaging factors.

The dovetail connection is reversible, because there are no adhesives or inaccessible screws use for making the connection. The beams can be simply lifted out of the dovetail socket when demounting the system. This is only possible however, when the floor laying on the beams is removed first.

Non-circular aspects

The two circular design qualities where this building system is lacking in circular potential is in the manageability and accessibility of the system.

The beneficial properties of hardwood are also the ones that complicate the manageability. The beech that this system was made out of, enables the creation of large spans. Large spans result in building parts with longer dimensions, although the cross-section is smaller than if the same structure would have been built with softwood. The large dimension of beams and columns makes it difficult to handle the components without mechanic aid and more people are needed to guide the process. Additionally, larger parts result in a higher weight per component.

Although there is no additional building layers covering the load bearing structure interiorly, the connection node of the LVL system is still not accessible. The dove tail connection is integrated inside the connection and not visible from within the building. Also, the tolerance around the node is minimal. The floor beam can only be elevated out of the connection upwards, which is impossible when there is a floor laying on top. Otherwise it is not possible to maneuver the components in other directions.

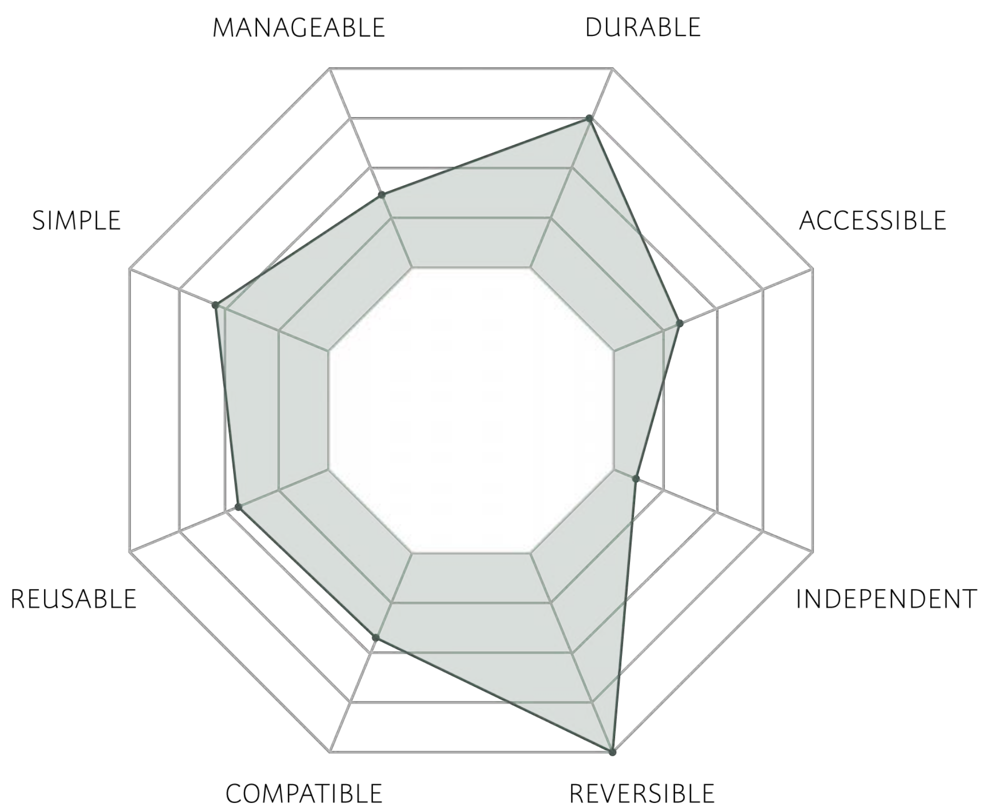


Fig. 12.16 By author, LVL dovetail system analyzed on circular design qualities

Appendix IV - Existing systems

Structurez

Suteki

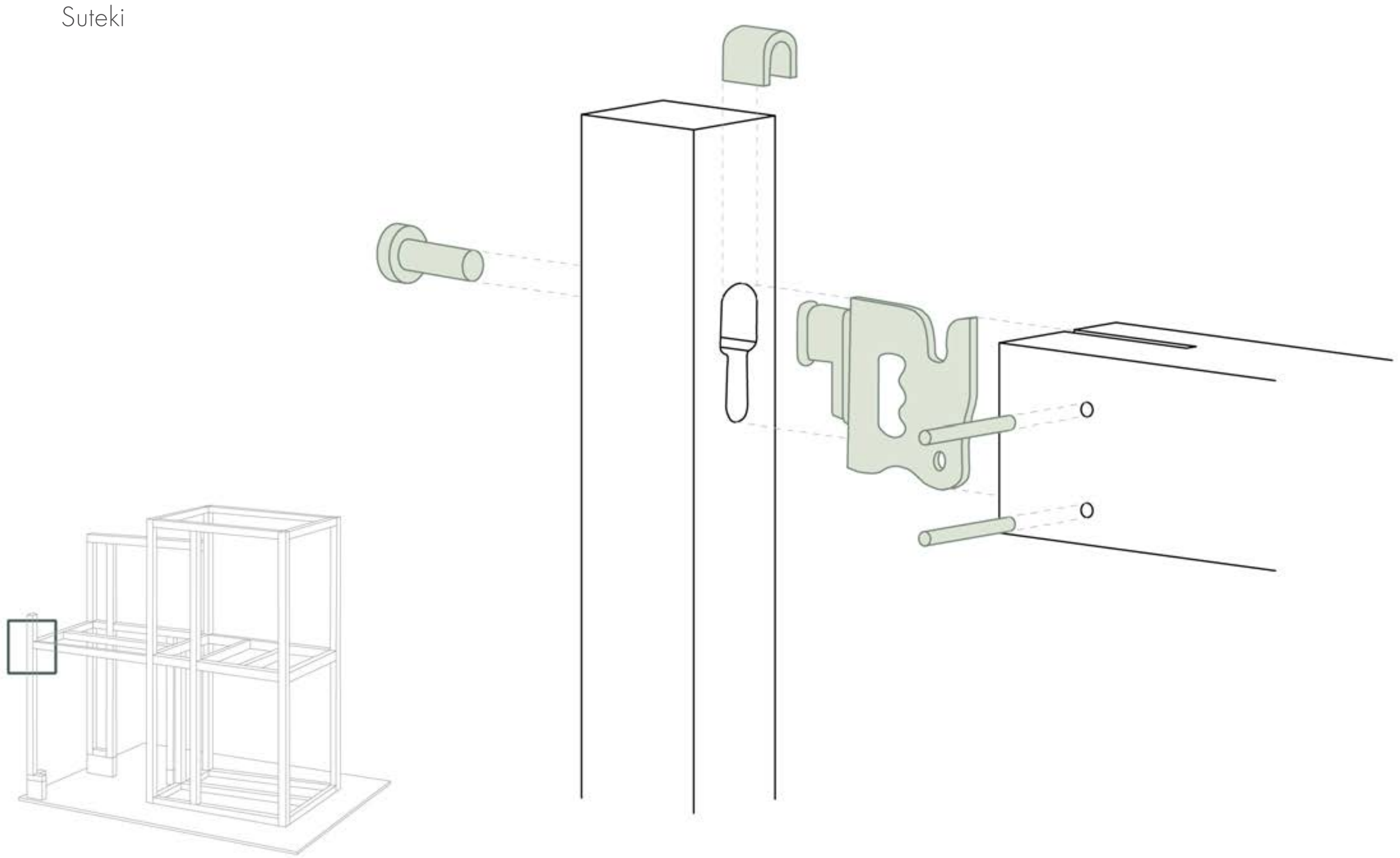


Fig. 12.17 By author, based on WoodInc (2021), axonometry building system

Unique qualities:
Easy to build
Made to measure

Dimensions building parts:
No standard dimensions

Maximum building height:
Unknown to the author

Demounting process:
Reverse of the original construction process

Material:
Softwood timber

Product:
Laminated

Fig. 12.18 WoodInc (2021) exterior building

Fig. 12.19 WoodInc (2021) Interior building layers

Appendix IV - Existing systems

Circular aspects

The reversibility is the highest performing circular design quality of the Structurez system. The connection of this system are established by using a metal hook component, which is anchored in the vertical timber components. The horizontal timber components are hooked onto the metal part and secured using pins. To demount the system, this process is executed in reverse. The are no adhesives used when constructing this system, making it easier to demount.

Non-circular aspects

The Structurez system, also called Suteki, is in theory quite a circular system. However, on a component scale the system is lacking on multiple circular design qualities. The three qualities performing the least are manageability, accessibility and compatibility.
The possibility to produce structures with large spans makes for larger dimensions of the parts and higher weight. This is also the reason that mechanic aid is needed while constructing this type of building system.
The connection node of the system is completely covered by finishing layers after completion. This makes it hard to deconstruct the system. The additional finishing layers as presented in projects where this system was applied, are made of a plaster-like material and are thus not easily removable.
The Structurez system is marketed as a system that allows architects to maintain their design freedom, because the system can be produced in all preferred dimensions. While this might be a positive aspect from a design viewpoint, it also means that the pieces are less compatible and not easily exchangeable throughout the structure or between other structures using the same system. Furthermore, there are 18 different connection types available in the Structurez system, also decreasing the compatibility.

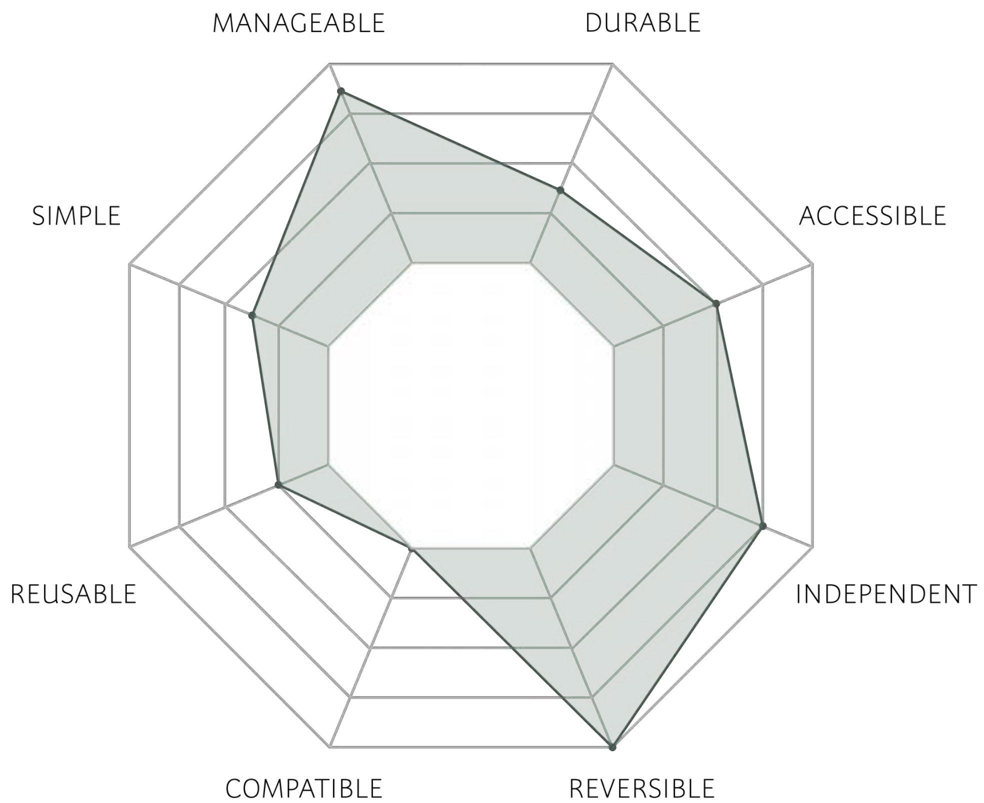


Fig. 12.20 By author, Structurez system analyzed on circular design qualities

Appendix V - System analyses

	Houtkern		Knoopwerk		Circle House		LVL Dovetail		Structurez	
	Description	Rating	Description	Rating	Description	Rating	Description	Rating	Description	Rating
Reusable										
Catalog of building components	The components are not cataloged	1	The components are not cataloged	1	The components are all cataloged	5	The components are not cataloged	1	Every column and beam is coded	4
Standard dimensions	The modules can have a width of 3-3,5 m and a length of 7-13 m. There is no standard modules, but between these ranges the dimensions are customizable. It is however customary to use the same dimensions for one project	3	Distance of 600 mm between timber components. The cross-section of the components is standard, but the length is customized to the design	5	The building components together make modules with standard dimensions.	4	Baubuche building components can be provided in all different dimensions. For this project there were standard dimensions with a grid of 5,10 m and a corridor of 2,4 m.	2	All desired dimensions are possible	1
Standard connection system	There is a standard connection for creating the modules off site and for attaching the modules together on site	3	Yes, a steel connection were sheets slide into each other and are fixed by steel pins	5	There is a standard connection system for the beam-column connection.	3	The beam connection was uniform for all beam components. The beam-column connection is different	4	The connections are all based on the same principle of steel connectors that are secured by pins. There are various different connection types that all require a specific connection anchor	1
Repeating patterns	The modules are repeated in rows to create a storey, but the layout of modules can be changed for each storey	3	The structural grid is not repetative. The only repeating pattern is the 600 mm between elements in the facade, so that plating materials can be placed directly to the structure without secondary studs	2	The beams all have the same length, resulting in a repeating pattern	5	The 5,10-2,4-5,10m grid is a repeating pattern	4	There are no repeating patterns	1
Limited use of adhesives or plasters	CLT, the connection requires no adhesive	3	Glulam parts, the connection requires no adhesives	3	The connection is mechanical	5	Baubuche is a laminated veneer lumber product	3	Laminated wood, the connection requires no adhesive	3
		2,6		3,2		4,4		2,8		2
Durable										
Long life span material	CLT softwood	2	Softwood glulam	2	Precast concrete	5	Hardwood beech	4	Laminated softwood	2
Surface treatment	No information provided	3	Only for outside use	4	No information provided	3	Yes	5	No information provided	3
Additional building layers covering the structure	The CLT material can be left unfinished or can be covered	2	The interior can be finished with plasterboard	2	There is no interior finishing layer but it can be applied	2	In this case there are no finishing layers applied on top of the structure. It is possible to do so	2	Finishing layers can be applied but are not required	2

Appendix V - System analyses

	Houtkern		Knoopwerk		Circle House		LVL Dovetail		Structurez	
Minimal amount of holes in components	The walls are screwed to the floors in a direct wood on wood connection. The columns are attached using a steel to wood connection. There are no additional holes needed when reused, because the prefab modules are not demounted during reuse	1	The steel connection is attached prefab to the timber components with four screws, but is not demounted when reused.	4	There are some holes required to be able to attach the steel connection pieces to the concrete components	2	The dovetail connection only requires a gutter to slide into and is secured with one full-threaded screw	5	The connection system requires no bolts or screw fasteners, but there are still holes needed to hook the connection anchors onto and for the steel pins	3
		2		3		3		4		2,5
Simple										
Minimal unique parts	If you view the module as one part there are very little parts, but the module itself consists of columns, walls, a floor, a ceiling.	5	There are two main different components: the connection cube and the timber components. The timber components have the same cross-section but different lengths	2	There is one connection type which requires two parts, the beams, columns and floor decks	4	Since there are no steel connection parts required, this structure can be made with minimal unique parts	3	The are various different connection anchors and the timber components can be all different dimensions	1
Costs little time to construct	A building of 4 building layers can be realized in 6 months. The modules themselves are prefabricated off-site	1	The connection is easy to establish. Initial construction will not take a long time	5	It takes one hour to build one unit, one floor	3	Since the connection requires only one fastener, the structure is quickly assembled. Only placing the components with machinery takes longer than by hand	2	The system is built in 15 m2/person/day	4
Minimal steps in assembly	On-site the modules only have to be connected to each other. Off-site, the complete module has to be fabricated	1	The steel plates are attached prefab and the connection cubes are formed. On site, the beams are slid over the connection cube and a hammer	3	The mechanic connection has to be installed on site. It is not the most straight forward system but also not the most complex	2	The connection requires only one fastener and is based on traditional joinery. There a minimal steps required for making the connections	5	Fastening the connections is straight forward and secured using just a hammer and the pins	3
Minimal experience or training needed	This construction method is not suitable for amateurs, mainly because of the weight and machinery needed	1	The structure is delivered in parts and with a construction manual	4	This construction method is not suitable for amateurs, mainly because of the weight and machinery needed	1	material and it takes experience to work with this material in terms of making holes. For the placement, no extra training than regular	3	This system is suitable for professionals, do-it-yourselfers and constructionworkers in training. A manual is provided with the building components	5
Repeating patterns	The modules are repeated in rows to create a storey, but the layout of modules can be changed for each storey	3	The structural grid is not repetative. The only repeating pattern is the 600 mm between elements in the facade, so that plating materials can be placed directly to the structure without secondary studs	2	The beams all have the same length, resulting in a repeating pattern	5	The 5,10-2,4-5,10m grid is a repeating pattern	4	There are no repeating patterns	1

Appendix V - System analyses

	Houtkern		Knoopwerk		Circle House		LVL Dovetail		Structurez	
Standard dimensions	The modules can have a width of 3-3,5 m and a length of 7-13 m. There is no standard modules, but between these ranges the dimensions are customizable. It is however customary to use the same dimensions for one project	3	Distance of 600 mm between timber components. The cross-section of the components is standard, but the length is customized to the design	5	Yes	4	Baubuche building components can be provided in all different dimensions. For this project there were standard dimensions with a grid of 5,10 m and a corridor of 2,4 m.	2	All desired dimensions are possible.	1
		2,33		3,5		3,17		3,17		2,5
Manageable										
Small dimensions	The modules are 3-3,5 m by 7-13m by the ceiling height	1	Cross-section wood is 90x90x±600mm, Connection cube of 90x90 mm	5	No information is provided, but the beams span an average apartment space. Estimate is a length of 3000 to 6000 mm	3	Primary beams: 200x400x5100mm Columns: 200x200xceiling height Secondary beams: 120x320x5100mm	2	Large spans are possible and most optimal for this heavy timber structure	4
Light weight	A houtkern module can be transported by truck as well as on a ship. Wood is lighter than a concrete alternative	3	Wood is 400 kg/m3, Connection piece is 1 kg	5	Concrete has a density of 2.400 kg/m3, the parts are relatively big thus heavy	1	Beech has a density of 700-900 kg/m3	2	The beams and columns are heavier to be able to span larger distances	4
Minimal mechanic aid needed	Less heavy machinery is needed on site because the modules are already prefabricated	1	No mechanic aid needed	5	Mechanic aid is required to place the parts into position	3	Since the components are quite large and heavy, they require mechanic aid to be lifted into place	3	There is no mechanic aid required	5
Minimal amount of people needed	The modules are large and have to be guided while the crane lifts the modules into place. Then someone needs to connect the modules together.	1	The parts are light and the connections straight-forward, so there is no need for a lot of construction workers	5	The beams have to be guided into place by a person on either end, while lifted by some in the crane.	3	The beams have to be guided into place by a person on either end, while lifted by some in the crane.	3	Because it is fast to install, there are not many workers needed to complete a structure in a reasonable time	5
		1,5		5		2,5		2,5		4,5
Accessible										
Minimal additional building layers covering the structure/connection node	An interior finish is not required	3	The structure is located between the thermal and airtight layer of the facade. Interior finish is not required	3	There is no interior finishing layer	3	There are no finishing layers required	3	Finishing layers are not required	3
Additional building layers are removable	An interior finish is not required	3	The finishing plates are directly attached to the structural components but are not required	3	There is no interior finishing layer	3	An interior finish is not required	3	That depends on what finishing layers are used. Removable building layers can be used. The supplier provides CircuWallPanels which are insulation panels that are complimentary to the connection anchor system	3

Appendix V - System analyses

	Houtkern		Knoopwerk		Circle House		LVL Dovetail		Structurez	
Visible connection system	The connection system between two different modules is not visible, because it is located between floors.	1	The connection is finished with plasterboard on the interior side and directly covered with OSB board on the exterior for lateral stability. When that is removed, the connection cubes are visible	5	The connection is not visible once the building is finished	1	The connection is not visible when the building is finished	1	It depends on the type of connection. Some connections are not visible because they are located in the intersection of beams and columns.	4
More tolerance around components and connection node	There is no tolerance around individual modules, because they are sandwiched between other modules	1	There is minimal tolerance around the node. To remove the pins, access from both interiorly and exteriorly is needed. Also, the components have to be moved sideways to be demounted, which cannot happen for an individual component	2	All building components are restricted by other building components and cannot be accessed individually	2	All building components are restricted by other building components and cannot be accessed individually	2	The pins are accessible from the sides of the beams. The beams can be removed if upwards tolerance is provided. That is, when there is no floor on top.	2
		2		3,25		2,25		2,25		3
Reversible										
Connection node can be demounted	The modules can be disconnected. When the complete building is demounted, the modules can be demounted as well.	4	The connections can be demounted using an especially made demounting tool. But only when the complete structure is demounted.	4	Since the node is mechanical, it can be demounted, but only if the floor elements are removed from the beam	5	The connections can be demounted, but only when the complete building is demounted	4	The connection nodes can be demounted, but most connections can only be demounted when the whole building is demounted	5
		4		4		5		4		5
Independent										
Components are individually connected	One module can be connected to four other modules simultaneously. So they are not individually connected or removable	1	The timber components are individually connected, but the lateral stability is realized by attaching a plate to the outside of the structure, connecting the components	3	Each beam is individually connected to the column	4	The floor lies on the secondary beam, which is attached to the primary beam, which is attached to the column directly. This makes them not individually connected	2	Each component is connected to another component with their own connection anchor	5
Little disturbance of other components when handling one component	One module cannot be removed from the structure without removing other modules, unless it is placed on the top floor on the corner.	1	Because of the lateral stability by plates, the components cannot be handled individually. Also, the components have to be moved sideways to be demounted, which cannot happen for an individual component	2	The floors lay on top of the beams. The beams can only be removed when lifted upwards, disturbing the floor. Four beams can be attached to the column, which cannot be removed without first removing the beams.	3	Individual components cannot be handled without influencing other components	1	Beams cannot be moved without removing the floor elements. But due to the upwards moving direction, it is easier to handle individual components than in a sideways installed connection	3
		1		2,5		3,5		1,5		4
Compatible										

Appendix V - System analyses

	Houtkern		Knoopwerk		Circle House		LVL Dovetail		Structurez	
Multi-functionality of single component	The same module can house different functions, by rearranging the walls. This can only be changed during the prefabrication phase and not	4	Components are reusable in a different design layout. The same structural principle is used for walls, roofs and floors	5	The beams cannot be used as columns or vice versa	1	All components were specifically dimensioned for this structure, and cannot be reused as another component	1	The holes for the anchors in the wood are made for a specific connection and part in a structure, so there is no multi-functionality of a specific timber	1
Standard connection system	There is a standard connection for creating the modules off site and for attaching the modules together on site	3	Yes, a steel connection were sheets slide into each other and are fixed by steel pins	5	There is a standard connection system for the beam-column connection.	3	The beam connection was uniform for all beam components. The beam-column connection is different	4	The connections are all based on the same principle of steel connectors that are secured by pins. There are various different connection types that all require a specific connection anchor	1
Standard dimensions	The modules can have a width of 3-3,5 m and a length of 7-13 m. There is no standard modules, but between these ranges the dimensions are customizable. It is however customary to use the same dimensions for one project	3	Distance of 600 mm between timber components. The cross-section of the components is standard, but the length is customized to the design	5	The building components together make modules with standard dimensions.	4	Baubuche building components can be provided in all different dimensions. For this project there were standard dimensions with a grid of 5,10 m and a corridor of 2,4 m.	2	All desired dimensions are possible	1
Repeating patterns	The modules are repeated in rows to create a storey, but the layout of modules can be changed for each storey	3	The structural grid is not repetative. The only repeating pattern is the 600 mm between elements in the facade, so that plating materials can be placed directly to the structure without secondary studs	2	The beams all have the same length, resulting in a repeating pattern	5	The 5,10-2,4-5,10m grid is a repeating pattern	4	There are no repeating patterns	1
		3,25		4,25		3,25		2,75		1

	Houtkern	Knoopwerk	Circle House	LVL Dovetail	Structurez
Material	2,8	3,5	3,5	3,5	3
Structural layout	2,7	3,7	4,3	2,9	1,4
Kit-of-parts	3	4	3,1	3,3	2,4
Building layers	2,3	3,3	2,3	2,3	3
Construction process	1	3,4	2,8	2,5	3,9

Appendix VI - Hardwood product properties

Product type	Glulam	Glulam	Glulam	Glulam from LVL	Glulam from LVL
Manufacturer/permit holder	Holz Schiller GmbH	Elaborados y Fabricados Gamiz S.A.	Studiengemeinschaft Holzleimbau e. V.	Pollmeier Furnierwerkstoffe GmbH	Hasslacher Holding GmbH
Product	Oak post-and-beam glulam	Oak glulam	Beech glulam	BauBuche GL75 beam	HASSLACHER BauBuche (GL75 XXL)
Wood species	Oak	Oak	Beech	Beech	Beech
Beam					
Construction	homogeneous	symmetric combined	homogeneous or symmetric combined	-	-
Height [mm]	76-280	80-400	≤600	80-600	80-2.500
Width [mm]	50-70	50-160	≤160	50-300	50-600
Length [m]	≤12/≤4 without finger joints in outer laminates	≤12	-	≤18	≤36
Laminates					
Thickness [mm]	19-23	20 ± 2	≤30	40 ± 3	40 ± 3
Width [mm]	50-70	≤160	≤160	50-300	50-300
Cross section [mm^2]	-	-	≤4.000	-	-
Length [mm]	≥300	300-1.200	-	-	-
Minimum number	4	4	3	3	3
Strength [N/mm^2]					
Bending $f_{m,k}$	31,5/59,0 without finger joints in outer laminates	33	28,0-48,0	75	75
Tensile parallel $f_{t,o,k}$	28,5/29,4 without finger joints in outer laminates	23	21	60	60
Tensile orthogonal $f_{t,90,k}$	0,6	0,6	0,5	0,6	0,6
Compressive parallel $f_{c,0,k}$	48,0	45	25	49,5	49,5
Compressive orthogonal $f_{c,90,k}$	9,0	8	8,4	12,3	12,3
Shear $f_{v,k}$	5,5	4	3,4	4,5	4,5
Stiffness [N/mm^2]					
$E_{0,mean}$	14.000	14.400	13.500-15.100	16.800	16.800
G_{mean}	800	850	1.000	850	850
Density [kg/m^3]					
ρ_k	650	690	650	≥730	≥730

Table 12.B HASSLACHER group (2019); Austrian institute of Construction Engineering (2021); Merz, Niemann, & Torno (2021) Glulam and LVL product properties

Rough dimensioning beam

Input data

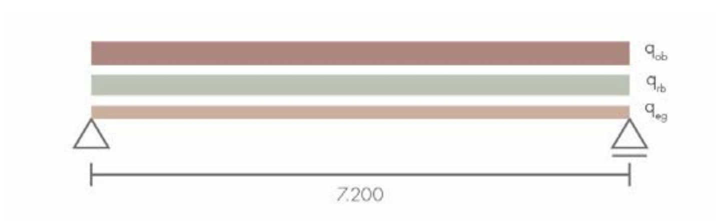
Lengte ligger	l	7200	mm
Breedte doorsnede	b	300	mm
Hoogte doorsnede	h	600	mm
Dichtheid materiaal	ρ	730	kg/m3

Global calculation height beam

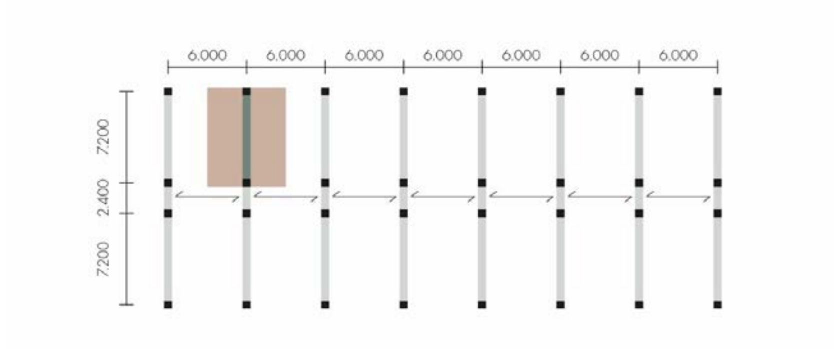
	gezaagd (mm)	gelamineerd (mm)
$h_{dakliggers}$	360	360
$h_{vloerliggers}$	360	600

Gewicht in strekkende meter	g	1,314	kN/m
Kwadratisch oppervlakte moment	I	5,40E+09	mm^4
Weerstandsmoment	W	1,80E+07	mm^3

Loads



Eigen gewicht	q_{eg}	1,314	kN/m



Belasting vloer incl. afwerking en plafond		81	kg/m^2
Belasting vloer incl. afwerking en plafond		0,81	kN/m^2

Meer categorieën rustende belasting op zelfde manier toe te voegen indien nodig

Totale rustende belasting	$q_{rb;totaal}$	0,81	kN/m^2
Hart op hart afstand	h.o.h.	6000	mm
Rustende belasting per strekkende meter	q_{rb}	4,86	kN/m

Appendix VII - Rough dimensioning beam

Tabel NB.1+2 – 6.2+6.4 — Opgelegde belastingen op vloeren, balkons en trappen in gebouwen

Klasse van belaste oppervlakte	q_k [kN/m2]	Q_k [kN] [a]
Klasse A (wonen en huishoudelijk gebruik)		
A-vloeren	1,75	3
A-trappen	2,0	3
A-balkons	2,5	3
Klasse B (kantoorruimten)		
B-kantoorruimten	2,5	3
Klasse C (bijeenkomstruimten)		
C1-tafels: ruimten in scholen, cafés, restaurants, eetzalen, leeszalen, ontvangstruimten	4,0 [b]	7
C2-vaste zitplaatsen: ruimten in kerken, theaters of bioscopen, conferentiezalen, collegezalen, vergaderzalen, wachtkamers, wachtkamers/ -lokalen in stations	4,0 [b]	7
C3-zonder obstakels voor rondlopende mensen: ruimten in musea, tentoonstellingsruimten enz. en toegangsruimten in openbare gebouwen en kantoren, hotels, ziekenhuizen, stationshallen.	5,0	7
C4-fysieke activiteiten: danszalen, gymnastiekzalen, toneel-/balletpodia enz.	5,0	7
C5-grote mensenmassa's: gebouwen voor openbare evenementen, zoals concertzalen, sporthallen met inbegrip van tribunes, bordessen en toegangsruimten, stationsperrons	5,0	7
Klasse D (winkelruimten)		
D1-kleinhandel	4,0 b	7
D2-warenhuizen / supermarkten	4,0 b	7
Klasse D (opslag en industrieel gebruik)		
E1-winkels	≥ 5	≥ 7
E1-bibliotheken	≥ 2,5 [c]	≥ 3
E1-overige	≥ 5	≥ 10
E2-industrieel gebruik	≥ 3 [d]	≥ 7 [d]

Opgelegde belasting per vierkante meter	$q_{ob;vierkante\ meter}$	5	kN/m^2
Opgelegde belasting	q_{ob}	30	kN/m
Blijvende belasting	q_{bb}	6,2	kN/m
Veranderlijke belasting	q_{vb}	30	kN/m
Totale belasting	q	36,2	kN/m

Strength check

Maximum moment	M_d	339,6	kNm
		3,396E+08	Nmm
Partial factor permanent load	γ_{bb}	1,2	
Partial factor changing load	γ_{vb}	1,5	
Maximum occuring tension	σ_m	18,87	N/mm^2
Strength bending material	$f_{m;k}$	75	N/mm^2
Unity Check strength	U.C.	✔ 0,25	-
Needed moment of resistance	W_{need}	4,53E+06	mm^2
Necessary beam height	h_{need}	301	mm

Stiffness check

E-modulus beam	E	16.800	N/mm^2
Deflection permanent load	w_{bb}	2,38	mm

Appendix VII - Rough dimensioning beam

Deflection changing load	w_{vb}	11,57	mm
Doorbuiging kruip	w_{bij}	19,03	mm
	w_{norm}	21,60	mm
Unity Check stiffness	U.C.	✔ 0,88	-
Needed moment of inertia	I_{need}	4,76E+09	mm^4
Necessary beam height	h_{need}	575,2	mm

Appendix VIII - Rough dimensioning column

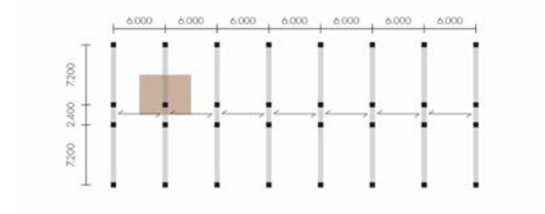
Rough dimensioning column

Input data

Hoogte plafond	l_c	3000	mm

Global calculation column

	gezaagd (mm)	gelamineerd (mm)
$b_{kolommen}$	150	150



Breedte (hart-op-hart)	$b_{h.o.h.}$	6000	mm	
Lengte (hart-op-hart)	$l_{h.o.h.}$	4800	mm	
Opgelegde belasting vloer	$q_{ob;vloer}$	5	kN/m^2	
Opgelegde belasting dak	$q_{ob;dak}$	1	kN/m^2	
Rustende belasting vloer	$q_{rb;vloer}$	0,81	kN/m^2	
Rustende belasting dak	$q_{rb;dak}$	0,81	kN/m^2	
Eigen gewicht ligger vloer	$q_{eg;l\ vloer}$	1,314	kN/m	
Eigen gewicht ligger dak	$q_{eg;l\ dak}$	1,314	kN/m	
Gewichtstabel	Kolom onder 1ste verdieping			
Profiel breedte	b	250	mm	
Profiel hoogte	h	250	mm	*Aanname*
Oppervlakte doorsnede	A	62500	mm^2	
Opgelegde belasting dak	$q_{ob;dak}$	1	kN/m^2	
	ψ_{dak}	0	-	
	$\psi_{verdieping;extreem}$	1	-	
	$\psi_{verdieping;overig}$	0,5	-	
Dichtheid materiaal	ρ	730	kg/m^3	
Gewicht kolom	g	0,46	kN/m	

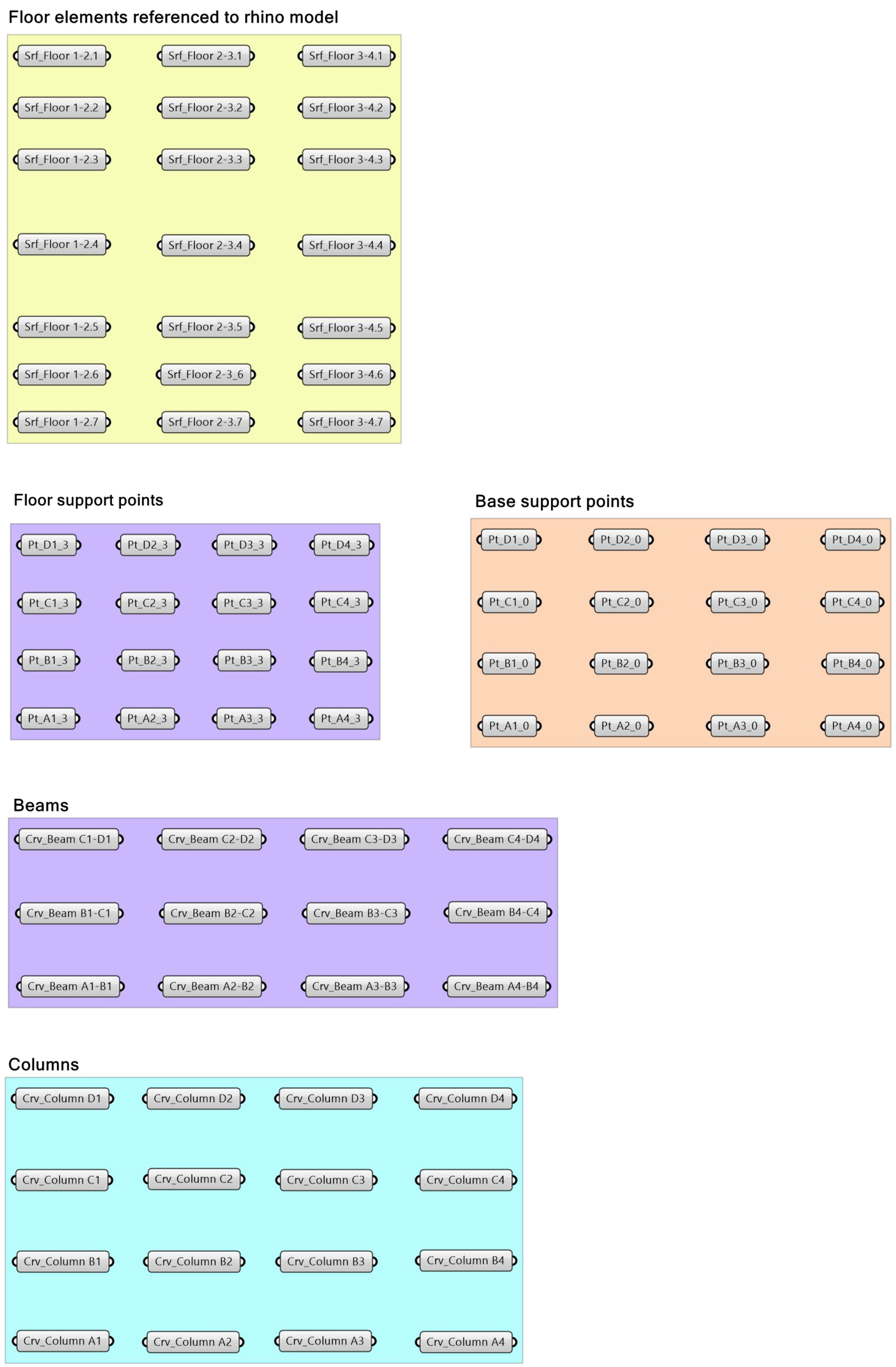
	Lengte [m]	breedte [m]	belasting/m^2	q_{bb}	$q_{bb;totaal}$	q_{vb}	factor ψ	$q_{vb;reken}$
Dak								
q_{ob}	4,8	6	1			28,8	0	**0**
Gewicht dakconstructie	4,8	6	0,81	23,33				
Gewicht ligger	4,8		1,31	6,31				
Gewicht kolom	3		0,46	1,37				
					31,00			
Extreem belaste verdieping 1								
Opgelegde belasting	4,8	6	5			144	1	**144**
Gewicht vloerconstructie	4,8	6	0,81	23,33				
Gewicht ligger	4,8		1,31	6,31				
Gewicht kolom	3		0,46	1,37				
					31,00			
Extreem belaste verdieping 2								
Opgelegde belasting	4,8	6	5			144	1	**144**
Gewicht vloerconstructie	4,8	6	0,81	23,33				
Gewicht ligger	4,8		1,31	6,31				
Gewicht kolom	3		0,46	1,37				
					31,00			
Overige verdiepingen								
Opgelegde belasting	4,8	6	5			144	0,5	**72**
Gewicht vloerconstructie	4,8	6	0,81	23,33				
Gewicht ligger	4,8		1,31	6,31				
Gewicht kolom	3		0,46	1,37				
					31,00			
Repeat for more storeys								
Amount of remaining storeys		2			**62,01**			**144**

Appendix VIII - Rough dimensioning column

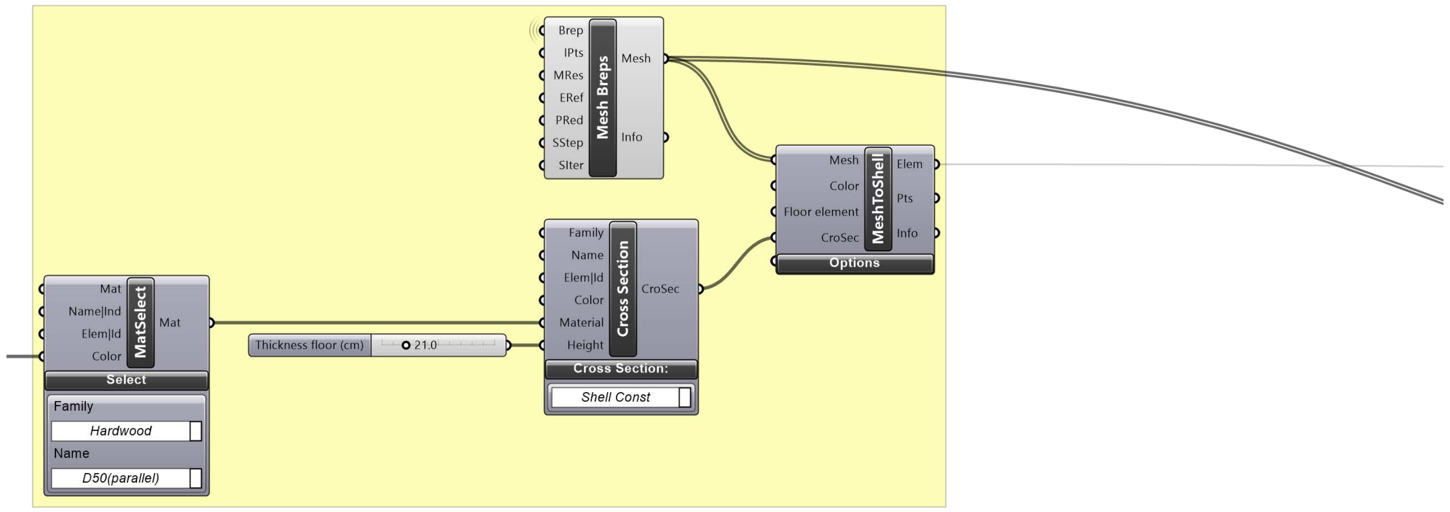
G (blijv. bel.)	155,02	Q (ver. bel.)	432
γ voor G	1,2	γ voor Q	1,5

Totaal in kN				
Partiële factoren				
Totale belasting	F_d		**834,0**	kN
Compressive strength check				
Compressive stress	$\sigma_{c;d}$		13,34	N/mm^2
Compressive strength (parallel)	$f_{c;0;k}$		49,5	N/mm^2
Compressive strength (orthogonal)	$f_{c;90;k}$		12,3	N/mm^2
Unity check (parallel)	U.C.	✔	0,27	-
Unity check (orthogonal)	U.C.	✘	1,08	-
Needed surface area (parallel)	$A_{need;parallel}$		16849	mm
Needed surface area (orthogonal)	$A_{need;orthogonal}$		67807	mm
Buckling check				
Moment of inertia weak direction	I_z		3,26E+08	mm^4
E-modulus	E		16.800	N/mm^2
Buckling length	l_{cr}		3000	mm
Critical buckling force	F_{cr}		6,00E+06	N
Buckling factor	n		7,19	-
Unity check	U.C.	✔	0,70	-
Needed moment of inertia	I_{need}		2,26E+08	mm^4

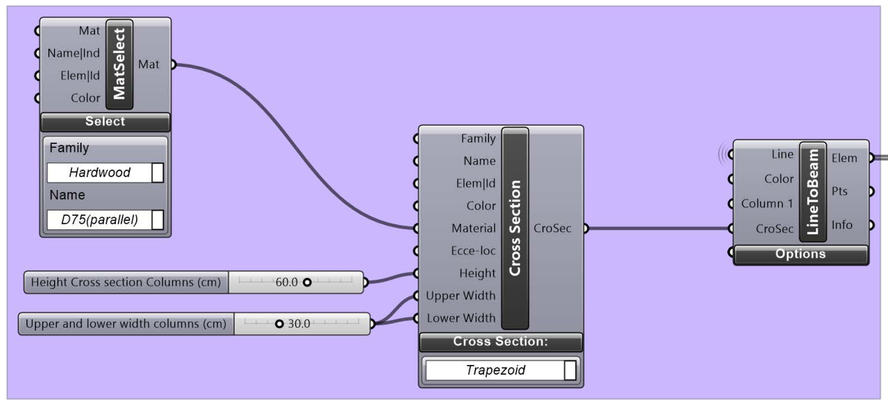
Appendix IX - FEA grasshopper



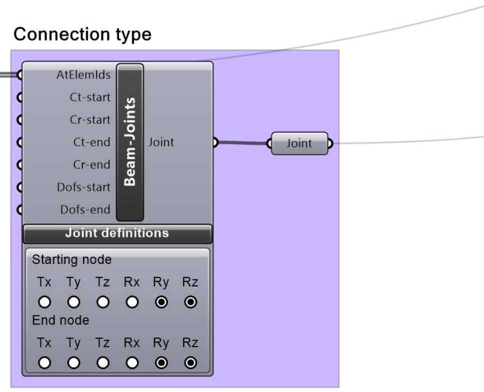
Floors: cross section and material



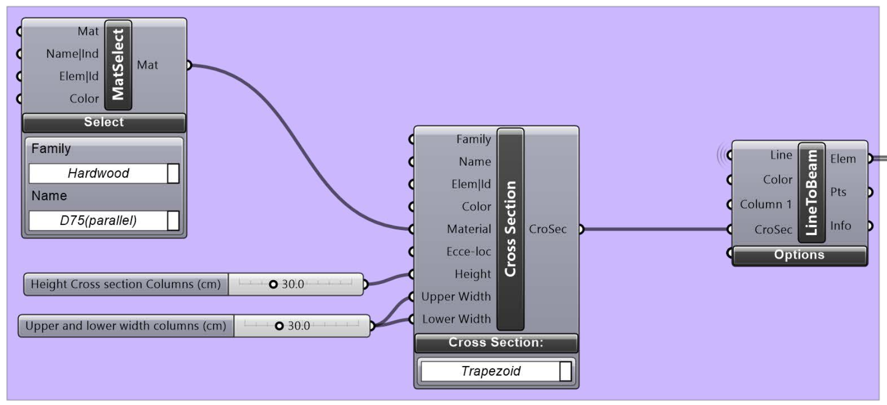
Beams: cross-section and material 7200 mm



Connection type



Beams: cross-section and material 2400 mm



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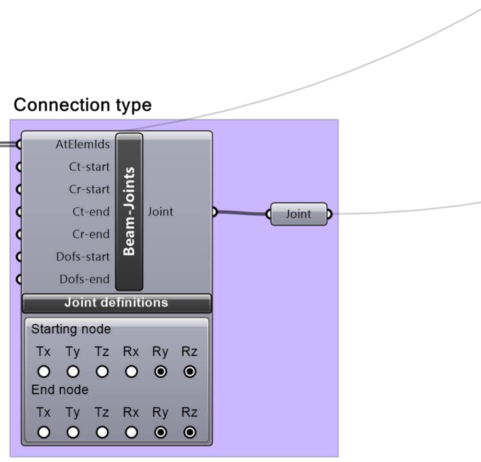
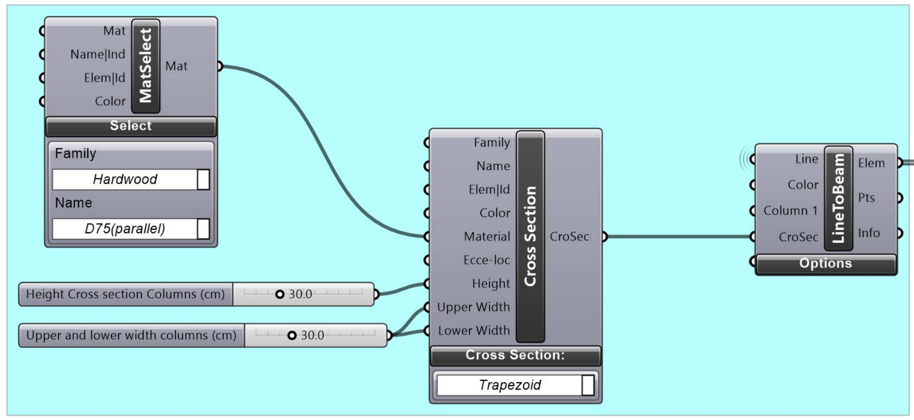
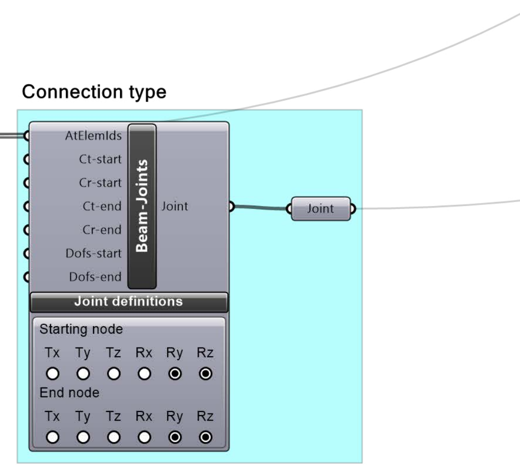


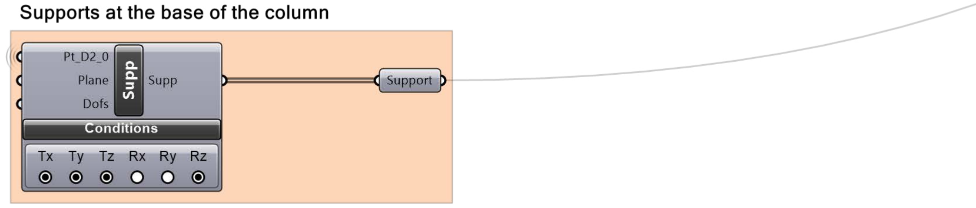
Columns: cross-section and material



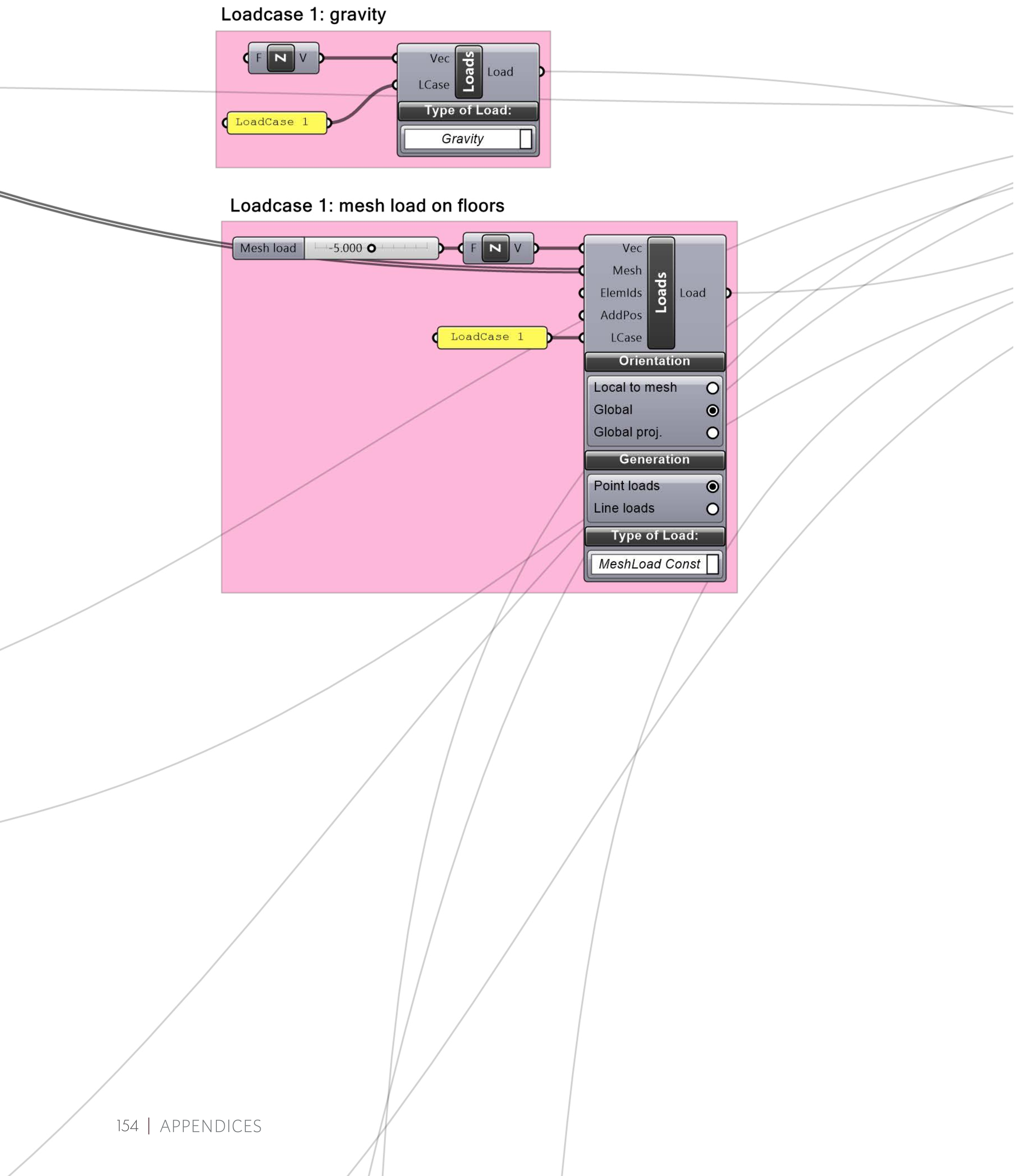
Connection type



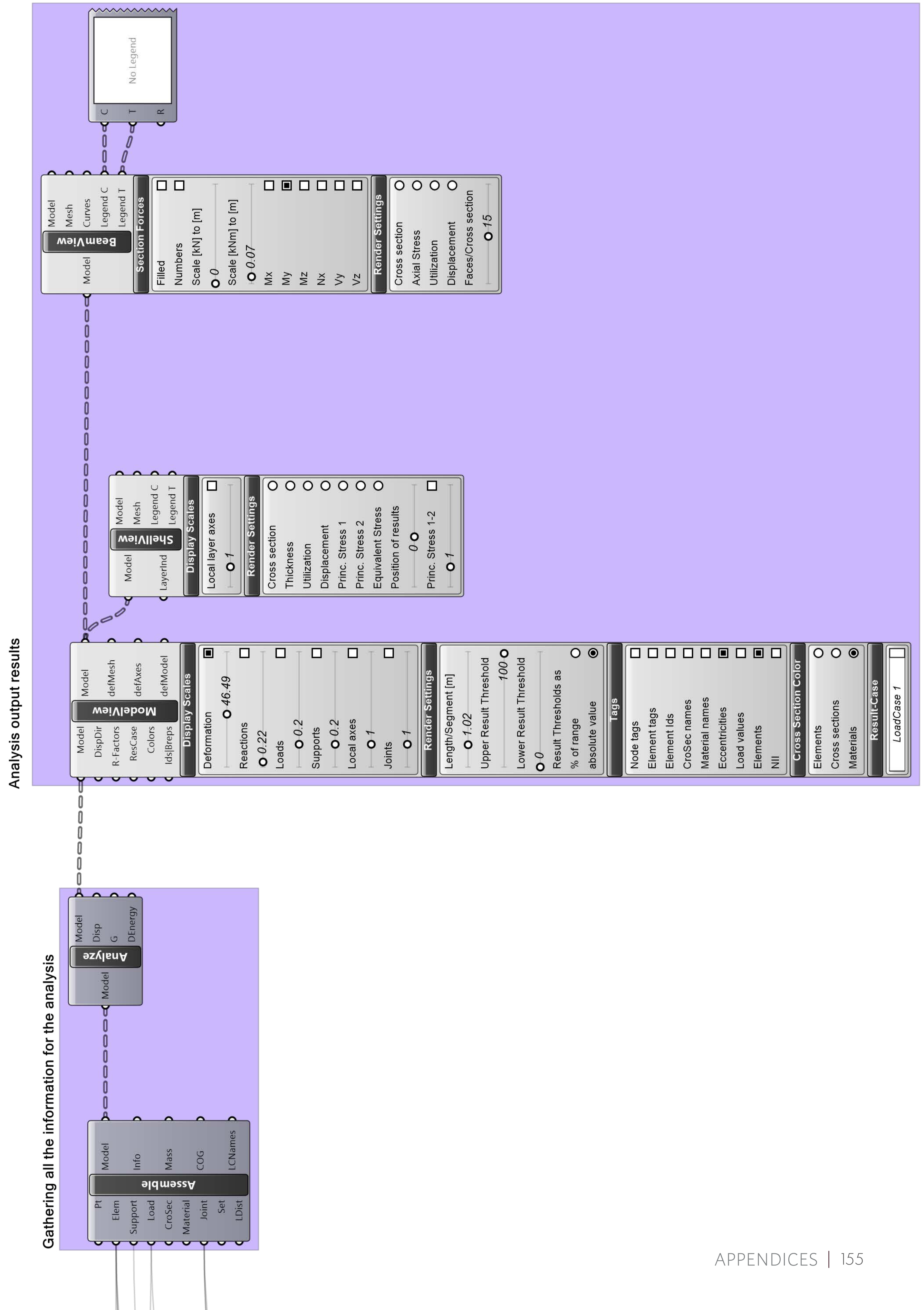
Supports at the base of the column



Appendix IX - FEA grasshopper



Appendix IX - FEA grasshopper



Master thesis research

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2023

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