PO-LAB: *In*Detail

P5 Thesis
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The version of this thesis has been shortened in order to protect confidential data provided by company ECOnnect involved in this research. For more information regarding non-disclosed items please contact ir. PMM Stoutjesdijk at p.m.m.stoutjesdijk@tudelft.nl

SUMMARY

TO A SUSTAINABLE FUTURE

In order to prevent large problems to the world's environment due to high global CO2 emission, emissions have to be reduced by 50-85% of their 2000 levels by 2050. There are certain sectors that have large potential for improvements in emission reduction, in which the building industry is leading (Ürge-Vorsatz & Metz, 2009). The building industry accounts for 40% of worldwide energy consumption, and continued growth is expected (Levine et al., 2007).

Currently, reducing the energy consumption of the building industry, is a crucial issue. The main focus is on the possibilities of reducing the operational energy consumption, for example efficient HVAC systems and innovative building envelopes. Of course this is an important aspect, and a lot of energy is saved with these technologies. But another large potential lies within the reduction of the initial energy, decreasing the energy consumption in the design, manufacturing and building process (Ürge-Vorsatz & Metz, 2009).

Material choices, manufacturing processes and end-of-life decisions all have a large influence on the embodied energy of buildings. With making smart decisions, the initial energy consumption during the manufacturing and construction process can be reduced significantly.

PO-LAB

Current research is done to make buildings more energy efficient, but mostly focused on operational energy consumption and less on embodied energy of buildings. Research in this field is already done, but it's not integrated within the building process yet.

PO-lab is a platform that responds to this lack of knowledge. PO-Lab is a 3TU project, initiated by Marcel Bilow and Tillmann Klein (TU Delft), Jos Lichtenberg (TUe) and Joop Halman (TU Twente) in collaboration with Pieter Stoutjesdijk (ECOnnect). The main objective of the 3TU PO-Lab is to provide a platform to test and prototype innovative ideas for the building industry. By developing this platform, not only the amount of research can be increased, but also the awareness of the current problems and possible solutions increases. The platform will facilitate experimental development of building materials, constructional solutions and new forms of connections and interfaces through full scale mock-ups. In fact a platform will be developed to literally investigate and test digital production technologies like CNC milled wood connections, but also a platform in its wider meaning, to investigate the effects and influences of file to factory production, to explore the potential in the field of sustainability, material use, logistics and the interaction of stakeholders within the chain of the building process.

The PO-lab will be an actual development platform, a 1-storey building that can grow according to its needs. The main structure, façade, roof, internal walls and building services can be designed, analysed, changed and so developed continuously. Next to the embodied energy it focusses on digital fabrication and explores future product development. (Bilow, Entrop, Lichtenberg, & Stoutjesdijk, 2015).

Before the PO-Lab building can be realised, research is required why and how digital technologies can be applied within the building industry. When this is determined, these findings can be used to elaborate a specific design.

RESEARCH

Changing process

The current building process, as result of the strong segregation of different disciplines, is considered inefficient, and a process that produces lots of waste. By adapting and implementing methods of other manufacturing industries these issues could be solved. Innovative digital manufacturing tools to create a more integrated building process. One digital model can be used during the whole development, design, production and construction phase. The integrated building process makes it possible to consider the entire lifecycle during the design phase. The architect, nowadays almost just a stylist, can be involved in the entire building process and possibly get the role of former master builders again. His role during the development process changes completely. The architects need to be capable to develop, design, engineer and manufacture the building system. Architects are involved during the entire process, from development until the end-of-life decisions.

Renewed approach
With the changing building process it is necessary to change the way we approach buildings. It provides new opportunities. The well integrated process provides the opportunity to adapt the living building principles. This principle can be separated in three aspects: industrial, flexible and demountable.

Industrial components that are completely prefabricated, which makes constructing on-site much more efficient. This method has the potential to create an improved balance between cost, time and quality. Digital manufacturing enlarges the potential success of prefabricated solutions. Due to a more integrated development process, and lower tolerances in building products, less problems on-site occur, which can result in a more efficient construction process

Flexible buildings, separated in two types of flexibility: process flexibility is provided by modular building principles to create customization. Mass customization in this case means: the consumer purchases a product or part of one that ultimately results in a customized solution but is actually made from standardized components that are mass-produced. Product flexibility, the adaptability of existing buildings, to make sure that the different lifespans will be equalised to optimize the lifecycle of the entire building. Prefab components need the ability to be disassembled, which makes it possible to perform maintenance, or adapt the buildings configuration to changing user requirements.

Disassembly capacities play an important part to make this adaptability feasible. Due to demountable components it is possible to change configurations of the modular building system to adapt to changing demands. Besides the adaptability, demountable components make the linear life-cycle circular. As a result of standardization, components can be disassembled and reused again in a subsequent project.

PO-LAB BUILDING SYSTEM
The concept (building system) is a unique modular building system that is completely CNC-fabricated, based on the design of Pieter Stoutjesdijk. All three aspects are integrated within one building system. No other example of such a system exists so far. The combination of modern production technologies and modular prefab building principle is one-of-a-kind. The modular building system makes it possible to build very efficient with little errors, and a low-labour construction process. Even untrained construction workers could assemble and disassemble the building.

With this concept, customization is available in another way than usual with digital technologies. Normally customization is achieved due to the fact that digital manufacturing tools can easily be adapted to produce different design. However, within this concept, customization is achieved by configuring standardized components in different variations. One can choose standard components from a library to configure a relative cheap building. When special components are required to make exceptional shapes, special blocks need to be engineered. This will make that specific design more expensive. Advantage of this concept is that the engineering is required only once. This makes it possible to decrease the prices, thus to create an affordable building system without losing quality.

Figure 1 The PO-Lab building design (Own illustration)

DESIGN TASK
The concept for a building system that is using prefabricated, modular, building components to construct a building, will form the base of this research. The feasibility of the concept has been proven in the literature research. However, the idea needs to be elaborated further to actually translate the concept into a feasible building system. How are the components connected; how is the façade integrated in the system; and how is the indoor climate controlled? These questions form the starting point, whereof the specific design task will be derived.

The following research will focus on the connection detail of this modular building system. Like every other connection detail it has to perform according codes and requirements. It has to be able to transfer the loads through the construction, secure the thermal behaviour and make sure the system is air- and watertight.

However, the project goals of PO-Lab require are more advanced. It demands this building system to be modular, adjustable and easy to disassemble. This requires a significant more complex connection detail. The CNC production technologies can really contribute in this aspect in making smart connections. It can provide accurate products that have low tolerance, thus water and airtight connections, but also make the assembly process can be much more efficient and fool proof. The fact that these connection detail will become very complex is not a problem for the computer controlled production method, and due to the fact that this system is standardized the complex detail has to be made only once. All the complex engineering takes place during the design, when assembling and disassembling the building no more complex activities are required.

FINAL DESIGN
Due to the methodological approach, this research succeeded in developing a sufficient concept connection detail as answer on the specified design task. By well defined criteria; the PO-lab goals, CNC limitations, DfM guidelines, and all DfE life-cycle phases are integrated in a proper concept. This concept could be translated into a suitable final design with support from prototypes and structural testing. After numerous iterations, and extra testing to specific aspects, a firm connection detail is developed. All requirements regarding structural behaviour and air and water tightness are achieved.

Further, all criteria are weighed, and the full product life-cycle is considered: Materials with low environmental impact are used; the elements of the detail are optimized to the CNC-limitations and nesting efficiency; the component shapes are optimized to make transport more efficient; on-site assembly can be fast and easy due to repeated processes; existing structures can be adapted to changing demands; and components and elements can get a sustainable end-of-life solution.

But the eventual viability of the design will be visible in the final prototype, the actual laboratory. The first prototype of a full scale section was visible at GEVEL2016. Here the concept of the building system and the connection detail were fully evolved into a final design and already showed much potential. Findings from this prototype can be used to create the actual PO-laboratory.

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INTRODUCTION

This thesis report is the result of the graduation project of Nick van der Knaap, to graduate on the master track 'Building Technology' at the faculty of Faculty of Architecture & the Built Environment, Delft University of Technology. This graduation focusses on the development of a connection detail for PO-Lab. This introduction briefly describes the relevance, PO-lab, the problem statement, objective and the methodology.

TOWARDS A SUSTAINABLE FUTURE

In order to prevent large problems to the world's environment due to high global CO2 emission, emissions have to be reduced by 50-85% of their 2000 levels by 2050. There are certain sectors that have large potentials for improvements in emission reduction, in which the building industry leading (Ürge-Vorsatz & Metz, 2009). The building industry accounts for 40% (IEA, 2008) of worldwide energy consumption, and continued growth is expected (Levine et al., 2007). Not only the large impact of the energy use of the building industry indicates its relevance, but also the fact that the costs of energy savings are the lowest compared to other industries.

These numbers about the current building stock are a convincing reason to start developing new strategies for the building industry. The seriousness of the problem is substantiated by the aims to halve the global environmental impact by 2040. Taking into account the world population is estimated to be doubled and the global wealth has grown by a factor five by 2040, the efficiency measures on environmental impact should be 20 times higher. Stated differently, this means a decrease of environmental impact of 95%. An increase in efficiency of only a factor three to five can be achieved by optimizations and improvements in current situation of the building industry (Klunder, 2005). However, to reach a factor 20, there has to be a radical change of thinking in the building industry. Building has become an industry of habits. Innovations in the industry are usually elaborations of techniques and processes which were already available. But innovations with new technologies and processes are required. (Lichtenberg, 2006).

Reducing the energy consumption of the building industry, is a crucial issue. Currently, architects and engineers try to achieve this mainly by lowering the operational energy consumption of buildings. For example, efficient HVAC systems and innovative building envelopes. Of course this is an important aspect, and a lot of energy can be saved with these technologies. But another large potential lies within the reduction of the initial energy, decreasing the energy consumption in the design, manufacturing and building process. The building industry should consider sustainability within a broader perspective, using energy saving processes, reducing use of natural resources and reducing waste production. Aiming for processes and methods that consider the entire life-cycle of a building. (Ürge-Vorsatz & Metz, 2009).

Designers should consider the entire product life cycle as addition to traditional design. These life cycle issues are found in: materials, production, transport, use, and end-of-life activities (Umeda, Nonomura, & Tomiyama, 2000). The changing design task helps to minimize material and energy consumption, waste production and emissions during the whole life cycle of a product, without losing the quality of the building products.

An important step in reducing the environmental impact in the building industry is to adopt the 'eco-design' process. Chan et al. (2013) state that the researchers and practioners nowadays acknowledge that eco-design is increasingly important during new product development. It is viewed as one of the key factors to sustainable and improved product design. Eco-design, also known as 'Design for Environment' (DfE), is defined by Knight & Jenkins (2009) as followed: *"the systematic integration of environmental considerations into product and process design."* The goal is to reduce the impacts of products on the environment, but with minimal costs. An important aspect of this eco-design in contrast to the traditional design is that the eco-design process considers its entire life cycles instead of only the production and use.

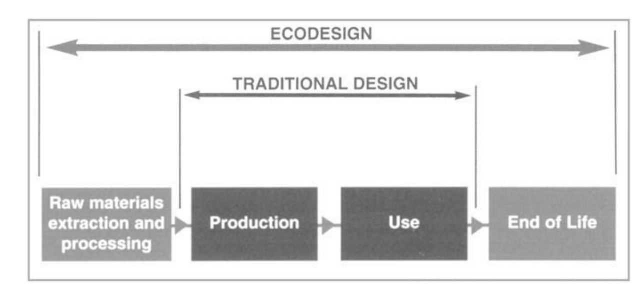


Figure 1 Eco-Design approach (Chan et al. 2013)

EMBODIED ENERGY

Adapting the 'eco-design' approach will lower the embodied energy consumption instead of just the operational energy. Embodied energy is all the energy required to produce or manufacture a product. This includes:

- Direct energy used during manufacturing (e.g. ovens, pumps, etc.)
- Indirect energy to extract and transport raw materials (e.g. trucks, excavators, etc.)
- Energy needed to produce the necessary infrastructure for these activities (e.g. roads, canals, etc.).

Buildings can be seen as complex combinations of various materials of which each contributes to a building's total amount of embodied energy. Besides the energy required to extract and process the raw materials into components and the energy needed for the transport and installation of the components, the energy involved in maintaining, removing and recycling or disposing can also be seen as part of the total amount of embodied energy related to a building.

As the operating energy of buildings is declining, the share of embodied energy in a building is going to play a significant role as the percentage of embodied energy compared to the total energy balance is rising (Mumma, 1995).

The impact of the amount of energy needed for building, maintaining and demolishing a building is well illustrated by an analysis by Ding (2007)of 20 Australian schools. According to this analysis, the amount of energy needed for building maintaining and demolishing those is about the same as 37 years of energy to operate a school. This includes heating, cooling and electricity use. This clearly indicates the importance of the selection of materials on the overall energy consumption of a building. As commonly used materials such as steel, glass, cement and brick require high temperatures for production. These temperatures can only be reached by burning fossil energy sources. Hence, reuse and remanufacturing of materials and components can contribute significantly to help creating a more sustainable built environment (van Nederveen & Gielingh, 2009)

While recycling can have a significant impact on the amount of embodied energy of a material, the process can still require a relatively large amount of energy for some materials. Reusing materials or building components has the potential to reduce the embodied energy even further. Reusing materials and components can still require cleaning, repairing or remanufacturing. However, it can have a substantial positive impact for the embodied energy in a building.

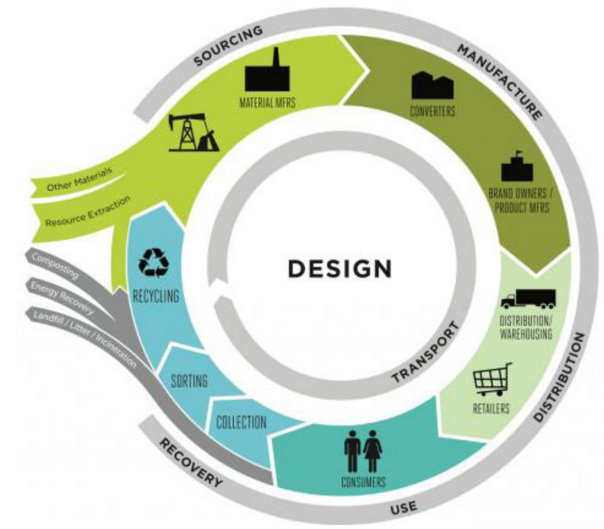
Not only material choice but also manufacturing processes, transport distances and end-of-life decisions have a big influence of the embodied energy of a building. It is noteworthy that usually durable, long-lifetime materials especially those with low maintenance requirements are found to have a lower embodied energy than materials with a short life-time or which involve a difficult recycling process. Less durable materials can have a lower embodied energy in manufacture while the embodied energy in maintenance is higher due to more frequent replacements. With making smart decisions, the energy use during the manufacturing, construction and demolition process can be reduced significantly.

TOWARDS A CYCLIC MODEL

As stated before, embodied energy in a building is largely influenced by its end-of-life processes. However, one could argue that the conventional building industry has limited knowledge of sustainable and efficient building. Buildings are fixed and permanent although they maybe need to transform at one day. Unfortunately, buildings can hardly change, adapt or be updated. For this reason, lots of buildings have to be demolished. Their material flow is linear and one-directional, starting from the extraction of materials, through material processing, assembly, use and finally ends with landfill in most cases. Such processes recognize one end-of-life solution, which results in a large waste production (Durmisevic, 2006). The prevention of waste asks for design approaches in which the manufacture, use, reuse, recycling and end-of-life disposal strategies aim for the lowest possible amount of generated waste.

The Cradle to Cradle design model is an example that aims for a new approach for the building industry. McDonough and Braungart (2002) argue for a revolution in the way we make things with their Cradle to Cradle principle. The principle implies that all the waste of our production and construction processes could be completely absorbed in the process of new construction. In the theory of cradle-to-cradle, waste equals food. This changes the perspective for new end-of-life solutions for materials or components of outdated buildings. Materials or components that no longer meet the demand can be used as raw material for another purpose instead of just using them as landfill. The linear material flow should become a more cyclic lifecycle model. One that provides transformation of materials during different stages of product or building life cycle. The material flow can be diverted towards reuse, remanufacturing and recycling of materials and components. (Smith, 2010)

Figure 2 Circular Economy, Design with in consideration all life-cycle phases in a cyclic process. (www.sandbirch.com)



PO-LAB

In order to make the shift in way building products are considered, in terms of sustainability, requires a major change in approach. Traditionally, the linear design process just considers production and use. This process neglects certain phases of the product life-cycle that are at least as important. A circular approach which addresses all phases of the product life-cycle, seems to be the solution. Implementing this way of thinking in the building industry, requires a renewed approach, in both the development process, and the way we see buildings. Both this subjects will be further elaborated in the following chapters.

PO-lab is a platform that responds to this lack of knowledge. PO-Lab is a 3TU project, initiated by Marcel Bilow and Tillmann Klein (TU Delft), Jos Lichtenberg (TUe) and Joop Halman (TU Twente) in collaboration with Pieter Stoutjesdijk (ECOnnect). The project will be used to do research in reducing the energy consumption in building construction industry. This depends on four main factors: Sustainable material production, resource efficient production, durable constructions and strategies for disassembly, re-use and recycling. The platform will facilitate experimental development of building materials, constructional solutions and new forms of connections and interfaces through full scale mock-ups. This makes it possible to test the architectural appearance and its real-life performance, which are at least as important as calculating the energetic effect over the entire life-cycle of a product.

The PO-lab will be an actual development platform, a single story building that can grow according to its needs. The main structure, façade, roof, internal walls and building services can be designed, analysed, modified and in this way developed continuously. Next to the embodied energy it focusses on digital fabrication and explores future product development concerning these aspects. The small pavilion will be made out of wooden, digitally manufactured (CNC milled) components. Which its production system based on the digital manufacturing ideas of Larry Sass, researcher at MIT (Bilow, Entrop, Lichtenberg, & Stoutjesdijk, 2015).

PROBLEM STATEMENT

PO-lab clearly defined their goals and concept, however the development of the concept into an actual building is not possible yet. Other projects, such as the building system of ECOnnect (Pieter Stoutjesdijk), already adopted some of the project goals into their building concept. This system cleverly uses digital production principles to efficiently produce a building system. Also the idea of using prefabricated components is smart, and makes it possible to assemble a building relatively fast. But, choices regarding other aspects of the building, e.g. using water protective foil, cause large contradictions in the concept and make the assembly inefficient and costly. Also the adaptability and end-of-life possibilities, which are important goals in PO-Lab, are largely neglected in the system of ECOnnect.

To translate the goals of PO-Lab into an actual design does require further research. A building system needs to be developed which considers all the requirements of PO-Lab. All the goals and criteria need to be consequently carried out in every aspect of the building, to create a feasible building.

OBJECTIVE
The PO-lab concept needs to be elaborated into a smart building that tackles the problems of the current building industry. This asks for an elaborated analyses of the current building industry, which can be used to specify strategies to change the current approach in the way we design and build. Based on these strategies the PO-Lab concept can be translated into more specified criteria for an actual building system.

Due to the amount of research that is required to translate the concept into a building system, several design tasks are formulated. This research will focus on the connection details of the building system. Besides the problems every ordinary connection detail has to protect the building from, like water and thermal changes, this connection detail will be much more demanding. To make the building adaptable and upgradable, quick assembly and disassembly is required. The digital production technologies can really contribute in this aspect in making smart designs. It can provide accurate products that have low tolerance, thus water and airtight connections, but also make the assembly process can be much more efficient and fool proof. The design of this connection detail will eventually be tested in the total building system.

The specified criteria can be used to further elaborate the connection into an actual concept design. To do this thoroughly, a methodological approach needs to be developed that considers all criteria in every phase and aspect of the design process. By using this approach it should be possible to develop a concept in a consequent way, which fulfils all the demands of PO-Lab.

METHODICAL LINE OF APPROACH
This research can be divided into four main parts; literature research, concept generation, realization and the review. The first part needs to define and support the general concepts of PO-lab, describe the eventual building system and elaborate the associated design task. The research parts consist of three chapters, which all answer sub-research questions that are stated at the start of this part. This literature research is done in collaboration with co-graduate on PO-Lab Jeroen van Veen. The first chapter contains the analysis of the current building process; general problems will be defined, and innovative solutions of other industries will be explained. The traditional and mostly conventional building industry should adapt certain ideas and methods from these other industries in order to develop. The end of this chapter will make an introduction on how the innovations of other industries can be implemented within the building process.

Next, the problems of the current approach to different building types will be analysed. Chapter three will, again, start with an overview of the general problems. After that, it will proceed with the open building approach, and explain its advantages to the previous stated problems.

The information of the two previous chapters will by combined and concluded into a new approach of designing and building. It will consider the aspects of industrial, flexible and demountable building. To elaborate and clarify these aspects, case studies will be examined. These projects already make use of the stated digital innovations in the approach of the building process and building type, but still have room for improvement.

The literature research ends by composing a set of sustainable design strategies into a framework for the further research. It proves the relevance of PO-Lab and the building system, elaborates the general project goals and defines a specific design task. The sustainable design strategies will be guidelines during the design process of the connection detail.

The second part of this research converts the ideas on a renewed approach of constructing into a concept for a connection detail A methodological approach is developed to create a concept. This methodology is used as a framework to consequently approach and evaluate design solutions, in all different stages, towards a final design.

The following chapters uses this methodology to create a concept. By separating the design task into smaller sub-aspects it is possible to generate and evaluate solutions for every design problem in particular. Based on the upfront specified criteria, the most convenient solutions can be selected. By combining these solutions, suitable concepts can be created. These concepts can be analysed and compared with more elaborated analyses and models. This will result in one specific concept proposal, elaborated in the next chapter. The decisions that are made to every sub-aspect will be elaborated and visualised into an actual conceptual design.

To make the conceptual design feasible for the actual building, it needs to be tested and prototyped. This happens in the third part of this research. The overall design is prototyped to see if it works like it is supposed to do. After testing and evaluating the concept can evolve into a final design. This final design is the elaboration of the connecting detail, and an integration of the connection in the building system to see how it functions.

The last part is the review. It will review if and to what extent the design meets the requirements of the specific design task. It also makes a shift from the design task, back to the entire building. It compares the building system to the conclusions of the literature research. It will determine if the designed building is a reasonable solution to solve problems of the current building industry. Further, this part will contain a chapter with recommendations to further develop this building system.

ORGANISATION
This research contributes to the 3TU project PO-lab. Two of the PO-Lab initiators are also guiding this research. First mentor Marcel Bilow, specialised in product development, will mainly focus on the product development of the specific connection detail. Second mentor Ate Snijder is specialised in structural mechanics and structural connections and has an affection to rapid prototyping. He will guide in the feasibility checks of the designed connection.

Another initiator, Tillmann Klein, is appointed as extra mentor due to his expertise on the PO-Lab but especially on the aspect of developing a methodology. Pieter Stoutjesdijk, owner of ECOnnect, collaborator in the PO-lab and teacher at the TU delft, will guide in subject of CNC fabrication and creating the actual laboratory.

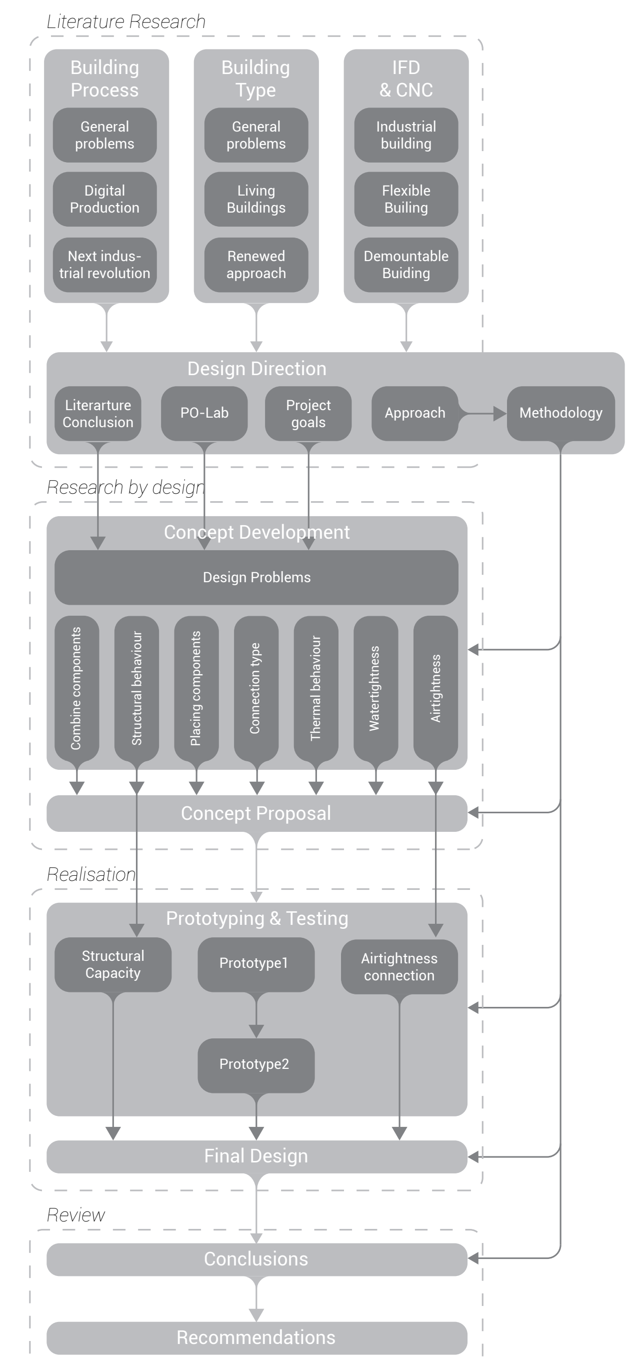


Figure 3
Methodical line of approach
(own illustration)

RESEARCH

INTRODUCTION

The first part needs to define and support the general concepts of PO-lab, and the associated design task. It needs to answer the question:

How to use CNC-milling technology to develop an innovative and sustainable product development (PO) laboratory?

The research part consist of three chapters, which all answer specific sub-research questions. These question are:

- *How do we solve the problems of the current building process and what can be learned from other industries?*

- *How can methods and technologies of Product Design and the manufacturing industry be implemented in the building industry?*

- *How can we use the improvements of the building process, to change the way we approach design and construction?*

The answers to these three questions provides a comprehensive base, which can concluded into a suggestion for a renewed approach for the building industry. This will be exemplified in the last chapter of this research part.

1. DIGITAL BUILDING PROCESS

Source illu.: www.uncubemagazine.com

This chapter contains the analysis of the current building process. The general problems will be defined, and innovative solutions of other industries will be explained. It will mention the necessity of the traditional and conventional building industry to adapt certain ideas and methods from the other industries in order to make improvement possible. The end of this chapter will make an introduction on how the innovations of other industries can be implemented within the building process.

1.1 GENERAL PROCESS

Quality and scope are, generally, wanted aspects of anything we make. Quality, in the way that we simply like things and objects that are well made. Scope can be defined as added features, which are more rather than less also favoured. In contrast, cost and time are undesirable elements. They limit the amount of quality and scope we can achieve. More quality and scope results in more time and money that needs to be spend. Therefore, the way to attain a certain combination of higher quality and greater scope is to spend a combination of more time and more money.

Quality x Scope = Cost x Time

The building industry in general, has accepted this rule as universal law. Other industries, however, do not agree with the need of this equation being in equilibrium. In the automotive, shipbuilding and aircraft industries, quality and scope can develop out of proportion to cost and time. This results in the formula being like this:

Quality x Scope > Cost x Time

Noteworthy is certainly the question why this is possible in these industries and not in architecture, as both produce complex objects. Cars, ships and planes must even be able to move, while buildings are static objects. On top of that, ships are larger than most buildings and still can move from one place to another. According to this, it seems too easy to dismiss the manufacturing industries for having no relevance for architecture (Kieran & Timberlake, 2004).

This statement from Kieran & Timberlake is too blunt. The comparison of a building to a ship makes sense in a way, but to base and compare the complexity of a ship to a building on size and the ability of movement alone seems too simplistic. The complexity of a building does not consist only of these properties but is also, and maybe in particular, about a building sitting in a context, a building being one-of-a-kind. However, the statement that the automotive, shipbuilding and aircraft industries can have a relevance for the building industry, remains intact.

Sarhan & Fox (2013) add that building construction projects would not only be one-of-a-kind, but also more complex and take place under lots of uncertainties and constraints. Repeating claims are heard of the construction industry being too far removed from manufacturing because every product is unique. Egan (1998) rejects this statement; he states that the construction industry does include many repeated processes. The construction industry has two options: *"to ignore all these problems in the belief that construction is so unique that there are no lessons to be learned; or seek improvement through re-engineering construction, learning as much as possible from those who have done it elsewhere"* (Egan, 1998).

The fact is that the construction industry is infamous for rejecting change and resisting variation. The industry is known for having a strong tendency to follow well-known procedures and steps for every project afraid of risks. (Marzouk, Bakry, & El-Said, 2011) Current research shows only 0,3% of the total value of the building industry is spend on the research, development and innovation, while other sectors reach to around 3 to 4%. This makes clear there is a scope for improvement in these fields (Eekhout, 2009).

Current process

Centuries ago, architect, engineers and contractors were all the same person. The designer was often also the maker. Barns were designed by those who used them; factories were designed by the engineer who needed it. Architects, 'master builders' in that time, controlled the whole design and realization process.

Nowadays, as the result of traditional procedures, design and the implementation of the design are treated as two independent products. This results in a conflict between these two phases, creating lots of 'waste' throughout the process, being: incomplete and inaccurate designs, conflicts between design and construction, lack of buildable designs, final products with significant differences to the values originally specified in the design, and problems to contractors due to last-minute design changes made by the designer. Designers struggle with, and usually ignore, the production conditions in which their designs will be implemented. (Sarhan & Fox, 2013)

One of the reasons the building industry is struggling to follow the advancements seen in the manufacturing industry for several decades, is that the designers of today have been separated from the makers. Today, the architect is excluded from the crafts of ‘making’, which turns architects more into stylists. Due to the complexity of today’s projects, the building industry is segregated into various disciplines that are all responsible for their own field. The architect has been separated from the contractor and the materials scientist is not on a par with the product engineer. This results in problems in communication between all disciplines. The communication that exists is more hierarchical than truly communicative, where one party hired another to fulfil a particular role.

Lean construction

The automotive, shipbuilding and aircraft industries have developed models that integrate all steps and acts of design and production. In the early 1950’s Taiichi Ohno, the head of Toyota at that time, introduced new production management principles to optimize the production process, lean production. He thought that by just using traditional methods they could not accomplish full integration. Lean construction is based on the mass production ideas of Henry Ford that are adjusted to achieve high quality, low cost and flexible outputs. The idea is to achieve this by removing the previous mentioned ‘waste’ from the process.

Lean principles are extensive, and beyond the scope of this research, but the theory is based on a few fundamental concepts. The first step in a lean process is to determine the customer’s needs from the process. These define the values of the project. The lean production approach has made itself distinctive by finding ways to reduce waste and increase efficiency. Seven types of waste or ‘muda’ as Taiichi Ohno called it in Japanese, need to be eliminated or refined in the production process (Jürgens, Malsch, & Dohse, 1993):

1. Overproduction: Produce only what is required.
2. Transportation: Efficient transport of materials and building products
3. Motion: Workspaces need to be clean and organized with the flow of assembly.
4. Waiting: No delay by poor integration.
5. Processing: Tasks that have no value to the customer include cleaning, paperwork, etc.
6. Inventory: Stock only what the customer needs.
7. Defects: Imperfections or missing parts can double the time for a simple task.

In lean manufacturing, teams of designers and producers come together to solve specific problems. Producers engage in design and designers engage in production. The process of making is no longer linear. In this way, the intelligence of all relevant disciplines is used as an advantage (Kieran & Timberlake, 2004).

These efficient models, like lean, from manufacturing industries could be implemented in the building industry as well. As Egan said, the construction industry is not one-of-kind, it contains many repeated processes. We should consider the efficient lean principles, and use them to innovate the building industry.

1.2 DIGITAL MANUFACTURING

‘By integrating design, analysis, manufacture, and the assembly of buildings around digital technologies, architects, engineers and builders have an opportunity to fundamentally redefine the relationship between concepts and production. The currently separating professional realms of architecture, engineering, and construction can be integrated into a relatively seamless digital collaborative enterprise- a digital praxis.’ (Kolarevic, 2003)

New production processes, with innovative digital design software, have made it possible for the various parties to share their discipline-specific information. As mentioned before, other industries are ahead of the building industry when it comes to efficiency, as well as controlling the complete design and production process.

Like the automotive industry, which adapted digital

manufacturing processes that make it possible to integrate different disciplines. The engineer is not only designing, but is also considering the production phase, to make sure the entire product lifecycle is respected. Therefore, while the architect turned more into a stylist, whose influence in the whole production process weakens, engineers in other fields are doing better by breaking down the boundaries between the thinkers and makers. (Kieran & Timberlake, 2004)

The use of computer-aided design and manufacturing (CAD/CAM) technologies in design and architecture is no longer a new, fancy gimmick, but it is becoming an emerging interest. These technologies change the approach of product design and architecture. They can be the leading edge of a chain of innovations in the whole design and production environment (Schodek, Bechtold, Griggs, Kao, & Steinberg, 2005).

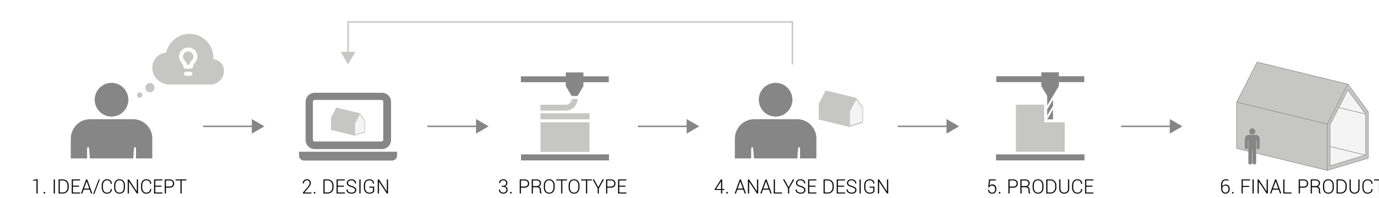
File-to-factory

File-to-Factory creates a seamless merge of the design process into fabrication. It involves direct transfer of data from a 3D modelling software to a digital manufacturing tool. It employs digital design and fabrication strategies based on computational concepts. (Oosterhuis, Bier, Aalbers, & Boer, 2004)

File-to-factory can form a link between the digital and physical aspects of design. This has the potential to improve the process efficiency and reduce mistakes occurring during the different phases of a building process. The building industry has the potential to become 30-40% more efficient with the integration of file-to-factory principles. (Kolarevic, 2003) Fabrication times could decrease, along with production cost as well as the amount of produced waste.

When implementing the file to factory-principles in architecture, the segregation between different disciplines is getting smaller. With engineers designing completely prefabricated building elements, a more efficient way of building becomes possible. With this transition in the building process, the engineer is challenged to not only consider the components functionally but also has to take its aesthetics into account. At the same time the architect has to develop a way how designs function and get assembled.
Moreover, by using new fabrication processes and possibilities, in the early stages of design, the overall quality of building products can increase. Features of existing production process could be explored for the building industry, or new ones could be developed. ’In the light of the efficiency of processes, and their enhanced possibilities, it would not be surprising that these integrated processes will become mainstream in the creation of architecture of the 21st century.’ (Stoutjesdijk, 2013)

Figure 1.1
File-to-Factory principle
(Own illustration)



1.3 THE 'NEW INDUSTRIAL REVOLUTION'

With the introduction of new production technologies, a new industrial revolution is born. 'The new industrial revolution' deserves its name to the fact that, unless it is only ten years old it is accelerating as quickly as the PC in its early days or, even further ago, the invention of the steam engine. After the digital revolution decades ago, digital technologies are finally taking their place in the manufacturing industry. Known as digital fabrication, a new way of manufacturing arose. A broad definition of digital fabrication is, as its name implies, a process that uses digital data, derived from 3D modelling software output, to control a fabrication process that uses additive or subtractive manufacturing techniques.

At first, the digital technologies were mainly used, in what is called 'Rapid Prototyping' (RP), to make prototypes during design processes. The small prototypes are created quick and easy, to analyse a design in the early stage of the design process. However, the digital technologies are used more and more to make fully functional products. Nowadays, digital manufacturing has conquered its place in many manufacturing processes. The same 3D model, used to make a small-scale prototype, can provide the input for manufacturing tools to create a full-scale prototype, or even the final product. Drawings on paper are no longer relevant. But this is not the case in the construction industry at the moment.

Thus, instead of only using digital technologies in the design phase, the whole process is making use of efficient digital manufacturing tools.

Mass production to Mass customization

The new digital manufacturing technologies do have large advantages, but if you want to make a million rubber ducks, it is impossible to beat injection moulding. The first duck would cost around €10.000 due to the production of an expensive mould. But when mass-production with this mould starts, one would nearly pay just for the raw material. If this is done with a 3D printer, the first duck will cost about €10, but no matter how much you produce, the price stays the same. (Anderson, 2013)

In contrary to the mass production process a new trend is developing, mass customization. Customers ask for personalized versions of mass-market products. The development of computer-driven technologies and their potential of flexibility have further awakened a sense of the arrival of this new era in industrial production, the 'new industrial revolution'. (Schodek et al., 2005)

"At this time, in this world, Ford's "one size fits all," no longer makes for a successful product, project, or service. (...) In this century we desire choice, expression, individuality, and the ability to change our minds at the last minute."(Kieran & Timberlake, 2004)

However, since most building projects are considered one-of-a-kind, this way of designing seems impossible to implement in the traditional design process. In the automotive industry larger acquaintance is present as the industry has got used to mass-customization. This industry has optimized their strategies and factories to produce an ever-growing number of models, to an increasingly diversified consumer demand, while controlling or even reducing the amount of used resources. Even components of different brands become exchangeable; this modularization is making the production process way more efficient. The design of such a strategy is very time, money and energy consuming, but eventually the production of a large amount of cars will be for a relatively low price. Still customers are able to customize their car to a certain extent. They can choose different types of motor; cars can vary in component on the bodywork, think of spoilers or fenders but everything is based in a similair base. All of these cars with different elements can be produced at the same production line, based on the same design principles. (Liu, 2011)

If we examine these strategies and processes from an architectural perspective, we immediately recognize that these are difficult to implement in the architectural design process. Time and money consuming activities, which the automotive industry does once and subsequently produce a large amount of cars, generally start from scratch on a project-to-project basis. There is an opportunity with parametric models, but due the different architectural context of multiple designs it is not possible to directly copy such models. (Schodek et al., 2005) This asks for a new approach of building design, an aspect that has potential for further exploration.

Global Production vs. Local Production

In contemporary traditional manufacturing processes, products are manufactured in large factories, from where the products are distributed all over the world. The factories work so efficient, with techniques like injection moulding, that it is not possible to manufacture a product somewhere else, in a small amount, which will be available for the same price. With the new digital manufacturing tools, the traditional process is able to transform.

'Fabrication Labs' occur all around the world. These 'FabLabs' can be fully functioning factories with the use of digital fabrication tools. Giving people the opportunity to locally manufacture their own design in small batches. The FabLabs make it possible to share their digital fabrication tools locally. (Anderson, 2013) In this way, high-end fabrication tools, with high initial costs, are available around the corner instead of on your own desktops. Making it more affordable as it is dividing the costs over different people and the amount of time they use the machines. Moreover, the more people using the manufacturing tools, the easier it is to earn back the high initial investment.

The transition from global to local production, fabrication without large factories, brings more additional advantages. At first, far less transportation is required, which is one of the five lifecycle phases that has a large influence on the embodied energy of a product. The transportation distances, both before and after the production process can be reduced. The materials do not need to be transported all over the world to reach the factory. Instead, materials can be found close by, or can even be residual products. In addition, while the final products of large factories are distributed all over the world, local production creates your product around the corner. Instead of products, the digital design data can be distributed over the world in order to produce it wherever it is needed. The products themselves are not distributed over the road or by airplane anymore, but the digital documents with which they can be created, travel fast and efficient via the internet.

Secondly, there are less costs on maintaining a large factory and the costs corresponding to the extensive supply chain. We cannot deny that most large-scale factories can produce cheaper than the local small-scale FabLabs. However, these factories will have a huge amount of additional costs, which a FabLab does not have. When making an honest comparison, it will show that local production of customized products can be more cost effective. So, instead of global mass production, a shift occurs to local mass customization. A last advantage of local production may arise from the interaction between creative minds who meet like-minded in FabLabs, enabling the exchange of innovative ideas. This can give a boost to the creative industries in a specific area.

Technologies

The most common techniques used in digital manufacturing are 3D printing laser cutting, water jet cutting and CNC-milling. 3D printers use additive technology to create products, this means that the product is built up layer by layer. It works nearly the same as a normal printer, but only in three dimensions. A traditional 2D printer takes dots from your computer screen and turns them into points or lines on a 2D medium. A 3D printer stacks these 2D lines into a 3D object.

Most people see 3D printing as a nice gimmick, but it is getting used more often in the professional field. Dental industry, with making crowns within a few minutes; Medical industry, to make prosthesis and the building industry started to print in 3 dimensions with concrete. (Anderson, 2013) Besides of the tests with printing concrete, the building industry mostly uses this technology for quickly making accessible prototypes and models directly from a computer model. This process of rapid prototyping has caught the imagination of many designers, and seemingly introduces the CAD/CAM field to them. (Schodek et al., 2005)

More suitable for the building industry are subtractive Computer Numerical Control-technologies. Where 3D printing makes use of additive technology, CNC milling creates products with subtractive technology. In other words, drilling a digital design out of a plastic, metal of wooden block. (Anderson, 2013) This makes it possible to create full-scale building components that can immediately be used on the building site.

This research specifically focusses on the use of subtractive CNC-fabrication techniques on plate material. Advantages and limitations are mentioned in this part. More information on CNC-milling can be found in APPENDIX A.

Advantages
The possibility to translate mathematically described lines and curves to paths makes is possible to produce product to the tenth of a millimetre. A router bit, cutting in a 2D plane, offers the ability to cut or route wood in high-resolution and complex shapes. The fact that a machine can be equipped with a series of tools provides to opportunity integrate different manual power tools within one machine. This makes it possible to use different woodworking skills at once and produce a finished product.

Added to that, provides CNC-milling the possibility to create products with a tolerance below the tenth of a millimetre. This makes it possible to create very accurate building products which can contribute to a building industry of more efficient assemblies and less errors.

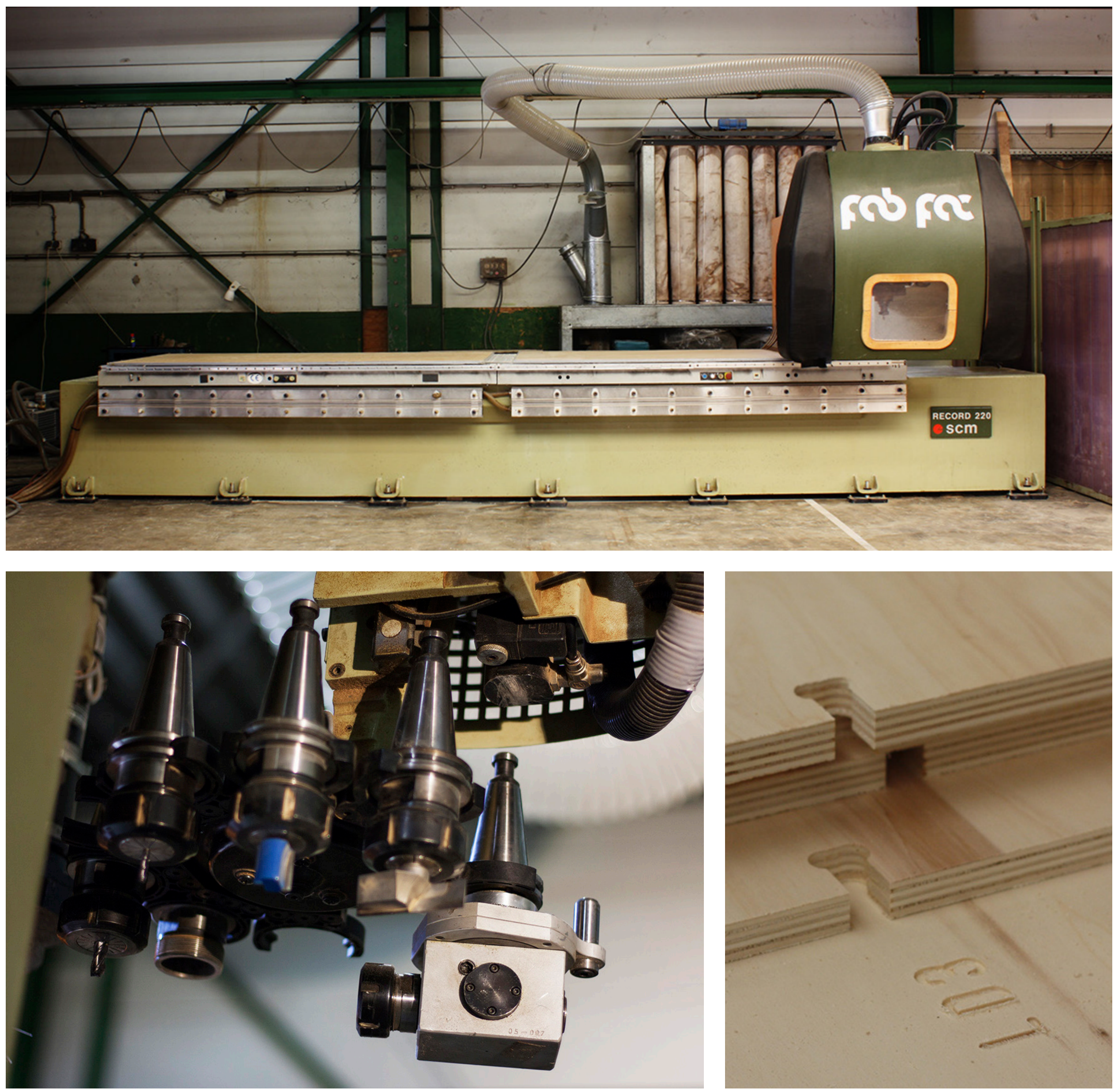


Figure 1.2
CNC-Miller FabFac
(fabfac.nl)

Limitations
There are some limitations with CNC-technology, these aspects are important to consider when designing. Firstly, since most of the labour is shifted to the design and planning phase, the design needs to be checked securely. Failures in the design that are only discovered after production are costly, because the process has to be done over from the start. Components that have faults usually are waste.

The CNC machines cannot produce full 3D parts, because the router bit can't mill from the bottom upwards, the z-axis is limited to cutting from the top downwards. The driver of the router 'thinks' in two-dimensional planes. The three-dimensional shape is built up from layering these planes. Therefore CNC-millers are seen as 2,5D.

Because in subtractive production methods material is cut away, the waste of high quality material is inherent to the process. Optimization tools for the maximum use of plates exist, but still a part of every panel is wasted, directly influencing the efficiency of the spanning structure. By optimising this nesting, much material can be saved. The subtractive way of producing also brings limitations in making inner corners of 90 degrees. The cylindrical shaped router can only make on over cuts of rounded corner. Depending on the radius of the router bit, the corner can become sharper.

1.4 CONCLUSION
In the 1990s the concepts of lean manufacturing and mass customization were seen as the business strategies of the future, offering a streamlined approach to delivering infinite variability while reducing cost (Joseph, 1993). Although the concepts of lean manufacturing and mass customization are beginning to have an impact on architecture, there is still relatively little connection between design software environments and manufacturing output. Therefore, most products today are still designed with a traditional way of thinking, and design and manufacture are rarely integrated. Schodek and colleagues (2005) call manufacturers that have CNC tools "islands of automation" that present potentials for mass customization, but require architects to engage in a meaningful collaboration with manufacturing in order to realize these benefits. By implementing technologies and processes of 'the next industrial revolution' into the building industry, it will provide opportunities to fully integrate the aspects of designing, manufacturing and building. The digital model, used for both design and analysis, with digitally producing a full-scale prototype, can be used directly as input for the digital manufacturing process to create the final product.

The gap between disciplines, the designing and the making, which makes the building process inefficient, can become smaller. The historical 'master builder' returns into the building process as one person or a small group that possesses this capability to both design and manufacture. If architects master these capacities, they become directly involved in the fabrication process. Instead of producing traditional drawings which are translated into buildings by constructors, the products of the architect would directly control the digital manufacturing tools to create the final product. The jobs of the architect and engineer become more integrated.

This research specifically focusses on the use of subtractive CNC-fabrication techniques on plate material. It provides the possibility to create products with a tolerance below the tenth of a millimetre. This makes it possible to create very accurate building products which can contribute to a building industry of more efficient assemblies and less errors.

The changes as result of this design and manufacturing process, in combination with the mass customization approach, asks for a new building system. High engineering time is required for specific products therefore, it would be non-efficient to use this design only once. Building systems, based on the automotive mass-customization strategy should be developed. A system that requires a lot of time to engineer and prototype. But, which could be customized to fit different contexts or circumstances. According to Terry Knight (2009), professor at MIT: *"there is a demand for that [digital frameworks for mass customization] now in architecture firms because we need to have designs that will be suitable for different contexts, but are within the same general family. So we need to produce a metadesign that we can adapt or changing circumstances. I'm convinced that this is the wave of the future."*

2. RENEWED APPROACH ON BUILDINGS

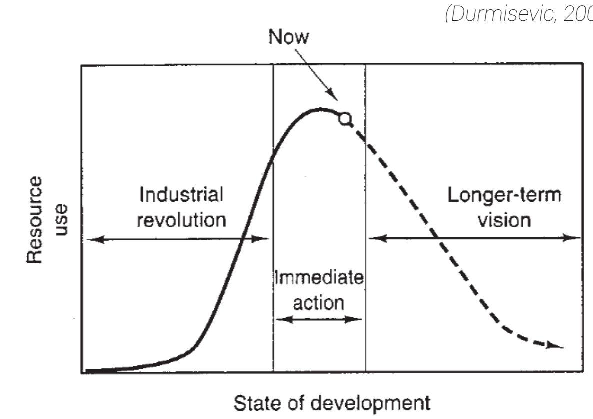
Source illu.: www.heijmans.nl

In this chapter the problems of the current approach to different building types will be analysed. It will start with an overview of the general problems and the current way a creating static building. After that, it will proceed with the living building approach, and explain its advantages to the previous stated problems.

As becomes clear, a change in the process of building asks for a matching method in the way we approach buildings. One could state that traditional building practices focus on three main factors; construction costs, building quality and time. This results in the extraordinary inefficient building processes from an economic, environmental and social point of view. In general, builders, developers and architects often see buildings as static and permanent and therefore forget to consider future changes. The focus lies on the three factors, which are in essence, all short-term factors. In a sustainable design these traditional competitive factors are seen as sub-factors being part of the systems in the three pillars of sustainability; environmental, economic, social.

In order to reach a sustainable approach in building and construction, the design focus has to go beyond that of the construction phase of a building. Instead of dealing with cost, quality and time (construction phase), long-term operational phases, as well as the demolition phase should be incorporated. The operational and demolition phase are mainly responsible for the negative influence of the building industry on environment, economic and social aspects (Durmisevic, 2006).

Figure 2.1
Long-term vision is required
(Durmisevic, 2006)



2.1 STATIC BUILDINGS

In the classical view of construction, a building is a static object that needs to meet the user's requirements, which are specified before the start of the design and construction. An assumption that user requirements and building specifications do not change afterwards appear to be the case. Clients who change their mind are lumbered with high additional cost. Contracts protect the builder legally against clients with changing needs and requirements.

The current static way of thinking is emphasized by the term maintenance as the goals of this is keeping the building as much as possible in its original state (van Nederveen & Gielingh, 2009). In the built environment it is common practice that buildings become non-functional although their expected lifespan from a technical point of view can be decades longer. This often results in premature demolition. The demolition of buildings, which are still in good condition, is hard to justify from an economic and environmental point of view. Destroying these technical sufficient buildings enlarges the influence of the building industry to the current obstacles the world is facing, having an effect on environmental impact due to energy use and waste production. The building industry has earned its negative label as it is seen as an inefficient industry with high failure costs, little profits and a large consumption of resources (Gijsbers, 2011; Lichtenberg, 2006).

Thinking of buildings as static objects is likely and necessary to change in the coming decades. Certainly, the requirements of users and owners, but also social, environmental and technological requirements will evolve continuously. Van Nederveen & Gielingh (2009) state: "A building should not be seen any longer as a static object that meets only initial needs, and which ignores the idea that life has an end. A building must be seen as a process, being capable to meet changing demands". Important to notice is the relevance of end-of-life activities in the building industry and the degree of which buildings provide a possibility to extent its functional lifetime.

Buildings are assumed to last longer when they are made of materials that are more durable. However, this only applies if buildings are demolished when the materials which they are made of do no longer meet the technical requirements. This is often not the case, hence demolition results in material and energy losses and is initiated by (Durmisevic, 2006):

• The frequent functional changes often cause the 'use life cycle' to be shorter than the 'technical life cycle'
• Materials being integrated into fixed assemblies, replacing one of the elements means the demolition of others
• The end of the life cycle of buildings is associated with demolition and waste generation

From these assumptions, one could suggest that the essential element of extending the life cycle of buildings and the materials they consist of, includes designing the ability to change all degrees of technical composition of a building. This transformation, indifferent of the materials used in the building, is related to disassembly and reconfiguration of elements. There has to be a new form of design approach to achieve this. The focus must lie on the long-term performance of a building and finding a match between its technical and functional composition.

2.2 LIVING BUILDINGS

In contrast to static buildings, the term 'living buildings' is introduced. The origins of the concept of 'living buildings' is best captured by one of Habraken's quotes: 'We should not to forecast what will happen, but try to make provisions for the unforeseen.' (Habraken, 1999) It is clear that, as the future cannot be predicted, a design which takes several scenarios into account has a better chance of meeting its future requirements.

The following differences between open and closed systems can be found:

• Conventional, closed, systems are primarily designed for assembly and are based on known structuring principles for assembly, which are: integration of parts, design of stuck assemblies, creation of modules and standardization of system levels.
• Open systems, on the other hand, create variety through greater functional decomposition. Such dynamic systems provide for the altering requirements throughout a building's lifecycle. The main aspects of an open system are: separation of functions, possibility for disassembly, flexible production processes that have no restriction for standard sizes and standardization on sub-assembly level in which mass production is connected to small size components.

In short, the focus has shifted from simple static elements in closed systems to complex components defined by dynamic configurations in open systems (Durmisevic, 2006).

"A traditional building can be seen as a materialized solution for user needs that existed before it was constructed" . This statement, made by Van Nederveen & Gielingh (2009), means that if the needs of the user change in time, the building may become useless, while its technical state is still acceptable. This raises the chance of the building to be demolished. This problem causes the construction industry to be a large producer of waste. The waste itself is not the only problem, also it causes an exhaustion of natural resources.

Conventional buildings are not designed to adapt to the changing demands of our society. Due to this fact, buildings and infrastructure are prone to constant transformation to accommodate changing needs that results in demolishment of buildings and erecting of new ones to be adapted to new needs. Everyday practice learns that a transformation of buildings inevitably involves demolition and the disposal of waste (Durmisevic, 2006).

When a careful look is taken at buildings, in general one can conclude that there is a mismatch between the functional life cycle and the technical life cycle of buildings and the elements that they are made of. This mismatch is dynamic and increasing and needs a strategic approach.

A transformable system has impact on the well-known three pillars of sustainable development: the social, environmental and economic systems. It is clear that every building has a negative impact on the environment when it's built and demolished. Embodied resources should be taken into account in each new building so they can be used in the future as a source for new resources. One could say that transformable structures should be designed for reuse, reconfiguration and recycling. This obviously has environmental benefits, but besides those they offer users of a building the opportunity to adapt their buildings more easily to suit their changing needs and advancements in technology. In this way also initial investments for new materials can be saved. Durmisevic comments on this theory that the quality of a building in the future will be measured by the flexibility of structures and their environmental efficiency. (Durmisevic, 2006)

There are some initiatives that adopted methods to tackle these problems. A well-known example in the Netherlands is 'IFD Bouwen', an abbreviation for Industrial, Flexible and Demountable Building. The IFD initiative is initiated by multiple governmental institutions to generate an impulse to the market of flexible building concepts, systems and products. According to Geraedts et al. (2011) the three facets (Industrial, flexible and demountable) are the main aspects that can contribute to living buildings. (Geraedts, Cuperus, & Shing, 2011; Gijsbers, 2011)

2.3 CONCLUSION

The renewed approach of buildings, described with the term living, seems a convenient solution to use improved methods of the building process. Living buildings have the opportunity to tackle the problems of the building industry that are stated in the first chapter. Such a strategy introduces another view on how to design building parts and components. How can we design and integrate building systems and components in a way we can replace or reconfigure them in a later phase? This means considering how these parts of an existing building can be accessed and replaced or removed. Ultimately the sustainability of design in the future will rely strongly on the disassembly potential of building assemblies (Durmisevic, 2006)

To translate this approach into specific solutions for a building system, it needs to be elaborated further. The next chapter will do this, guided by the three main aspects defined by the IFD initiative. Industrialisation, flexibility and demountable are essential aspects to make living buildings work.

Figure 2.2
'Leren door demonstreren', an overview of Dutch IFD-projects (Durmisevic, 2006)

3. IFD BUILDING WITH CNC-TECHNOLOGY

Source illu.: www.demodev.org/

This chapter combines the research of the prior chapters into the elaboration of the living building concept. It will consider the three aspects of IFD: industrial, flexible and demountable. To elaborate and clarify these aspects, case studies will be examined. These project already make use of the stated innovations in the approach of the building process and building type, but still have room for improvement. The end of this chapter will combine all the research into a proposal how to use translate the living concept into a building system.

3.1 INDUSTRIAL

The building industry is, in general, inefficient due to errors and unstructured processes. In the classical building industry, contracts spread all the responsibilities on the consequences of failure, and prevents stakeholders to take high risks. This leads to badly integrated projects, with disadvantages to all of the stakeholders. Owners are losing money, architects cannot increase the quality of their design and contractors have many risks and bear a major part of the financial aspect.(Smith, 2010). To deliver quality and cost benefit, a more integrated process is required. Studies show that projects with collaborative relation between stakeholders are more successful for all of them. Key element to obtain an integrated process is participation of all stakeholders as early in the project as possible.

Kieran & Timberlake (2004) confirm rethinking the traditional building process as useful. "The traditional building paradigm is to gather all of the parts of a building at the site and then assemble them piece by piece. This process leads product engineers to think in a piecemeal manner when designing building products. If we were to construct our buildings on site utilizing pre-assembled components, the engineers could think in a more effective holistic part-to-whole manner."

Industrial construction uses prefabricated components that are system-built in a uniform way, in factory controlled conditions. The prefab components are assembled on-site to create a complete building. (Geraedts et al., 2011) With an integrated model, decisions regarding prefabrication can be made up-front so that possible failures of the design can be noticed early in the development process and solutions can be found to meet the required economic, environmental and social requirements.

Prefabrication

Prefabrication is not revolutionary. In the history great architects and engineers, among others Fuller, Wright and Gropius, developed prefabricated mass housing systems. All of these systems were competent and technically ready to bring on the market. However, there were some problems with these systems. There was no possibility for manipulation of maintenance over time. Mark and Peter Anderson stated: "One of the lessons that can be learned from the many previous attempts at prefabricated housing production, is that uniquely proprietary systems of single-source components are too costly to develop and have almost always ended in economic failure, even when excellent in design, detailing, and production concept." (Smith, 2010)

The availability of digital technologies in the processes of production, both in the design and fabrication phase, is changing the production ideology. It is not only affecting the development of prefabricated building technology, but also the entire supply chain. The architect that is also becoming the maker. The integrated process, which is achievable by using digital production technologies, makes it possible to notice and solve design problems early in the development process. Smith (2010) states that: 'Digital fabrication is potentially a method by which the promises of prefabrication— complementary increase in design and production quality—may be realized.'

Using prefabrication principles can result in benefits on quality, time and costs. The amount in which a specific design suits the demands of a client is directly related to decisions, and the balance, between these three factors. For a given program, the design team usually establishes the relationships between quality, time and cost. If one of these will change, this has an effect to all. For example, one chooses a material of low quality, in order to save money, or to allow a project to be completed on time.

The prefabrication process, a practice of assembling components in a factory, and transporting complete assemblies to the site to complete the entire building, contains the potential to bring a more balanced relationship between costs, time and quality.

Costs
Prefabricated buildings are thought of as more cost efficient than traditional on-site construction methods. Costs during the building process mainly depend on three aspects: material, labour and time. In theory, by reducing one of the three, the overall cost will also reduce. Prefabrication has conceptual solutions to reduce all of those aspects.

The primary method to reduce the cost is to reduce the amount of material used during the building process. With on-site construction, the materials are, after purchasing, immediately transported to the building site. On-site, the materials are stored, waiting for installation. Often these materials are over-ordered to make sure the right quantity is available for when mistakes are made in calculation or damages occur on the building site. In prefabricated constructions, manufactured in factories, most of the material used is will not only serve a single project. The materials can be stored in the factory and used whenever they are needed. Besides the over-ordering, material use can be reduced by a more efficient production process. Factory activities are more predictable and less prone to exterior influences, resulting in the production of less waste material, reducing the overall amount of material.

From a labour point of view, most of the reductions can be made due to a more efficient on-site building process. The assembly activities of prefabricated components are elementary and repetitive because nearly every component works on the same principles. This makes it easy to install all building parts. When everything is well-thought upfront in the development and design process, the chance of errors can be minimized and assembly speed and ease can be optimized. However, when multiple components do not fit it can result in a costly process of adjusting or redesigning (part of) the components.

Although money can be saved by efficient material use and reducing labour. Factory-produced components may initially be more expensive. Setting up an entire factory requires a substantial investment. Therefore, small projects are not likely to be completely prefabricated, unless they use standardized components, as it is too costly to modify the factory setup. The quantity of components and their repeatability in the project must guarantee the investment on heavy machinery. Besides the initial costs, transport cost can be considerably higher with prefabrication. Prefabricated products often require larger trucks to transport, need stronger cranes on-site and more coordination is required.

Prefabrication considers the difference between initial and lifecycle costs. Traditionally, initial costs often decide whether a project is built on-site or off-site. However, this is not always the best approach in decision making. A building may be built with low initial costs, but in its overall lifespan this may not

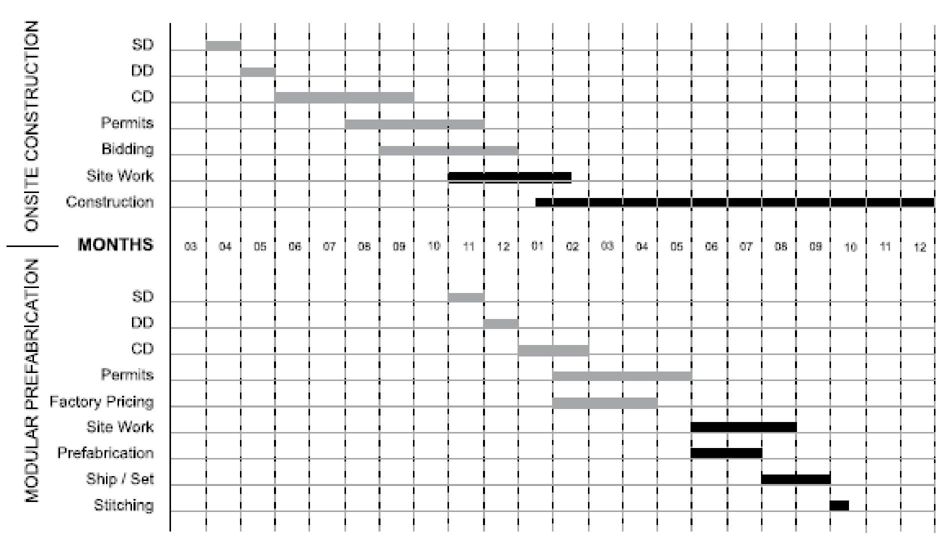


Figure 3.1
Time savings due to prefab (Smith, 2010)

be the most beneficial. Prefabrication is a lifecycle investment, perhaps the costs are high initially, but the prefab products can provide higher value on the long term.

Time
The greatest distinction of prefabricated systems can be made within the reduction of construction time. The savings in time are the result of the ability to simultaneously construct components in the factory, and do all the work required on-site. A large part of the testing and production can be done, while site work is already being prepared. This can result in significant time reductions. Traditional on-site construction is a linear process where often subcontractors have to wait until the previous job is finished before they can start. Prefab offers more predictability in achievable deadlines.

Another benefit by doing an adequate amount of work in the factory is that weather circumstances do not influence the process. With prefabricated components, the assembly process on-site is becoming more convenient. Only little assembly activities are required, which reduces the chance of large errors occurring.

All of these aspects make it possible to create a 50% time saving over the whole construction, see figure 4.1 (Smith, 2010).

Quality
On-site construction still depends on craftsmanship with skilled labourers, where other industries are using increasingly automated processes. Prefabricating products with automated processes will increase the precision of products. CNC milling for example, is accurate to the tenth of a millimetre. This allows for more control over the end result of prefabricated products. Products available from off-site manufacturers will be of higher quality, because the assembly takes place in a factory environment that has good work conditions. And due to automated processes fewer hands have touched the products, decreasing the chance of mistakes.

Along with high quality of the individual products, the manufactures have the ability to create lower dimensional tolerances. Due to this low tolerances, the relation between prefab components, or prefab and site-built components is more accurate. This will increase the quality of the overall end product of a project, by making a fast and easy assemblies with a lower chance of errors.

Advantages prefabrication
Owners and users expect a reliable product at the end of the construction process. Prefabrication limits risks and eliminates highly multi variable problems of construction. Off-site methods do not only allow for products with a higher quality, but they are also more likely to be completed on time and within budget. The outcome is more predictable. This can be done through standardized components that have been tested to be successful, or in a unique project that is elaborated with several prototypes before it is taken into production. The involvement of digital manufacturing technologies can increase the success of the industrialized processes.

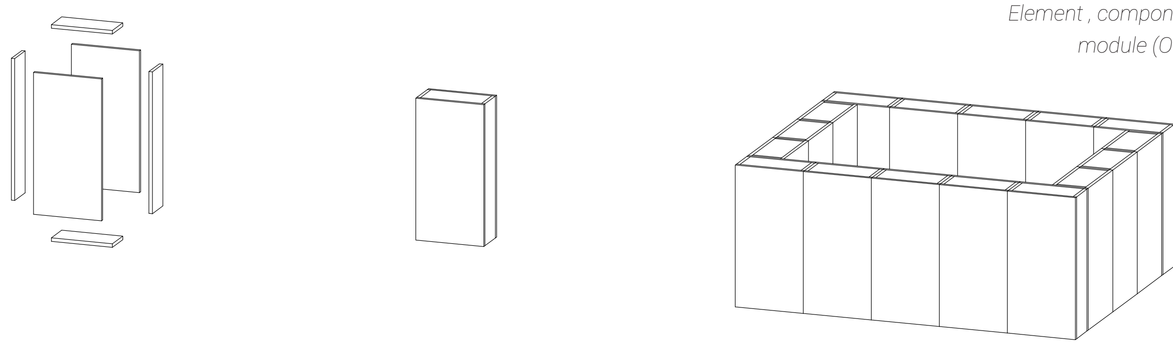
Onsite construction does not necessarily mean low-quality. However, to achieve high quality often a combination of more time, skill and cost is needed]. When using offsite construction methods high quality is achievable at lower cost and in less time. High skill is only necessary in the factory for a smaller amount of labourers.

Industrialized building products
The previous paragraphs proved that implementation of prefabrication in the building industry could have a positive effect. However, the way of interpreting the prefabrication principle does play a major part in the success of a building. Important aspects hereby are the level of prefabrication and product type. Both will be discussed in the following paragraphs.

Level of prefabrication
The level of prefabrication separates building products by the amount of work that is done on- or off-site. Eekhout (1997) describes three building products that can be used as prefabricated parts. They can be sorted hierarchically in order of increasing complexity and added value:

- The prefabrication process in the factory starts with shaping of base material into elements. Material is the smallest, most elementary, mono-material part

Figure 3.2
Element , component and module (Own Illu.)



of the hierarchical order. These parts, mostly mass-produced, will undergo multiple machining off-site in order to become a building product which will fulfil one specific function.

• When assembling multiple elements, with different functions, into one part an element is created. An element is always a (composite) part of different materials in order to be able to fulfil several functions. These elements can be transported to site to configure them into a building.

• The third in the hierarchical order is the component. Elements do not necessarily need to be transported to site in order to assemble them into a building. This process is also possible within the factory. The different elements are combined into a module, which can be transported to site and hardly needs any further building activities. By configuring several components onsite, a liveable building is realized.

• Module is the next step. A module is a bigger component that can fulfil multiple functions, e.g. completely prefabricated bad room consisting of different components. The module as such is an operational unit, which can be place onsite and immediately be used.

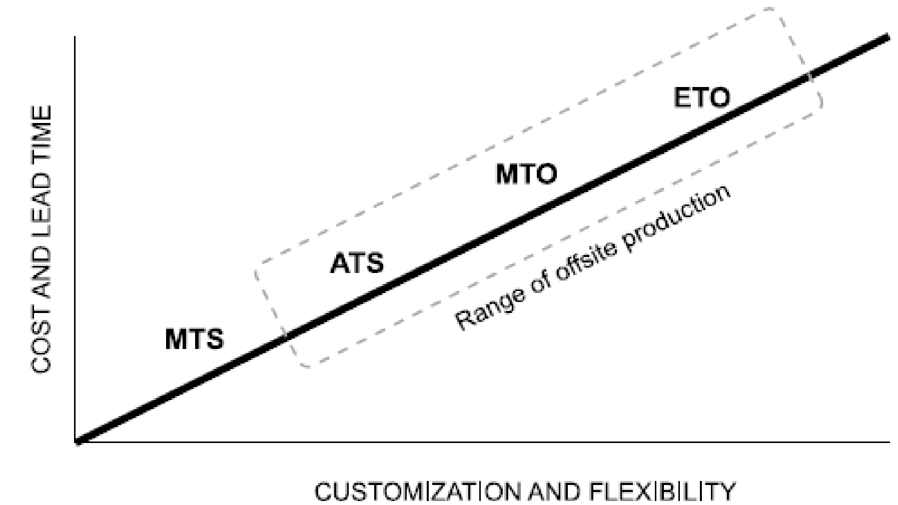
Product type
Building prefabrication can be a process of assembling standardized or custom parts. However, those two terms are not elaborated enough to capture the differences in complexity of the manufacturing and fabrication industry. Fabrication technologies vary for each project. The main concerns for the manufacturer are costs, engineering time, process time, batch size and flexibility. Four terms arose to describe the different prefabrication products and the associated effort that has to be spend in manufacturing (Eekhout, 1997; Smith, 2010):

• Made-to-Stock (MTS) or building product: MTS products are best handled through inventory replenishment strategies. In order to keep inventory full, manufacturers have used standardization, by reducing complexity and increasing repetition. Supplier-managed inventory has proven successful for some companies and projects, where suppliers take on the job of determining requirements, and maintaining and distributing materials. Examples of MTS products include warehoused building goods such as lumber, wood, steel, and aluminium sections, ceiling tiles, and panel material such as gypsum board or plywood.

• Assembled-to-Stock (ATS) or standard-product: ATS products have set designs and established standards. Many of the attributes of MTS are found in ATS, but customization is introduced. The principles of assembly line production and mass customization are often associated with ATS, where customers request variation within a set system of form and relationship of elements to one another. Outside of the building industry, computer companies and shoe companies are now offering customizable options for their standardized products. Examples of ATS fabrication in architecture include International Standard Building Units and Mobile Homes.

• Made-to-Order (MTO) or system-product: MTO products are pulled forward through their supply process to arrive onsite just in time. These products are not sitting on shelves in MTS or have a set geometry as

Figure 3.3
Difference in prefab products, expressed in time & cost vs customization and flexibility (Smith, 2010)



in ATS, but have determined the design and engineering options within a product. MTO are not made until the last responsible moment but do require more lead time than ATS products due to their increased variability from product to product sold. Examples include custom windows, doors, and other elements that have a myriad of options and are made custom for a project within a product line. Many modernist prefab systems on the market today represent MTO.

• Engineered-to-Order (ETO) or special-product: ETO might also be called designed-to-order. These products represent the most complex and demanding products available. This is, by far, the largest category of building creativity and development in architecture. It also represents the greatest challenge for manufacturers and fabricators trying to determine how to deliver entirely custom products at competitive pricing. ETO products generally have the longest lead times and the highest price points. Examples of ETO products for building include precast elements, facades, and other per-specification construction.

By using a suitable product for a specific design, prefabrication can be a tool by which the design team can control the costs, quality and time. If a product does not have the necessity to be customizable, perhaps a simplified design is sufficient. ETO manufacturers design and engineer every specific element, component or module before it goes into production. Some prefabricators carry out all the engineering in-house with specialized departments, while others outsource detailed design aspects. ATS manufactures put a lot of engineering into one element or component that has the capability to be used multiple times in different contexts.

Depending on the requirements and possibilities, the ideal solutions regarding the level of prefabrication and building product, can be selected.

Digital manufacturing in Architecture: CASE STUDY 1
FROM LARRY SASS TO WIKIHOUSE
The first company that attempted to create a fast and cheap building structure, based on digital manufacturing techniques is the Wikihouse.
Lawrence Sass is one of the founders of CNC fabricated buildings. With digital manufacturing techniques becoming more and more popular, Sass researched how to incorporate CNC milling into architectural design. Since 2004, he is using digital manufacturing techniques to actually realize his designs.

With his innovative technique, Sass (2007) presents that he is able to produce highly customized wood framed buildings. The structures are built from flat wooden elements, CNC produced out of plywood that can form small structures when assembled on-site. Taking the knowledge of the level of prefabrication into account, it is possible to conclude that this system used prefab elements that are engineered-to-order.

The assembly can be done without the use of power tools, due to new types of joinery which work by interlocking mechanisms between components by friction only. This makes it possible to build it without any use of adhesives. Using this integrated wood joinery has the advantage that nearly anyone, regardless the knowledge of construction work, is able to build it. Compared to traditional labour intensive construction methods, this system is much more efficient to assemble on-site.

The system makes it possible to rapidly deploy small buildings which are designed exclusively for a specific community, which follows its own design rules and has its own desires and constraints. Other advantages are a lean building process, flexible computer integrated manufacturing strategies and reduced design cycle life. This principle makes a direct link between the generative design, and manufacturing and evaluating of building structures. (Sass, 2007)

WikiHouse, founded by Palvin, takes the ideas of Larry Sass to the next level and turned it into an open-source design platform in which everyone can be involved. One can download a model containing a large 'puzzle' that consists of just 2D element which can be brought together to create a 3d structure. All components are made of plywood and can be

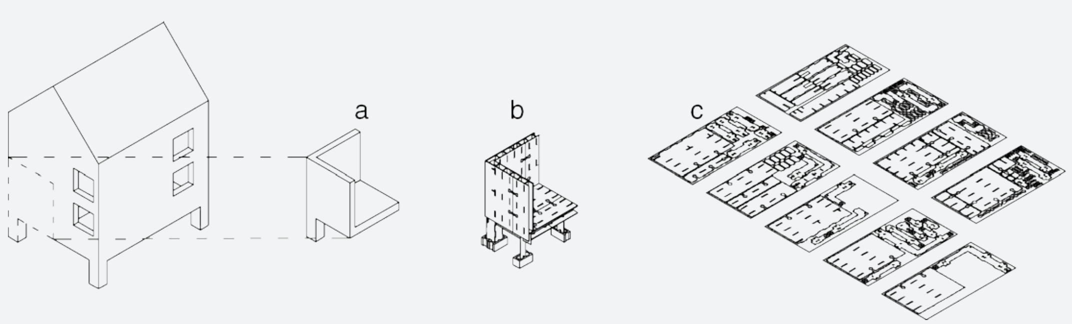


Figure 3.4
The principle Larry Sass developed: from a design description (a) to a 3D construction model of plywood components (b) to horizontal cut sheets for CNC milling (c) (Sass, 2007)

produced with a CNC milling machine. This meets the ideas of switching from global to local production. The digital files are shared all over the world, to create the building locally.

After milling the entire design, a huge amount of different parts is created. With the smart use of codes, one can puzzle all the parts together into a small building. There is no need for any knowledge about woodworking, every non-builder can assemble it. It is even constructed without the use of any screw by the clever use of friction fit connections. This makes it possible to construct the whole structure relatively fast. Afterwards the insulation, ducts and cladding can be installed.

Figure 3.5
Principle WikiHouse
(Wikihouse.cc)

Conclusion
However, there are some disadvantages to this whole idea. First, the open source concept gives problems as regards to the responsibility of the building safety and other regulations. But also the concept of the building system itself has some downsides. The large amount of parts can make the assembly unnecessary complicated. And when the parts are assembled into a structure, relatively quick, it still takes quite some time to finish the whole building.

The WikiHouse building system can be labelled as an ETO or special product', made out of elements. This means that every design requires newly engineered details, which is time and money consuming. To find a building system for PO-Lab, a more standardized system is required.

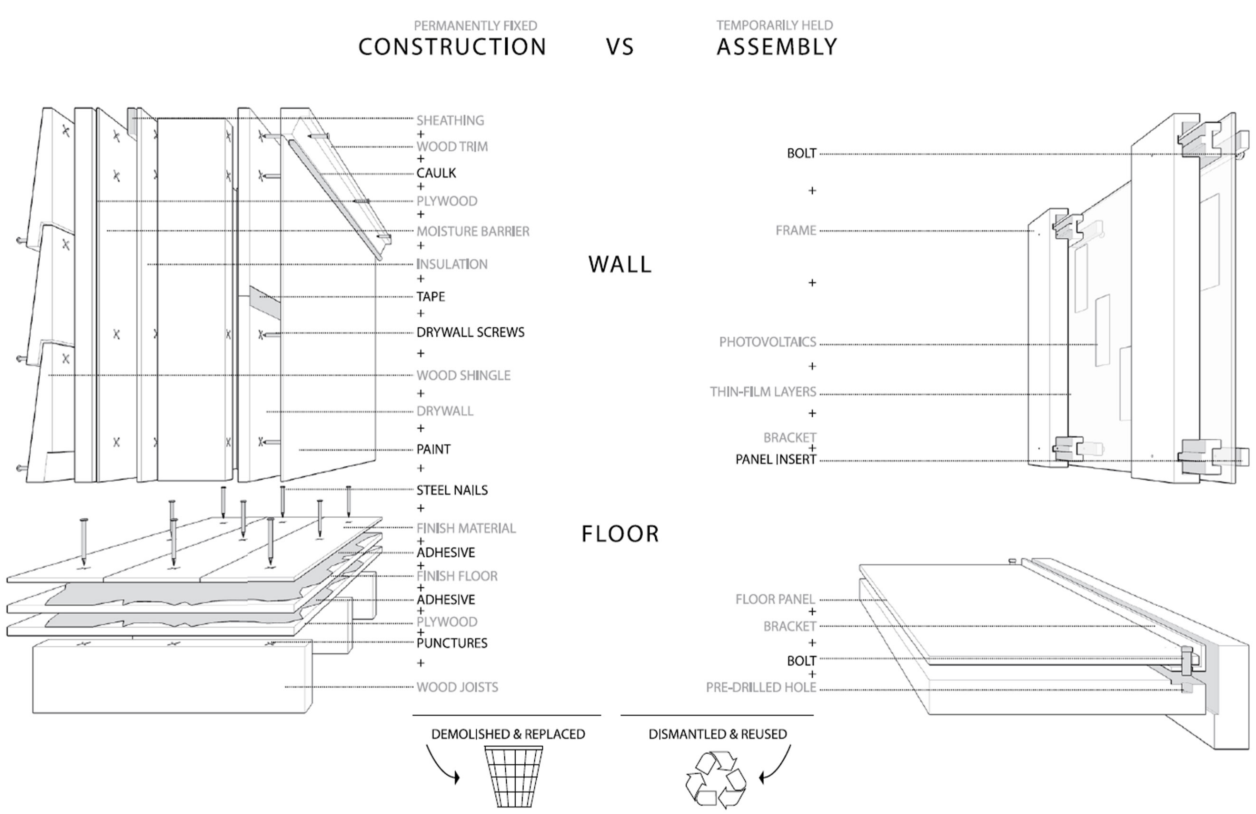
Conclusion

Industrial buildings aim to resolve the issues of construction. Both waste reduction and value generation are achievable if one succeeds to make a prefabricated building system work. (Ballard, 2005) Off-site fabrication of buildings suggests that parts come together in the factory to a level in which assembly on-site can occur easily. This method has the potential to create an improved balance between cost, time and quality. Digital manufacturing enlarges the potential success of prefabricated solutions. Due to a more integrated development process, and lower tolerances in building products, less problems on-site can occur. This can result in a more efficient construction process Wikihouse, first case study for cheap and fast realizable building, shows the drawback of an industrialized building that is not standardized. Of course it shows potential, but is has downsides to actually become an alternative as building system.

Engineering the fitting parts and subassemblies for building is still an expensive portion of labour and time. Complex buildings, that are difficult to assemble and built, are generally more costly. Prefabrication of building products have the opportunity to integrate details that can be easily assembled on-site. Prefabrication prevents unforeseen assembly problems, because probable errors can be noticed and resolved in the factory. An assembly of good quality, is not exclusively effective from an assembly and construction perspective. For logistical prefabrication, assembly principles that are important to consider include the following, list adapted from Allen and Rand(Allen & Rand, 2009):

• Uncut units: Dimensional and modular coordination between subassemblies that will be assembled on-site so that little or no cutting or manipulation is required.

Figure 3.6 Conventional vs industrialized building (Smith, 2010)



• Minimize elements: This idea is to limit the number of elements to be shipped and erected. This reduces not only labour but also the possibility for failure at joints. The fewer the joints, the better. If the part is not needed it should be removed or integrated into another assembly.

• Easy to handle: While designing prefabricated elements, care should be taken to not design elements that are either too large for fabrication, shipping, or erection (hoisting) from a size or weight perspective. There should be clarity in how the element is installed—either it is directionless or is clearly unsymmetrical for easy install. Keying elements with codes is also a coordination method.

• Repetition: When it is unimportant to have special or unique conditions, using repetition in the construction sequence leads to higher-quality and faster erection. This becomes more important on larger projects where standardization cost reductions can be captured.

• Simulation and prototyping: When possible simulations of construction sequencing should be performed to anticipate potential conflicts. BIM has allowed much of this to occur through 4D and 5D analysis. In addition, prototyping and mock-ups allow for early prefabrication errors to be worked out. Not only mock-up of a system in the factory, but a test on-site for assembly ease.

• Accessible mock-ups: Teams can place prototypes on-site for observation by crews erecting the project. This can especially be important if multiple individuals are installing. Education is critical to the construction process, but it is more important in prefab when efficient design methods are being capitalized.

• Accessible connections: It is vital to design assemblies so that on-site installers can reach work simply. Placing elements at an accessible height to standing and assemblies to occur once the superstructure is erected from the decks themselves allows for ease of installation. Sequences that do not allow workers to access parts in order to bolt, screw, seal, or nail must be reworked on-site. This includes connections that are behind columns, spandrel beams, corners, and so forth. This is also true as connections may need to be accessed for maintenance or disassembly.

For the building industry to progress and take advantage of the benefits of factory production, the development of a more elaborated system is required. A building system with final assemblies should be created in the factory as much as possible, and as little as possible on-site. A movement towards more interchangeable parts, and increased production rate by favouring direct assembly off-site versus fitting parts on-site can increase productivity.
In order to reach the goal of living building, flexibility, adaptability and end-of-life solutions require more attention. The next chapters will focus on these subjects.

3.2 FLEXIBLE

The second aspect of the IFD principle is flexibility. As concluded from the previous chapter, prefabrication can be an intelligent way of constructing a building. However, adding the aspect of flexibility is an important concern to address the problems of the current building industry. Instead of a building system to be primarily producer-oriented, it should be more customer-oriented (Eekhout, 2009).

Flexibility can be defined in different ways, in this research it is defined as: 'Flexibility is a property of a building or building product which makes it possible to make adjustments in order to respond on (changing) demands and wishes' SEV (2007). Flexibility can be separated in two phases of the building life cycle:

1. Flexibility during the building process (process flexibility)
2. Flexibility during the use phase of the building (product flexibility)

Flexibility during the building process can be seen as freedom of design. It is essential that users have possibilities to make decisions regarding the appearance, or the dimensions of a building. An important aspect of the flexibility during the design and completion is the possibility to make adjustments until a late stage in the design and building process. Good integration of process flexibility makes it easier for the executive and development parties to give the users influence in several building aspects. For example: the division of the required spaces, the desired building services, the level of finishing, the aesthetic appearance or a combination of these aspects.

In contrary to the process flexibility, the product flexibility is about changing existing objects. A modification can be necessary because the user is not satisfied with the quality, size or configuration of the current building. The process flexibility is responsible for the ability to modify buildings or parts of it, so the building satisfies the demands of the user again.

Process flexibility

Customers ask for variety. When implementing prefabrication in the build environment concerns for a monotonous effect occur. Architects and builders use technology towards social and cultural ends. If this technology does not provide any possibilities to variation, clients and users will eventually demand it. This fear for mass production of prefabrication gives it a bad reputation, a reputation that standardization creates uniformity in lifestyle and landscape (Smith, 2010).

The lack of variability leads to an emergence for customization of products. This can be achieved in several ways, e.g. by offering different standard designs, by designing a building with different configurations of standard modules or components, or by complete freedom of design in every specific case. WikiHouse for example uses ETO (figure 4.3) products to allow customization. However, a more standardized solution is more feasible as a large scale building system.

As before, the comparison with the automotive industry can be made in order to provide customization for the customer. Not that every client can order a special one-of-a-kind car, but that the tools and methods, that are used to develop and produce the one of a kind product, could be automated to produce more customized products with small increase in cost per unit. Although the manufacturing industry is moving towards customization more and more, the concepts of mass production are still used and valuable in design and construction.

Modular Design

Modular design is a design technique that has the potential to improve the process flexibility in the building industry. It can be used to develop complex products using similar components. In essence, components which are used in a modular way must have features that allow them to be coupled together in order to form a complex assembly. Modular design can be considered as the process of producing components that can only perform individual functions, but when components are combined they are able to provide a variety of functions. Another important factor of modular design is the fact that it prioritizes the minimization of interactions between different components. This enables the components to be designed and produced independent from each other. Each component should support one or more functions (Kamrani & Sa'ed, 2002). The manufacturing of these components often involves large series that are not intended for a specific project, but this is not a necessity. Mass customization enables these components to be assembled in a range of individual combinations and variations despite the fact that they are manufactured in large standardised series. Mass customisation in this case means: the consumer purchases a product or part of one that ultimately results in a customised solution but is actually made from standard components that are mass-produced (Geraedts et al., 2011).

In industrial design, mass customization is much more common. Variation are not like a one-of-a-kind building that in no way is similar to the one construct before. Products from industrial design has many similar products with slight adaptations. (Smith, 2010) So to say, the differences between architecture and industrial design are in quantity, repeatability and size. To entirely integrate mass customization into the building industry is hardly possible with the current methods of project development and delivery. However, within the industrial design a few models exist that have the potential to be integrated into the building industry. The following three models are partly adapted from Schodek and colleagues (2005) and Klein (2013):

• Slot modularity: same fundamental components, with appearance variability within each discrete product. An example from industrial design is the car radio. Nowadays, car dashboard designs only allow brand specific devices. But a few years ago, car radios could be interchanged from car to car. Without being stuck to a specific brand, nor for the radio or car. The car owner was able to select any device that met his or her demands in particular.

• Bus modularity: a base structure that supports a number of attachments, sometimes called "platform design". A bus is an element to which all other components are connected. A good example to illustrate bus modularity is the USB connector. Several devices that can be connected to a computer such as mouse, keyboard and printer, use the same connection. All the different devices, fit in every USB-port.

• Sectional modularity: parts that are all different but share a common connection method. Components with upfront determined standard dimensions can be placed next to each other, according meet the requirements. Lego is a good example. The notch and groove of the Lego blocks make use of sectional architecture, which provides the opportunity to connect all the different pieces to each other.

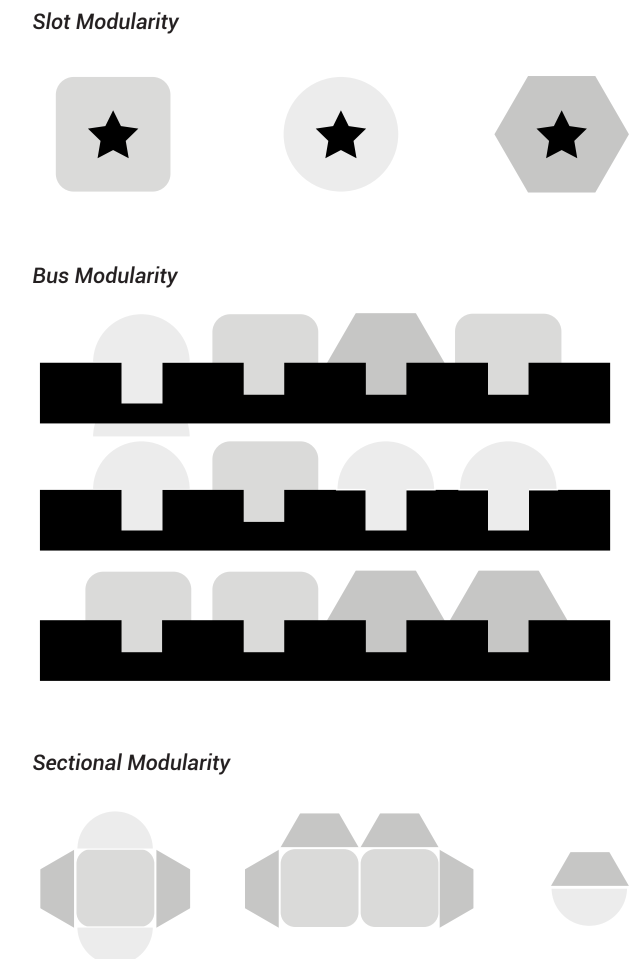


Figure 3.7
Three types of modularity
(thecreativehome.com)

Applying modular design

Most of the designs will not be completely integrated, nor completely modular. The building industry will be focussed to choose the specific approach towards modularity depending on the function of a building system. Industrial design has different concept development factors that decide which kind of modularity is required: product changeability, standardization, performance, manufacturing cost and system engineering. The architect has to think more like an industrial designer in order to develop a modular building system, as buildings are becoming more like products. It does not concern one-of-a-kind- buildings, but products that can be produced in larger batches with repetitive production methods. Integrated or modular products require distinctive design strategies, with a different focus to the concept development factors (Smith, 2010).

Modular design requires an integration of design, engineering, and detailing. Prefabricated modules, components and elements which are made in larger sub-assemblies allow a shift of the work to the factory where the coordination of production may be better managed and integrated. This provides the opportunity for an efficient production process, that results in very accurate components.

Product flexibility

Users have specific requirements for their buildings, which are fulfilled with a suitable design. However, these requirements and demands are continuously evolving. When a building does not meet the demanded requirements anymore, it is functionality at risk. Users are no longer satisfied with their building and have to come up with solutions. Most of the times this means renovation of the current building or finding another (new built) building that does comply with the new requirements. Both of these solutions are energy consuming, and have a negative influence on the social and environmental impact of the building industry (Huffmeijer & Damen, 1998).

In order to avoid these problems and to create a more sustainable building industry we should look for a flexible building stock that makes it possible to expand the building's lifespan. Compared to the current building systems there are many opportunities: during the development phase, where the wishes and demands of the costumer currently are neglected; during the use phase to respond to changing demands; or at the end-of-life of the buildings and its components.

The lifespan of buildings depends on three related, main aspects: technical, functional and economical lifespan. In which the shortest is responsible for the usability of a building. In order to optimize the total lifespan of the building, the lifespan which leads to a limitation in usability should be addressed.

The technical lifespan is described as: 'the period in which a building is sufficiently reliable and can continue to perform the desired functions.' (Huffmeijer & Damen, 1998) This is the period where the building is suitable to the technical requirements that are desired. These requirements may result from building codes, and possibly specific demands of users or clients. Figure 4.9 visualises the technical lifespan in a schematic graph.

The technical performance of building decreases as the time continuous, by the aging and deterioration of building parts. The deterioration of technical performances of building components cannot be undone, it can only be controlled. With maintenance and replacement of specific parts, the technical

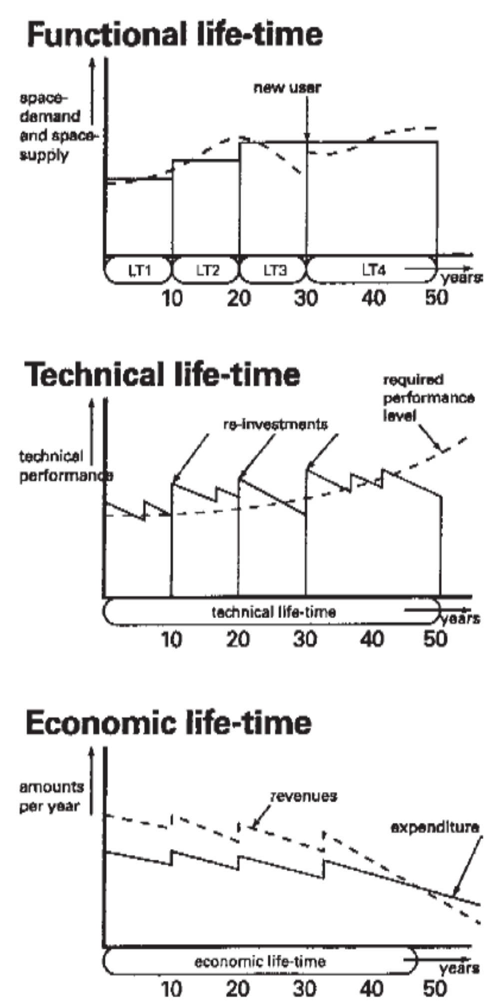


Figure 3.8
Different lifespans
(Durmisevic, 2007)

performance of a building can be extended. On the other hand, the requirements of the technical performances will increase as the time passes by due to improved technical standards. The intersection point of these two lines defines the technical lifespan. Before the intersection point, the building performs better than required. Past this point under-performance will occur, which results in a building that is not convenient anymore.

The functional lifespan has similarities to the technical lifespan. It ends when the building is not able to perform as requested by the users. Unfortunately, this process, in many cases, does not run simultaneous with its technical lifespan. This results in buildings that are not functional to its users anymore, but are still in a good technical condition.

When there is a lack of appropriate buildings, every square meter will be used effectively, even when the building exceeded its technical lifespan. However, with a surplus of suitable buildings the price will drop until it reaches a level where the benefits are not proportional to its costs. At this point, the economic lifespan of a building has come to its end (Gijsbers, 2011).

To these three aspects, a fourth possible factor can be added. An aspect which is neglected in most cases concerns the ecological lifespan, defined by Van den Dobbelsteen (2004) as followed: 'the time span after which demolition and reconstruction becomes environmentally more favourable than renovation and reuse.'

Adaptable design

As mentioned, the shortest lifespan will determine if modifications are required, or if a building is no longer appropriate. From a technical point of view three options are available when the building exceeds its lifespan: renovation, reallocation or demolition. Economically, the most profitable or financially feasible options will be preferred. Functionally three options are possible: finding a user that has lower requirements, accepting the fact that the building cannot perform properly to all requirements or change the building configuration. Due to shortages on the housing market this last option happens to be the case (SEV 2007). But when none of these possibilities are an option the building unfortunately has to be destroyed, even when it is still in good technical condition. The demolition of buildings before the expiration of their technical lifespan is destruction of capital. At the development of a building, clients invested in building parts that could last longer. From an economic view, the building is depreciated excessively soon. The building still has value in the form of building parts, but to keep it functional new investments are necessary.

Ideally, technical, functional, economic and ecological lifespan would all be as long. However, in reality this is practically impossible. The main goal of the designer is to develop a building or product were the functional life span meets the demands of the client. Design decisions are made to optimize the technical qualities to the program requirements. However, the designers have difficulties to predict the development and changes of the user requirements during the existence of a building. This results in a building which is a custom made suit for the first owner. Unfortunately, future owners will probably not suit the same size. Therefore, it is desirable that the technical requirements of a building can grow simultaneous with changing and increasing functional requirements.

If technologies allow it, the functional and technical lifespan can be equalised, or buildings are designed to adapt in order to equalise differences in lifespan. When developing a building system, that has the capacity to respond on changing demands, it enlarges the potential that the intended functional and technical lifespan actually can be achieved. In short, there is a demand for flexible buildings. With the possibility of adapting the lifespan of buildings, the need for new (replacement) buildings can be decreased and less useless demolitions will occur. With as direct positive effect, a lower environmental impact of the building industry. Less waste from both the building and demolition process arise, fewer resources need to be extracted from nature, and the production, transportation and processing of manufactured goods can all be reduced significantly. The impact of the building industry on the environment, with problems as soil degradation, soil pollution, energy use, air pollution and water pollution can be decreased (Gijsbers, 2011).

Solving the flexibility during the use phase of a building,

Digital manufacturing in Architecture: CASE STUDY 2
EENTILEEN ARKITECTUR
Eentileen, a Danish architectural firm tried to implement the ideas of a modular building system and took the idea of CNC milled building parts to the next level. Instead of the large amount of 2D parts that are brought to the building site, they deliver larger components that are prefabricated. The components are constructed out of 2D CNC milled elements and assembled in the factory. This saves even more time on the building site, and makes the process more labour independent.

With designing multiple different components, and assembling them in various configurations, a diversity of buildings can be realized. The system uses standardized MTO and ATS (figure 4.3) products which make it possible to produce fast and relatively cheap. The standardized components are placed within a specific structure, which can be grouped under bus modularity.

A great improvement over Wikihouse is that the same components can be used every time a new building is designed. Maybe a few customized components need to be created, but these will be based on the same principle as the standard components. This will require only little extra engineering time. Due to the fact that the components can be standardized, it is even possible to interchange them if required.

However, the system still has some downsides. The bus modularity principle always requires a structure in which the modular components can be placed. The structure cannot be standardized in this system, so engineering and designing is required within every new design. Compared to Wikihouse, this CNC produced building system, comes closer to an 'living' building. But it is not still there yet. To provide a possible solution for PO-Lab, a next step is required.

Figure 3.9 Eentileen CNC (pre)fabricated components (Designboom.com)

can be done on different scales. It can involve minor adjustments inside the building, to make modifications to the design without structural interventions. Another option is an adjustment to the entire building, which asks for a major technical and structural modification to change the building configuration.

The kind of flexibility that is required depends on the type of modification and period in which the modification needs to be done. Gijsbers (2011) states that modifications inside the building occur mainly on a short term. These modifications are implemented to respond to changing trends or norms and are merely aesthetic. After e.g. 5 years, also more physical modifications inside the building become desirable. For instance the relocation of inner walls to create new spaces, the upgrading of building services or maybe breaking through structural elements for wall or window openings. The structural composition of the building will likely only need to change after a longer period by changing user composition. The amount of adaptability of the building system is crucial to the flexibility in the long term. The more modifications can be made, the longer the functional lifespan of a building can be.

Conclusion
Static buildings require high investments, but as a result of the fast changing user demands, these investments are risky. A 'living' building is build up from materials and components that may exceed the lifetime of any individual building. This shift from the entire building to a focus towards components makes constructing buildings with an uncertain lifetime suddenly feasible.
Typically, buildings need to be functional for a period of at least 30 years to make the initial investment feasible. In the model of 'living' buildings where the focus lies on sustainable components and materials with a lifetime which may be more than 50 years, the risk in capital investment may decrease significantly. While the building itself, which the components and materials are part of, may exist only 5 to 20 years. In 'living' buildings, materials and components are manufactured, assembled, disassembled and remanufactured or reused, presumably many times during their lifetime.

A prefabricated, modular building system shows much potential to become a customizable, living building. Instead of customization due to ETO or special products, mass customization can be achieved by using ATS of MTO (figure 4.3) products. Mass customisation in this case means: the consumer purchases a product or part of one which results in a customized solution, but is actually made from standard components that are mass-produced.

However, an important aspect that needs to be considered is the adaptability of structures that require updates in order to expend one of their lifespans, the product flexibility. The ability of transformation of a building is based on three aspects(Durmisevic, 2006):

• Transformation by elimination of the element
• Transformation by addition of the element
• Transformation by relocation of the element

To achieve this flexibility, prefabricated building products need to be demountable in order to apply one of the three aspects. Prefab components require the ability to be disassembled, which makes it possible to perform maintenance, or adapt the buildings configuration to changing user requirements.

3.3 DEMOUNTABLE

More and more buildings today are built according to prefabrication methods making use of standardized components. The prefab components are designed to be easy to install on-site or to mount onto the building, but lack the ability to be demounted when needed. At the same time this makes the assembly of buildings a complex activity of carefully connecting designed components and materials in the right sequence. This results in an increased risk of mistakes and corresponding large impact on the building process. Added to that, it is a process which can be seen as very labour-intensive in terms of people and energy needed (Crowther 1999).

The energy put in to the building process can be seen as lost at the end of the building's life cycle, as large amounts of non-recycled material go to landfills or incinerators. On top of this, heavy equipment is needed for demolition, which is again an activity that requires a vast amount of energy. Demolition processes directly account for 90% of waste production within the building sector and for approximately 50% of the embodied energy of a building (Durmisevic, 2006). The reason for this inefficiency is that buildings are in the first place not designed to be demountable. Furthermore, the components that they are made of are not designed to be reused or reconfigured, and the materials that these components consist of are often composed of composites which are designed in such a way that recycling is very difficult, energy intensive or even impossible. There are many attempts to disassemble existing buildings to extract reusable elements. As these building are not designed for the purpose of disassembly in the first place, it results in these activities to be very time-consuming and labour intensive. This makes it arguable if these activities are even feasible from an economic point of view. This way of building with fixed structures results in demolition being a typical end-of-life activity for the building structures of today, as buildings are not designed with the goal to recover their materials, elements or components they consist of for reuse, remanufacturing or recycling. Designing for disassembly can improve the end-of-life choices for the building, a component, an element or material which is no longer needed due to functional or technical reasons.

There are several recent developments which support the call for another perspective for the building industry. Those developments are:

- Energy prices are increasing
- The costs of landfill as end-of-life activity are increasing as a result of taxes
- Natural resources are diminishing
- Growth in demand for resources
- Development, maintenance and demolitions costs are increasing

As use of resources and poor end-of-life solutions like landfill become more expensive, the building industry needs to change its perspective as there are not only environmental reasons anymore, but also an increasing amount of arguments from an economic point of view. Flexible building and designing for disassembly can help to achieve this aim. According to Durmisevic (2006) the aim of sustainable design should be a design of transformable building structures made of components assembled in a systematic order suitable for maintenance and the ability to replace single parts when needed.

An important aspect to come to a new design strategy, which incorporates disassembly, is to know how buildings operate and behave through their life time and what influences the way they are interpreted. Basically, buildings are collections of materials and systems put together to deliver particular functions. Materials and components are part of two different life cycles. The functional lifecycle, the durability of the material or component to fulfil certain functions. And the technical lifecycle, which describes the durability of the material or component till its point in time of structural failure (e.g. wear, corrosion, etc.). Each material, element, component, or building as a whole has a functional lifecycle, as well a technical lifecycle. Conventional buildings commonly use fixed spatial systems as a consequence of the integration of technical components into a closed system. This results in a great dependency between technical and functional materials and elements combined in a system. Changes within the building can result in the demolition of a part of it as elements cannot be extracted from the building intact. This is a very static approach to a system which is dynamic in essence and ignores the

discrepancy between the functional and technical life-cycles of different materials and elements.

Level of disassembly

Figure 3.10 shows the different levels of disassembling a structure. Integrated in the picture is the amount of energy that the different levels contain. The building consist of the most energy, because a lot of energy is put into it to entirely construct it. The material contains the least energy, only the energy that is required to subtract it from its resources. The higher level of disassembly can be achieved, the more energy can be saved and reused.

Building

In the previous chapter this aspect is already known as product flexibility. It focusses on replace of broken components and rearranging of component to adapt to changing customer requirements. By doing this, the least energy will be lost. Due to the detailed elaboration in the previous chapter, this won't need any further explanation.

Building to component

One key element of the ability for disassembly of structures is that it enables the disassembly of parts of a building back into components. These components can be reassembled in new combinations. Alternatively, if they are no longer functional or desirable in the building itself, the components can have a second life somewhere else. Components having multiple lives can extend their functional lifetime to match their technical lifetime better. This results in components, and materials which they consist of being used in a more optimal manner.

It is imaginable that changes need to be made on the building during its operational life. The building will then be partially disassembled and re-assembled. To avoid too much waste, assembled components may be reused. These components can be assembled in the same or another building. If it is impossible to reuse the components as one, they can be disassembled into smaller elements. If fixtures and connections of components and modules are designed for this purpose, disassembly can be highly simplified. (van Nederveen & Gielingh, 2009)

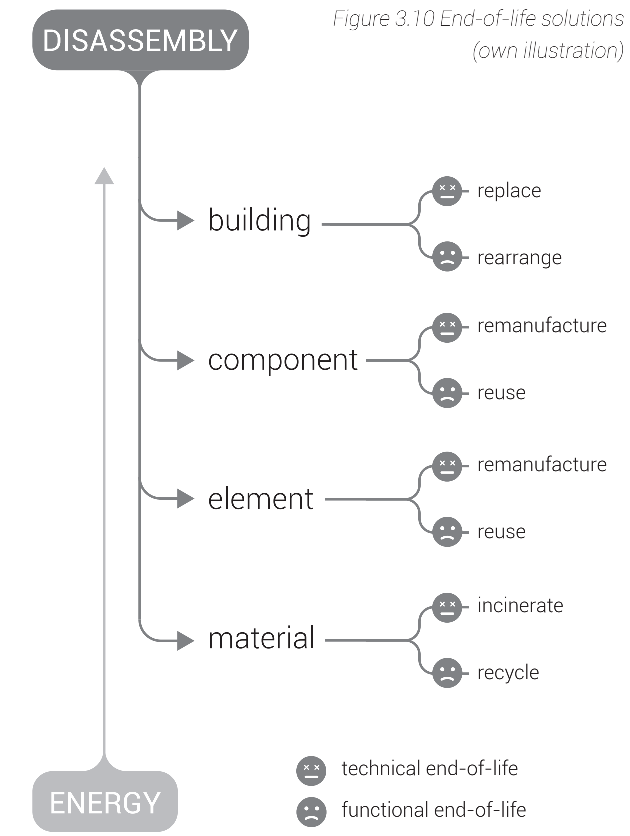


Figure 3.10 End-of-life solutions (own illustration)

Component to element

There are components that are no longer useful for a building but that may be applicable to be reinstalled on another building. If components cannot be reused as a whole, it is possible that they can be disassembled into smaller elements which are than (partly) remanufactured into new component assemblies. The technology to remanufacture used parts is already well-developed in the automotive industry. Aside from saving on materials and avoiding of waste, remanufacturing also saves great amounts of energy. Energy that would otherwise be used for scrapping or melting. In the example of the automotive industry,around 90 percent of the energy otherwise needed for the production of new components is saved by remanufacturing. If components that are not suited for remanufacturing, the materials from which they are made may be suited for recycling (Van Nederveen & Gielingh, 2009).

Element to material

Design for disassembly, in this way, can serve as a material and component source for new buildings. Instead of extracting natural resources from the earth, the existing buildings are used a primary material source.

Advantage demountable building
Designing flexible buildings with exchangeable, reconfigurable and reusable components, seen from the perspective of 21st century requirements, results in the reduction of construction and demolition (C&D) debris, conservation of landfill space, reduction of the environmental impact of producing new materials, and reduction of overall building project expenses through avoided purchase/disposal costs. Furthermore, flexible buildings are easier to adapt to new requirements. (Chini, 2003 & EPA, 2005)

Environmental benefits
• Reduction in waste streams
• Conservation and restoration of natural resources

Economic benefits
• Reduction in operating costs
• Creation, expansion, and shaping of markets for green product and services
• Optimisation of life-cycle economic performance

Social benefits
• Heightening of aesthetic qualities
• Minimizing the strain on local infrastructure

Relation engineering time and standardization
According to Van Nederveen & Gielingh (2009) re-use and remanufacture strategies can be taken into account in the design phase. This can be emphasized more by stating this is even essential for a 'good' design as it has a strong relation for the choice of material and the way in which components are joined.

Lego bricks exemplify this shift in thinking somewhat. Lego bricks can be used to make different objects and have a lifetime which is much longer than of the objects itself. Van Nederveen & Gielingh (2009) state that for very elementary components this may not seem relevant, but the challenge lies in reusing components, elements or materials on a structural level when working with 'living buildings'.

A building system is dependent on a long engineering time per unique component. This means that designing and optimizing a single component requires lots of time compared to manufacturing time. Once a component is engineered completely, which means optimizing material use, optimizing dimensions for machine use, optimizing machining time, it can be reproduced infinitely without the input of extra time for engineering. This concept can be beneficial if it is combined in a system with a component library. Such a library consists of standard components which can be used to form a large variety of unique designs. Once the available components in the library are not complying with a customer's needs, new elements designed for a single project can be designed and produced with low additional costs. This is possible as the system uses a standardized connection and dimension system which principles can be reused in new designs. Buildings, based on a modular system, may benefit from parametric design tools that use a library of generic, parametrically defined components to design them. This does not only include geometric appearance, but also information about the process of assembly and disassembly and the tools needed for these processes (e.g. component length, amount of connections, floor height based on structural analysis). This can reduce engineering times for the development of new modules.

Each time a new component is needed, it can be added to the library once it is engineered. In this way such a component library keeps growing, whilst the possible system configurations grow with it. Designing and engineering new components demands a lot of time, as it is a complex process concerning a considerable amount of different aspects (finishing quality, machining time, machining cost, machine dimensions, material dimensions, etc). Optimizing these aspects as far as possible is important in this stage as it saves costs and time in the future. For one single component the engineering time can be out of proportion compared to the revenue. However, adding it to a library with standard elements allows these modules to be reused in new configurations with very little effort. As the library grows, the configuration possibilities grow while the costs go down.

Ten Key Principles of Design for Disassembly
To make demountable buildings work 10 principles are set-up (Guy & Ciarimboli, 2005):

1. Document materials and methods for deconstruction: As-built drawings, labelling of connections and materials, and a "deconstruction plan" in the specifications all contribute to efficient disassembly and deconstruction.

2. Select materials using the precautionary principle: Materials that are chosen with consideration for future impacts and that have high quality will retain value and/or be more feasible for reuse and recycling.

3. Design connections that are accessible: Visually, physically, and ergonomically accessible connections will increase efficiency and avoid requirements for expensive equipment or extensive environmental health and safety protections for workers.

4. Minimize or eliminate chemical connections: Binders, sealer's and glues on, or in materials, make them difficult to separate and recycle, and increase the potential for negative human and ecological health impacts from their use.

5. Use bolted, screwed and nailed connections: Using standard and limited palettes of connectors will decrease tool needs, and time and effort to switch between them.

6. Separate mechanical, electrical and plumbing (MEP) systems: Disentangling MEP systems from the assemblies that host them makes it easier to separate components and materials for repair, replacement, reuse and recycling.

7. Design to the worker and labour of separation: Human-scale components or conversely attuning to ease of removal by standard mechanical equipment will decrease labour intensity and increase the ability to incorporate a variety of skill levels.

8. Simplicity of structure and form: Simple open-span structural systems, simple forms, and standard dimensional grids will allow for ease of construction and deconstruction in increments.

9. Interchangeability: Using materials and systems that exhibit principles of modularity, independence, and standardization will facilitate reuse.

10. Safe deconstruction: Allowing for movement and safety of workers, equipment and site access, and ease of materials flow will make renovation and disassembly more economical and reduce risk.

Figure 3.11
Renzo Piano pavillion (1983) is one of the early projects adapting design for disassembly principles (rpbw.com)

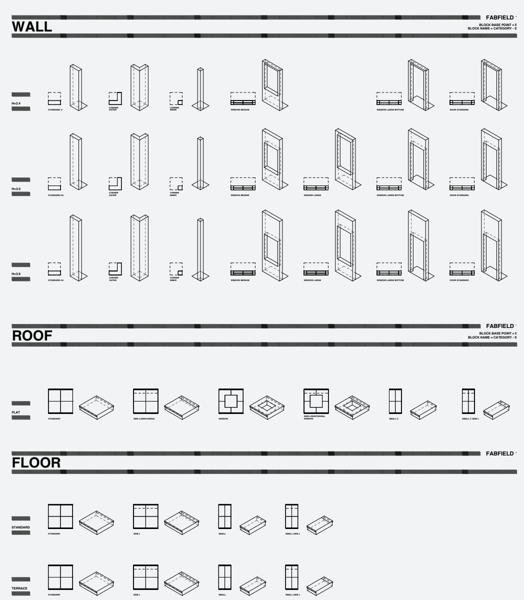
Digital manufacturing in Architecture:
***CASE STUDY 3* ECONNECT**

ECOnnect tries to tackle the problems found in Wikihouse and Eentileen. The ECOnnect system, like Eentileen is build up from various prefabricated building components. Where Eentileen makes use of custom made project specific elements, ECOnnect wants to create an ever expanding library of standardized building blocks.

ECOnnect knows a fast and easy assembly process which can be executed by two workers. The structure can be erected within a few days for a small single story building. The shortcomings of the system are well illustrated by the activities which still require high human labour and take a lot of time. While the structure can be build reasonably fast, the façade, for instance, takes a considerable amount of time to attach due to the traditional building methods used. The innovative concept for the building structure has potential for other building parts which still use more traditional building methods. Parts in which this is the case are: façade, roof, waterproofing, interior and installations.

Large advantage is the idea of the library, this makes it possible to easily configure new structures without needing extra engineering

Figure 4.12 Huis ter Heijde (Pieter Stoutjesdijk)



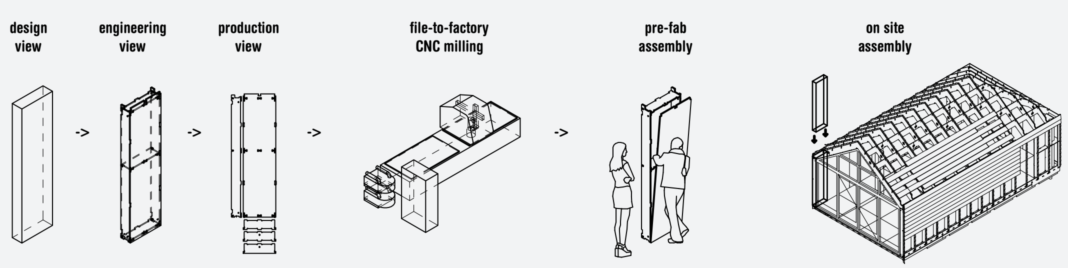


Figure 4.13 Building system ECOnnect (Pieter Stoutjesdijk)

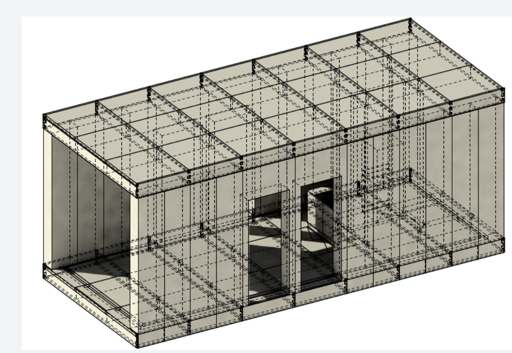
time. Figure 4.15 shows two of those examples.

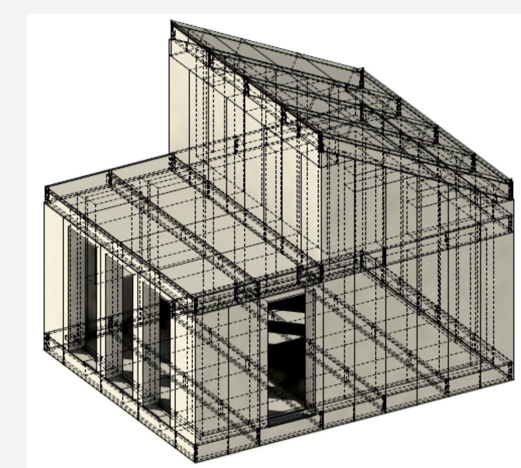
However, the system got it downsides:
- Not optimized for disassembly
- Concept not implemented in all building parts (façade, roof, waterproofing, interior, installations)
- Tolerances CNC vs. human errors (e.g. façade screwed onto high precision building structure voids the opportunity for high detail finishing)

Conclusion
The ideas are a good starting point for finding a building system that can tackle problems that the building industry is facing nowadays. But there are still some improvements required.

Figure 4.14 Possibilities ECOnnect (Pieter Stoutjesdijk)

MAPA Architects	Woody15
25.000 Euro	*30.000 Euro*
Milling time: 20h	*Milling time: 25h*
Prefab assembly: 47h	*Prefab assembly: 45h*
On site assembly: 47h	*On site assembly: 55h*





Conclusion

By reusing and remanufacturing a new form of design practice will start. Buildings can be designed by using the components that are available on the market. A designer can search from the components which are available and ready to use for the design, in contrast to start designing a building from a blank piece of paper. As the number of components on the market increases, the design of a building becomes a process of component configuration. Van Nederveen & Gielingh (2009) state about this: "It is no longer a predominant top-down problem solving process, but also - concurrently - a bottom-up solution-provision process". By re-using components in this way the cost and CO2 emissions can be reduced significantly due to the savings on material and energy use.

Van Nederveen & Gielingh (2009) present an important shift that needs to happen in the lifecycle management of buildings, namely the shift from building centric thinking to component and material centric thinking. The lifecycle of components and materials may obviously vary from the lifetime of the building which they are part of. As the lifetime of the components can be longer than that of the building, it is important to keep track of the history of the components.

In the business model Van Nederveen & Gielingh (2009) put forward, the production of base materials and components from natural resources is seen as waste. Added to that, recycling of materials in also seen as form of waste. Large amounts of energy need to be used to shred or melt the material for it to be useful as raw material again. This could be avoided by reusing components or materials. Obviously storage of components is inevitable in this model as disassembly and remanufacturing may differ from the time they need to be reassembled. They do make clear that in the lean point of view this is seen as a waste, while in the new paradigm reusing may become added value.

Virtual marketplaces can improve the cycle time for reuse of components significantly. These could therefore reduce the amount of 'waste' seen from a lean point of view. Marketplaces like this do exist for consumer products. The most well-known and operating internationally is eBay. Most successful marketplaces operate on a national level. However such a place does (not yet) exist for building components and materials. In order to make this useful for the designer, intelligent search engines are needed that suggest the use of certain components or materials that are available. An important turnaround in the procurement process is initiated by this concept. Normally procurement managers would have inquired to the supplier what was needed, while in this concept the opposite would happen. Suppliers give an overview of the relatively inexpensive materials and components they have to offer and are readily available or available soon. Designers than have to find out how the components and materials can be used in their design.

ECOnnect is one of the first attempts to create a standardized library with exchangeable components. By using this standard components it becomes possible to create low priced, high quality buildings. To apply such systems in designing and constructing does require a major change in the conventional methods of the building industry.

4. DESIGN DIRECTION

Source illu.:
PO-Lab factsheet

This chapter concludes all the previous literature research into a framework to research the elaboration of an innovative building system. It will explain the concept of the PO-Lab building system, its project goals and the design task.

4.1 CONCLUSION RESEARCH

The building industry is largely responsible for the immense environmental impact of the industrial sectors. To reduce environmental impact, and provide a more sustainable building industry for the future, we need to make the industry more energy efficient. Energy efficiency mainly focusses on reducing the operational energy consumption, and less on embodied energy of buildings. However, PO-Lab want to focus its research to the field of lowering the embodied energy. To improve the effects of the building industry, changes towards the building process and the way we build are required. The focus of PO-LAB lies on five main factors: Sustainable material production and transport, resource efficient production, durable constructions, fast and easy to construct and strategies for disassembly, re-use and recycling.

Changing process

The current building process, as result of the strong segregation of different disciplines, is considered inefficient, and a process that produces lots of waste. By adapting and implementing methods of other manufacturing industries these issues could be solved. Innovative digital manufacturing tools to create a more integrated building process. One digital model can be used during the whole development, design, production and construction phase. The integrated building process makes it possible to consider the entire lifecycle during the design phase. The architect, nowadays almost just a stylist, can be involved in the entire building process and possibly get the role of former master builders again. His role during the development process changes completely. The architects need to be capable to develop, design, engineer and manufacture the building system. Architects are involved during the entire process, from development until the end-of-life decisions.

Renewed approach

The changing building process is necessary to change the way we approach constructing. It provides new opportunities. The well integrated process presents the opportunity to adapt the living building principles.

Industrial components that are completely prefabricated, which makes constructing onsite much more efficient. This method has the potential to create an improved balance between cost, time and quality. Digital manufacturing enlarges the potential success of prefabricated solutions. Due to a more integrated development process, and lower tolerances in building products, less problems onsite occur, which can result in a more efficient construction process

Flexible buildings, separated in two types of flexibility: process flexibility is provided by modular building principles to create customization. Mass customization in this case means: the consumer purchases a product or part of one that ultimately results in a customized solution but is actually made from standardized components that are mass-produced. Product flexibility, the adaptability of existing buildings, to make sure that the different lifespans will be equalised to optimize the lifecycle of the entire building. Prefab components need the ability to be disassembled, which makes it possible to perform maintenance, or adapt the buildings configuration to changing user requirements.

Disassembly capacities play an important part to make this adaptability feasible. Due to demountable components it is possible to change configurations of the modular building system to adapt to changing demands. Besides the adaptability, demountable components make the linear life-cycle circular. As a result of standardization, components can be disassembled and reused again in a subsequent project. Thus, make the life cycle of the components circular.

The literature research could be concluded into a list of strategies which should be adapted in order to the design a building that fulfils the requirements of a living building. The list of strategies is visualised at the next page (Table 4.1).

DESIGN	- Development of scenarios for building use - Integrate building process - Engineering time in relation to standarization
MATERIAL	- Use of recyclable or reusable material - Avoid harmful substances - Use of low weight materials - Consider energy to obtain material in in relation to material lifespan
PRODUCTION	- Minimize residual waste in production - Digital technologies to improve quality and minimize production tolerances - Minimize human labour, thus assembly errors - Decrease energy use in production
TRANSPORT	- Minimize product bounding box - Avoid vulnerable parts
ASSEMBLY	- Dry assembly - Parallel assembly - Minimize on-site building activities - Minmize use of heavy equipement - Provide easy handling methods - Provide feedback for correct assembly
USE	- Provide possibilities to adapt lifespan to changing demands - Easy to maintain - Minimize energy use
END OF LIFE	- Design for disassembly in all levels - Aim for highest EoL-activity - Consider durable materials in relation to lifetime and reuse
COSTS	- Consider all decisions in relation to economic feasibility

Table 4.1 Sustainable Strategies

4.2 PO-LAB

PO-Lab encourages the relation between the manufacturing and construction industry. While most of the world around us uses fully automated production technologies to produce goods, the building sector seems to work still inefficient, following traditional procedures. We don't buy cars or furniture's because they are built by robots, but it makes them more affordable. The conclusion is simple: *'Don't use expensive technologies to make even more expensive architecture, but use the potential of these technologies to create high quality, low energy consumption affordable buildings that respond to our demanding challenge towards an energy neutral future.'* (Bilow, Entrop, Lichtenberg, & Stoutjesdijk, 2015)

PO-Lab uses the digital technologies to develop a modular building system, which is based on standardized components to configure affordable and fast constructible buildings. It responds to the growing awareness of sustainable necessity among both governmental institutions and costumers. Not only by making buildings sustainable in operational use, but by considering the environmental impact of the overall life cycle. This building system is a sustainable solution in the way of reducing embodied energy.

The main objective of the 3TU project is to provide a platform to test and prototype innovative ideas for the building industry. By developing this platform, not only the amount of research can be increased, but also the awareness of the current problems and possible solutions increases. In fact a platform will be developed to literally investigate and test digital production technologies like CNC milled wood connections, but also a platform in its wider meaning to investigate the effects and influences of file to factory production, to explore the potential in the field of sustainability, material use, logistics and the interaction of stakeholders within the chain of the building process. The innovative, CNC fabricated lab plays a big part in the success of the project. Due to its modular behaviour it can be updated and upgraded with new innovative ideas, which are thought and prototyped by the students.

The concept (building system) is a unique modular, flexible building system that is completely CNC-fabricated based on the design of Pieter Stoutjesdijk. No other example of such a system exists so far. The evolvement of the combination of modern production technologies and modular prefab building principle is one-of-a-kind. The modular building system makes

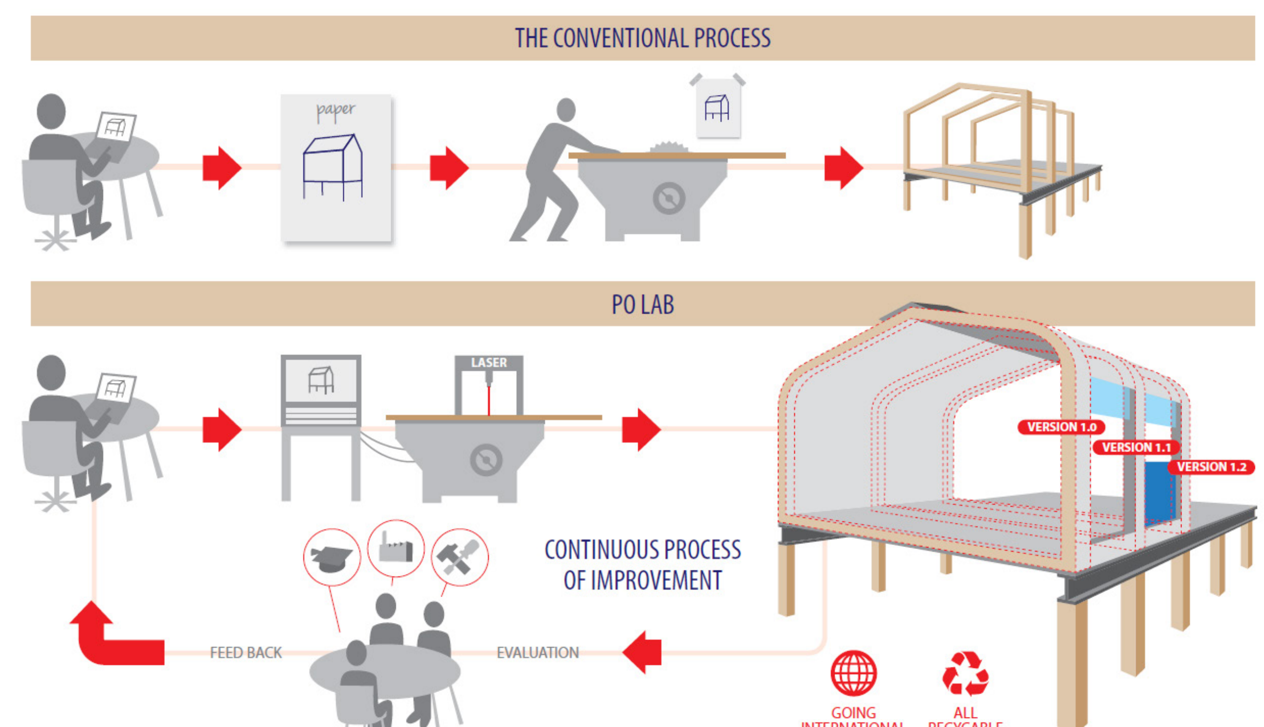


Figure 4.1 PO-Lab (Bilow, M. et al. 2015)

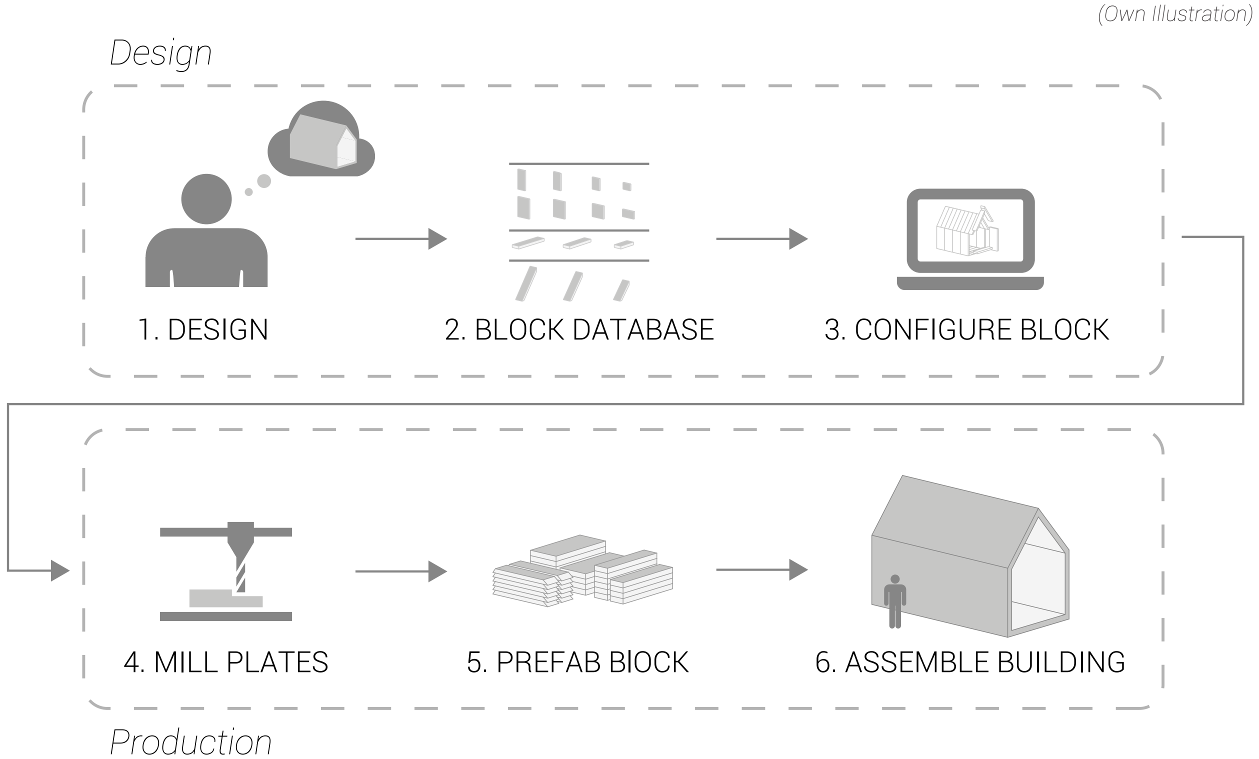
it possible to build very efficient with little errors, and a low-labour construction process. Even untrained construction workers could assemble the building.

The system consist of three different main standardized components, the floor, wall and roof. All completely CNC milled out of OSB panels. A variety of panel materials can be milled with a CNC milling machine. The most common wood panel products are oriented strand board (OSB), medium density fibreboard (MDF), and multiplex. The quality ranges from plywood, which is made from laminated wood veneers, to MDF, which consists of sawdust bonded by a cohesive which amounts to about half of the weight of the material. Within this research, cost, weight and sustainability are considered as important criteria. Therefore, OSB is chosen as overall plate material to construct the building system.

With this concept, customization is available in another way than usual with digital technologies. Normally customization is achieved due to the fact that digital manufacturing tools can easily be adapted to produce different design. However, within this concept, customization is achieved by configuring standardized components in different variations. One can choose standard component from a library to configure a relative cheap building. When special components are required to make exceptional shapes, special blocks need to be engineered. This will make the design more expensive. Advantage of this concept is that the engineering time only is required once. This makes it possible to decrease the prices, thus to create an affordable building system without losing quality.

Besides PO-lab, this building system could also be used as a solution to the current refugee turmoil. This building system could provide much low-priced emergency shelters in a short time span.

Figure 4.2 Design process
(Own Illustration)



4.3 PROJECT GOALS PO-LAB

The goals of the team are clear but also demanding. The concept not about following a trend, or the fulfilment of an architects dream. The current situation on the market asks for smart use of technology and material. It's about testing how far a system has to be developed to create the future of our buildings. It's about integration of components and functions, but also about the implementation of knowledge that will enhance the building system step by step.

Based on the strategies of eco-design, creating a product with low environmental impact is about addressing the entire life cycle; choosing the right material; producing and fabricating efficient in order to minimize waste; trying to reduce transport distances; minimizing the energy use; and designing for disassembly and recycling of materials. PO-Lab combines these life-cycle with their ideas how the building (system) should function and translated these aspects into five project goals:

- Sustainable material production and transport
- Resource efficient production
- Fast and easy to construct
- Durable constructions in regard to functionality
- Strategies for disassembly, re-use and recycling.

Sustainable material production and transport
By using digital technologies the transport distances, both before and after the production process can be reduced. The materials do not need to be transported all over the world to arrive at the factory. Instead, materials can be found close by, or can even be residual products. In addition, while the final products of big factories are distributed all over the world, local production creates your product around the corner. Instead of products, the digital design data can be distributed over the world in order to produce it wherever it is needed. The products are not inefficiently distributed over the road or by airplane anymore, but the digital documents travel fast and efficient via the internet.

Resource efficient products
To integrate the different disciplines into an efficient building process, and to enlarge the accuracy of the components, digital manufacturing technologies are used. More specifically, CNC fabricating will be used. Based on the ideas of Larry Sass, CNC fabricated buildings have evolved over the years. From the WikiHouse concept of Alastair Palvin, until the concept of Pieter Stoutjesdijk and Eentileen to create a library of CNC prefabricated components.

Besides the integration of disciplines, CNC fabricating brings more advantages. Fabricating products with CNC technologies can be very efficient, with only little residual products. And because the building system consist of completely prefabricated building components, the assembly process can be optimized because it takes places in well controlled factory conditions. This can result in a high quality building products, producing only little waste material.

Fast and easy to construct
The building system aims to be fast and easy to build. By minimizing the installation time the purpose of a semi-permanent building product becomes more feasible. The aim 'easy to build' is translated in a requirement to construct the building with a maximum of 2 people, without the use of heavy machinery or cranes.

Durable constructions in regard to functionality
A database of several components, with different functions, can be used to compose your building. By making the components modular elements, they become able to apply in various contexts for different clients. Various configurations are possible, providing the opportunity that everyone can create a building to their own desires and demands. In order to fit the need of the customer ideally, the possibility to make the building system adaptable becomes an important goal. This means that disassembly strategies need to be considered. In order to make adaptability an added quality, the disassembly should be easy, fast and without the damaging the components.

Strategies for disassembly, reuse and recycling
After constructing and adapting the building, at a certain point, the building does not suit the requirements anymore. Instead of destroying the entire building, like the current building industry does, the building could be disassembled back into its components. The building itself can be outdated, but the components could have the potential to be used in another building project. The use of standardized building components provides

the ability to reuse the components like Lego blocks. As result of the components that are exchangeable between different projects, it is possible to build a house out of used components. Hereby, the materials, and its embodied energy is not lost. Again the time and ease to disassemble the components plays an important role in the quality of the building system.

When the component's lifespan is completely expired the components itself can be disassembled and brought back into the ecological cycle. Important aspect is to avoid harmful materials.

Aesthetics

The façade of the PO-Lab will be covered with external façade system to protect against the weather circumstances. This means that the façade determines the outside appearance building system, not the components. Because of the modular properties of the building system, the façade has to adapt the modular principles, as well as the components, in order to create an integrated building system. The inside appearance is mainly dependent on the finishing of the components. To save construction time, activities to interior finishing should be decreased.

Costs

To make sure the building system becomes a feasible alternative to replace the current fast constructible building solutions, their prices should be comparable. Wood, as main building material, is relatively cheap. In combination with the CNC production technique, and prefab characteristics the building system has low chances for errors onsite. Added to that, the standardization of the building components makes is possible to produce them in large series. Due to these aspect, the system has the potential to be low priced.

Important aspect to keep in mind is the design and engineering of such a modular component. This is a complex and time consuming activity, and therefore also costly. But, due to the fact that this only has to be done once, it will not significantly increase the product costs..

4.4 DESIGN TASK

The concept for a building system that is using prefabricated, modular, building components to construct a building, will form the base of this research. The feasibility of the concept has been proven in the previous literature. However the concept needs to be elaborated further to actually translate the concept into a feasible building system. How are the components connected; how is the façade integrated in the system; and how is the indoor climate controlled? These questions form the starting point, whereof the specific design task will be derived.

The following research will focus on the connection detail of this modular building system. Like every other connection detail it has to perform according codes and requirements. It has to be able to transfer the loads through the construction, secure the thermal behaviour and make sure the system is air- and watertight.

However, the project goals of PO-Lab require are more advanced detail. It demands this building system to be modular, adjustable and easy to disassembe. This requires a significant more complex connection detail:

• A modular building system demands that all the different components should fit upon each other, which asks for a similar connection principle, with connections at similar locations.
• The connection should bear different kind of loads, without oversizing the detail drastically.
• The connectione between the components needs to be water and air tight without doing much work afterwards that is time consuming.
• In order to make the assembly of the building uncomplicated, it is desirable that fittings and seals are integrated within the components.

The CNC production technologies can really contribute in this aspect in making smart connections. It can provide accurate products that have low tolerance, thus water and airtight connections, but also make the assembly process can be much more efficient and fool proof. The fact that these connection detail will become very complex is not a problem for the computer controlled production method, and due to the fact that this system is standardized the complex detail has to be made only once. All the complex engineering takes place one time, when assembling and disassembling the building no more complex activities are required.

Figure 4.3 PO-Lab Building system without connecting detail (own illustration)

RESEARCH BY DESIGN

INTRODUCTION

The second part of this research needs to convert the ideas on a renewed approach of constructing, into a concept for the connection detail:

How to connect digital (pre)fabricated building components, to create a modular building system, with takes in consideration its entire life cycle? (PO-Lab)

It develops a methodological approach to create a concept. Design task in this research is to develop a convenient connection detail that suits the concept and goals of PO-Lab. Translated in research question:

Some questions arise that need to be answered in this part:

How can a methodology, to develop a sustainable digital-prefabricated building product, be generated that has (user) requirements as leading aspect?

- What methodologies are used in product development?
- How can user requirements be integrated?
- How can sustainable aspect of modularity be integrated in (building) product development?
- How is the methodology used to generate a concept?

What are the criteria for a connection detail in a modular building system (PO-Lab)?

- What are the exact project goals, that can be derived from the sustainable strategies?
- How can the project goals be used in the development of a (concept) design?

The following chapters will answer these questions, and use this answers to provide a specific design for the connection detail of the actual laboratory.

5. METHODOLOGY

Source illu.: www.peakroutes.com

5.1 APPROACH

A modular building system in combination with file-to-factory production process is rather unique. The role of the architect during the development process changes completely. Architects need to be capable to develop, design, engineer and manufacture the building system. They are involved during the entire process, from development until the end-of-life decisions. To structure the process of finding the most convenient solution for a specific design task asks for a methodical approach. However, a methodical approach, to translate specific (user) requirements into a design solution for a building system, does not exist yet. This part of the research tries to develop a consistent method, to establish the 'best' design solution for a connection detail, of a modular, CNC fabricated building system, on the basis of predefined criteria.

This specific research aims to develop a connection detail. However, the structure of this methodical approach can also be used to develop other aspects of modular building systems that make use of file-to-factory production processes. This method can be useful for designers of (building) product that are commissioned by users, owners or building developers. The method makes it possible to respond to a certain demanded future scenario. For example, the integration of technical measures, within the building system, that make it possible to adjust the buildings functionality to changing user demands or desires.

This chapter will describe the general methodology to come from a broad conceptual design task, to a final design. The following chapters will use this methodology, as a design aid, to establish a design solution for a specific connection detail.

5.2 METHODOLOGY SEQUENCE

Methods to analytically approach a product development process can be derived from the product development industry. (Eekels, 2003) Some of the methods used within this industry are also applicable in the building industry (Rutten, Zeiler, 2005). Associative and creative methods, such as brainstorming, are less applicable in this case due to the fact that specific goals are formulated which the building system has to fulfil. By using analytical and systematic methods, adopted from product development, it is possible to step by step realize a building product that meets the specified goals.

The methodological approach provides designers a framework to develop their products based on digital and modular principles. The analytical methodology is divided into seven different stages; a. design problems, b. criteria, c. alternative selection, d. concept comparison, e. concept proposal, f. prototyping and testing; into g. final design. The different phases will be explained and elaborated individually in particular paragraphs.

A. DESIGN PROBLEMS

The methodology starts with a specific design task for a project. In this case, the project would consist of a building system to actually build the PO-laboratory. From this project several design tasks can be derived, namely: façade design, connection details, building services and interior design. Due to the complexity of a particular design task, they can be elaborated further in multiple sub-aspect. There is a focus on embodied energy, and by separating the different layers of a building, it is possible to analyse these aspects independent of each other. (Kamrani & Sa'ed, 2002) However, it is not possible to completely neglect the other layers of the building structure.

For every aspect, alternative solutions can be developed and analysed as such. To be able to analyse the different aspects and their alternatives, criteria need to be generated in order to make an equal comparison between all alternatives to make weighed decisions.

B. CRITERIA

Depending on the project, criteria can be specified. In design an important task is the identification of

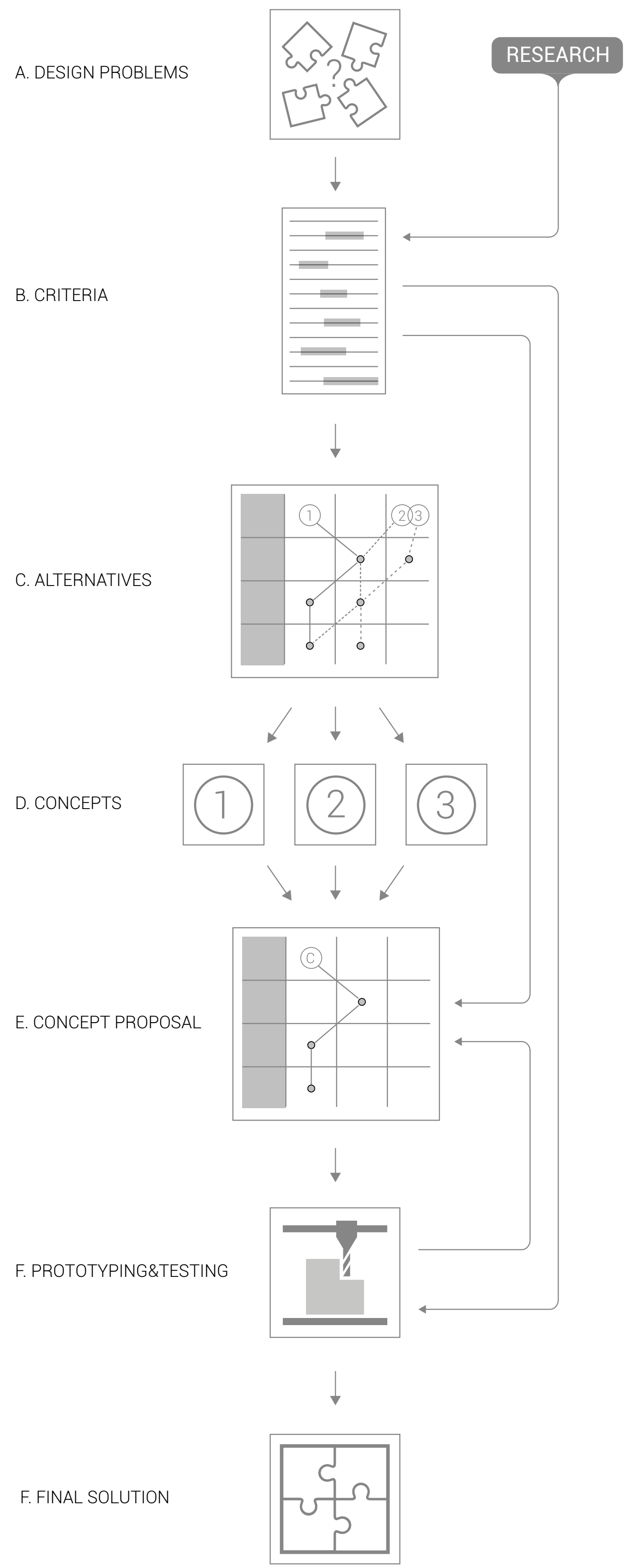


Figure 5.1 Methodology (own illustration)

the user's needs. A precise description of what the user wants and needs is required. The product has to be described fully in terms of functional needs and physical limitations. Later these aspects form the product specifications (Griffin, Hauser, 1991; Otto, Wood, 2001; Magrab, 1997).

A successful product in terms of market share and user loyalty depends strongly on the user. Highly satisfied users are more likely to buy and use products of the same organization then less satisfied users. (Durmisevic, 2007) Customer satisfaction can be illustrated further by the model of Kano. According to this model there are three main types of product requirements that affect customer satisfaction (Berger et al., 1993):

• Must-be requirements are the basic needs for a product. As these requirements are expected to be fulfilled in the product a customer buys, the manufacturer gets no credit if the product satisfies to the requirements. In fact, customers are extremely dissatisfied if the must-be requirements are not met. Must-be requirements are unspoken and not measurable, customers are either satisfied or dissatisfied.

• Performance requirements are spoken needs that can be measured for importance and can be ranged in the amount of fulfilment. Customers ask for these specifications and expect them to be met. As the degree to which the requirements are met the customer satisfaction increases as well. Performance requirements can also serve as a way to compare different products by scoring them on the different criteria. This can determine a product's performance in terms of customer satisfaction.

• Attractive requirements are unspoken and unexpected by the customer, because these are not known to exist. These requirements are future oriented and innovative. Creative, unexpected ideas result in a high customer satisfaction rating. Although, it is notable that attractive requirements quickly become expected.

Requirements & Ambitions

The criteria in this methodology can be subdivided in: requirements (must-be) and ambitions (performance), visualised in figure 5.2. The eventual design must meet the specific must-be requirements, in this case structural safety and sufficient building physics. Ambitions can be derived by specifying the strategies of sustainable building design, for a particular project, to form a goal. These strategies can be deduced from user, manufactures and environmental goals.

Design for manufacture (DfM)

However requirements of the user can be accounted as most important, they lack some criteria which are important for the manufacturer. A user can have specific wants for a product indifferent of how it is made.

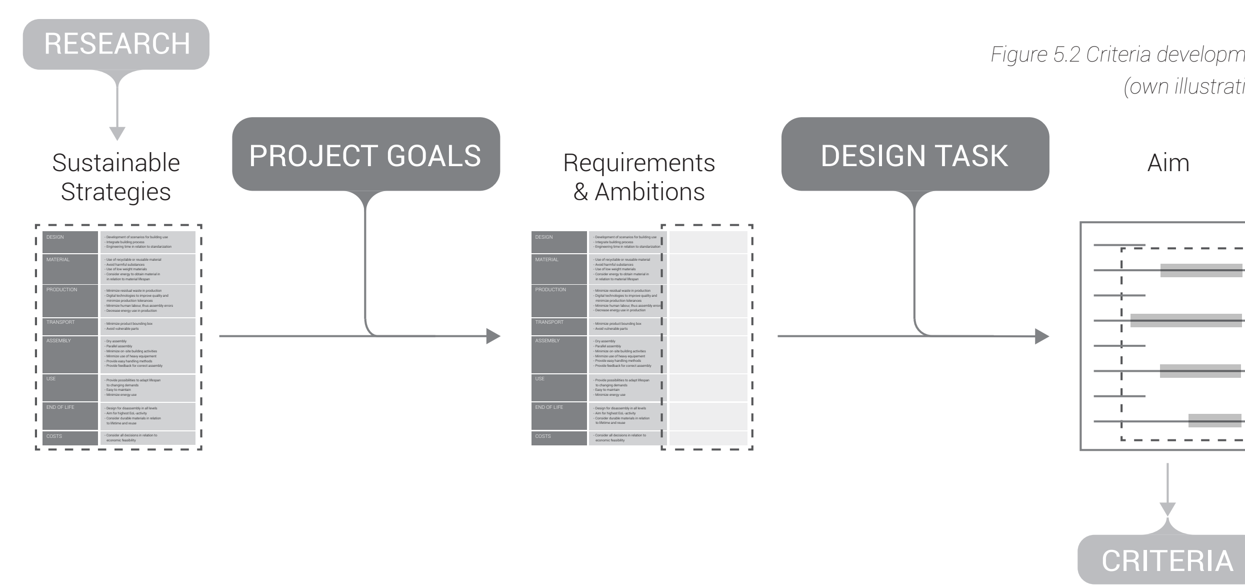


Figure 5.2 Criteria development (own illustration)

Design for Manufacturing (DFM) are the integration of product design and process planning into one common activity. The goal is to design a product that is easily and economically manufactured. The importance of designing for manufacturing is underlined by the fact that about 70% of manufacturing costs of a product (cost of materials, processing, and assembly) are determined by design decisions, with production decisions (such as process planning or machine tool selection) responsible for only 20%.

Criteria concerning manufacturing can be derived from strategies of the previous research chapter.

Design for environment DfE
While some requirements from the users and manufacturers incorporate environmental aspects in the criteria. E.g. an aim for a limited use of materials, is related to environmental aspects as well as to costs. Important is to consider all phases of the product life-cycle. This is already widely discussed in prior chapters, therefore no further explanation is required. The attention all specific life-cycle phases is assured by separating the criteria for each phase. This makes is visible if one specific phase is neglected.

Aims
From a specific design task, aims to fulfil this ambitions, can be determined. This aim specifies in what amount a design solution is convenient to an ambition. The higher a solution scores for an aim, the more suitable the solution is to be used in the eventual design. Figure 5.3 shows an example ambition with a possible aim. First the ambition gets a specific description. Next the specific design task defines an aim in what amount the ambition needs to be fulfilled. This can be linked to a score. Lowest score is 0. If a 0 is appointed this means it does not meet the aim of the design task. From 1, the solutions are sufficient to the ambition. The higher the score, the more convenient the design.

It is important to take the different views of the parties involved in the process and the influence of those on the context (environment) into account when setting up the criteria. When designing a product, it is critical to take user requirements into account as users are largely responsible for the success of it. However, the point of view of users can conflict with or are independent from criteria derived from the demands of the manufacturer or concerns from an environmental point of view. In order to define universal criteria which incorporate and combine different needs and requirements it is essential to have knowledge of the requirements from the three different aspects (user, manufacturer, environment)

Weight
The demands of the client can be integrated into the criteria by ranking them to the priority the client gives to a specific criteria. This can be done by the decision method of individually comparing all the criteria to each other, and make for each comparison a decision on which criteria is the most important.

This method, that in a matrix determines for two individual criteria which is the most important, is suitable to achieve a consistent order of priority in the set of requirements. (Eekels, 2003) By doing this for all the criteria, a division can be made between important (weight 3), less important (weight 2) and relatively unimportant (weight 1) criteria.

Topic

Ambition

Ambition discription
'PO-lab' requirement: 'PO-lab' resembles the modular building system, the laboratory is one possible configuration of the system.

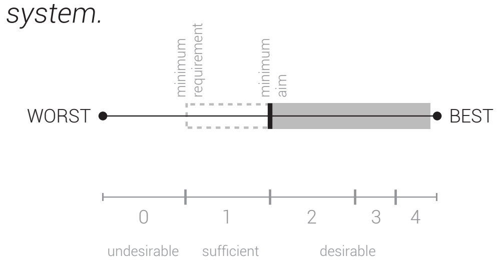


Figure 5.3 Ambition with associated aim (own illustration)

SCOREMATRIX VOOR FUNCTIONELE EISEN OP INTERVALNIVEAU							
Functionele eisen	A	B	C	D	Totaalscore	C (=n/2)	Totaalscore + Constante
A		5	2	4	11	2	13
B	0		1	5	6	2	8
C	3	4		3	10	2	12
D	1	0	2		3	2	5
(n=4)					30		46

Figure 5.4 score matrix (Gijsbers, 2013)

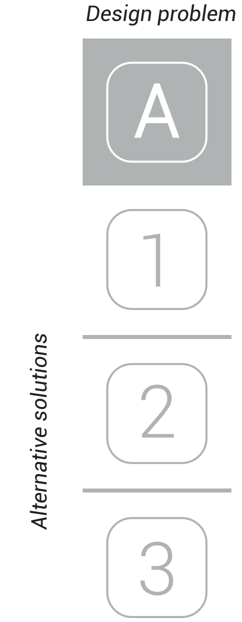
Table 5.4 presents a clear example of the score matrix that compares different criteria to each other to order them. To keep it elementary only four fictive criteria are presented (A, B, C and D). A criteria scores a 1 if the criteria in the row is considered more value as the criteria in the column. By enumerating the scores an order arises.

An advantage of this method is its simplicity. A major drawback is that this method indicates an ordinal result, and therefore no value should be given to the distance between the various criteria in the rankings. (Roozenburg, Eekels, 1998)

C. ALTERNATIVE SELECTION
It is too complex to approach this design task as an individual problem Therefore the design task will be divided into several sub-aspect. Every particular aspect can be analysed in more efficient way. For every aspect multiple alternative design solutions can be created. These are still conceptual and simple and fast to generate. The different alternatives can be evaluated to the criteria that are specified upfront. From the formed criteria the subject specific ambitions can be selected to only evaluate the design problems to relevant criteria.

The satisfaction of an alternative solution is defined by multiplying the fulfilment of an aim, with the specified weight of the certain ambition. The score determines the level an alternative solution suits the specific ambition. This has to be done with every criteria that concerns the solution. Adding all the scores will result in a final score. The highest number will present the 'best' choice. (Figure 5.5)

Doing this to all alternative design solutions, will show the most promising solutions. Combining the most promising alternatives will result in a concept proposal. This method requires a certain creativity of the person who uses it. It is advisable to involve multiple people in a creative session, for example brainstorming. It enlarges the chance that the number of developed concepts increases and will probably offer a larger variety of solutions. (Gijsbers, 2011)



Evaluation

A		WINNER 1	2	3
Criteria	weight			
- Ambition1	2	6	4	4
- Ambition2	2	6	2	4
- Ambition3	1	2	1	1
- Ambition4	2	2	4	6
	Score	16	11	15

Table 5.5 Evaluation example (Own illustration)

D. CONCEPT COMPARISON

Selecting the alternatives will probably not give one clear solution for a concept. Some options can result in nearly identical scores. Due to the subjective aspect of decision making, this process may contain inaccuracies. Therefore, it's impossible to neglect solutions for design problems that show several convenient options. This will result in numerous concepts.

After elaborating these concepts more in detail, a more honest comparison can be made. This elaboration can consist of both theoretical and physical analyses methods. This is where CAD/CAM can accelerate the design process. By using rapid prototyping technologies, scale models can be made very efficiently. With analysing this models designers can make a good estimation of the final result.

E CONCEPT PROPOSAL

After elaborating and prototyping multiple concepts that are created with the previous mentioned methods, different concepts can be compared. This will conclude in one concept proposal which seems the most convenient for the specific design task.

F PROTOTYPING AND TESTING

To analyse the proposed concept, full-scale prototypes and test need to be done made. With making prototypes, possible problems will become visible. By making multiple iterations this can become a cyclic process. If a specific problem is noticed, one can go back to the concept and see how to solve this problem. The subsequent prototype can, again, be evaluated to the specified criteria. This process will continue untill all problems are solved.

Just like with rapid prototyping, digital production technologies make it possible to repeat the full-scale prototyping process multiple times without much extra effort. Every prototype uses the same (slightly) adjusted drawing as input for the CNC production methods. If one reaches a prototypes that works, the digital data can immediately be applied for the production of the actual design.

Also physical test can be done, e.g. structural analyses or water tightness. These must-be requirements are crucial to the feasibility of the design.

G FINAL DESIGN

After analysing the prototypes and doing physical tests a final design can be the result.
[stap van prototype to final design]

5.3 CONCLUSION

This methodological approach provides designers a framework to develop their products based on a specific set of criteria. The analytical methodology is divided into seven different stages; a. design problems, b. criteria, c. alternative selection, d. concept comparison, e. concept proposal, f. prototyping and testing; into g. final design.

In all different design cases, the methodology comes to the assessment of an design solution to the related requirements. The method can be used to generate design options and draft recommendations and to justify the final design on a quantitative basis. The approach is systematically because by making of combinations and multiple different solutions, a concept design to the problem can be created. This happens in a structured and analytical way.

6. CONCEPT DEVELOPMENT

Source illu.: Own illustration

This chapter consist of the development of a concept that meets the goals stated in the prior chapter. The concept development process, guided by the methodology developed previously in this research, will be elaborate and explained. The methodology is used consequently, with repeating acts, to assess the different researchable sub-aspects of the connection detail.

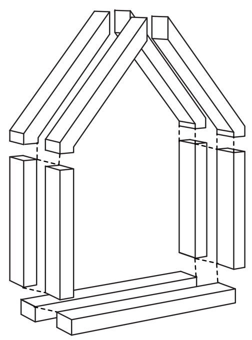
Firstly, the design problems will be determined, and particularly elaborated. A scheme with the design aspects will form the base in which all alternative design solutions can be sorted. These alternatives are described, judged and compared with each other. To do this in a proper and equal way, specific criteria will be determined. Based on the evaluated alternative solutions, the most promising ideas can be selected for form a concept for the connection detail. It can happen that several options seems convenient, or that a specific alternative cannot be combined with other alternatives. These solutions can be elaborated more in detail, or tested with prototypes, to determine which it most suitable.

This concludes in a convenient solution for every design aspect. Combining the most suitable alternatives will result in a concept proposal for the connection detail of PO-Lab's building (system). This concept will form the starting point for further research.

6.2 DESIGN PROBLEMS

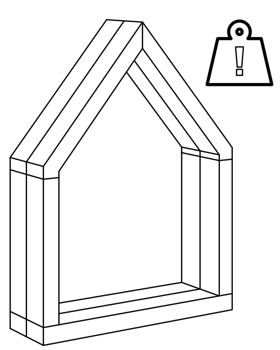
All of the requirement from the building system result in a very complex design task for the connection detail. It's almost impossible to approach this design task as one object. Therefore the demands of the connection detail are divided into several sub-aspect, which can all be analysed individuality. For every aspect multiple alternatives can be generated, which can be evaluated to the project goals that are going to be translated into specific criteria.

Combining components



The main concept of the building system consist of component library, from where components can be selected and joined to configure a building. The way these modules are combined have a large impact on how the final building system would function. Horizontal forces, mainly wind load, need to be in equilibrium with the support reactions. In the direction parallel to the structure, the stability can be provided by the façade elements that form a diaphragm. This transforms the moments, resulting from horizontal loads to axial forces that are transferred to the foundation. But how can the façade components be connected to form a stable element? Also the freedom of design and the possibility to adapt the building can be largely affected by the way the different components are combined. If extra parts are used to combine the components, can the building still be adapted?

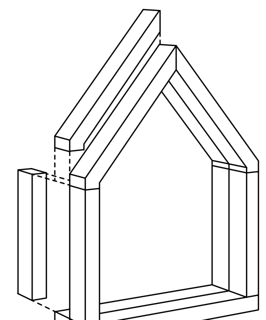
Structural behaviour



Depending on the requirements of a specific design, it is possible to predict the forces that the connection details have to bear. However, in this case we are dealing with a modular design that has no specific design. The decision on the structural behaviour of a connection detail, e.g. hinged of fixed, will have a major impact to the design possibilities.

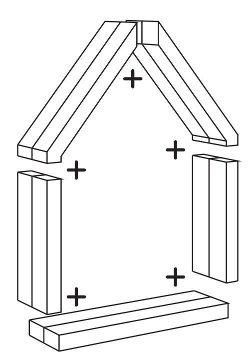
Wind loads, perpendicular to the structure, can be transferred by the head façade elements. These act as diaphragms. However, due to the distance they can be apart from each other, or particular designs without a head façade, more stability measures along the long side are required to form a stable structure. This requires designing the trusses so that they singularly or in combination with other elements provide stability within their plane. Thus, the structural behaviour of the connection influences the design possibilities with the building system, and the extra activities on-site that are required to make the building stable.

Component Placement



Combining the components is an important aspect in how the components interact. But the placement sequence and direction also has to be considered. The placement will play a major role in the functionality of the prefabricated system. The building ease and speed are influenced, but also the behaviour of the building system during the use phase. Depending on the component placement, the adaptability could be influenced, for example, components could be removed individually from the building to make small adjustments. With a common building (system) this would not be really necessary, but with PO-Lab is could be useful. Removing single elements provides the potential to test different façade elements. A conflict that has to be taken in account is that, the possibility to adapt a certain aspect, which can be useful, does not affect the quality and ease of the whole system.

Connection type



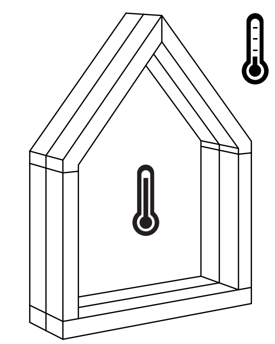
The concept of PO-Lab demands a building system that can be installed quickly, and also be disassembled again. The connection type will have a large contribution to this adaptability, as described at page 46.

Connectors play a key role in determining the

disassembly capacities of the product. The type of fastening method employed, determines whether the product is to be disassembled using a destructive or a non-destructive disassembly approach. For example an ordinary screw, which is perfect to connect two parts, but when it has to be disassembled and re-used again troubles will occur. On the order hand, super smart and fast furniture connection systems exist. Can these be implemented in a building system, are they able to bear all the possible loads? In order to find the most convenient solutions there needs to be an equal comparison between possibilities to assemble, but also the possibilities to disassemble it.

Research showed that when all considerations related to entire life cycle stages of a product were included, the best connection type for DfD came out to be the integral or discrete fasteners. (Güngör, 2006) So the connection types are limited to this category and therefore adhesive fasteners are ignored in this research.

Thermal behaviour:



The concept's physical behaviour is based on a vapour-permeable system. A system which is not very familiar within the Dutch building industry. In surrounding countries like Germany and Belgium, this system is more standard. With vapour open construction, the outer material is more vapour permeable than the inner material of the component. As a result, the outer wall is wind- and air-tight, while the relative humidity is regulated in the construction without affecting the insulating values.

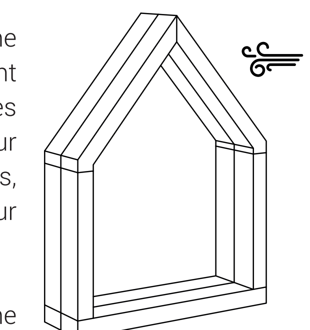
The vapour, arose in the components during construction, can be transported to the outside of the building. Vapour permeable buildings give more comfort and quality of living, because the living conditions in the building envelope is optimal. Instead of a fully insulated closed construction (a plastic bag), a vapour permeable building is naturally breathable.

However, it asks for specific measures. Both the inside and the outside have to be vapour permeable to ventilate. And it asks for special insulation types that can transport vapour. That are insulators of natural materials with closed cells.

Water protection:

Within the concept of vapour permeable constructing, the outside of the construction needs to be more vapour permeable than the inside. The structural inside is made of OSB, which is not very permeable. Another material for the outside is required. There are multiple options available but all with up and down sides. Some are very easy to implement in the detail, but others are requiring a lot of time during the assembly of the components, or have a very large environmental impact. To find the most suitable option, a consideration between the criteria of engineering time, assembly of the component, and the assembly speed and ease of the entire building is required.

Air tightness



The airtightness of the structure is another important aspect that influences the quality of the vapour permeable concept. Thus, affects the thermal behaviour of the building system.

In order to secure the insulating capacities of the construction, the building system needs to be 'completely' air-tight. An air-tight construction have the advantages of energy savings, because there is no heat loss or infiltration of 'cold' outside air. Secondly, the comfort within the building is easier to regulate. Air-tightness means no draft. The means the air quality inside can be controlled more effectively in case there is a proper HVAC system available.

6.3 CRITERIA

Before the evaluation of the design problems, and their matching alternatives can be executed, it's necessary to formulate a number of criteria which the eventual product or design has to fulfill. These criteria can be divided in requirements and ambitions.

Requirements

The requirements are specified by codes and regulations regarding construction details. These criteria are crucial to the viability of the eventual design. Smith (2010) mentions the following principles that should be considered by design and construction professionals when devising details for either onsite or offsite construction, adapted from Allen and Rand (2009) and Linda Brock's (2005):

1. Water:
• Eliminate openings in building assemblies
• Keep water away from openings and building assemblies

2. Air infiltration:
• Tight tolerances
• Air barrier surface
• Seal or gasket joints

3. Energy:
• Control conduction (insulation, break, air gaps)
• Control radiation (reflective surfaces, and air gap)

4. Condensation:
• Keep interior surfaces at temperature above dew point of the air (insulation, breaks)
• Warm side vapour retarder
• Ventilate cold side of vapour retarder to release moisture
• Catch and remove condensation through gravity

5. Sound:
• Airtight, heavy, limp mediating surface
• Quiet attachments
• Sound attenuating surface

6. Structural:
• Temperature movements
• Moisture/phase change movements
• Dead and live loading (abutment joints for dissimilar structures)
• Settlement and creep (separation joint)

Other requirements are derived from the limitations of CNC production process and already described at page 22. Also requirements of the user (PO-lab) is added. An important demand is the maximum weight of 50 kg for an individual component in order to construct the building with two people. The 50kg is derived from the building codes.

Ambitions

Ambitions are derived from the sustainable strategies that concluded the literature research part. They consider all six life-cycle phases to consider all aspects of DfE: Material, Production, Transport, Installation, Use and End-of-Life. The topic of design is added to complete the table. Divided over these aspects are: DfM guidelines, limitation of CNC producing and general demands from the user (PO-lab) on the design of this concept. The ambition of cost is derived from the project goal to develop a low priced building system that can compete with other easy constructible building systems. This is an overall criteria that needs to be considered in every individual aspect.

All ambitions are presented in table 6.1, an individually elaborated further in appendix C. Within this elaboration the ambitions are translated into an aim, which will be used further on in this research as evaluation criteria for the selection of the most convenient solutions. The weight of these ambitions are specified by the score matrix, a method explained in the prior chapter. By using this method the importance of every ambition is considered in a scientific way. The overview of this matrix is showed in Appendix D

These ambitions can be used to choose the most feasible solution for every sub-aspect. With their project specific aim and weight, the upfront specified ambitions ensures that the chance to neglect or overvalue a specific aspect, in the decision making, is minimized. This creates a clear and consequent design process, from concept generation until the eventual design.

The scheme on page 76 appoints the relevant criteria to every particular design problem.

DESIGN	- Development of scenarios for building use - Integrate building process - Developing effort in relation to standarization	- Freedom of design - Level of Finishing
MATERIAL	- Use of recyclable or reusable material - Avoid harmful substances - Use of low weight materials - Consider energy to obtain material in in relation to material lifespan	- Environmental impact
PRODUCTION	- Minimize residual waste in production - Digital technologies to improve quality and minimize production tolerances - Minimize human labour, thus assembly errors - Decrease energy use in production	- Batch size - Nesting efficiency - Milling time - Amount of elements - Assembly complexity
TRANSPORT	- Minimize product bounding box - Avoid vulnerable parts	- Vulnerability - Loading efficiency
ASSEMBLY	- Dry assembly - Parallel assembly - Minimize on-site building activities - Minmize use of heavy equipement - Provide easy handling methods - Provide feedback for correct assembly	- Ergonimics - Weigth - Amount of components - Amount of joints
USE	- Provide possibilities to adapt lifespan to changing demands - Easy to maintain - Minimize energy use	- Adaptability - Maintenance - Accessibilty
END OF LIFE	- Design for disassembly in all levels - Aim for highest EoL-activity - Consider durable materials in relation to lifetime and reuse	- EoL-activity - Lifespan - Disassembly ease
COSTS	- Consider all decisions in relation to economic feasibility	- Costs, in combination to lifespan and reuse

Table 6.1 Ambitions derived from strategies (own illustration)

Table 6.2 Criteria appointed to specific design problems (own illustration)							
Function	Combining components	Structural behaviour	Placement components	Connection types	Thermal comfort	Water resistance	Airtightness
Criteria	• freedom of design • assembly complexity • loading efficiency • ergonomics • amount of components • adaptability • accessibility • disassembly ease	• freedom of design • assembly complexity • milling time • loading efficiency • adaptability • amount of joints	• amount of elements • milling time • assembly complexity • ergonomics • adaptability • maintenance	• envirn. impact • milling time • nesting efficiency • assembly complexity • amount of elements • amount of joints • ergonomics • adaptability • disassembly ease	• envirn. impact • assembly complexity • amount of elements • weight	• envirn. impact • milling time • nesting efficiency • amount of components • ergonomics • disassembly ease • E-o-L activity	• envirn. impact • process time • nesting efficiency • amount of components • ergonomics • disassembly ease • E-o-L activity
Contadiction	Modularity of the design vs. ergonomics & amount of components	More connections and more complex details, to reach more freedom of design	Able to remove single component but a lot other problems occur	Amount of joints vs reuse Disassembly vs strength	Make sure to compel with vapour open system	ergonomics vs. amount of components Disassembly need to be protected	assembly complexity vs. amount of components env. impact vs ergonomics

6.4 ALTERNATIVES

This different design problems are the result of complex and comprehensive design task. Therefore the design task will be divided into several sub-aspect. Every particular aspect can be analysed in more efficient way. For every aspect multiple alternative design solutions can be created. All of those alternatives for every design problem are presented in this scheme. These alternatives are very conceptual and not elaborated yet. The broad ideas of the different solutions will be compared in a consequent way with the help of the criteria. From the formed criteria the subject specific ambitions can be selected to only evaluate the design problems to relevant criteria.

The satisfaction of an alternative solution is defined by multiplying the fulfilment of an aim, with the specified weight of the certain ambition. The score determines the level an alternative solution suits the specific ambition. Adding all the scores will result in a final score. The highest number will present the 'best' choice.

This chapter will do this for every design problem in order to find the most suitable solutions to propose a proper concept.

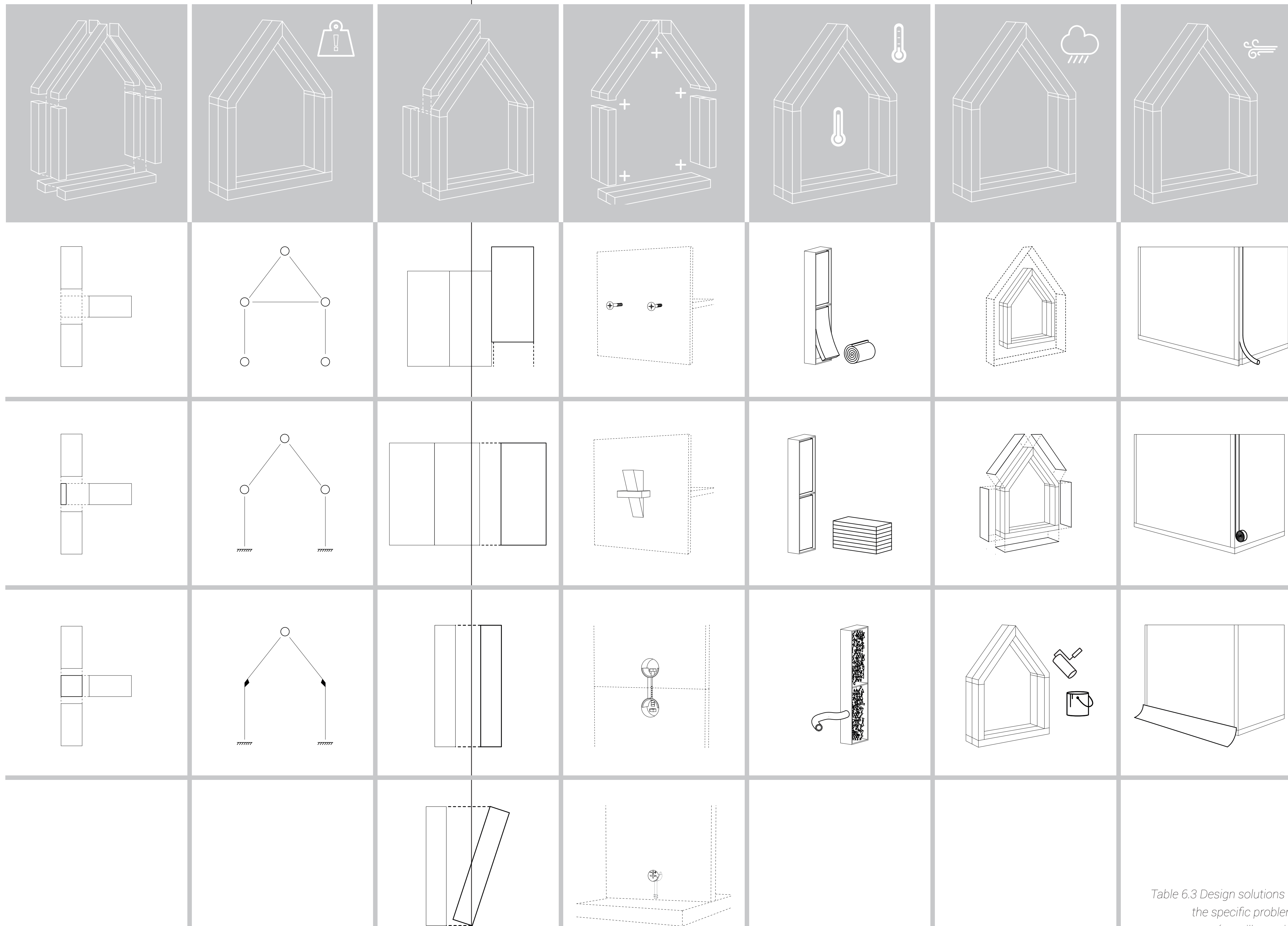
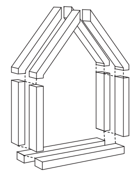


Table 6.3 Design solutions for the specific problems (own illustration)

COMBINING COMPONENT:
The overview of alternative solutions gives three different solutions to combine the floor, wall and roof components.

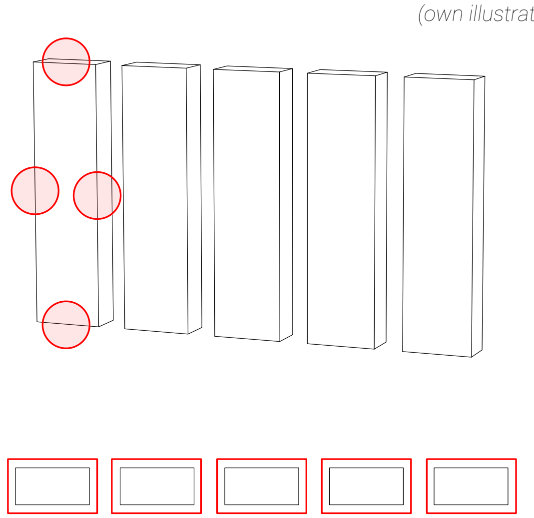


Directly combined:
When combining all the components directly upon each other, every component should be able to bear all kind of different loads. Of course, it is not able to avoid over-sizing structural elements, if a modular system is developed. But the over-sizing and freedom in design should be in balance. An advantage of this solution is the possibility to remove single components. If new components need to be tested, it is easy to replace them.

Down side is the amount of connections that are required to solve the stability. Horizontal forces, parallel to the structure, are transferred by the façade elements that form a diaphragm. This transforms the moments, resulting from horizontal loads to axial forces and transfers them to the foundation. Connections in different directions are needed to make a stable structure.

+ Able to remove one element
- Heavy loads
- Many connections

Figure 6.1
Four connections required to make a stable structure (own illustration)



Beam
The next solution is to use an edge beam which makes a connection between the single components. This lowers the adaptability of one specific element, because not every single component can be removed. But the adaptability of the entire building is still possible by adjusting the length of the beam.

By connecting the component they work as one structural element. These structural elements of combined components make a stable building, without designing large oversized connection details.

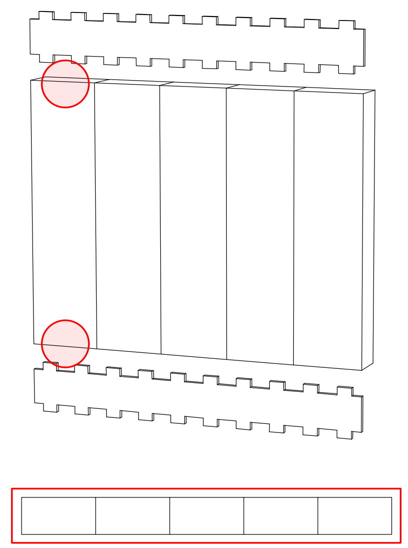


Figure 6.2
Two connections required to make a stable structure (own illustration)

+ Stable
+ Less connections
- Not able to remove 1 component

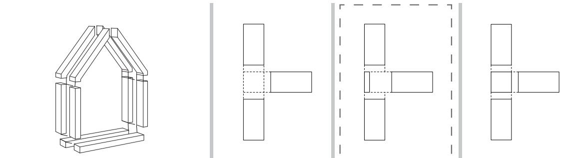
Component:
Instead of a beam, an extra component is the third option. Upon this component, all the other components are assembled together. Just like the side beam, the extra component makes the assembled components a stable unit. However, the length of the module is more difficult to adjust. And the connections that are saved in making a stable wall component are introduced again to connect all the components.

+ Stable
- Many connections
- No ability to change design.

Final choice: beam
By evaluating the different alternatives to combine the different components. The side beam turns out to be the best solution. In this way the components can work together as larger structural modules. By connecting the components in such a way, the number of connections needed to make a stable structure, is lowered. This has positive effects to the assembly speed and ease of the building. Also the structural consequences from creating openings in wall components can be absorbed by the side beam.

Adding a beam to connect the components makes the adaptability more difficult. The components cannot be removed without removing the beam. In a common building, this is not a big problem, but PO-lab want to test different façade in the building. Thus, an extra component is needed that can contain different infills. Compared to the adaptability of a specific elements, the adaptability of the entire building is more important. If the configuration of a building needs to change, the dimensions of the beam also requires adjustments. A beam that can change in length is something that has to be considered when the actual design of the beam takes place.

Table 6.4 Final choice component combining (own illustration)



Criteria	weight			
- freedom of design	3	9	6	3
- assembly complexity	1	1	3	3
- loading efficiency	2	6	4	2
- adaptability	3	9	6	3
- accessibilty	1	1	2	3
- ergonomics	2	2	4	4
- am. of component	2	6	6	2
- Disassembly ease	3	3	9	9
	Score	37	42	29

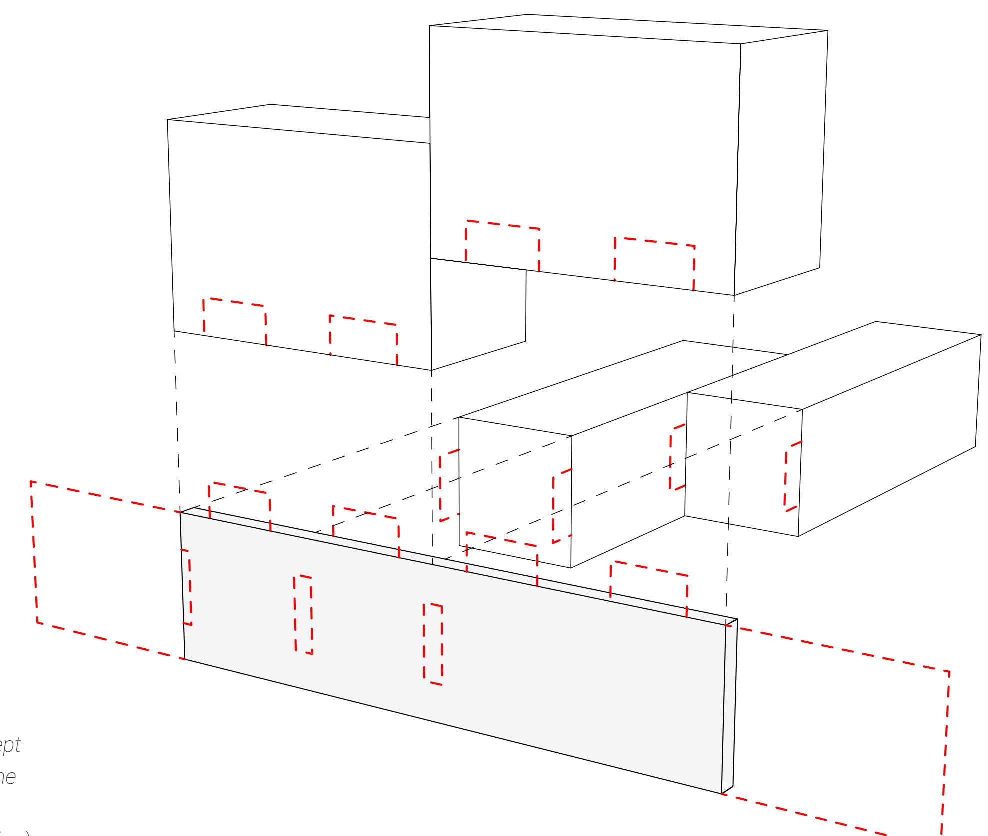
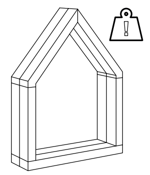


Figure 6.3
Design concept to combine the components (own illustration)

STRUCTURAL BEHAVIOUR



The overview of alternative solutions gives three different solutions to the structural principle of connection between the different components.

Hinged connections:

By using only hinged connection the freedom of By using only hinged connection the freedom of design is reduced significantly. If all the connections are hinged, it is not able to design a completely stable building with one of the façades open or large openings in the floor. The consequence of this configuration is that both stability within the trusses' own plane, nor provisions against the splash effect are provided. This is thus not stable in its own plane. Both should be solved by measures lateral to the truss: bracing or diaphragms that connect the truss, secondary stability elements like a head façade or stability core. This will result in a building system with very little freedom of design, or complicated structural measures should be implemented.

On the other hand is a hinged connections easier during assembly of the building. It's easy to place the modules, only one connection has to be fixed and all the connections are the same, so no complicated assemblies on-site are required.

+ No complex connections
- Hardly no freedom of design
- Extra structural measures required

Fixed connection at the bottom:

With a fixed connection at the bottom of the components, the problem concerning the lack of freedom in design can be solved. The fixed bottom connections, which create a couple of forces within the detail, takes by far most of the bending moments resulting from vertical and horizontal loads. One of the main advantages of the principle is that it provides stability in its plane, without need of secondary stability elements. A stability core, or head facade is not necessary when applying this principle. This has its benefits in designing with the building system, resulting in a more extensive freedom of design. This solution makes it possible to create open head façade and large openings in the floors.

However, the couple does double the connections point, thus probably the amount of joints that need to be fixed. Another downside of this principle is that the bottom connections have to bear nearly all the forces, so they have to be more complex. Also different connection details have to be developed and produced, one detail for the bottom connection and a connection for the rest of the structure. This makes it more complicated to develop the component, but also has negative effects on the building ease. Due to the different connection it's more complicated to assemble the components.

+ More freedom of design
- Complex detail
- All forces on bottom
- Different detail top/bottom

Fixed connections:

The third and final alternative for the structural behaviour of the connection details is using only fixed connections. Again the freedom of design is satisfactory, now that all connections can bear multiple forces. And because all the connections are the same, just like the hinged connections, the building ease is improved.

Again this principle has downsides, because there are more connection point that needs to be assembled. And by using this principle, the connections are slightly oversized when the design contains head façades or no openings in the floor.

+ Freedom of design
+ Easier to adapt
+ Distributed forces
- Double connections
- Oversizing

Final choice: All fixed

The evaluation chart presents the solution with only fixed connections as most promising alternative. By creating the ability for the connection to bear horizontal and moment forces, the quality of the building systems can grow. By doing this in all connections, instead of, just at the bottom connection, building ease and force distribution is significantly improved. The criteria; freedom of design, adaptability and ergonomics, are all optimized with this solution.

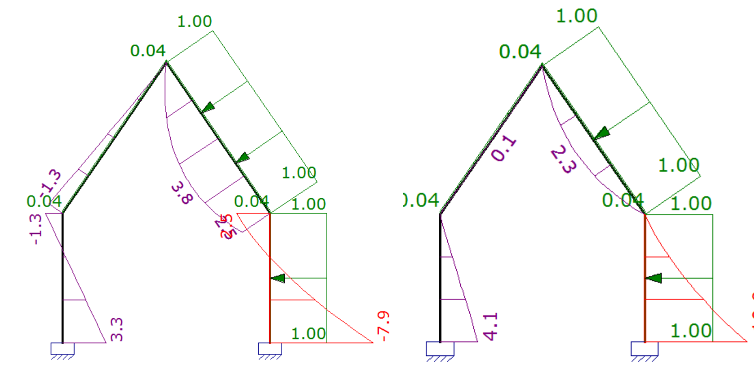


Figure 6.4
Structural analyses of bottom fixed vs fully fixed. Moment reduction from 10.9 to 7.9kNm
(own illustration)

Fixed connections do need a couple to transfer the loads. The integration of the couple in the design of the connection detail requires several connection point. Preferably with as much distance between them as possible. A larger distance between the connection point means that the connections can bear more moment forces. This can be concluded from the formula:

F(force) = M(moment) x a(distance)

F is the force that the connection need to transfer. When decreasing this force, also the joints could be smaller, or less joints could be used.

The couple that has to be created, does double the amount of connection points. However, this does not immediately double the amount of joints. The forces is more distributed, which can decrease the required number of joints. This actual number of joints, and the dimensions of the connection point will be developed further on in this research in the prototyping chapter.

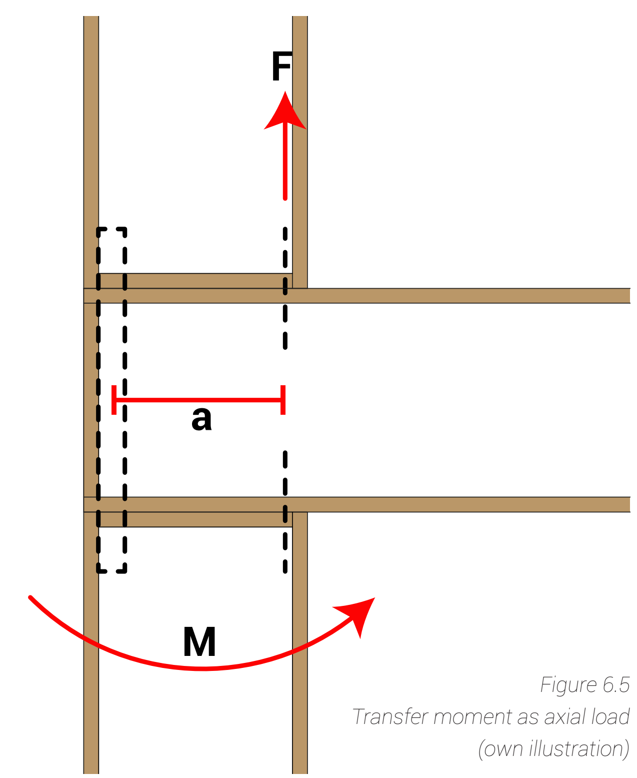
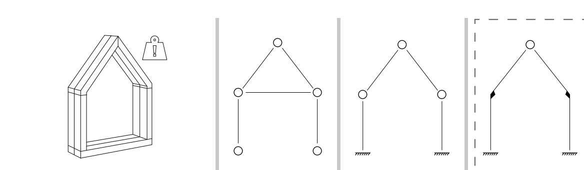


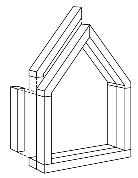
Figure 6.5
Transfer moment as axial load
(own illustration)

Table 6.5 Final choice
Structural behaviour
(own illustration)



Criteria	weight			
- freedom of design	3	3	12	12
- milling time	2	6	4	4
- assembly complexity	1	3	3	2
- loading efficiency	2	4	2	2
- adaptabilty	3	3	6	9
- amount of joints	2	6	2	4
Score		31	31	37

COMPONENT PLACEMENT



The overview of alternative solutions gives three variations in possibility to place the modules

From above:
Placing the components from above will make the assembly of the entire building quiet easy. The components are lifted over the assembly point. When dropping the element, as the result of its own weight, it's immediately in the right spot and it is not able to move anymore. Resulting in a rather fast and easy assembly. When removing the component, they can be lifted off again.

This lifting has a disadvantage. The dimension and shape of the component make is difficult to lift it. As result of the stacking components, it is not able to remove a single element

+ Fit first time
+ Does not move
- Lifting
- Remove single element

From the side:
Sliding the components towards to others from the side has the advantage that there is no lifting involved in the placing and disassembly of the modules. Which makes is easier to place them. However, the modules do not fall into place. This can lead to inaccuracies in the assembly of building.

The sliding do requires some adjustments to modules which can affect the quality of the module. The load behaving can be worse, or the assembly of the modules becomes more complicated.

+ No lift
- Inaccurate
- Complex module
- Structural behaviour?

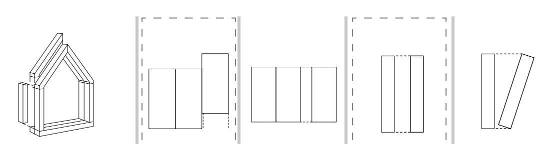
Slide from front:
Sliding in from the front instead of the side has one big advantage. It is possible to remove one modules on itself. But just like the alternative before it requires a more complex module, and it does affect the assembly ease and accuracy of the whole system. Is the removal of one module such a big necessity that all modules need to be adjusted, and probably not in a good way?

+ No lift
+ Remove one
- Inaccurate
- Complex module

Tilt from the front:
Besides sliding, tilting could be another option to place the component. The bottom part of the component is lifted over the notch of the side beam. Next, the top part is tilted into place. Again it is possible to remove a single module. However, it does make the whole system more complex. The top and bottom of the module would be different, and extra space is required for the tilting.

+ No sliding
+ Remove one
- Complex module
- Extra space required to tilt movement

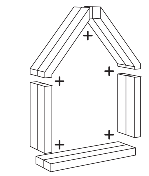
Final choice: lift from above / slide front
The scores of the different alternatives are practically identical. The comparison between the different alternatives is consequent to all solutions, but it is still rather subjective. The designer decides the score to a specific subject, which can be judged as his opinion. In order to increase the objectivity regarding the decision of the component placement, it would be an improvement to elaborate both alternatives further. The elaborated designs can provide a more grounded for base for a decision on which alternative would be the best solution.



Criteria	weight				
- Am. of elements	1	3	2	2	1
- milling time	2	6	4	4	4
- assembly complexity	1	3	2	2	1
- adaptability	3	9	6`	12	6
- maintenance	2	2	2	6	4
- ergonomics	2	6	4	4	2
	Score	29	20	30	18

Table 6.6 Final choice component placing (own illustration)

JOINTS



There are 4 possible alternative solutions to join all the components and elements together.

Woodworking
Most of the production process is done with the CNC milling machine, therefore it looks obvious to use this production process to make the joints as well. Wikihouse, for example, makes use of several wooden friction fit connections. However, to connect the whole building, the connections have to bear quiet some loads, and wood is not the strongest material compared to others. In order to distribute all these loads the connections should be rather big.

It requires protruding parts to connect several elements or components. The protruding parts are joined with wooden inserts. This results in inefficient components; inefficient nesting, inefficient transport and inefficient assembly.

Another downside is the tightness of the wood connections. By analysing the last ECOnnect building it became clear that wood connections do not resist well against vibrations. The connections that were fixed already, came loose due to activities at the other side of the building.

+ No extra parts
- Large modules
- Weak material
- Difficult assembly process

Figure 6.6 CNC-milled friction fit connection (fraaiheid.com)

Screw
Next solution is the ordinary screw. A fast and easy connection methods which does not require any complicated adjustments to the component, nor the beam. On the other hand, the screw is not very though, so probably many are required to bear all the loads. Other disadvantages are the disassembly and reuse capabilities of the elements. If the screw is used one time to construct the building, the next the time its load bearing capacities will be dropped significantly.

+ Fast
+ Easy
- Weak
- No disassembly

'Bolt & Nut'
A good alternative to the screw is a bolt/nut-connection. It is not as fast as the screw but it has the advantage that it can be disassembled rather easy. Depending on the type of bolt it can take more loads, allowing less bolts to bear all the loads.

+ Disassembly
+ Though
+ No complicated modules
- Slower

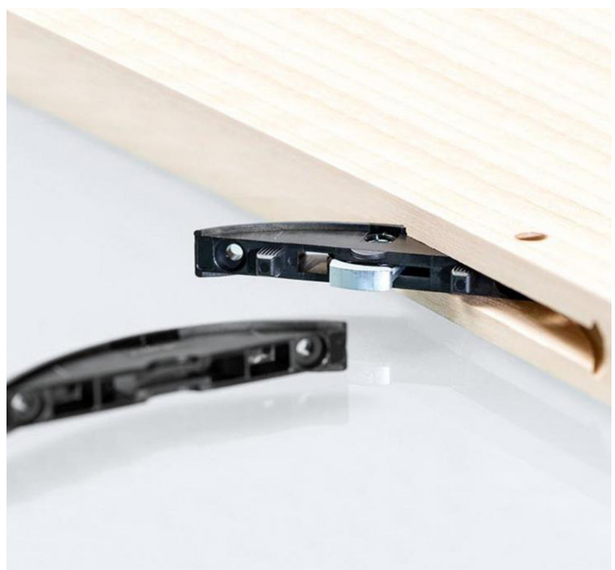
Figure 6.7 CNC-milled bolt/nut connection (raum.fr)

Smart connection
The last alternative is originating from furniture connecting systems. Examples like the lamelloP14 or Hettich's rastex are commonly used connections systems, to assemble several parts fast and easy. Another benefit of this solution is the possibility to be disassemble the joint just as fast as it is assembles. However, a building system or furniture does differ a lot. Mainly in the loads they have to bear. It also requires some complex processes to integrate these connection types into the component. In theory a good solution, but are they effective in a building system?

+ Disassembly
+ Fast
+ Easy
- Complex
- Strength??

Final choice: Smart connection / Bolt&Nut
Again a close call results of the evaluation chart. Both, the common bolt/nut, and the smart connections seem options with much potential. The mechanical way of connecting provides the opportunity for disassembly, and thus reusing the components. Both of the options have up and downsides. Smart connections could speed-up the assembly process, but it will definitely require more process time in the factory. With the bolt/nut-connection this is the other way around.

Looking to the possibilities at these criteria, the smart connection seems the most promising, however, there is a hazard. The structural capacities of this joint. Both of the connection types will be elaborated further to make a more reasoned decision.

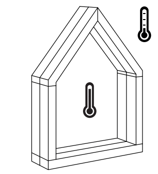


Criteria	weight				
- env. impact	1	3	1	1	1
- milling time	2	2	8	6	4
- nesting efficiency	3	3	9	9	3
- assembly complexity	1	1	3	3	2
- am. of elements	1	1	2	2	2
- amount of joints	2	2	6	4	6
- ergonomics	2	2	6	4	6
- adaptabilty	3	6	3	6	9
- disassembly ease	3	6	3	9	9
Score		26	39	44	42

Table 6.7 Final choices connecting type (own illustration)

Figure 6.8 Smart connections (top) CNC-milled lamello connection (lamello.nl) (bottom) Rastex connections (hettich.com)

THERMAL BEHAVIOUR:
There are 4 possible alternative solutions to secure the thermal behaviour of the particular components.



Isovlas
Isovlas is a common solution on vapour-open buildings. Isovlas is manufactured from flax, which is also used to make linen. The fibres are mixed with a binder for durability. This mixture is made into flexible batts. These batts are cut to the right size in order to fill the whole component. Disadvantage of this solution is that the cutting is pretty time consuming.

+ Flexible
+ Light
- Time consuming process

Natural plates
Second solutions are plates that made of natural cells. Instead of flexible batts, they arrive in plates that are pre-cut to the right size which saves quiet some time during assembly of the components. Downside off this insulator is that it is not very applicable as a 'filler' of a component. The materials is pretty slender but heavy. If the whole component needs to be filled, it is going to take a lot of material, which will result in a component that is too heavy.

+ Pre-cut to size
- No filler
- Heavy

Cellulose
The third insulation material, which allows vapour to be transported out of the building, is cellulose. It basically are left-over paper in tiny flakes. The flakes are blown into a cavity of the component to fill it up completely. Using the right amount of pressure will fill the entire component, even the smallest corners. This is a fast process, where one person can insulate a component in a few minutes.

+ Fast
+ Fills the whole component
+ Residual material (low environmental impact)
- No openings allowed

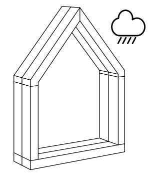
Final choice: Cellulose
Cellulose insulation is obtained by grinding residual paper in fleecy flakes. Often unsold newspapers are used a base material. The result is a durable, relatively inexpensive and well-insulating material. Cellulose is available in slabs bound with resin that is released during the production, but it is usually used in flakes. These are blown into "hollow" areas of the home, or cavities of building components. Because the blowing is done with high pressure, the material is placed precisely in the shape of the hollow space. This ensures that an extremely good air seal is formed. Which is very important for an insulator because stagnant air gives an optimal thermal insulation

Table 6.8 Final choices thermal comfort (own illustration)

Criteria	weight			
- envirnmental impact	1	1	1	3
- assembly complexity	1	1	2	2
- am. of elements	1	2	1	2
- weigth	2	3	1	3
Score		7	6	10

Figure 6.9 Applying cellulose insulation (isofloc.com)

WATER PROTECTION:



To make the vapour open building system work, a water protective, vapour open material is required to cover the components. The scheme presents 3 solutions.

Foil:
Water protective, vapour-open foil is commonly used in the current building industry. It is easy and effective, but with an innovative and modular building system problems will occur. PO-Lab's building system aims to be fast constructible, adding foil as a water protection does not satisfy to this requirement. Analysing the ECOnnect building, which used this method, concluded that assembling the whole building was faster than applying the foil. Besides the fact that it is rather slow, it also affects the adaptability of the building, because it is hardly possible to disassemble and re-use the material.

+ Effective
+ Easy
- Slow
- No adaptability

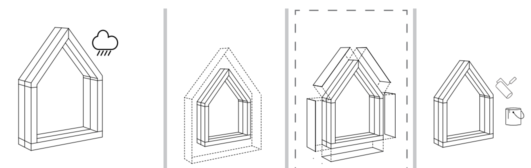
Protective plates:
Instead of protecting the building at once with a layer of water-resistant foil, the components itself could be water-resistant. One way to achieve that is by using a different outer material on the component, for example Pavatex or Celit. These plate materials can be cut to size with the CNC miller, and will be integrated into the component. This minimizes the assembly activities on the building site, because the assembling takes place in the factory. However, this alternative creates a hazard. The edge, separating the components, will require extra attention in order to prevent the water from penetrating through the water protective layer.

+ CNC producible
+ No extra activities on-site
+ Does not affect building system goals
- Vulnerable edges

Impregnating:
Pavatex is an option as a water-resistance plate, but the common OSB plates could also be impregnated with a water-repellent coating. In this way no different plate materials are required within one component. A large disadvantage to this procedure is the environmental impact of the coating. Most of the coating produce toxic waste, and when a component is abandoned, it still consist the toxic residual products, which makes is more almost impossible to give the components a sustainable end-of-life solution.

+ CNC producible
+ No different materials
+ No extra proceedings onsite
+ Does not affect building system goals
- Edges
- Bad environmental impact

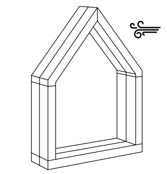
Final choice: Protective plates
The evaluation chart presents the protective plates as most promising. Celit allows water vapour to escape unhindered. Positive for a pleasant indoor climate. Constructions that use water protective plate material as the outside vapour barrier are free of condensation problems. Structures with vapour open wood fibre insulation boards, isofloc insulation and airtight interior finishing are completely free of condensation according to the German standard DIN 4108, T.3. The wood should not even be treated preventively against fungi or insects.



Criteria	weight			
- environmental impact	1	1	3	1
- milling time	2	6	4	4
- nesting efficiency	3	6	3	3
- am. of components	2	2	6	6
- ergonomics	2	4	6	6
- disassembly ease	3	3	9	9
- EoL activity	3	3	9	3
	Score	25	40	32

Table 6.9 Final choices
Water protection
(own illustration)

AIR TIGHTNESS



Airtightness is the third requirement make a vapour open building system. The scheme presents 3 solutions to seal the building system.

Rubber band:
A rubber band with adhesive tape can stick to the flanks of the components to create an airtight connection. With a tight assembly of the components, the compressed rubber will create a sealing. To place the rubber, no extra adjustments are required on the component. This is also a disadvantage, because the location of the rubber is not predefined. That can cause troubles during the assembly of the component.

+ No changes to the components
- Assembly becomes harder
- No re-use

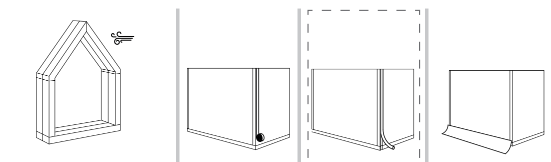
Rubber profile:
A solid rubber profile also creates an airtight sealing due to the compression between two components. Instead of attaching it with adhesive tape, this rubber is clamped in the component. This requires an extra milling path during the milling of the elements. However, this time can be recovered during the assembly process of the component. The milled path predefines the location of the rubber. This lowers the chance to make mistakes during the assembly.

+ Predefined location
+ Re-use rubber
- Extra process time

Adhesive strip:
The adhesive strip is a more common solution in the building industry to seal a building airtight. The building is completely assembled until the last component. Afterwards the building is completely sealed by covering all the edges with an adhesive strip. For the same reasons as the water protective foil as solution to the previous sub aspect, the adhesive strip causes problems with the assembling speed onsite. Besides the fact that it is rather slow, it also affects the adaptability of the building, because it is hardly possible to disassemble and re-use the material.

+ no extra difficult engineering
- Speed
- Ease
- No reuse
- No disassembly

Final choice: Rubber profile
Chosen is to use a rubber profile which is clamped in the sides of the components. The difference between rubber band with adhesive tape and the clamped rubber is not that big, but it mainly differs in End-of-Life solution. The rubber profile can easily be replaced when broken or reused in an other component. When sticking the rubber to the component this becomes more difficult, or impossible. Certainly with the fact that rubber is a material with high environmental impact, it's important to provide good End-of-Life solutions.



Criteria	weight			
- environment impact	1	1	1	1
- milling time	2	4	4	6
- nesting efficiency	3	6	6	9
- Am. of components	2	6	6	2
- ergonomics	2	4	4	2
- disassembly ease	3	6	6	3
- EoL activity	3	3	9	3
	Score	30	36	24

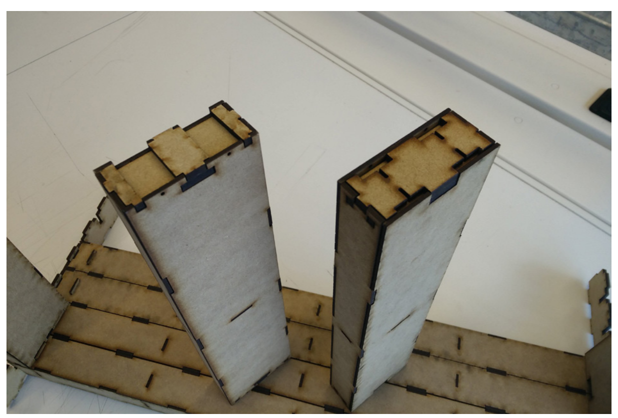
Table 6.10 Final choices
Airtightness
(own illustration)

6. 5 CONCEPT COMPARISON

Two design problems have multiple solutions as suitable alternatives, visualised in scheme 6.11. In order to find a clear concept proposal, these sub-aspects need further elaboration. Starting with the placing of the components, which is analysed by making small prototypes. Subsequently, the type of connection is further elaborated. In this case the structural behaviour of the different joint was leading in making a final decision.

Placing the components

One main conflict resulted from the evaluation chart on the sub-aspect of placing the components. The conflict between the removal of one element, versus building speed and ease. Is the removal of one module such a big necessity that all modules need to be adjusted, and probably not in a good way? Both sliding and lifting are worked out into a prototype to analyse and evaluate the pros and cons of both solutions.



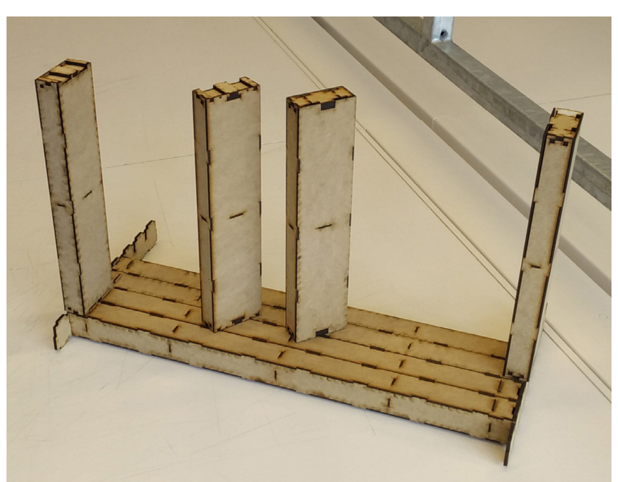


Figure 6.10 Two different solutions to the design problems. (Own illustration)

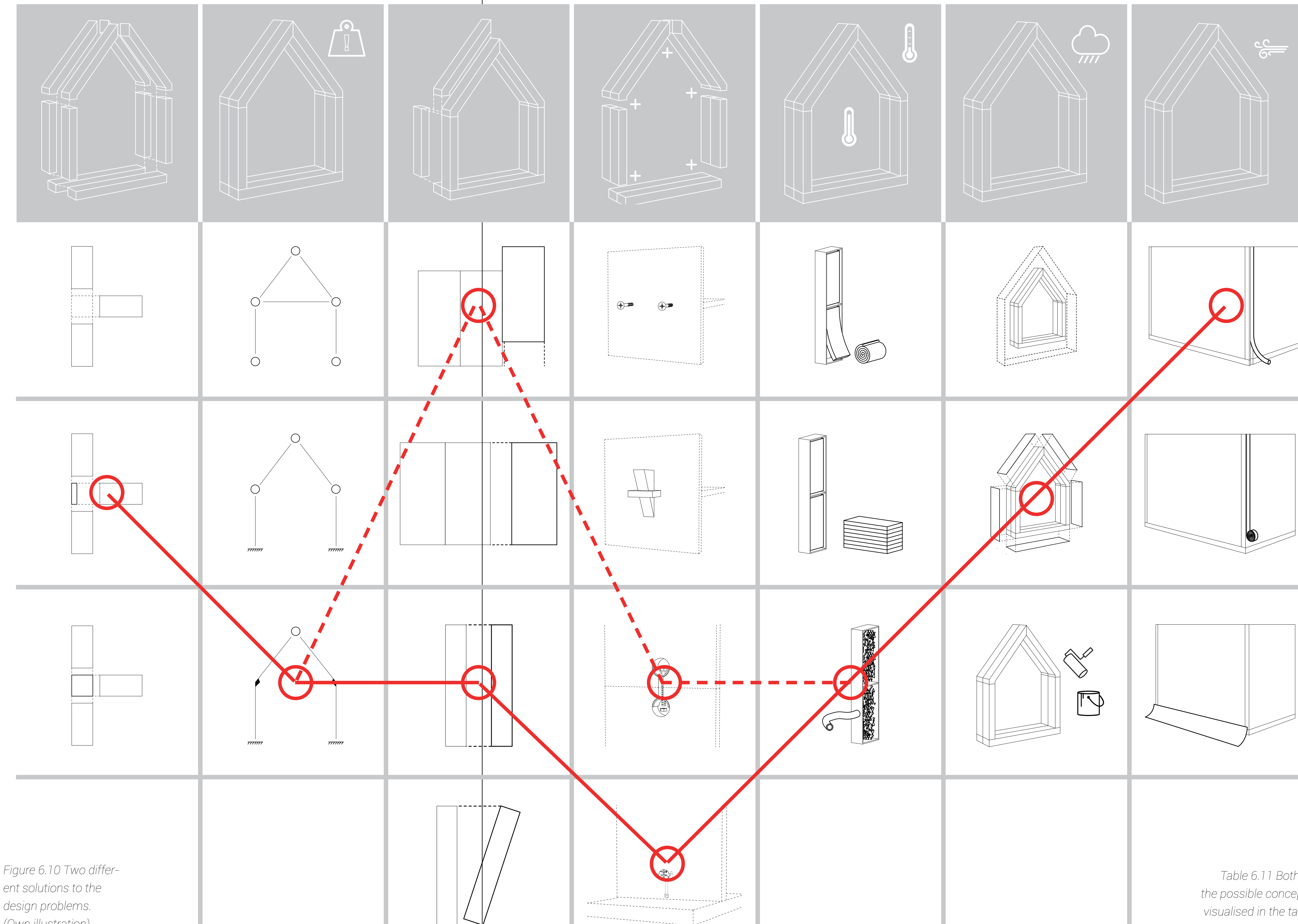


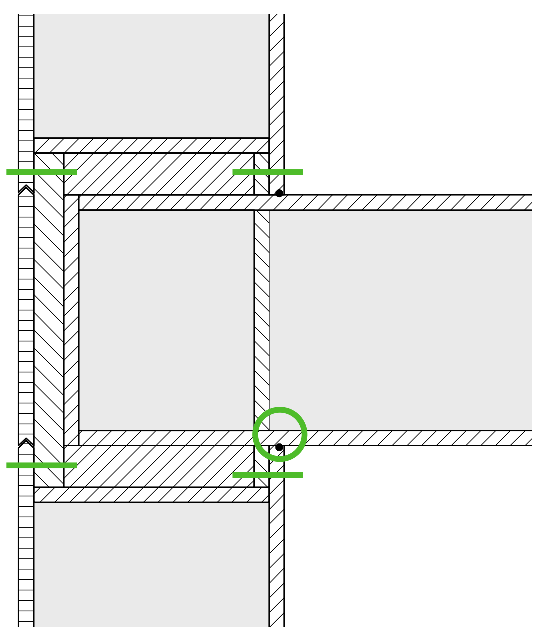
Table 6.11 Both of the possible concepts visualised in the table (own illustration)

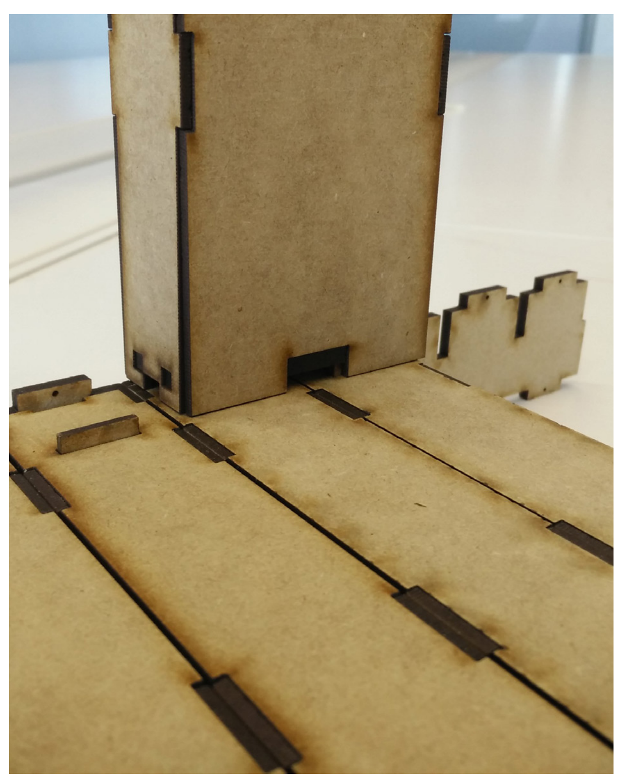
The outcome of the first sub-aspect, which resulted in a beam to combine all the components, provided a starting point to create the two designs of both alternatives. On this beam, roughly designed as showed in figure 6.3 (page 83), the components have to be placed. Starting from 2D sketches, a 3D Rhino model could be developed. This model made it possible to get an idea of the assembly ease and speed of the components. However, it is difficult to predict how the designs will behave when it is actually build. Therefore, a physical 1:10 scale model is made. With the use of digital prototyping technologies, in this case the laser cutter, a prototype could be produced directly out of the 3D model that already existed. This is one of the advantages of the production with digital manufacturing tools.

Lifting

The design that involves lifting is quiet straight forward. Two connections point, both on the beam and floor, stick out above the top level of the floor. Two openings are created at the top and bottom of the wall component to fit over these connection points. To place the component, it's lifted above the connection notches, and lowered to its correct place. There are no tolerances in the design due to the fact that the components perfectly fit upon each other. The component cannot be in the wrong position, which makes the assembly process fast and easy. One drawback can be mentioned, it is not possible to remove a single component

Figure 6.11
a) 2D-drawing of the lifting concept
b) 3D-drawing of the lifting concept
c) 1:10 prototype of the lifting concept
(Own illustration)





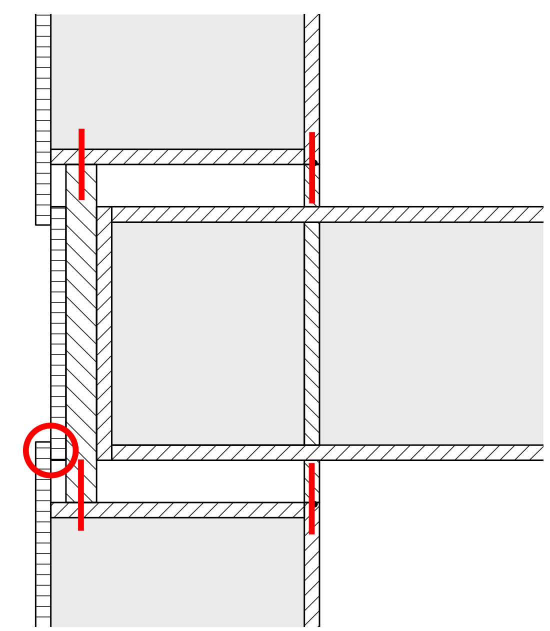
Sliding

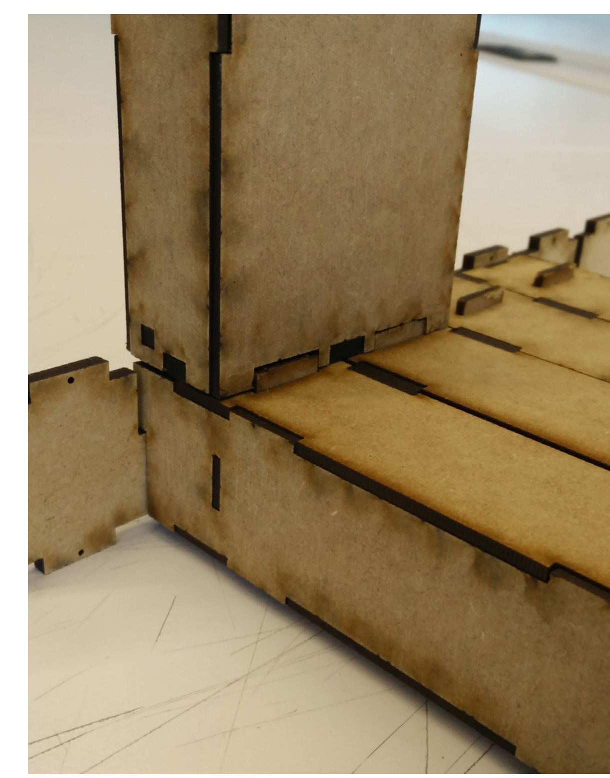
The problem of removing one element can be solved by sliding the component to its place. However, the prototype immediately shows the disadvantages of this solution. Compared to the previous solution, this design is more complex to assemble. It is harder to get the component in the right position, and the sliding does give some friction. This will only become worse in a full-scale design.

Even more problem occur when implementing the aspects of air and water tightness. From the analysed alternatives, the rubber seems as most promising the achieve airtightness in the building. However, by sliding the components complex edges occur, which are difficult to seal with a rubber profile. Thus in order to make the alternative of sliding the components into place work, another solution to achieve airtightness is required.

By comparing and analysing the alternatives, the lifting seems the most convenient for the final concept.

Figure 6.12
a) 2D-drawing of the sliding concept
b) 3D-drawing of the sliding concept
c) 1:10 prototype of the sliding concept
(Own illustration)





Structural analyses
To choose the eventual connection type, the structural capacities of the different alternatives need to be elaborated further. The smart connections are commonly used to construct furniture, where are much lower forces compared to building systems. Therefore this research tries to validate if the furniture connections are suitable as joints for a building system.

The configuration of PO-lab is used to specify the loads that the connection details have to bear. The building has a width of 4800mm, height of 6500mm and a sloped roof with 60 degrees angle. The PO-Lab structure is modelled in matrix frame to determine the forces that the construction, mainly transferred by the connection detail, has to bear. This result in moment forces of 3.1kNm and 4.6kNm. These numbers are used as boundary conditions for the connection details.

To translate the moment into an axial forces, it's converted into the tensile strength that the notches have to bear. This is done with the moment formula:

M = F * a

Tensile strength inside notch
M_{max} = 3.1 kNm
A = 300mm = 0.3m
F = M/a = 3.1 / 0.3 = 10.33 kN
Divided over 2 connections ->
10.33 / 2 = 5.17 kN per joint

Tensile strength outside notch
Mmax = 4.6 kNm
A = 300mm = 0.3m
F = M/a = 4.6 / 0.3 = 15.33 kN
Divided over 2 connections ->
15.33 / 2 = 7.67 kN per joint

Resulting from these rather elementary calculation, the maximal tensile strength on the joint is determined. The joint need to be able to transfer these loads, derived from the moment, into the notch. The maximal tensile strength that the joint need to transfer is 7.67kN. It has to do this without the failure of the joint or notch. The maximal compressive strength that the notch can have before is collapses is 335 N/mm^2. (Derived for CES Edupack)

With these values, it's possible to do an assumption on the structural capacities of the different joints. By multiplying the contact area of the joint to the OSB, with the maximum compression in the wood, the maximum transferable load can be determined.

$F = A * \sigma_{max}$

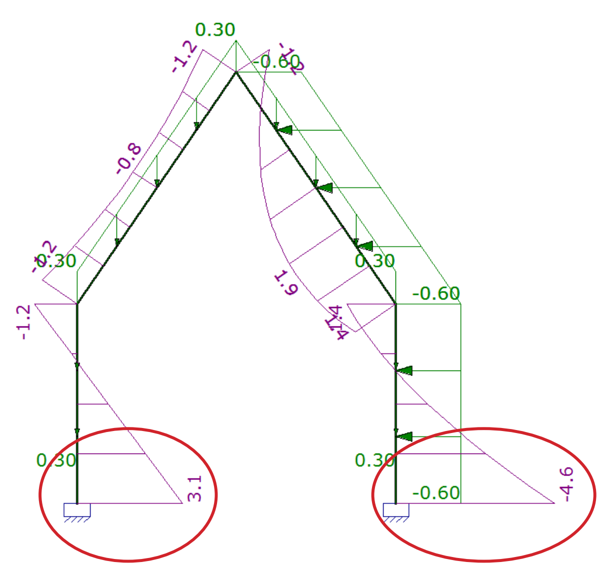
Lamello P14
Max. 130kg -> 1.3 kN (provided by the supplier)
dus 7.7 / 1.3 = 5.9 -> 6 connections
This will not fit on 15 cm notch

Figure 6.13 Resulting forces, derived from the Matrix frame model (Own illustration)

Section of PO-LAB, 4800mm width, 7000m heigth, 60 degrees sloped roof.

Windload: 1 kN/m^2
Horizontal forces from roof component: 50kg each

Max moment A: 3.1 kNm
Max. moment B: 4.6 kNm



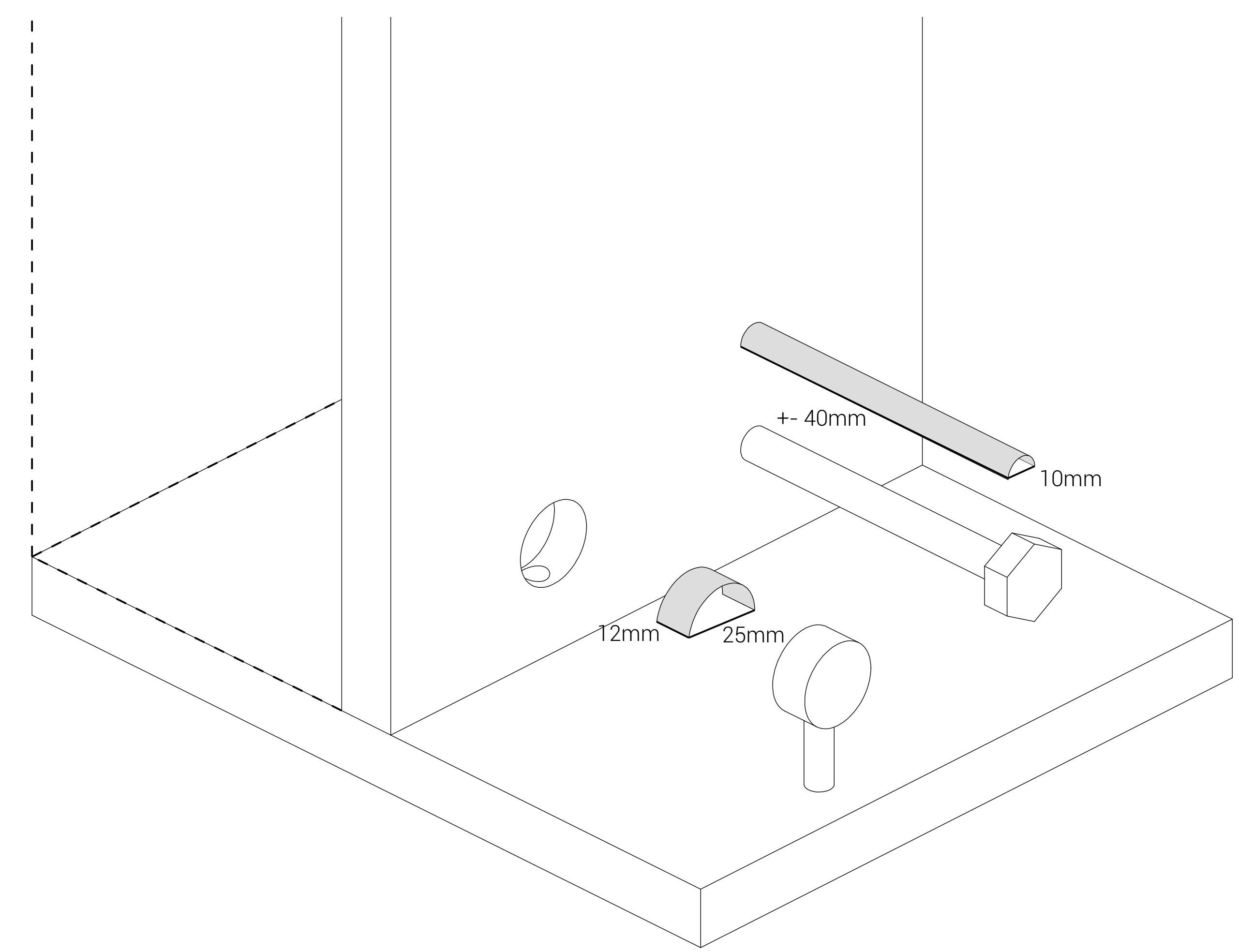
Rastex 25
Compression on OSB = area * Max stresss
Area = 427 mm2
427 * 3.5 = 1.5 kN
So, 7.7 / 1.5 = 5 -> 6 connections required
Also this will not fit

Bolt/nut
M10 bolt compression on OSB = area * Max stress
area = 628 mm2
628 * 3.5 = 2.2 kN
so 7.7 / 2.2 = 3.5 -> 4 connections required

The M10 could be a convenient solution. However, to improve the aspect of onsite building speed, less connections would create an improved building system. Instead of M10, the bolt could also be bigger or the length could be increased. For example, a 50mm notch would increase the contact area to 785mm2
785 *3.5 = 2.75 -> 2.8

The structural optimization of the boltnut connection will be research more into depth, with an elaborated structural analyses, furtheron in this thesis.

Figure 6.14 Contact area's of the Rastex and M10 bolt to the wood (Own illustration)



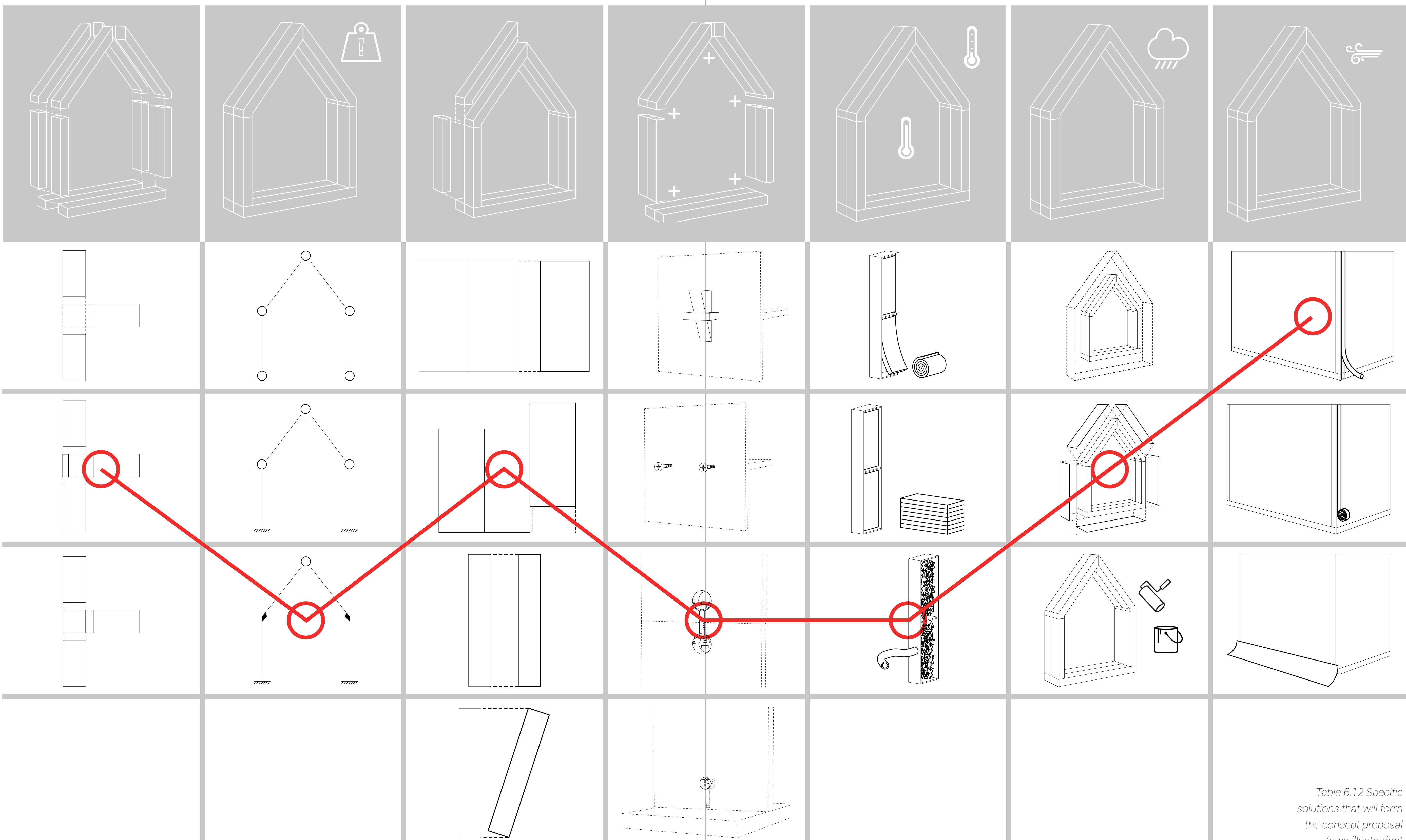
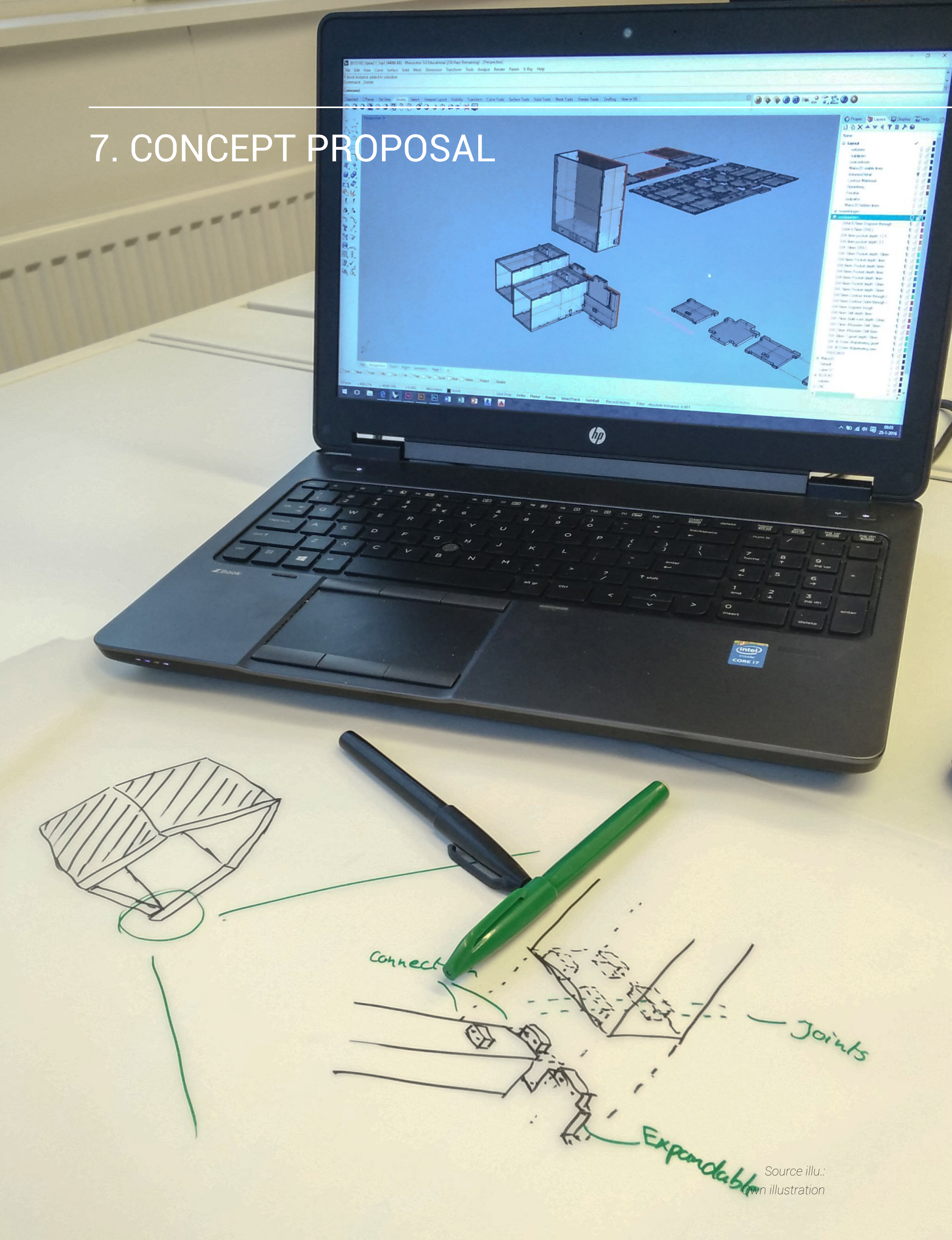


Table 6.12 Specific solutions that will form the concept proposal (own illustration)

7. CONCEPT PROPOSAL



Source illu.:
Own illustration

7.1 CONCEPT PROPOSAL

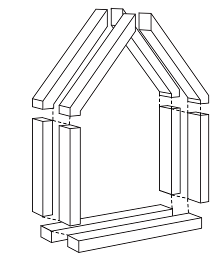
This chapter combines the most promising alternative solutions from the previous chapter to create a concept proposal. After evaluating, testing and making several iterations with the chosen sub-solutions, a concept is proposed . The following pages will explain and highlight how the solutions are integrated into one design, and how it will function.

Figure 7.1 2 Wall components, combined with 2 floor components by using a beam (Own illustration)

Figure 7.2 Exploded view of 2 Wall components, combined with 2 floor components by using a beam (Own illustration)

Combining components

As a result of the evaluation, the beam seemed the most suitable solution to combine the different components. By making inserts and protruding parts, in and on the beam, it is possible to slide and tilt the components towards the beam and combine them.



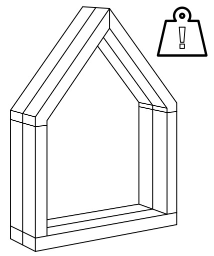
Vertical inserts make sure the floor will be placed on the right location. The inserts by itself are too small to transfer all the loads that the floor has to bear. Therefore with a bevelled layer is added to the beam. This layer makes is possible to transfer the loads over the full width of the floor component. Due to its weight, the floor will be secured in its place.

The wall component contains holes, where the protruding parts of the beam and floor fit exactly. By placing the wall over these elements, a solid combination of the floor, wall and beam is created.

Figure 7.3 Exploded view of the beam

Four layers of the beam:
a. Bevelled layer to transfer floor loads.
b. Layer to combine floor and wall
c. Layer to combine floor and wall, and close the openings
d. Water protective plate material

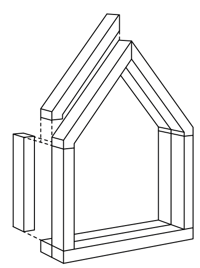
Structural behaviour



The aspect of structural behaviour is solved by making a fixed connection both at the top and the bottom. Therefore a truss section is capable of transferring horizontal loads to the foundation without the help of external solutions such as head façade or a stability core.

The notches of the beam and floor that are used to make a firm combination between the components provide the fixed/clamped connection. Depending on the depth of the wall component, a couple of forces can be created. Due to the design decision of making the modular building system, the depth is determined on 300mm. This will be the arm, to measure the axial force due to moment. The specific force on the protruding parts will be calculated and tested further on in this research.

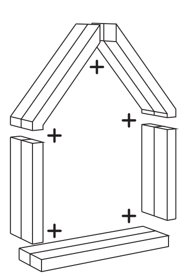
Component placement



Both the floor and wall components will be placed from above. Two protruding parts on the head of the floor component can slide in the vertical insert of the beam to fix its location. The bevelled parts which is attached to the beam, is also integrated on the floor component. These two bevelled parts will interlock to transfer the loads.

Wall components are lifted over the connecting elements on the floor and beam. The holes in the component have the exact same dimension as the notch from the beam and floor. Therefore the walls will be fixed in the right location. Due to this fixation, it is easy to assemble the components on-site.

Connection type



To join all components into a firm connection detail, a bolt and nut joint is used. The bolt penetrates the component and beam to unit all the different parts. The nut is integrated within the bottom and top of the wall components. The OSB being 18mm thick, requires three layers of wood to make the holes within the wall component, to fit the notches. This provides the opportunity to insert the nut in the component during the assembly in the factory. This asks for special measures by assembling the component, but eventually is will accelerate the on-site assembly process.

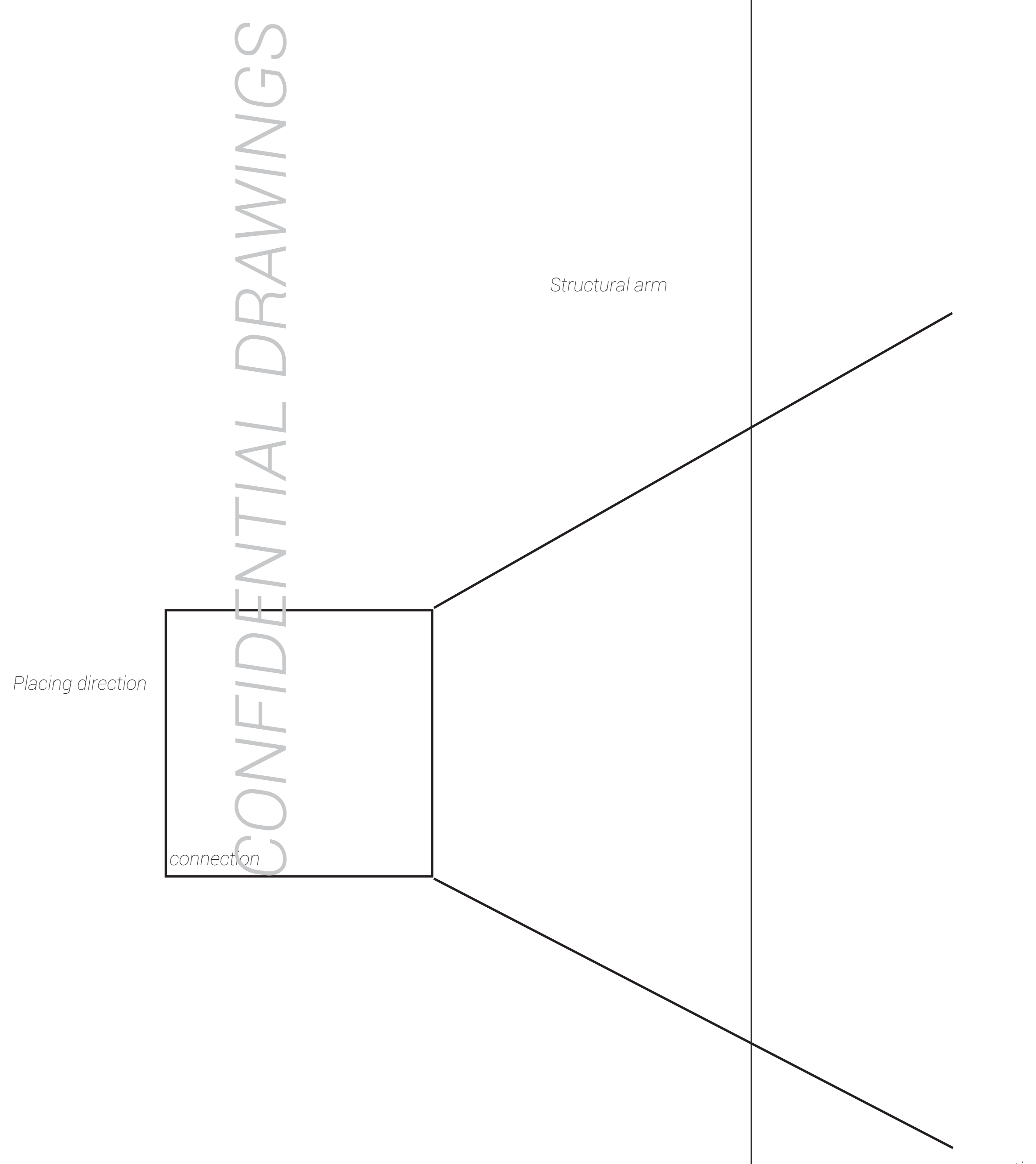
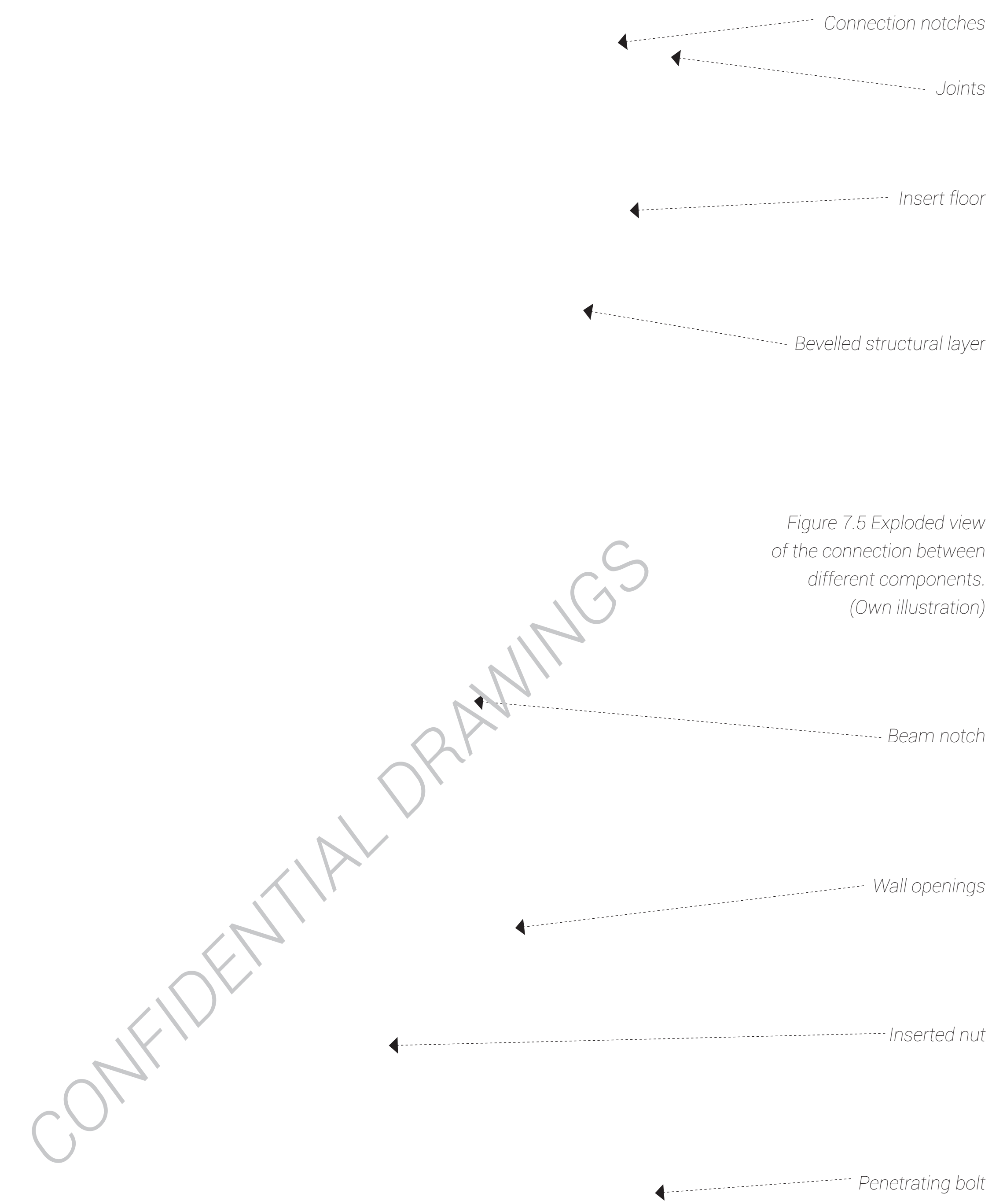


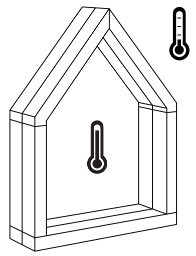
Figure 7.4 2D-view of the connection between different components. (Own illustration)

Figure 7.5 Exploded view of the connection between different components. (Own illustration)



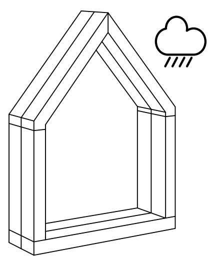
The dimensions, the type of nut and the amount of joints are still variable. This is dependent on the structural requirements on the connecting detail. This will be elaborated in the next chapter 'Prototyping &Testing'.

Thermal behaviour



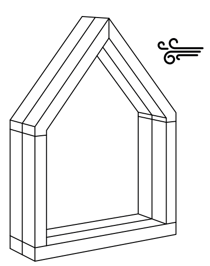
To ensure the thermal comfort of the building system, the components are injected with cellulose insulation flakes. The paper flakes are blown into the component to saves time in the assembly process. Downside of this method is that openings in the component are not. It needs to be completely closed, otherwise the injected flakes will escape the component.

Water protection



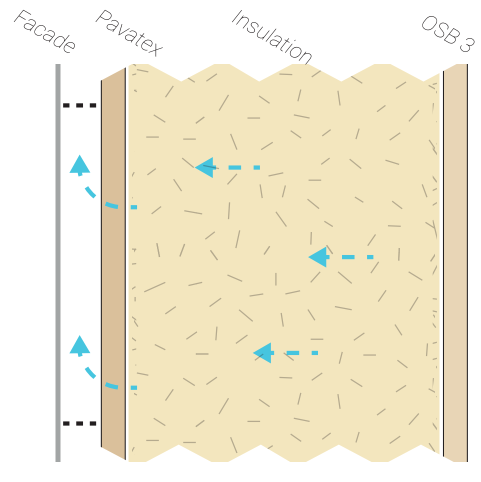
Water protective plate material is integrated within the components to guarantee that the structure will be protected against damage from moisture. The plate material is assembled on the outside of the component to keep the OSB from contact with water. Both the horizontal and vertical edges will require special profiles. This concept uses interlocking edges, milled on the sides of water protective plate material, to prevent the water from penetrating.

Airtightness



Last requirement to make the vapour-permeable building concept work is airtightment. Airtight sealing between the components are required to achieve this. This seal is made by compressed rubber profiles. The rubber profiles are integrated into the sides of the component by pressing them into to a prefabricated cavity. However, different types of rubber are possible to make the sealed connection. There are several option in shape, but also in the toughness or insert depth of the rubber. The next chapter will contain more elaborated research the find the most convenient rubber to secure the edges.

Figure 7.6 Vapour-open principle (Own illustration)



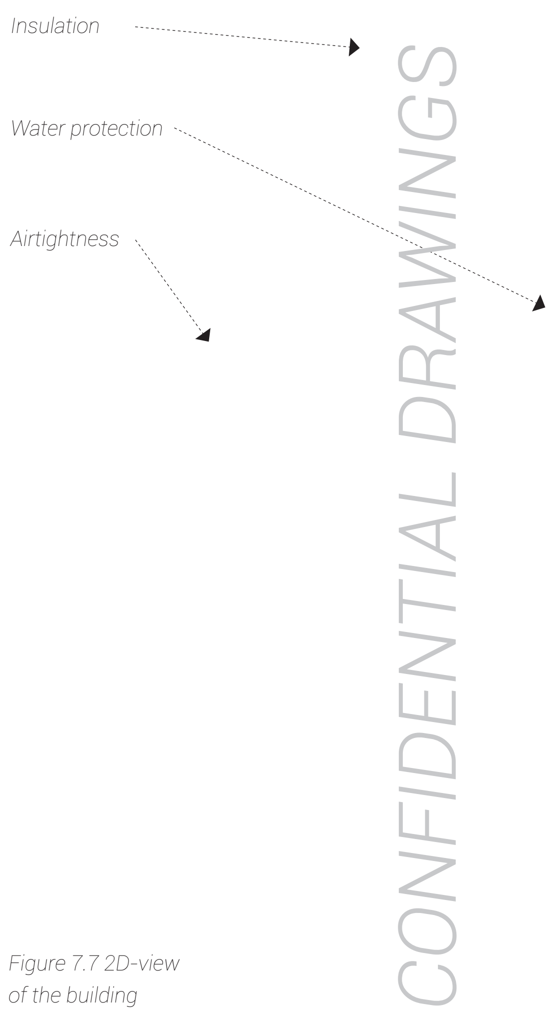
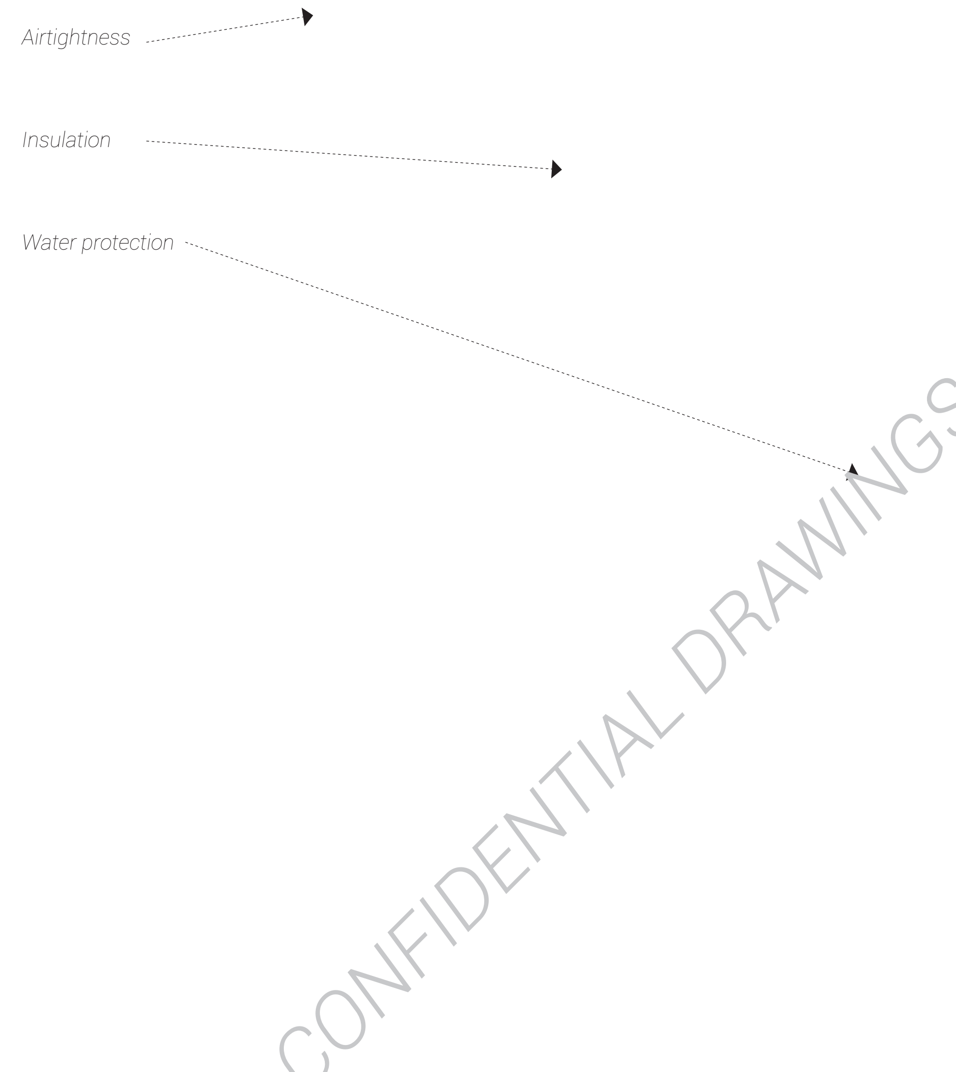


Figure 7.7 2D-view of the building physics of the connecting detail (Own illustration)

Figure 7.8 Exploded view of the building physics of the connecting detail (Own illustration)



REALISATION

INTRODUCTION

To make the conceptual design feasible for the actual building, it needs to be tested and prototyped. This happens in this of the research. The overall design is prototyped to see if it works like it is supposed to do. The next chapters elaborate the concept proposal in a more detailed design. Several iterations are worked out in prototypes to analyse and test the conceptual ideas. Based on these results the design could be further optimized to create a more feasible building product. Important aspects that needed to be tested are:

- The accuracy of the elements and components
- The building physics of the detail
- The structural behaviour of the connection detail

The advantage of digital manufacturing became visible within this chapters. The digital 3D model, used to make the concept proposal, could be translated into digital data for the CNC miller rather easy. The problems that were noticed by analysing the prototypes could immediately be modified in the 3D model, which again provided the data for the next prototype.

After testing and evaluating the concept can evolve into a final design. This final design is the elaboration of the connecting detail, and an integration of the connection in the building system to see how it functions.

8.PROTOTYPING & TESTING

Source illu.:
Own illustration

8.1 PROTOTYPING & TESTING

A large advantage of CNC fabricating is the low tolerance of the produced elements. This can be very useful in improving the assembly ease of the components, but also in improving the assembly ease of the components into a building, on-site. To remain the high accuracy of the CNC fabricated products, the assembly of the different elements into a component should avoid activities that bring down the low tolerance. The accuracy of the assembly process will be analysed in the prototypes.

To enhance the vapour-open concept, airtightness is an important aspect. To ensure the insulating capacities of the components, it need to prevent air from passing through. This required the components to be airtight. Beside the single component, the connection between them also need to be airtight to prevent air leakages. This sealed connection is tested with different design solutions and rubbers

The third aspect is the overall structural behaviour of the connecting detail. In order to prevent the building from collapsing, the structural capacity of the connection is an important aspect. During the concept development decisions are made to improve the freedom of design, however these have consequences to the structural behaviour of the connection. They need to be able to bear the stresses that are resulting from the moment force, without using external stabilizing solutions. To achieve this, and to optimize the connection to the loads resulting from moments. The type of bolt, and the dimensions of the connecting elements can be optimized to the results of a bending tests.

8.2 PROTOTYPE 1

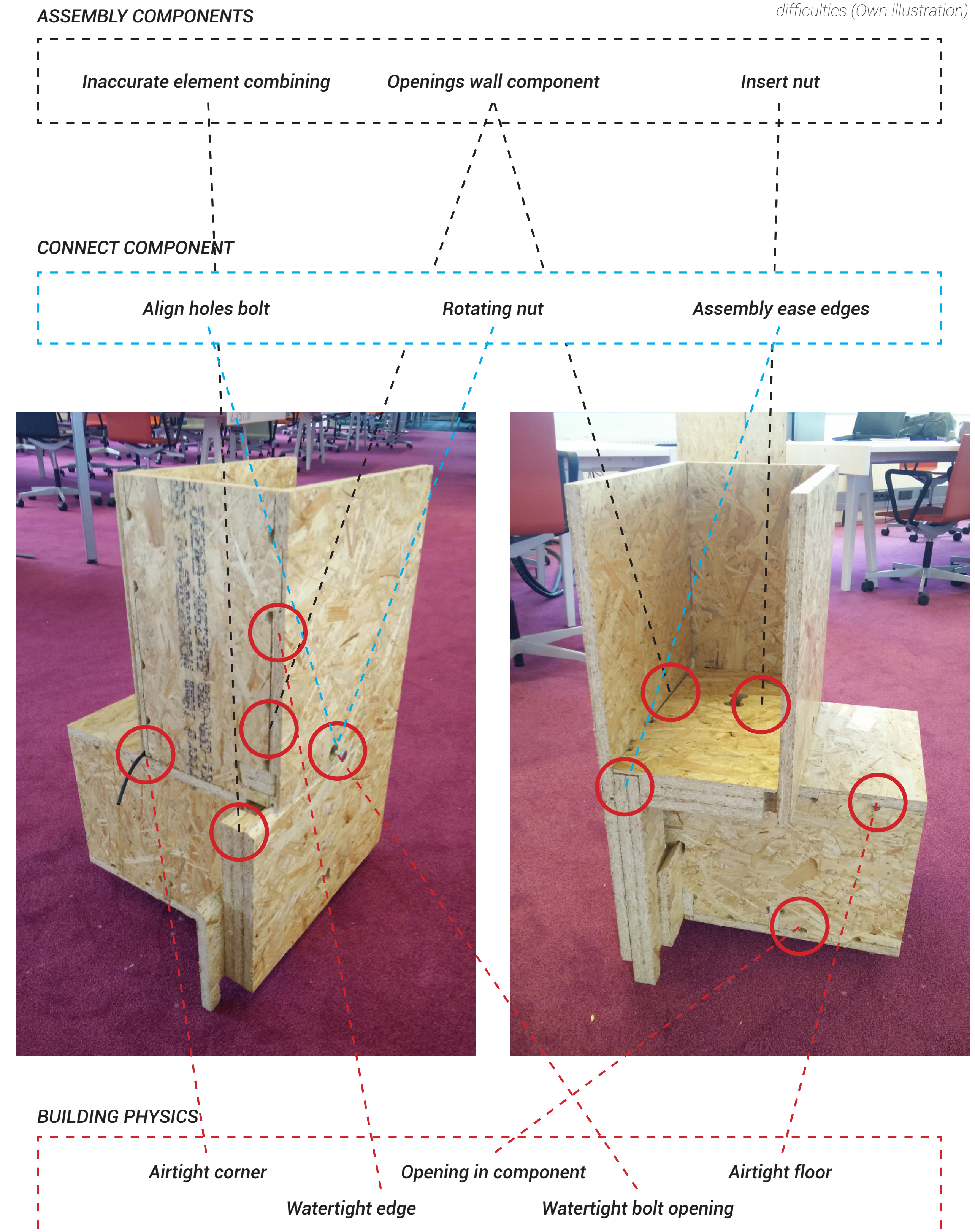
This first prototype is a section of the concept proposal. It contains one short floor component, a half beam and a section of a wall component. However, this prototype contains all the designed solutions, which makes it good enough to do the first analyses. The analyses is divided in three parts; assembly of the component, connection of the components and the thermal behaviour.

Figure 8.1 Digital drawing as input for the CNC-miller to create prototype1 (Own illustration)

CONFIDENTIAL DRAWINGS

Figure 8.2 Some detail of prototype1 (Own illustration)

Figure 8.3 Prototype1 with appointed difficulties (Own illustration)

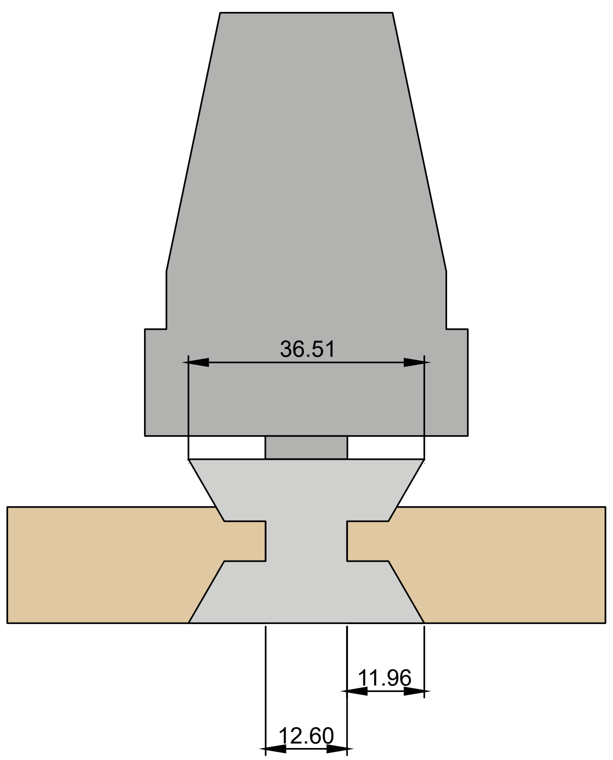


DIGITAL MODEL

The first problems occurred with translating the digital model to CNC data. The dimension of the components and elements are optimized to the limited dimensions of the CNC miller and the wood plates. The components are a multiplication of 300 to ideally fit the limitation of 1220mm width. However, some drill bits for special profiles require more space than normal 16mm drill bits.

For example, the drill to make the water protective edges. It has a total diameter of 36,5 mm, with only 12mm cutting into the wood. This means that 34mm extra space next to the element is required for the drilling bit. So to fit two 600mm plates in one wood panel of 1220mm, the milling path need to be located on the edge of the plate, or one path needs to mill two edges at the same time. Otherwise it is not possible to fit the two components on one plate.

Figure 8.4 Drill bit for interlocking edges, to optimize nesting, its dimensions need to be considered carefully (Own illustration)



ASSEMBLY COMPONENTS

Assembling the beam and the components showed some difficulties due to the accuracy. The beam consists of 4 layers OSB which need to be assembled completely straight upon each other. However, this seemed rather difficult. When screwing the layers together they slightly moved, which resulted in inaccuracies. Along with the inaccuracies, small gaps occurred between the different layers.

Figure 8.5 Inaccuracies between the different layers of the beam (Own illustration)

The same problem occurred with assembling the wall component. The bottom part also consists of a multi-layer element that has difficulties to its accuracies. Tolerance problems in the entire component occur due to this inaccurate element.

To fix this, the next prototype should contain predefined placed to connect the different layers in fixed places and secure them more tight.

The last difficulty with assembling the component was the insertion ot the nut in the bottom part of the wall component. Due to personal mistakes in the drawings the nut can move in a vertical direction. This makes it difficult to bring the bolt toward the nut. The next prototype contains improved drawings to solve this.

Figure 8.6 Solution to remove inaccuracies of the different layers. (Own Illustration)

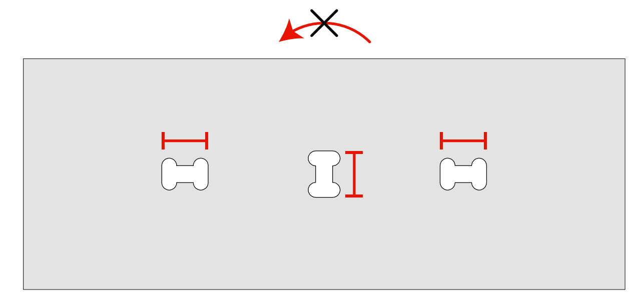


Figure 8.7 Inaccuracies resulting in gap between the different elements (Own Illustration)

Figure 8.8 Inaccuracies of the inserted nut at the bottom and top of the floor (Own illustration)

CONNECT COMPONENTS

Chamfers

To combine the components, several elements need slide and fit over each other. The connecting notches, sticking out of the floor and protruding from the beam, need to fill the holes in the wall component. This connection is designed with the 0,3mm tolerance of OSB. However, to inaccuracies in the assembly the tolerance need to be bigger. The place where 2 or more components meet should contain a bevelled edge to enlarge the assembly tolerance locally. This makes the assembly process on-site more efficient.

Figure 8.9 Chamfers are required to improve the assembly ease around tight openings (Own illustration)

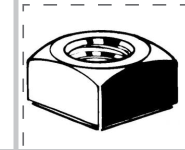
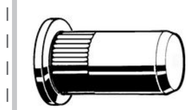
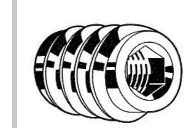
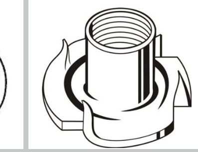
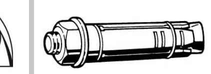
Rotating nut

Another problem arose when the components were connected by the bold and nut connection. Due to the mistakes in the drawings, the nut was hard to reach with the bolt. But eventually it succeeded. However, with rotating the bolt into the nut another problem occurred. The nut rotated within the component. Just an ordinary, hexagonal nut was used, and clearly this was not the right shape to keep it in place. Therefore, the second prototype should contain a more advanced fitting for the bolt.

Several different options are capable as fitting for the bolt. Five of them are analysed, on different of the upfront specified criteria, to find a suitable solution to replace the hexagonal shaped nut. The square nut, rivet nut, insert nut, tee nut or expansion anchor are examined to the process time, milling time required to insert the solution; the ease of assembling it into the component; the life span in comparison to the comparison to the components life span; the reusability, and cost. This is presented in table 8.1

The square nut shows the must potential, mainly due to its low price (only 20 cent), because cost is an important criteria. Other solutions score better in terms of reuse, because the can be removed out of the component when this is abandoned. For example the insert nut which is 75 cent. But the energy and time required to do this are out-weight by the low costs. Also the milling time for the square nut is relative low because it can be drilled from the top, with a basic drilling bit. The insert nut, for example, needs a hole drilled from the side, which is difficult with the CNC machine. The tee nut is also cheap with only 40 cent, however, it needs to be milled from the top and side in order to fit in the component. Altogether the square nut is the most promising.

Table 8.1 Comparison of different bolt fittings

Criteria	weight					
- milling time	2	6	2	4	2	4
- assembly complexity	1	2	3	3	3	3
- life span	2	6	6	6	6	6
- EoL	3	3	3	6	6	3
- costs	3	12	6	6	9	3
Score		29	20	25	26	19

THERMAL BEHAVIOUR

Airtight component

Most difficulties of the first prototype occur in the air and water tightness of the detail. Starting with the airtightness of the single components. There are 2 reasons that result in openings in the component. Due to consequences of the CNC production process, openings exist in places where sharp corners need to be milled. To close these gaps, a tiny drill bit could be used to make sharp corners, or a special detail need to be engineered in order to compensate the rounded corners.

This means a conflict between **engineering and `milling time.** The 5MM drill is 40 times slower than the standard drill bit. So very component will take much longer to produce. The engineering of the more advanced detail will only take one extra a day of detailing once. Thus the more detailed insert is the most convenient solution when considering the long term.

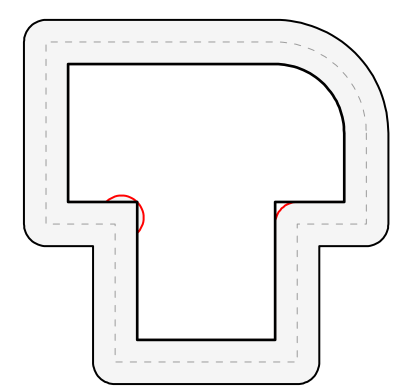


Figure 8.10 More process time required to close the rounded openings (Own illustration)

Figure 8.11Less assembly ease to close the openings (Own illustration)

The other openings are caused by the chamfers that make it easier to insert the elements in each other. To get rid of these gaps, the chamfers need to be erased, which will result in a more difficult component assembly process. Another solution to close this gap is to use the engraving path of the CNC miller to create a slope that fits the chamfer.

This means a contradiction between assembly ease vs process time. Regarding the weight of the different criteria, assembly ease is considered more important. By erasing the chamfer, the assembly ease reduces slightly. However, the extra engravings require much more process time because every wall component contains this detail minimal 10 times. So by multiplying the weight, with the impact on the criteria, removing the chamfer is the most convenient solution.

Airtight assembly

The airtight assembly between the components is achieved by using rubbers as a sealing. However, at two points, this is not (well) integrated yet. First, the corner of the wall component, where the rubber is pulled around the corner but is not capable of making a sharp edge. A rubber in a 90 degrees angle is required. This will make them more expensive, because they have to be custom made. But, due to the mass produced components, all the rubbers are the same, which makes it feasible, according to costs, to use customized products.

The other problem occurs around the sealing between 2 floor components. In prototype 1, no measures are integrated to make it airtight. But a solution is certainly required. Two options are elaborated, visualised in Figure 8.12. Solution 1 makes use of the weight of the floor. The components weight causes pressure on the rubber. Due to the uniform pressure along the entire floor component, a sealed edge is created. A disadvantage to this solution is that the floors are overlapping. In terms of disassembly this causes problems. To remove the bottom floor component, the one above always has to be removed. Like laminate flooring, there has to be a specific start and end. This can cause difficulties when adjustments to the structure are required.

The second solution uses the technique that is also used as sealing between the wall components. A rubber profile will be integrated into the edge of the component, and will create a sealing by the pressure in-between the components. However, this means that the floor component needs to slide along the rubber to fit into place. This can cause difficulties when assembling to building, or the rubbers can be damaged.

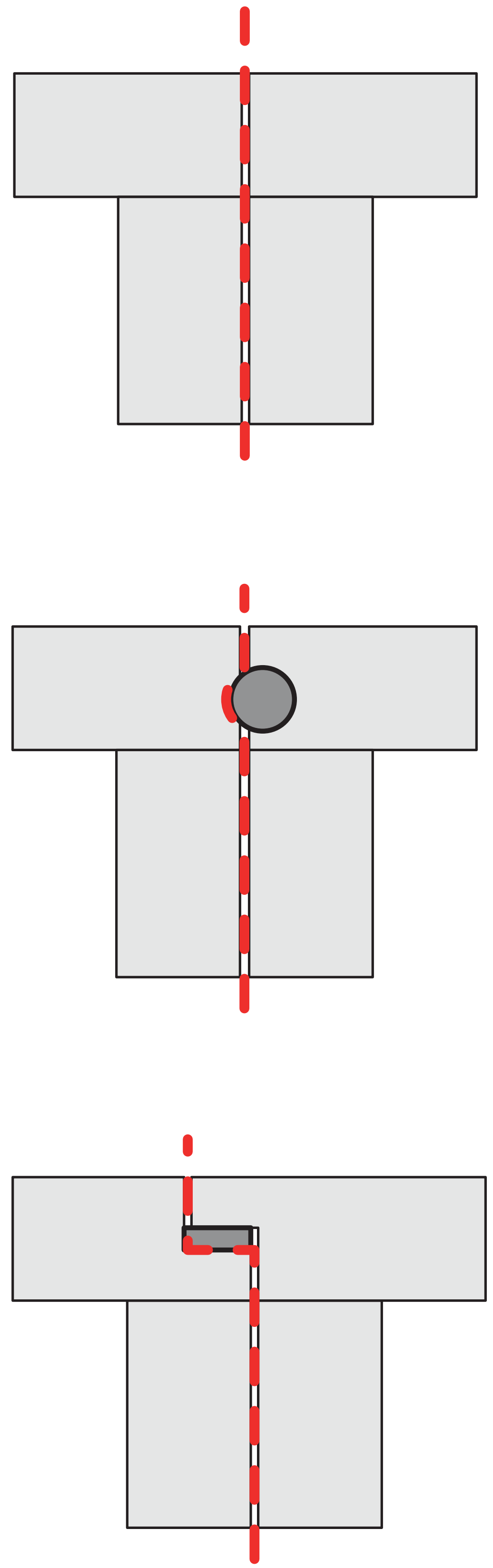
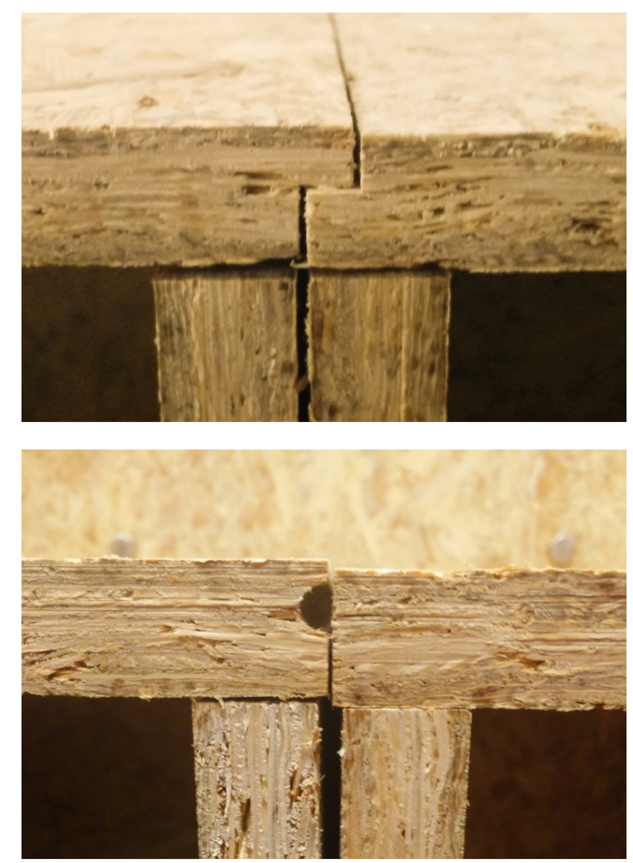


Figure 8.12 Different airtightness solutions between the floor components (Own illustration)

The best solution will be a consideration between **adaptability of the building system versus the building ease(ergonomics) and lifespan**. Option 1 is easier to assemble, but gives limitations to the building adaptability of the building system. Option 2 provides a more adaptable building system, but the protruding edge of the rubber can cause problems. Considering the criteria and their weight, option 1 is the most convenient due to the high importance of adaptability. However, the toughness of the rubber and its insert depth are crucial on its applicability. Therefore these aspects will be elaborated more in detail further on in this research.

Figure 8.13 Different airtightness solutions between the floor components in prototype (Own illustration)

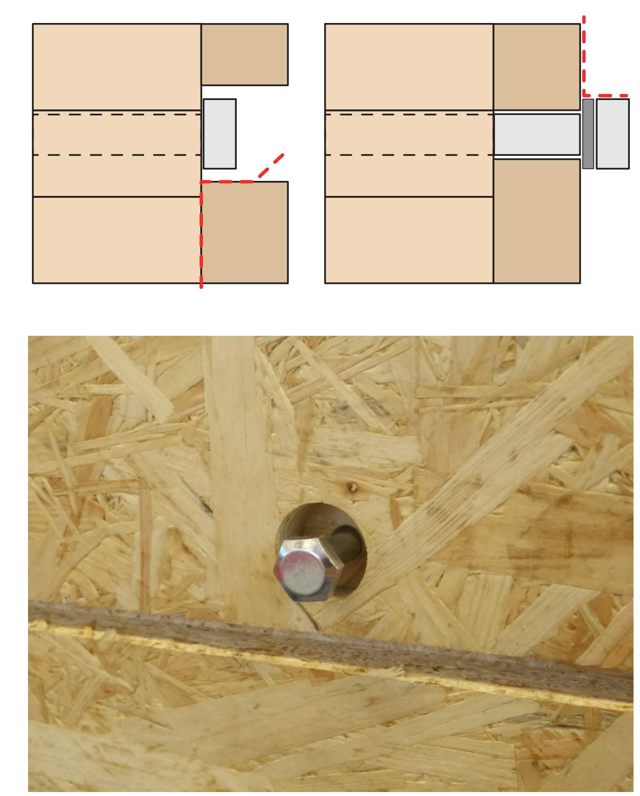


Watertight

Two problems occurred by making the detail watertight with the integrated water resistant plate material. First the vertical edge between two wall components. But this solution is rather easy, the profiled shape used at the bottom of the component, can also be used at the sides. However, the **assembly ease** of the components on-site need to be considered and should be analysed with the next prototype. An alternative solution is a water protective tape to seal the edge, however this lowers the **assembly speed and possibility to adapt** the design.

The penetration of the bold through the water protective plate material is also a potential leak. The head of the bolt is completely perforating the plate material, which makes is possible for water to reach into the component. This can be solved easily by reducing the hole, and covering it with a rubber ring.

Figure 8.14 Penetration of the bolt solved with a rubber ring(Own illustration)



8.3 PROTOTYPE 2

This second iteration consists of 2 floor components, 800mm beam and wall component. This prototypes solves most of the difficulties and questions from the previous version. However, also new problems occur, mainly with the assembly ease of the components, and by placing and removing of the components.

Figure 8.15 Digital drawing as input for the CNC-miller to create prototype2 (Own illustration)

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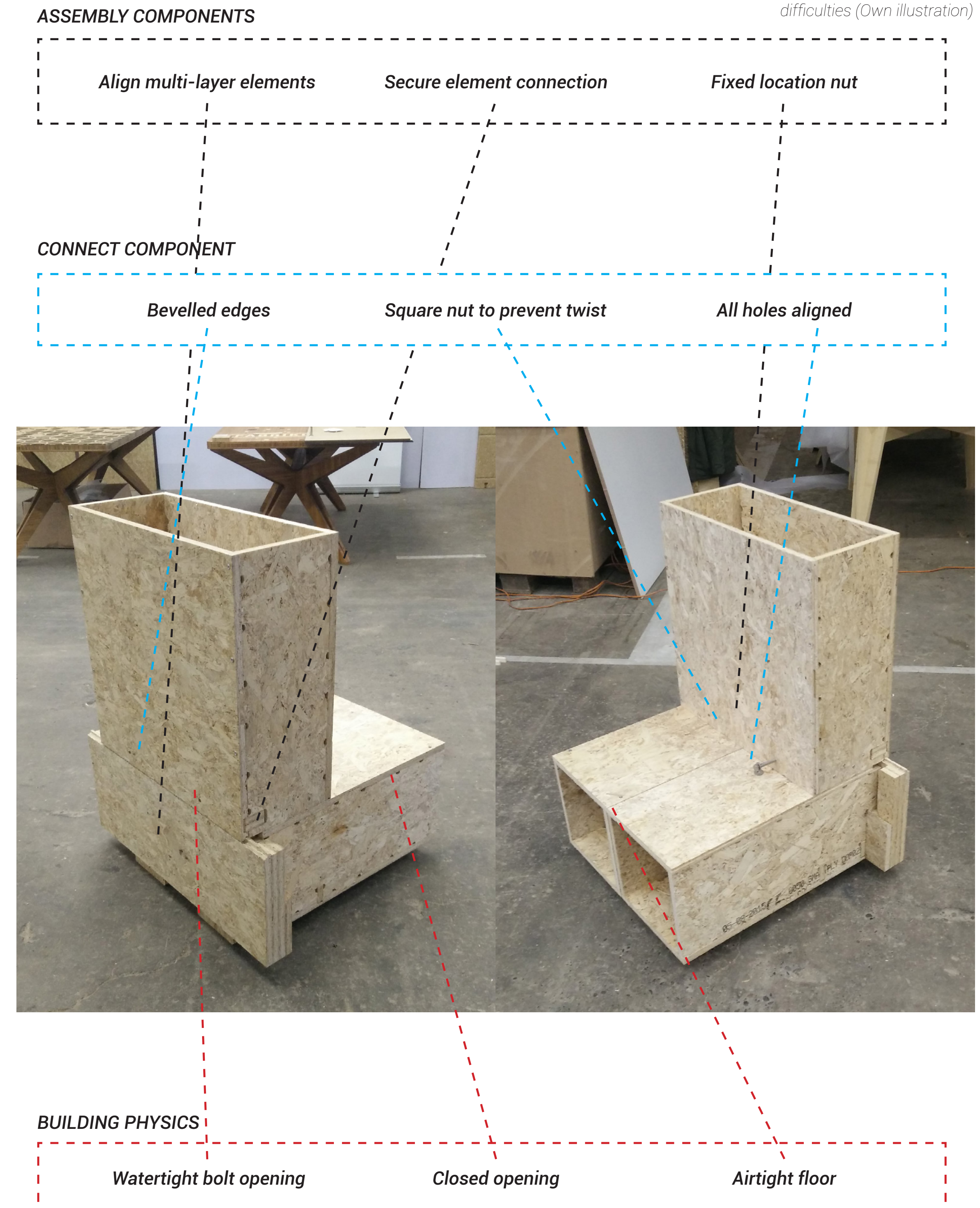
Figure 8.16 Prototype2 with appointed difficulties (Own illustration)



SOLVED PROBLEMS

Assembly components

The multi-layered elements are aligned with the help of inserts that fix the parts in two directions. This results into very tight assemblies of the single components

By getting rid of the inaccuracies the insert of the squared nut within the bottom of the wall component also becomes much easier and more accurate.

Connect the component

The edges of holes, where the notches can insert, are bevelled with a 45 degrees chamfer to simplify the assembly of the wall component with the beam and floors.

Due to the squared nut, and the correct alignment of the different components by the accurate elements, it is easy to fix the bolt through all the different parts. This result in a firmly connected second prototype.

Figure 8.17 a) Multi-layered parts accurately connected to create low-tolerance prototype, b) inserted square nuts that do not move in place and c) beveled edges to improve building ease (Own illustration)

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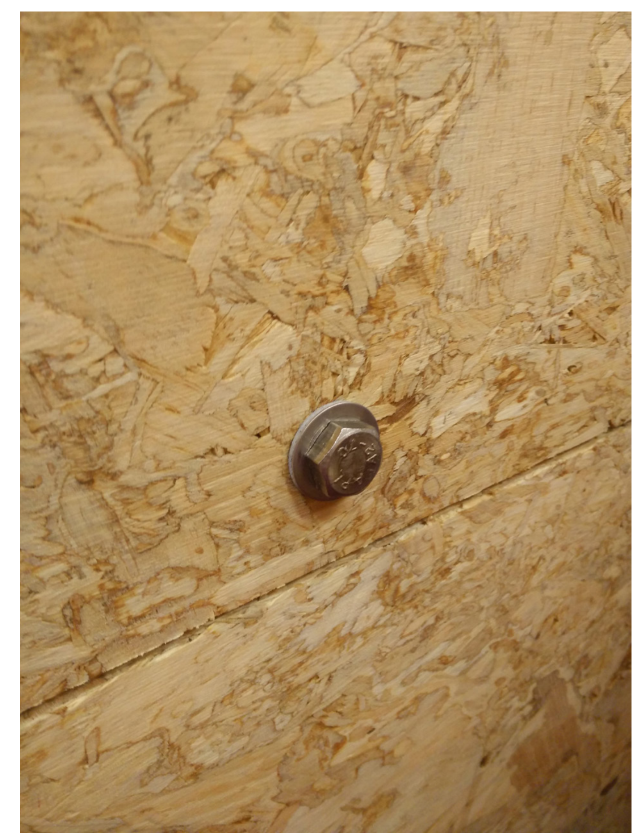
Thermal behaviour

The single components are completely closed by engineering a more complicated detail at the point where two elements insert in each other. Figure 8.18(b) show this detail. Due to an engrave path on the edge of the opening and a rounded edge of the insert. The two parts fit identically.

Also the airtightness between the floors is solved by inserting a rubber profile. However, what kind of rubber need for this occasion will be elaborated further on in this research.

The water-tightness issue around the penetrating bolt is solved by decreasing the diameter of the holes and by covering the holes with a metal ring that contains a layer of EPDM rubber. When tightly fixing the joint, the rubber will be pressed towards the hole by the metal ring. If enough pressure is applied the rubber will create a water tight seal.

Figure 8.18 a) Watertight around the joint, b) airtight element connections and c) connection between 2 floor components (Own illustration)



PROBLEMS TO SOLVE

Adaptable beam

By creating openings and inserts in the multi-layered beam it succeeded to align and firmly connect them together. But to enlarge the adaptable behaviour of the building system, is important to be able to in- or decrease the length of the beam. The beam consisting of several layer is helpful to find a solution to make this possible. By cross laminating the different layers with demountable connections, in theory, it should be possible to adjust the length of the beam on-site. This is will however make the assembly on-site more difficult. A conflict between assembly ease and adaptability occurs. It indeed does reduce the assembly ease, however, if the length of the beam is not adjustable, the entire building needs to be disassembled and a new beam needs to be produced to adapt the building to changing demands. When that adjusting of the length can be done on-site only a few components need to be removed, depending on the adjustment that needs to be done. Due to choosing the floor air sealing showed in prototype 2, and by making a adaptable beam, it becomes possible to enlarge or reduce the length of the entire building on both sides.

Important aspect to consider when developing this beam are: the structural connection between the parts, and the demountability. The layers are stacked together and then firmly fixed. However, in the other direction the connection is more important because the connection has to distribute loads to the next part. Besides combining the several components, the beam has an important job in carrying loads above components that contain openings. The beam may bend of deform by the load of the components above. This asks for a fixed connection method that creates a couple of forces. The larger the distance between the couple, the smaller the connection can be.

Important to the connection between the layers, is the ability do demount it rather easy. This means that adhesives need to be avoided. Mechanical joint that would be sufficient are bolts or screws. The amount and size of these joint can be further explored in a possible future research.

Figure 8.19 Beam that is adaptable in length (Own illustration)

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Carry, Place & Remove component

The components used in the prototypes are parts of the eventual components, but still it is rather difficult to carry, place and remove them. It is difficult to get grip on the smooth plates, and it the components are full size and weight this problem will even enlarge. Therefore, a solution for this problem need to be found

One of the solutions is to use the holes that are already available in the component to prevent the production process to take longer. The holes that are always available during assembly are the openings for the bolts. These are only 10mm wide, which is too little for a finger to get grip, but are always at the exact same location. Therefore a handle is designed that fits these holes, which provide a good grip on the component.

Thickness inner flange

The inner flange of the second prototype is still rather slender. From the digital matrix frame model is derived that the difference in loads between the two flanges has a ratio of 2 to 3. So the inner flange need to be 2/3 of the outer flange thickness. In prototype 2 it is only 1/2. 2/3 is not possible due to the fixed thickness of the OSB plater material. There for the thickness needs to be doubled.

Figure 8.21 a) Trouble getting grip on the wall components and b) floor components can be lifted with the bolts (Own illustration)

Figure 8.20 Notch in floor need to be doubled (Own illustration)

8.4 STRUCTURAL TEST

One last test is required to define the final design, the structural capacity of the connection detail. A simple structural analyses is already made to select the most suitable connection type. But to verify the viability of the connection detail, a more elaborated analyses is required. This will be done by testing the detail in the tensile testing machine.

To improve the functionality of the eventual building system, a connection detail is required that provides stability within the plane of the section. A section of the building is be examined on horizontal loads that result from wind and roof. In order to bear these loads and create a stable structure, the connection needs to be able to transfer moment forces towards the foundation. By analysing the section of the building in matrix frame (page 94) the moment forces are obtained. Due to the horizontal loads, moment in two directions occur on both of the bottom connections.

In order to obtain structural stability, the moment forces need to be transformed into an axial load. By clever design decisions, the connection contains a couple that is able to do this. Two notches, 300mm apart from each other, can convert the moment into tension and compression.

The largest moment, on the side of the wind load, will create compression in the inside and tension on the outside of the structure. The tension is transferred by the outer notch into the large beam. The beam is connected to the foundation, and the floor component by the bevelled layer. The compression is bared by the floor elements. This is visualised in figure B.

On the other side of the structure the direction of the moment is reversed. This means the compression and tension work the other way around. The inside notch need to bear tensile strength, and the outer notch compression. From these notches loads are transferred to the floor components. Figure A visualises this load case.

Inside notch
M_{max} = 3.1 kNm
A = 300mm = 0.3m
F = M/a = 3.1 / 0.3 = 10.33 kN
Divided over 2 notches ->
10.33 / 2 = 5.17 kN per notch

Divided over 2 connections ->
5.17 / 2 = 2.59 kN per joint

A

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B

Outside notch
Mmax = 4.6 kNm
A = 300mm = 0.3m
F = M/a = 4.6 / 0.3 = 15.33 kN
Divided over 2 notches ->
15.33 / 2 = 7.67 kN per notch

Divided over 2 connections ->
7.67 / 2 = 3.84 kN per joint

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Test1 'What joint?'

From the theoretical structural analyses the crucial aspect of the concept is determined. Crucial element within the detail is the notch, especially the holes around the joints. This will be the element that requires further testing.

The height of the notches and the location of holes for the bolt are derived from the CNC-limitation of being capable in milling on only one side, and by the design of the detail consisting of a three layered bottom element. This place of the hole is a fixed location. To optimize the notch to its structural capacities, variations in thickness, type of joint, number of joints or the type of wood are available. The following paragraph will describe, test and analyse these different options to optimize the connection detail for its structural competence. As standard plate material OSB is considered a most suitable. This research does not focus on the structural implications of CNC-milling panel material technology, so the selection of the panel material is not defined by its structural suitability. Within this research cost, weight and sustainability are considered as most important criteria. To make a reliable verdict about the most optimized solution three test set-up are developed to test the different options.

1. A tensile test to measure the required force to pull a M10 bolt out of the notch. This will be the standard to which to several other options can be compared.
2. The second test wants to test the type of joint. Instead of a M10, a M12 bolt is used, to determine the advantage of a bigger connection.
3. The third test focus to determine the difference between OSB, the standard plate material, and the stronger birch wood.

Standard set-up (M10, 18mm OSB 3)

The test for the standard set-up contains the notch, with the same dimensions as in the design, of OSB 3 with a hole to fit the M10 bolt. The bottom of the notch and the bolt, or an equal dimensioned piece of metal, are attached to the tensile test machine. By putting a tensional force to the piece of metal, a compressive force occurs at the top of the bolt opening. When the maximum stress of the OSB 3 is reached, the wood will crack, and the bolt will be pulled out of the notch. Assumptions are made with hand calculations. The first test result will validate this figure, and give an estimation to the structural capacities of the notch.

Larger connection type (M12, 18mm OSB 3)
By using a larger connection type, the connect area, hence the area to distribute the forces to the OSB, increases. In theory, is should require a higher tensional force to pull out the connection. The bigger connection is more expensive and has more environmental impact. But, if it could reduce the amount of connections in every notch, thus with a factor 8 in the entire connections detail, these disadvantages are not relevant anymore.

Different plate material (M10, 18 Birch wood)
The third test examines the material properties of a stronger plate material. This research focuses not to the structural implications of CNC-milling panel material technology, so the selection of the panel material is not defined by its structural suitability. Within this research cost, weight and sustainability are considered as most important criteria. Therefore, OSB is chosen as overall plate material to construct the building system. However, the notch are specifically designed to solve the structural aspects, therefore the material selection can differ. In this case is chosen to test birch word. The mechanical properties of birch wood are higher than OSB, however it is a more expensive material. This asks for a comprehensive consideration between costs for extra, or other connections types, in comparison to the cost for other material.

Results
Detailed results of the test can be found in appendix B. In this paragraph they are summarized to draw a conclusion on the type and number of joint that is required in the detail.
It shows that M12 is not necessarily stronger than M10 in the 18mm OSB. The lowest result of M10 and M12 are respectively 3731kN and 3705kN. Therefore it is genuine to conclude that M12 is not a suitable solution.

If we compare the results with the required strength of the connection we can conclude that a single M10 in OSB is not convenient. Therefore a decision need to be made to solve this. The birch wood is a suitable solution because it will double the maximum strength of the notch, however it is also possible to increase the thickness of OSB to 36mm. This is already the case in

Figure 8.22 a) Set-up test 1 and b) the results for the 9 different tests (Own illustration)

the beam that connects the components. If the notch in the floor element will be replaced by a birch wood element, this would be the only birch in the connection. From the aspect of material savings, it would be better to double the OSB to keep only one material is the design. Therefore the final design will contain both 36mm of OSB on the inside and outside notch.

Test2 'Strength overall detail'
To get more reliable verdict about the structural behaviour of the overall connection, a more elaborated test is required. A full scale mock-up to simulate the actual loads. To examine the moment forces in both directions two set-ups are necessary. Figure 8.23 shows the set-up, which is tested with both tension and compression. In this way a moment in both directions could be simulated.

Both tests turned out rather positive. The tension test collapsed at a moment of 2.1kNm where 1.6kNm is required. The compression test even reached until 3.1kNm before collapsing, when 2.6kNm was the minimum. Due to the safety factor of 2 at the joints, these were not the weakest point anymore. The notch in the floor failed at the connection to the side plate of the floor (picture in Appendix B). In the compression test, the beam appeared to be the weakest part. The different layers of the beam were tear apart while these were glued. So for the actual design other glue would make the connection even stronger.

This test was purely to examine if the connections were convenient to carry all the loads occurring from the wind and horizontal forces of the roof. However the horizontal forces from the roof can also cause deformation in the entire section. Especially in constructions creep can occur over time. In order to analyse this phenomena a new series of tests for every connection in the section is necessary. With the result of these test, the actual deformation and creep could be determined. In this research these are disregarded to prevent going in to deep. If the deformation turns out to be too large, the horizontal forces of the roof can be taken by a floor element at the bottom on the roof components, or a steel cable at the open floor is a necessity.

Figure 8.23 a) Set-up test inner notch, b) Set-up test outer notch and c) results after the test (Own illustration)

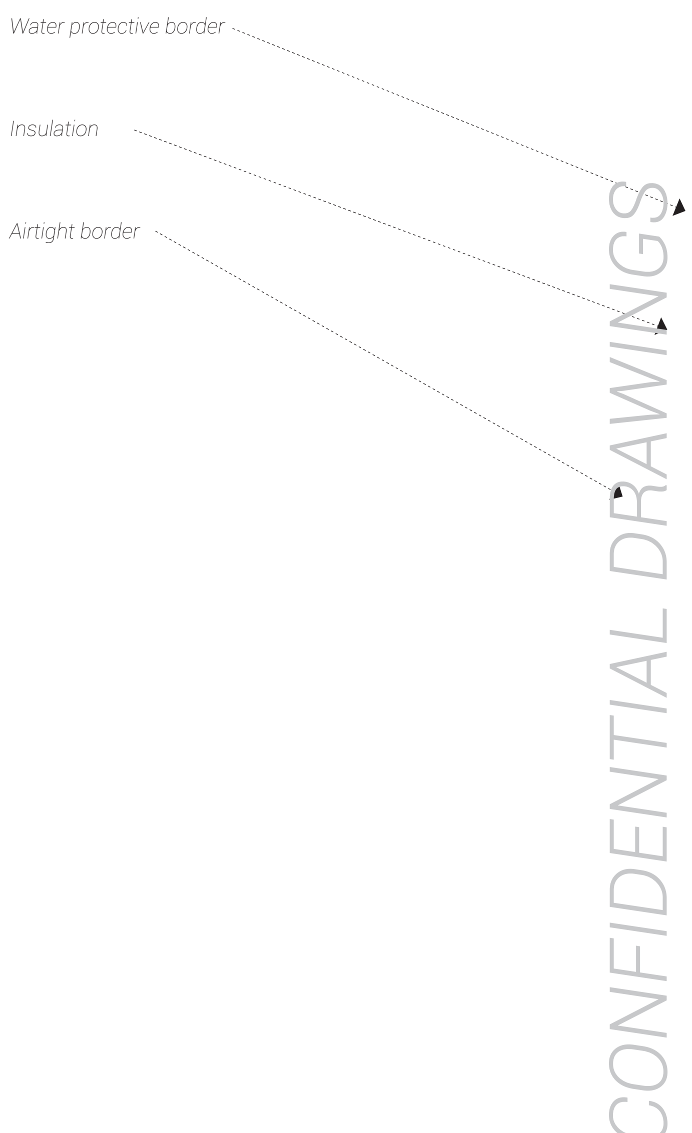
9. FINAL DESIGN

Source illu.: PO-Lab

By prototyping and testing, the feasibility of the proposed concept is examined, resulting in a final concept for the connection detail to construct PO-Lab building. This chapter starts with figures showing all important aspects of the detail. Then the design will be more elaborately explained per specific component, explaining solutions in detail and showing the materials and production process used.
When the final concept is explained, the influence to the full building system will be considered. The life cycle of the entire system will be covered; production (including cost estimation), assembly, maintenance and end of life.

Figure 9.1 3D line drawing of the PO-Lab design with the modular CNC-produced building system (Own illustration)

Figure 9.2 A section of the PO-Lab design, showing the water-protective (blue), insulating (yellow) and airtight (red) borders (Own illustration)



9.1 FINAL BUILDING SYSTEM

During this graduation research, successfully an intelligent building system is developed, designed and prototyped. The PO-Lab is the first building which shows that it's easy and fast to construct the building which significantly lowers the change on mistakes and therefore avoid unexpected additional costs.

The indoor climate is based on a vapour-open principle which assures a healthy environment within the building. This normally asks for special measures by adding extra layers of foil, but due to the high accuracy production process it becomes possible to integrate this within the building components. The vapour-open, water protective foil, commonly used in the building industry, is replaced by pavatex plate material as outer layer of the prefabricated modular wall and roof components. Due to the 0.1mm tolerance of the CNC milling machine it was possible to make the edges watertight with interlocking tongue and groove profiles.

On the inside of the components the airtightness is assures by an integrated rubber. Between the wall and roof components a round rubber profile is milled in sides. The floor component contains a flat rubber which is clamped between overlapping edges of the components.

The fact that the components consists of an completely airtight assembly and 220mm layer of insulation (RC-value 9), provides the opportunity to create passive houses. Thus a building which requires little energy for space heating or cooling. This makes the building much more energy efficient, and therefore will even lower the ecological footprint.

Figure 9.3 The vapour-open principle, water is transported out of the construction due to difference in vapour diffusion. The cavity between the component and facade will transport the moisture out of the structure (Own illustration)

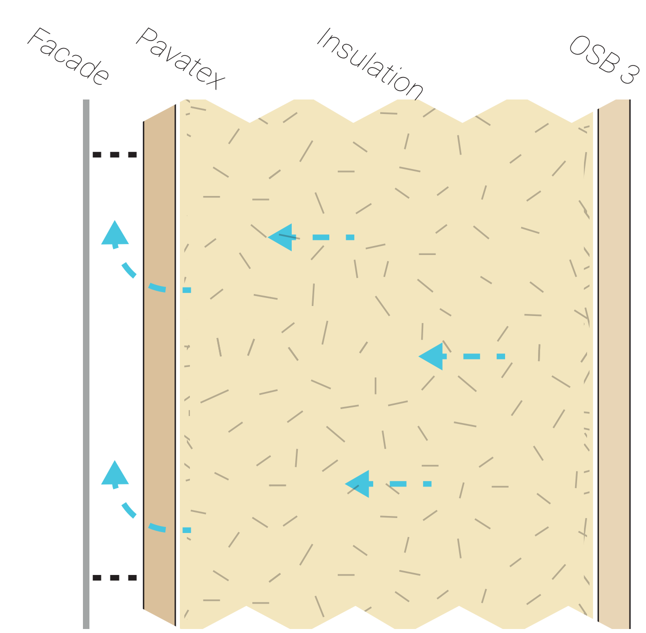


Figure 9.4 Integration of air and water tightning in a component due to the ability to produce with low tolerance (Own illustration)

Component:	Beam
Plates required:	2440 x 1220
Milling time:	10 minutes
Assembly time:	5 minutes
Weight:	5 kg

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Connecting beam

Key component to assemble and connect all different components is the connecting beam on the sides of the building. The beam contains inserts and notches to connect the other components. This will be further explained at the specific components.

The requirement for a flexible building made inevitable to create a beam that is adaptable in length. This is achieved by constructing the beam of multiple layers. Each layer fulfills its own function, but together they make a solid whole. This solid beam connects all the components into a stable building. It transfers the loads of the floor with the first, beveled layer and the inserts in the second and third layer. This second and third layer also contain notch both at the bottom and top. These make it possible to connect the wall and roof into a stable plane, and make a connection to the floor. The fourth and final layer assures the watertightness of the construction.

The end of each layer contains a dovetail joint. By interlocking these joint, and cross laminating the different layers, a sturdy beam is created.

Figure 9.5 Data for the milling machine to create a beam component (Own illustration)

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Figure 9.6 a) Connection point between two floor components and b) the double layered notch and the third bevelled layer are visible (Own illustration)

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Component:	Floor
Plates required:	5000 x 1220
Milling time:	20 minutes
Assembly time:	20 minutes
Weight:	45 kg

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Figure 9.7 Data for the milling machine to create a floor component (Own illustration)

Floor

After placing the beams on the foundation, the floor can hang between those beams. The end of each floor component consist of two protruding parts and a bevelled wooden element. The positioning of the floors in the correct position is secured by the protruding parts. The bevelled layer interlocks with the bevelled of the beam which makes a firm connection to transfer all the loads the floor has to bear.

One component spans the total width, at this moment the maximum length is limited by the dimensions of the CNC. If this length increases from five till ten meter, it would be possible to create longer floors. However, this will require more advanced calculations as regards to the structural behaviour of the components.

The floors are fully insulated to assure the thermal behaviour of the bottom floor components. On the first floor the insulated components provide a good sound barrier between the different levels of the building. Besides the insulation in the components, the floors also are connected airtight. The flat rubber profile creates an airtight seal due to the weight of the floors. The combination of these two aspects guarantee a good indoor climate.

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Figure 9.8 a) The protruding parts and bevelled layer to connect to the beam and b) inserted rubber to make airtight structure (Own illustration)

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Component:	Wall
Plates required:	5000 x 1220
Milling time:	25 minutes
Assembly time:	20 minutes
Weight:	49 kg

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Wall

When the beam and floor are assembled it's possible to place the wall components. Both the beam and floor contain a notch that fits the bottom of the wall component. The wall is placed over the notch and immediately is secured in the right position. Due to the low tolerance it's not possible to place the component in a wrong way.

To secure the wall on its place, it is fixed with an integrated bolt/nut connection. The nut is inside the component during the off-site assembly in the factory. This nut is always located at the same position, therefor you will immediately notice when the component is not exactly in the right position.

Just like the floor component, the walls contain integrated solutions to protect the building against water, thermal fluctuation and sound. Water is kept outside with water protective plate material. Thermal comfort is created with rubber air seals and insulation. The insulation also protects again outside noise.

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Figure 9.9 Data for the milling machine to create a wall component (Own illustration)

Figure 9.10 a) The inserted nut at bottom and top of the floor and b) inserted rubber and tongue/groove edge to make air and watertight structure (Own illustration)

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Component:	Roof
Plates required:	5000 x 1250
Milling time:	25 minutes
Assembly time:	25 minutes
Weight:	47kg

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Roof

The roof components contain a combination of principles used in the floor and wall component. To connect the roof to the other components, the connection principle of the wall is duplicated. Two notches fit in the bottom of the component and are fixed with bolts. To make the large span of the roof without supporting beams, the components are constructed as box profiles just like the floors. Losing the supporting beams makes it easier and faster to install the roof components.

At the top, the components interlock. Two opposite roof components work together as a vault. The horizontal forces that are resulting from this shape are bared by the floor components and the fixed connection with the two notches. The connection between the vaults is created with overlapping elements in the ridge of the roof. This combines all roof components in a sturdy whole.

To secure the water tightness at the top connection, a rubber profile is pressed into the resulting groove. This is the last piece to finish the water and airtight building structure, which can be build in little amount of time and low chance of errors but still very affordable.

Figure 9.11 Data for the milling machine to create a roof component (Own illustration)

Figure 9.12 a) The top connection of two roof blocks and b) inserted joint, rubber and tongue/groove edge to make firm, air and watertight structure (Own illustration)

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9.2 PO-LAB

Production

The design consist of 24 beam, 36 floor, 30 wall and 48 roof components. The off-site production of PO-Lab can be divided in two phases. Milling the elements out of the OSB plates, and assembling the elements in components.

Process

The process time, thus the time to mill all individual elements with the CNC miller for PO-Lab is around 50 hours.

- 24 beams are required to connect all different components for PO-Lab. The relative small objects still takes 10 minutes to mill because of the many holes for the bolts, and the fact that the beams consist of four layers. Milling time beam: 10 x 24 = 240 minutes

- Both levels of PO-Lab together contain 36 floor components. Despite the large size of the floors it takes 20 minutes to mill. On one milling path after, only the 16mm drill bit is used which makes it possible to mill everything with high speed. Milling time floor: 20 x 36 = 720 minutes

- The wall components are more time consuming. Due to the fact that the connection between multiple components need to be water and airtight. Special drill bits are required to make a tongue / groove and a groove profile to insert a rubber. These delicate drill bits drill slower, therefore the total milling time of an wall component is around 30 minutes. Milling time wall: 30 x 30 = 900 minutes

- The last component take the most times to mill. Partly because of the special drill bits that are required, and partly because of the number of elements. Milling time roof: 35 x 48 =1680

Total milling time PO-Lab: 3090 / 60 = 51,5 hours

Including the time that is required to replace the plate material and redo failed elements, this will take 2 full weeks. This looks a very time consuming job, but compared to traditional construction techniques lots of time is saved with the on-site assembly.

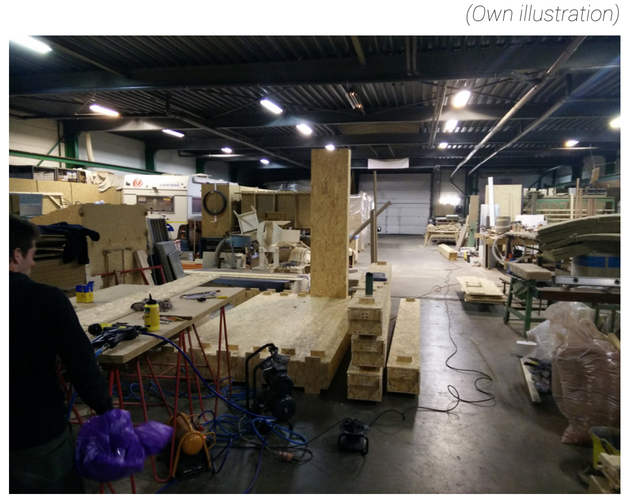
Assembly

Besides milling, assembling takes much time. But in the two weeks that are required to mill all elements it's possible to assemble the components simultaneously. Besides putting together the elements, the assembly also consist of integrating rubber seals, nuts and insulation.

The assembly has to be done with at least 2 persons. The mentioned assembly times are estimated in total for 2 persons.

- Assembling the beams is a rather easy job. The layers are glued and nailed together. Assembly time beam: 5 x 24 = 120 minutes.

Figure 9.13 a) Milling the final parts and b) Assembling the component off-site (Own illustration)



- Floor components contain more parts, therefore are more time consuming to assemble. Besides the large number of parts, some of them also a build-up of multiple elements. Assembling these elements takes longer than expected. Assembly time floors: 15 x 36 = 540 minutes

- The wall component consist of less elements, but contain two very labour intensive parts. Integrating the nuts within the top and bottom of the wall is a very accurate activity. If mistakes are made the whole component is no longer convenient. This results in an assembly time of around 20 minutes. Assembly time wall: 20 x 30 = 600 minutes

- Roof components can be seen as floor with integrated nuts at the bottom to connect to other components. In the middle of the component two more parts with integrated nuts are required to connect the facade to the building structure. Due to these labour intensive parts, it takes 25 minutes to assemble the whole element Assembly time roof: 25 x 48 = 1200 minutes

Total assembly time PO-Lab: 2460 / 60 = 41 hours

Another full week is required to assemble all components. Due to the fact that the milling and assembling of the components can be a simultaneous process, the production of the whole PO-lab should be possible in 2 or 3 weeks with two man.

Design:	PO-Lab
Plates required:	138
Milling time:	51,5 hours
Assembly time:	41 hours

Figure 9.14 Number of production PO-Lab Building (Own illustration)

Figure 9.15 Components ready for transport (Own illustration)

Transport

After producing and assembling the components can be brought to site completely prefabricated. The beam and wall component have an very efficient shape in regard to transportation. The separate beams are very slender and therefore can ideally be used to fill gaps in cargo's of other component. Of wall components, with the size 600x2400mm, 3 blocks fit to each other and 4 in the length of a truck. This means that all wall blocks and beams of the PO-Lab easily fit in one cargo.

The floor and roof have less optimized shapes. The floor has protruding notches at both sides and the roof components contain a slight angle. However, all blocks are the same, therefore it is possible to interlock different components. This means that the overall length of multiple interlocked components increases, but more components can be placed next to each other. By doing this, the component can be loaded still quiet efficient.

All in all, it will cost about 3 truck to transport an entire house. Compared to other, more conventional, buildings this is still rather efficient.

Assembly

The production phase of the house already consist of the assembly of individual components. Completely prefabricated, they are transported to site where no further activities are required to assemble them. This makes the on-site assembly process very efficient and easy. The assembly can be divided into 7 different steps:

- Make foundation, with on top adjustable connection point to suit the low tolerance concept.
- Place beams as grid for the specific design
- Slide ground floor components in place
- Place wall blocks over the notch of floor and beam
- Repeat the last three steps to make the next floor
- Complete the structure with roof components
- To finish the building, the facade need to be assembled

At least two persons are required to do this job. When more persons are available different steps could overlap, which would decrease the assembly time drastically. With two people, the whole structure of PO-Lab should be build able in two days. Depending on the requirements of the client different facade materials are applicable.

To de-install the whole building, the same sequence should be followed in reversed order.

Figure 9.16 Assembly sequence PO-Lab (Own illustration)

CONFIDENTIAL DRAWINGS

Use/Maintenance

It's possible to replace specific components or to change the configuration of the building. Due to the segmentation of the beams, extra components can be removed or added. One could remove a facade and add extra blocks to create more space. This takes some time, thus money. But is much easier than moving to another place, or even construct a new building.

End-of-Life

With design for disassembly as one of the main design criteria, end-of-life possibilities are well considered within the design for PO-Lab. This makes it possible to remove the building components when a building is not sufficient anymore and reuse them in another building. By using a library of standard components to configure a specific design it's possible to exchange components between different building. When a component is used multiple times it may happen that some elements need to be replaced, for example the rubber seal.

At a certain point the technical lifespan of a component ends. This requires the possibility to recycle them. The wooden sheet material could be recycled as resource for new plate material. The nut, already integrated in the components, should be removed first. One should consider if the energy required to do this is lower then the energy that is saved by recycling. If the recycling actually happens depends largely on the responsibility of the user of the disposed product.

REVIEW

INTRODUCTION

This last part will review if the design meets the requirements of the specific design task. It also makes a shift from the design task, back to the entire building. It compares the building system to the conclusions of the literature research. It will determine if designed building is a reasonable solution to solve problems of the current building industry. Further, this part will contain a chapter with recommendations to further develop this building system and overall concept.

10. CONCLUSION

10.1 PO-LAB

The main objective of the 3TU PO-Lab is to provide a platform to test and prototype innovative ideas for the building industry. By developing this platform, not only the amount of research can be increased, but also the awareness of the current problems and possible solutions increases. In fact a platform will be developed to literally investigate and test digital production technologies like CNC milled wood connections, but also a platform in its wider meaning, to investigate the effects and influences of file to factory production, to explore the potential in the field of sustainability, material use, logistics and the interaction of stakeholders within the chain of the building process.

The inefficiency of the current building industry has been proven in the first chapters of this thesis. These chapters point out the merging interest to change the current approach of the way we design and build. The common processes are considered inefficient, as result of a strong partition of disciplines. The conventional building industry is infamous for producing lots of excessive waste.

By adapting and implementing methods of other industries these issues could be tackled. Lean manufacturing principles could be used to minimize the waste from the building process. Innovative digital manufacturing tools have the potential to create a more integrated building process. With these renewed methods, changes toward the way we approach buildings are available to improve the social, environmental and economic impact of the building industry. Industrialized components can makes constructing onsite much more efficient. In order to provide customization, flexible buildings based on modular building principles, are a sufficient solution. Flexibility of existing buildings is at least just as important to reduce the impact of the building industry. Demountable capacities play a crucial role to make adaptability feasible. By integrating the adaptability, demountable components can make the linear building life-cycle circular.

PO-Lab uses the renewed approach to create an affordable, innovative building (system) for the mass. The digital manufacturing process, in combination with the modular building concept, ideally fits the aspects that PO-Lab wants to improve. Five general goals are specified by PO-Lab to develop the laboratory by using innovative production technologies and the modular building principles:

- Sustainable material production and transport is provided by the possibility of sharing digital data to locally manufacture building components. This reduced transport distances of both materials and prefabricated building products.

- Resource efficient production is possible by using CNC fabrication technologies to make prefabricated components. CNC milling can be an efficient way of producing building elements. By pre-assembling these elements into components, in optimized work conditions, this process of making components becomes very efficient with only little waste production.

- Durable construction with regards to functionality is achieved by making it possible to adapt the building on changing customer requirements. This aligns the technical, functional and economical lifespan and prevents buildings from premature demolition.

- A fast and easy constructible system is achieved by standardized, prefabricated components. Designs are made with standardized components. The slightly reduces the freedom in design, however much time in engineering every design is saved. Besides savings in development, the prefab components result in a uniform assembly process. Which makes it possible to construct a building much faster than traditional building systems.

- By adding the features of demountable components, strategies for disassembly, reuse and recycling are integrated. Components be replaced to maintain or update a building. When the building is eventually not functional anymore, the components can be disassembled and reused in other projects.

However, adapting this principles will result in uncertainties. Will standardization limit us or bring us further, and what level of freedom is required to make a viable building system? This involves the relation between quality and scope, in combination with costs and time. A formula showed in this research before.

There is not an ideal answer to this question. But with knowledge of digital technologies and the renewed approach of building, it is possible to optimize this formula. By standardizing the modular components, it's possible to construct high quality housing in little amount of time and for low cost. The scope, or freedom in design, in this case lowers slightly due to the limited availability of components in the library of the building system. If these components do not provide the opportunity to construct a required building, this asks for new components. Due to the high engineering time, these components will be relatively expensive.

Designing such a building system raises more questions; who is responsible, who makes the decision and when do we have to make them? This research tried to find answers to these questions during the development of the specific design task, the connecting detail of the building system. By the guidance of a methodology the decision making during the process became faster, easier and better substantiated.

10.2 METHODOLOGY

The role of the architect during the development process changes completely. Architects need to be capable to develop, design, engineer and manufacture the building system. They are involved during the entire process, from development until the end-of-life decisions. Decisions on the aspects of degree in standardization in relation to freedom in design need to be made upfront. To control this process, methods of product development are introduced. This industry is more familiar with integrated design processes.

The methodological approach provides designers a framework to develop their products based on digital and modular principles. It divides the specific design task into sub-aspects that are faster and easier to evaluate. To minimize the chance to neglect or overvalue a specific aspect in the decision making, criteria are specified before the evaluation starts. The criteria are derived from the general requirements of connection details, and the sustainable strategies as result from the literature research. To use these criteria in the development of a concept for the connecting detail, they had to be converted into ambitions with a specific aim and weight. The ambitions are specifically established for the innovative building system of PO-Lab. It includes aspects of CNC-fabricating, modular building and demountable structures. Translating these ambitions into aims is a time consuming process, with different opinions. But it's advisable to do this with multiple people in order to make more considered decisions.

Altogether, the methodology provided a useful guidance in the concept development process. Minor downsides were the subjectivity in determining the fulfilment of a specific aim, and the fact that some generated concept were not viable. Impossible combinations of promising alternative solutions resulted in waste of time, because concepts were developed that were not feasible.

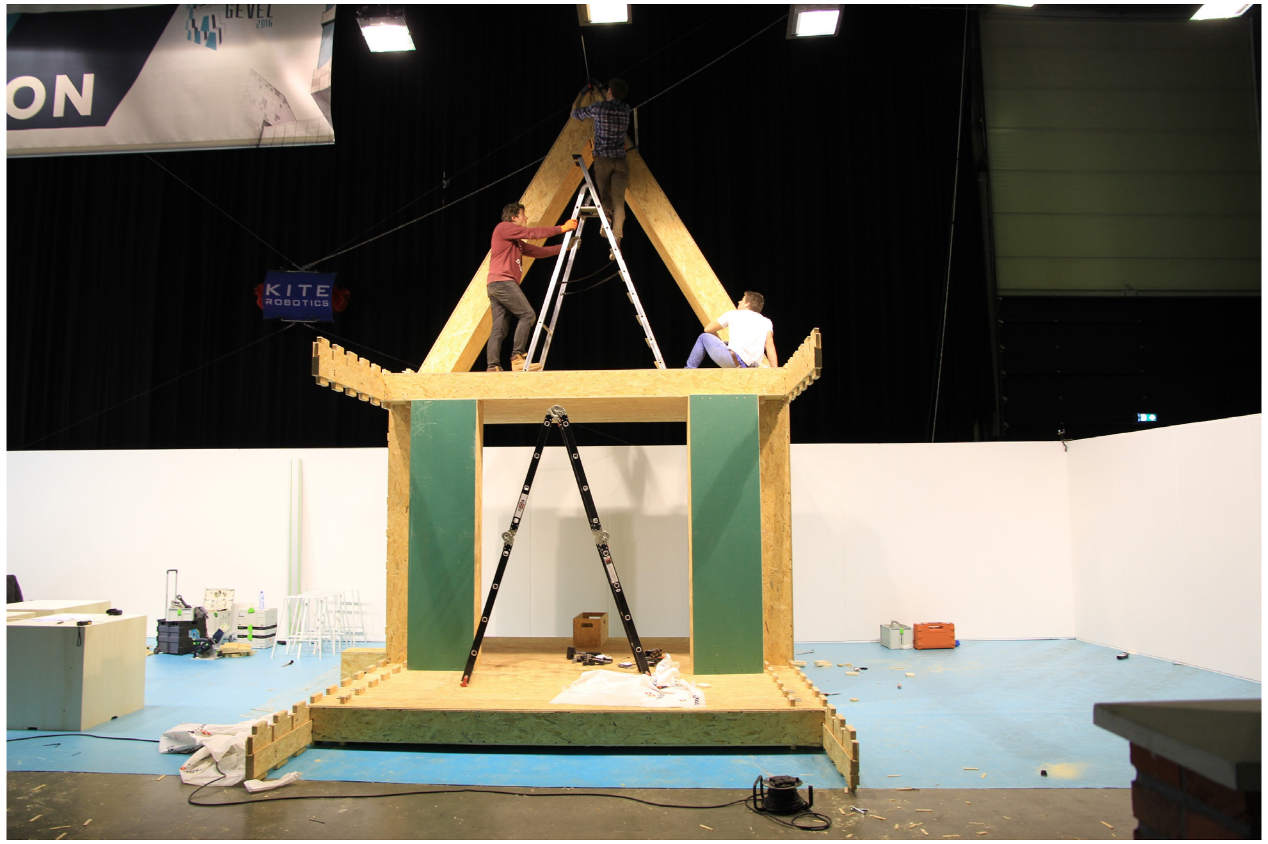
10.3 CONNECTION DETAIL

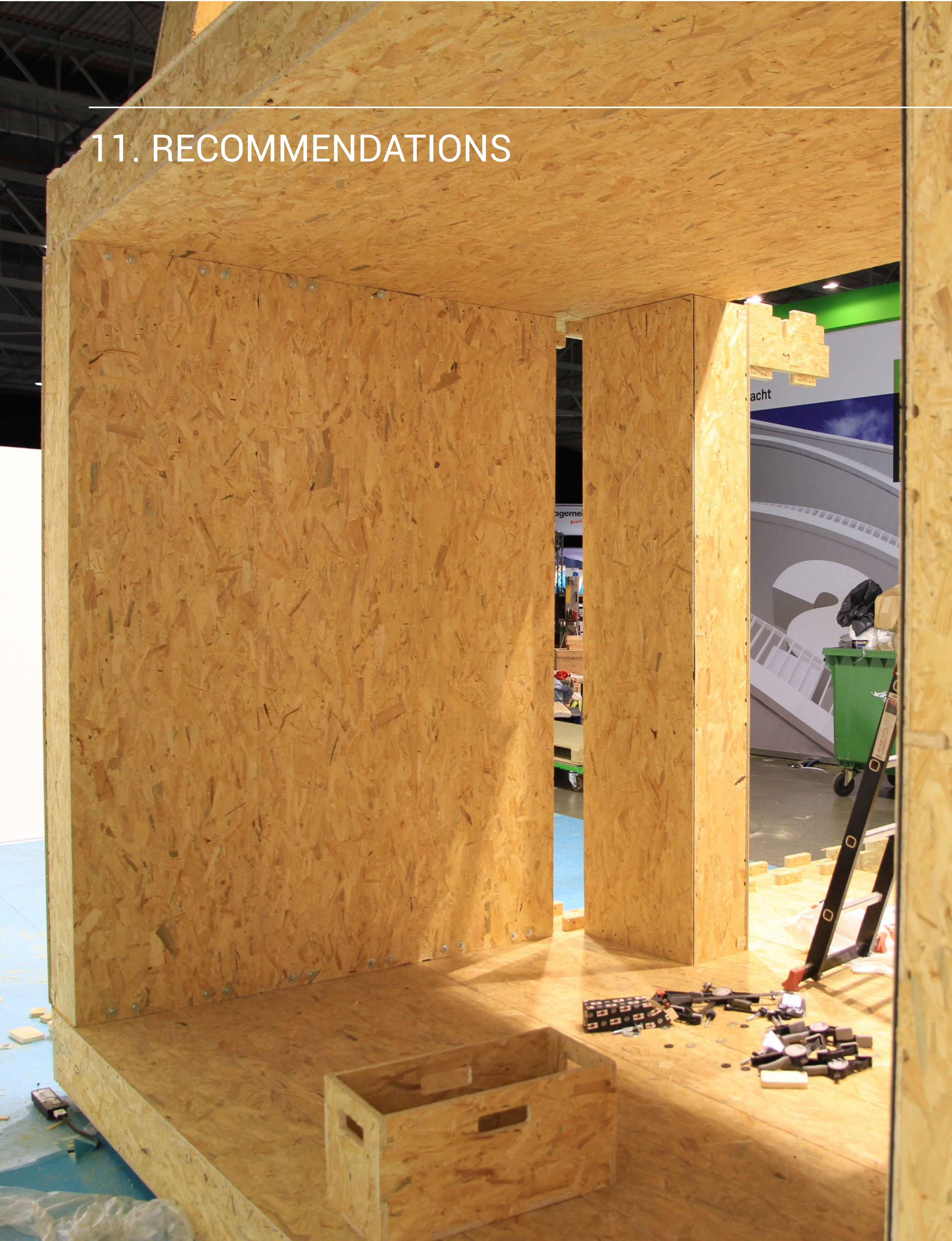
Due to the methodological approach, this research succeeded in developing a sufficient concept connection detail as answer on the specified design task. By well defined criteria: the PO-lab goals, CNC limitations, DfM guidelines, and all DfE life-cycle phases are integrated in a proper concept. This concept could be translated into a suitable final design with support from prototypes and testing. After numerous iterations, and extra testing to specific aspects, a firm connection detail is developed. All requirements regarding structural behaviour and air and water tightness are achieved.

Further, all criteria are weighed, and the full product life-cycle is considered: Materials with low environmental impact are used; the elements of the detail are optimized to the CNC-limitations and nesting efficiency; the component shapes are optimized the make transport more efficient; on-site assembly can be fast and easy due to repeated processes; existing structures can be adapted to changing demands; and components and elements can get a sustainable end-of-life solution.

But the eventual viability of the design will be visible in the final prototype, the actual laboratory. The first prototype of a full scale section was visible at GEVEL2016. Here the concept of the building system and the connection detail were fully evolved into a final design and already showed much potential. Findings from this prototype can be used to create the actual PO-laboratory.

Figure 10.1 Building at GEVEL2016 (Own illustration)



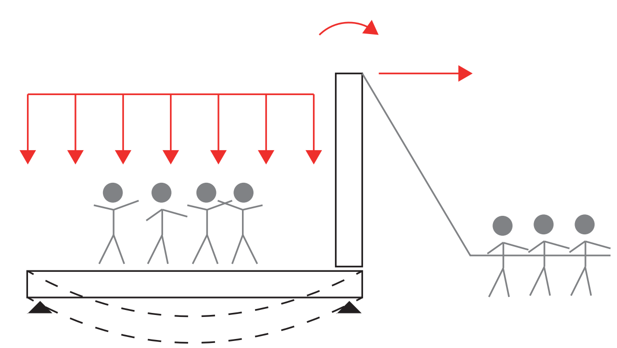


11. RECOMMENDATIONS

11.1 BUILDING SYSTEM

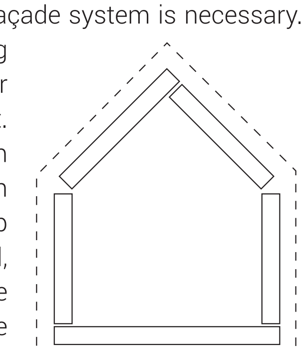
Structure

The connection detail is an important aspect in the realization of PO-lab. With this research the actual laboratory becomes more feasible. However, in order to actually construct the building, some other aspects require further research. First, the structural behaviour of the whole system. Within this research assumptions are made to test and define the exact dimension of the connecting elements. However, as mentioned, the analyses of the structural behaviour of the overall detail was an assumptions. To see if the connection really works, a full scale test is required. A complete floor and wall component should be assembled, and potential forces need to be simulated. Also the structural behaviour of the components as such need to be examined in this way.



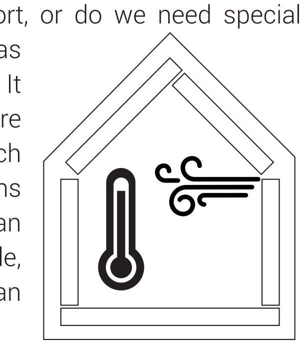
Facade

Second, the weather protective façade. The designed connection prevents water to infiltrate into the building. However, it is not possible to use this connection and the water protective plate material as barrier against the elements. To protect the structure from rain, snow, wind and dirt, an exterior façade system is necessary. Important with designing this façade is to consider the criteria of the concept. To design a façade system that is complementary with the general ideas of PO-lab and the connection detail, it's essential that the façade is judged on the same criteria.



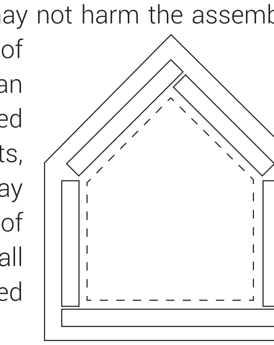
Thermal comfort

Third, is controlling the thermal comfort within the building. The connection detail prevents thermal bridges and creates a well-insulated system. But to optimize the thermal comfort heating, cooling and ventilating are a necessity. How can this be done in a modular system? Are common techniques used to provide the thermal comfort, or do we need special measures to follow the ideas of the adaptable concept? It can be possible that there are components available which have integrated ventilations units. Calculations can conclude that, for example, every 20m2 requires such an element.



Technical installations

Fourth crucial aspect in most modular systems, is the integration of technical installations. Solutions can be thought that improve the thermal comfort, but the technical installation may not harm the assembly, or disassembly ease of the system. Making an adaptable system, based on modular components, asks for an innovative way of integrating ducts. Think of plug 'n play methods to install components with integrated ventilation units.



All of these subject could be translated into different design tasks. In order to make sure that the general ideas of PO-lab and the connection detail are consider, it's advisable to use the methodology as guidance. In this way the same criteria are used in decision making on every particular aspect.

11.2 PARAMETRIC DESIGN

Buildings, based on a modular system, may benefit from parametric design tools that use a library of generic, parametrically defined components to design them. The system uses a standardized components, connections and dimension systems, which principles can be reused in every new designs. This does not only include geometric appearance, but also information about the process of assembly and disassembly and the tools needed for these processes (e.g. component length, amount of connections, floor height based on structural analysis and required ventilation). A parametric system, understandable by the mass, could be developed. In this way the mass can configure a home to their own demands, like The Sims.

11.3 BUSINESS CASE

Besides the software to do this, also decisions regarding responsibility should be defined. The library of components can grow, and abandoned building can be disassembled back into components. This results in second hand components that can be reused to construct new buildings. In this way it is maybe possible to approach this components as leasable objects. As a pavilion is required for a year, they could build it with this system. Or beach pavilion, which are nowadays constructed every summer, and demolished in the winter. They could lease these components for the summer months to easily build their pavilion, and at the end of their season, the building can be efficiently disassembled.

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APPENDICES

APPENDIX A

CNC MILLING

THIS TEXT IS OBTAINED FROM:
Vischer, L. (2015). Shaping CNC-cut plywood structures (Doctoral dissertation, TU Delft, Delft University of Technology).

The CNC milling process is a phenomenon within the larger digital processing technology. The first CNC (computer numerical control) machine was built in the 1950'ies, NC-processing has since developed to be a key manufacturing process across many industries. These processes provide significant production flexibility; it enables high geometrical complexity for shaping of a wide range of materials that can be processed. In the 1980'ies, NC machine vendors developed a graphical interface for programming of the machines, these systems developed into the current CAD-software (S.T. Newman, 2008).

Process
The manufacturing process can be divided into three steps: the design phase, post processing where the design istranslated into a set of operations for the machine, and the actual manufacturing.

Design process
With a construction system that is based on mass customization and uses an CNC-milling machine, a difference is that all operations throughout the process need to be incorporated into the design. A construction kit type building needs to fit perfectly and any errors cannot be easily fixed. Design errors can be costly in terms of material and time waste becauselittle further processing of the work pieces is desired after production by the CNC-machine. All the components of the product need to be final and perfect.

Design considerations include process limitations such as assembly, tooling freedom or tool palette; these imposeguidelines for the design. Within these boundaries a high shape freedom remains. Efficiency is achieved by optimizing aspects like processing time and material use. Using the wrong tools or tooling approach for a process can achieve the same end product quality with a reduced economic efficiency. The design can be drafted in any 3D-drawing program that can export standardized CAD/CAM file formats.

Post processing
The design is a drawing in CAD-format that needs translation to a language that the CNC machine understands. The translation of these two or three-dimensional design drawings to the manufacturing software of the machine - telling it how to process the material step by step – is called post processing, and comes in the form of CAD/CAM-software applications. The role of these applications has shifted from merely data translation to optimization of the production process. With these tools the designer gains control over the exact operations the machine, assisted by algorithms that optimize parts of the process (S.T. Newman, 2008).

The versatility of the NC machines has increased, as well as the complexity of the information fed into the machines. Currently there are many different types of CNC machines with a variety of properties and functions and a variety of 3D modeling software. An example is VisualCAD, a plugin that drives the VisualCAM post processing application. In this application the designer can choose the routers bits that are used, enter the material and dimensions of the work piece and set the way surfaces are finished.

After importing a 3D design with .stl .iges, .step format, from 3D drawing applications, the post processing application translates the chosen or calculated toolpaths – the path that the router travels over the workpiece - into 'G-code.' This is a code telling the machine what to do, step by step.

Post processing gives the operator control over how the machine processes the workpiece: the cutting and surfacing speed and the finishing quality and type. In some projects with developing surfaces, the surface is roughed by wider routers that can remove more material per sweep, and then finished by finer routers that increase resolution. Post-processing consists of the following steps: firstly, the end machine is selecting, with its specific properties and abilities. After that, the raw materials dimensions and orientation are adjusted

to the machine coordinate system. Next, the materials of the objects and tools are selected, so the post-processing application can automatically determine the rotation and cutting speed of the router. The machinist then manually selects the machining actions per part of the work piece. The post-processor then generates the complete toolpath and translates it to G-code. The machinist can check his input by simulating the machining actions in a virtual display. This allows errors to be detected easily. When the machinist is satisfied, the G-code can be exported to a .nc-file and fed into the machine.

The manual input concerns the machinist to consider issues as grain direction, cutting speed and direction, choice of cutters and finishing quality. Older systems require more intensive manual labor: for example, the machinist needs to define which lines are handled in which way, like the axis or the tangent of the router needs to follow the outside, inside, middle of the drawn line.

Other post-processing applications can optimize economic use of base material. A nesting application uses an algorithm to fit as many pieces as possible within one base sheet, reducing waste.

Manufacturing process
The following aspects of CNC-cutting are to be considered when designing: A CNC-machine with gantry usually has tooling freedom in x, y and z-axis. Because the tool is always above the panel, milling the bottom side of the panel is impossible. This freedom is referred to as 2,5D milling.

Other than lasercutting or waterjet cutting, CNC-milling uses a rotary tool bit that removes material by blades on the outside of the cylindrical tool. At an increased router bit diameter, the blade on the outside of the tool gains speed, and more material can be removed resulting in faster cutting speeds. A router bit of 16 mm in diameter can move at 4m per minute and cut the full depth of an 18mm thick panel where a 5mm diameter moves at 0,5m/minute at a maximum depth of 3 mm per pass.
The router bits are round which means an internal corner is rounded off. If an internal corner is necessary, and the material needs to be removed because another part needs to fit, this is solved by cutting away material from the side, called a dog bone.

The work piece has to be fastened to the table to prevent movement. Some machines have a vacuum system that pulls an air permeable panel (spoil board) to the table, as well as the panel from which the work piece is cut. This is a soft surface that allows the router bit to cut through the work piece and a little bit into the panel. MDF is often used. The suction clamping strength is relative to the surface area of the work piece: the larger the part, the larger the clamping force. Small parts can move when being cut due to the force of the router and the small surface area. These parts can remain attached to the main panel by small 'bridges' that are manually cut later when the panel is finished.

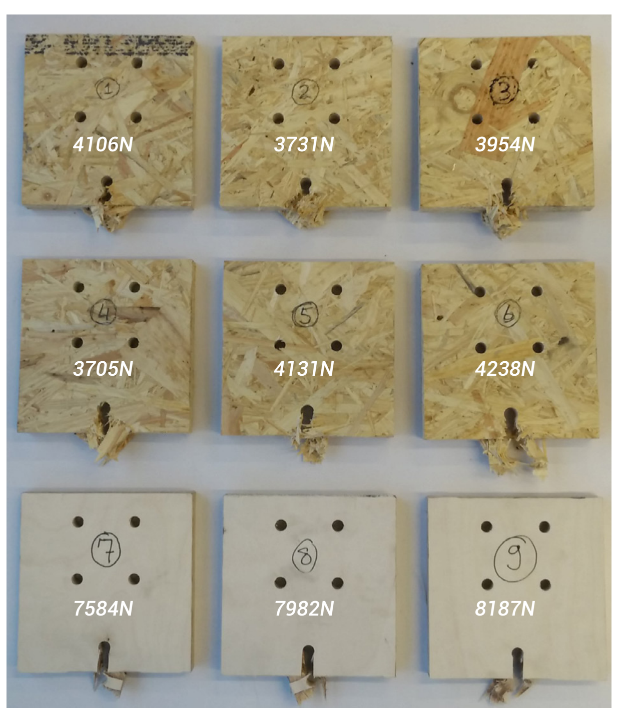
The machine operates within a virtual coordinate system that is aligned with the actual space in which is milled. Before the milling process can be started, the machinist needs to make sure that the machine is setup exactly as the configuration condensed in the G-code assumes, basically, the origin and orientation of the machines coordinate system and that implemented in the G-code need to be aligned. To reset the base plane of the table to zero, it is often done to take off a thin layer of the top layer of the spoilboard by milling. Also all the tools that will be used in the production need to be in the right slot as programmed. Because there could be a slight offset between virtual and actual coordination system, a margin of 20mm around the sides of the panel should be used.

APPENDIX B STRUCTURAL TEST

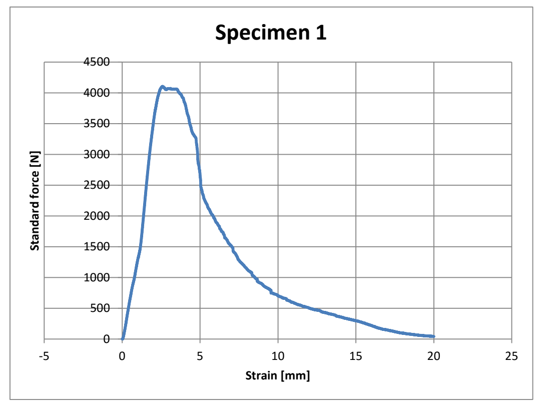
18mm OSB
M10

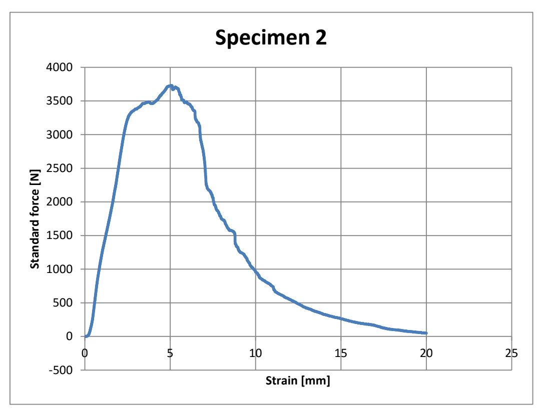
18mm OSB
M12

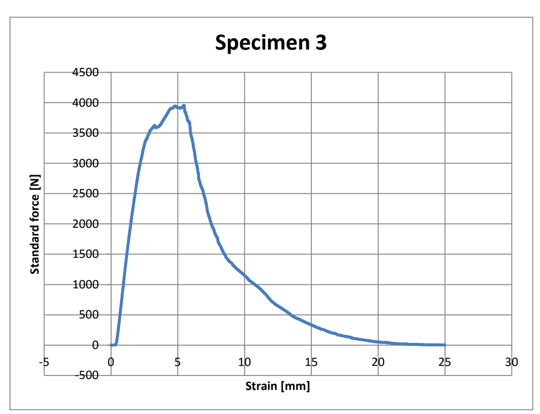
18mm Birch
M10



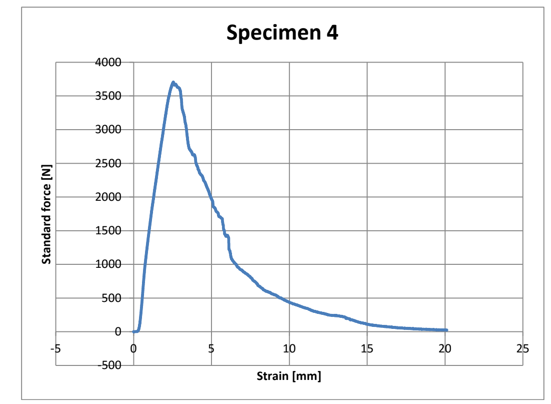
18mm OSB
M10

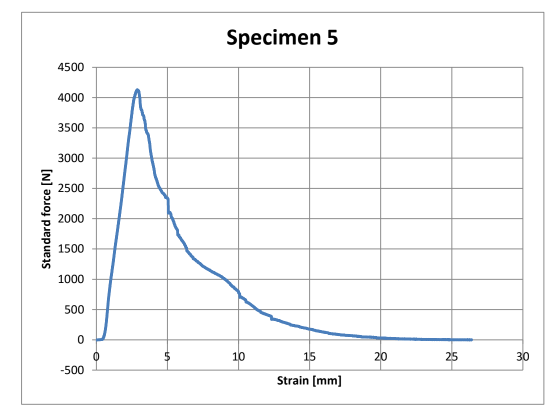


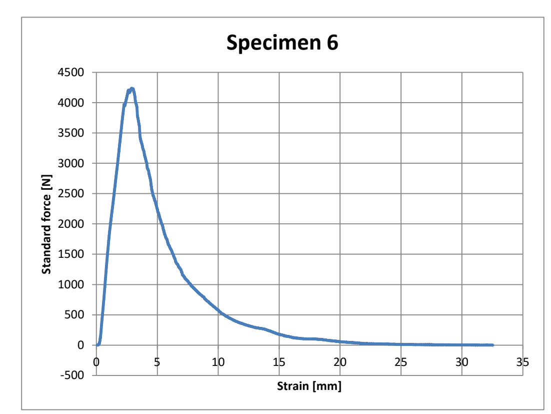




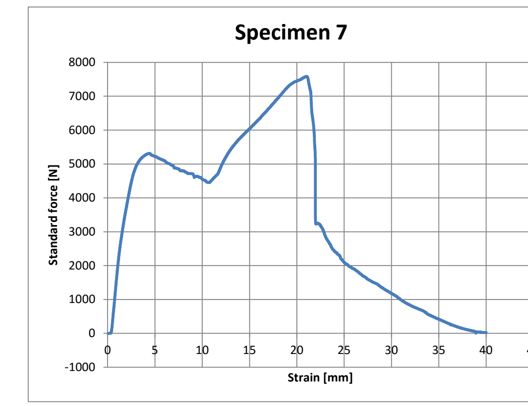
18mm OSB
M10

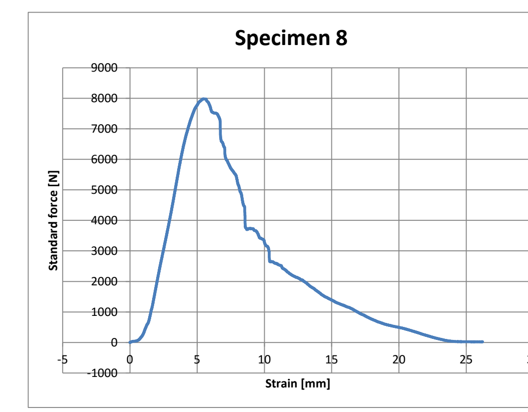


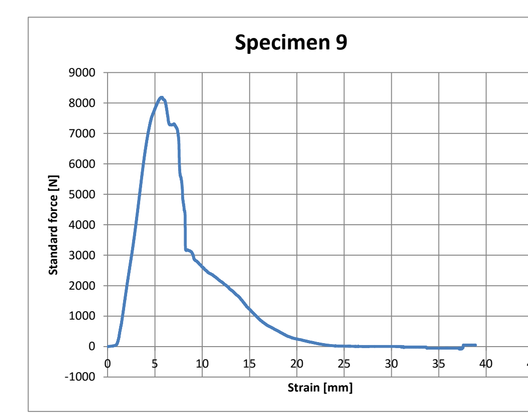




18mm OSB
M10

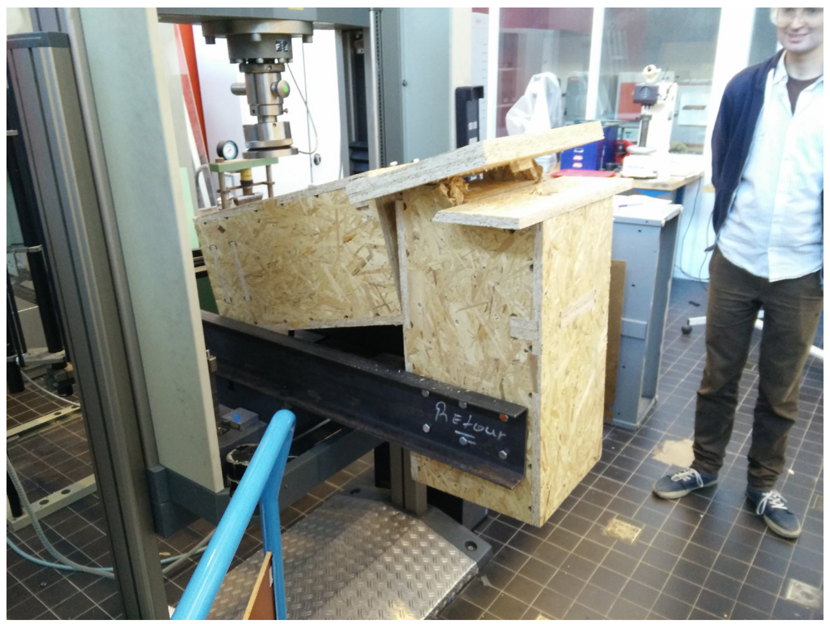


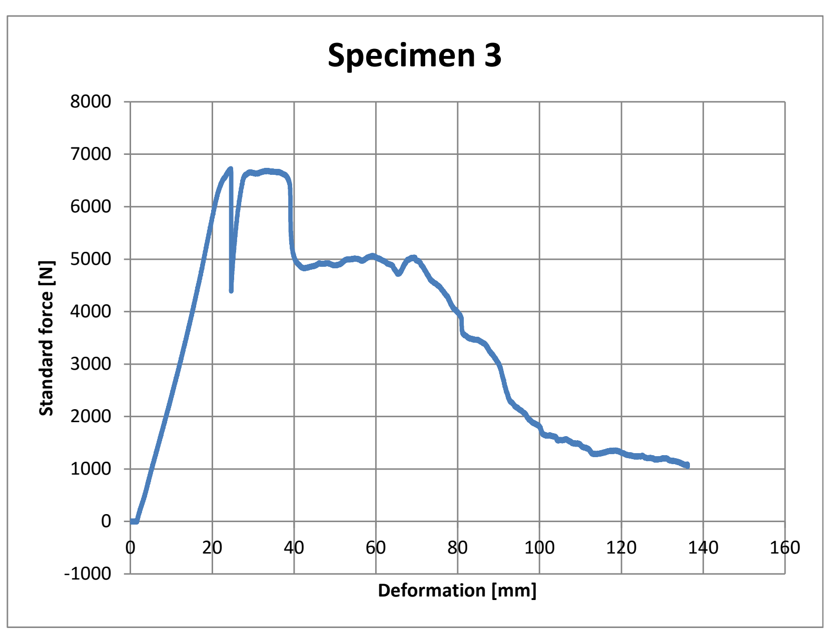




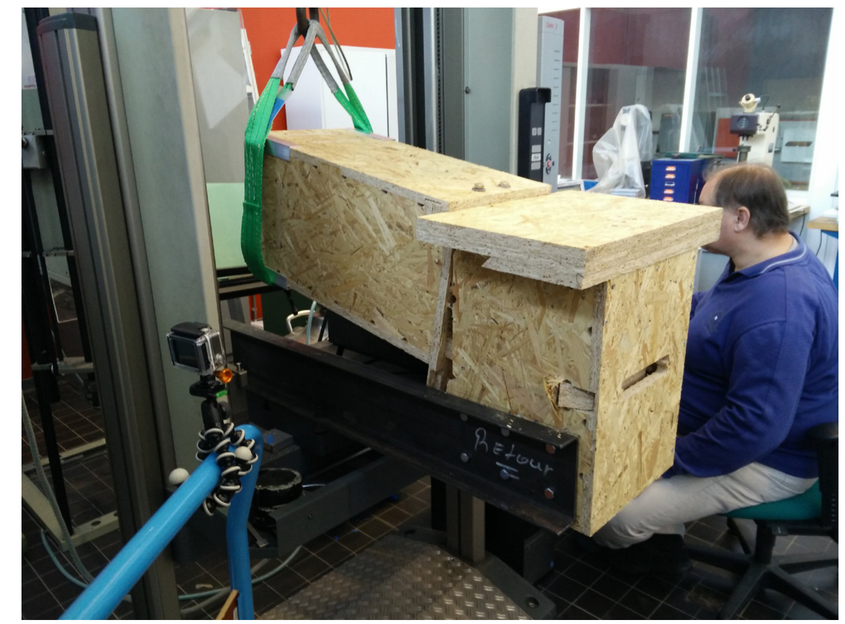
STRUCTURAL TEST2

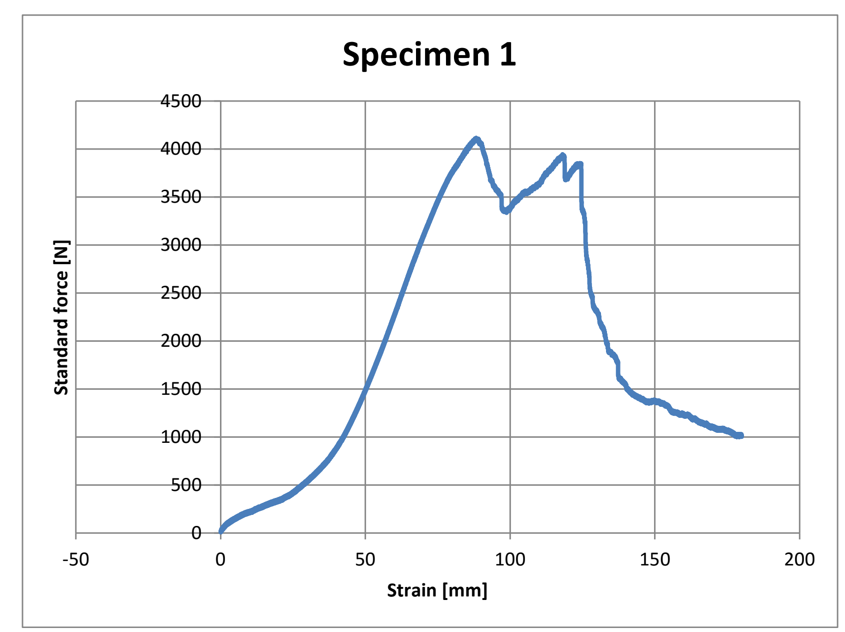
Compression

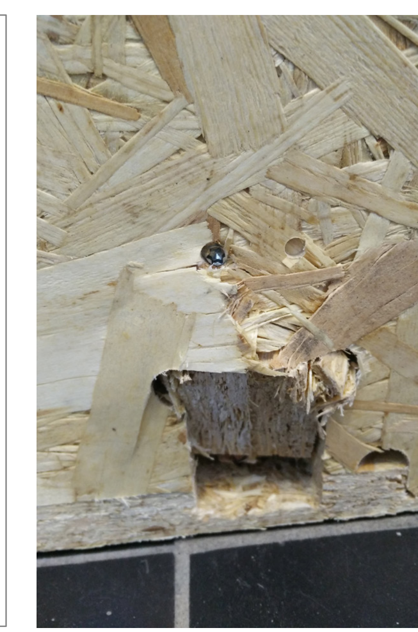




Tension





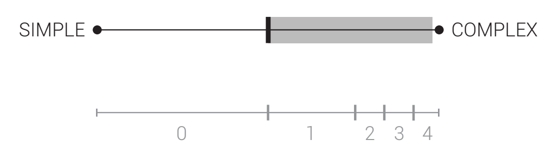


APPENDIX C CRITERIA

DESIGN QUALITY

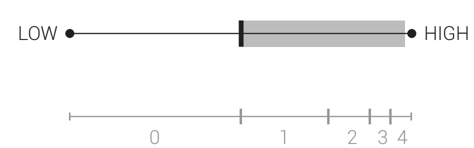
Freedom of design

The influence of an alternative to the design freedom of the whole system. Starting from a building system which can create simple building forms, until a building system which can have more, and more complex configurations.
ECOnnect: the minimal freedom of design requested for ECOnnect is for example that it needs to be able make a opening as big as an entire facade or to make voids in the floor.



Finishing (aesthetic)

The level of finishing/detail of the building system, both interior and exterior.
PO-Lab: The PO-Lab is going to be an laboratory to test building products, so it's not necessary that the level of interior finishing is high. Connections can be visible because it is interesting for the building technology students to see how the building is made. The facade needs a higher level of finishing to give a high-tech appearance, e.g. preferably no visible screws.



LIFE-CYCLE

Material

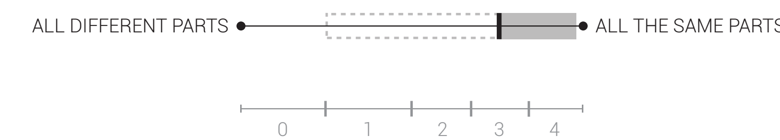
Environmental impact

The impact of the entire lifecycle of the material needed. This includes the energy needed for all phases in the lifecycle, toxics that are released during production, use and after end-of-life and the ability to recycle the material at the end of its life.
PO-Lab: With the sustainable ideology of the PO-Lab, the used materials should also follow this idea. They need to have a low embodied energy, should not release any toxic waste and the complete lifecycle needs to be optimized.

Production

Batch size

The batch size of a specific part which is not produced by CNC-milling (for CNC-milling the batch size does not matter as it can produce individual parts as fast as lots of similar parts).
PO-Lab: The innovative building system claims to be fast, cheap and modular. Therefore one-of-a-kind products do not fit within this statement. On the other hand, parts that can be produced in large numbers are, in general, cheaper.

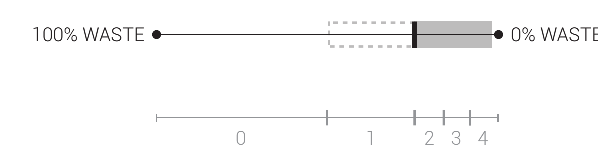


Milling time

Time needed to process the whole component before assembling it. This is the total milling time that is required. The milling time can increase significantly when too many different drill-bits are used
PO-Lab: Reducing milling time will make producing more efficient, thus cheaper

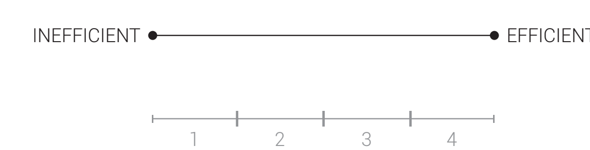
Nesting

Additions to the modules can adjust the shape of the 2D elements that are milled. The current elements are optimized to exactly fit the 5200mm by 1200mm plates. If additions are made some elements may not fit on a plate anymore. This can lead to more residual material.
PO-Lab: Reduce amount of waste, max 25% waste



Assembly complexity

The time needed and complexity to assemble an entire module.
PO-Lab: The elements cannot be too complex and labour-intensive.



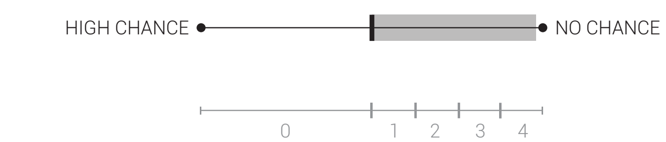
Amount of elements

The amount of elements required to assemble a component. This are milled elements, but also elements of other materials that are integrated in the component for different reasons.
PO-Lab: Reducing the number of elements will make producing more efficient, thus cheaper

Transport

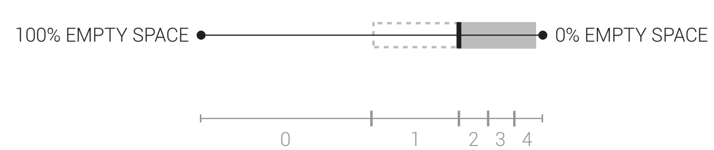
Vulnerability

Protruding parts may be vulnerable for damage during transport and increase the chance of damage or asks for extra protective packaging around these parts.
PO-Lab: kosten en tijdaspect



Loading efficiency

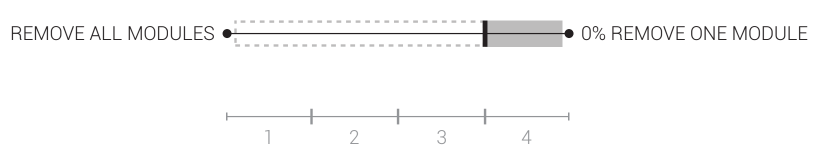
Inefficient loading due to odd shapes or parts can lead to residual space in trucks or containers.
PO-Lab: Even though the modules are fabricated close to the actual building site, the system still needs to be designed for optimal transport conditions. Therefore the modules shapes and dimensions should be optimized for transport.



Use

Adaptability

The amount of adaptability can vary from a concrete building that needs to be demolished completely as one particular part is not sufficient anymore, until a building that can be taken apart in multiple pieces when they turn out to be outdated or damaged.
PO-Lab: This project has the ambition to make it possible to remove components or parts of components from the structure. It also should be possible to extend or shorten the structure by adding or removing blocks.



Maintenance

The possibility to replace broken modules or parts of it.
PO-Lab: PO-Lab tries to optimize the lifetime of the different parts. Therefore broken parts of modules that are still useful needs to be replaceable in order to expand its lifespan and reduce the amount of waste.

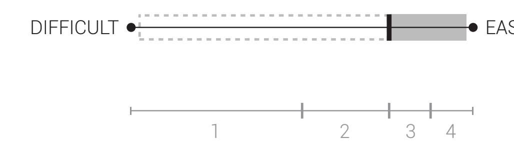
Accessibility

The possibility and ease of the accessibility of essential elements for modifications, additions or partial disassembly by the user.
PO-Lab: all connections should be accessible by the user.

Assembly

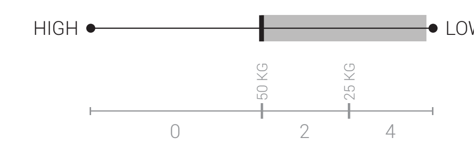
Building ease/ergonomics

The obviousness and ease of assembly, and the handling and understanding of the modules assembly. Amount and complexity (electric tools, costs, weight, force to be applied) of the tools that need to be used.
PO-Lab: the system should be 'foolproof'.



Weight

The weight of the assembled module. The lower the better.
PO-Lab: one module must be able to be placed by two persons. This resembles a weight of a maximum of 50 kg (25 kg / person) determined by Dutch building standards.



Amount of components

The amount of components required to assemble the building. This are milled elements, but also components or elements of other materials that are required to finish the building for different reasons. (foil, tape, gutter)
PO-Lab: Reducing the number of components will make assembling faster, thus faster. The assembly time should be considerably lower than conventional prefab building methods.

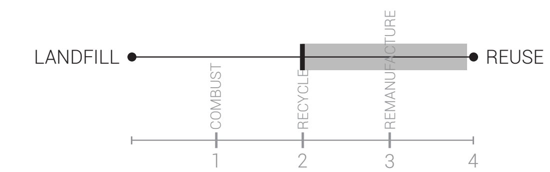
Amount of joints

Total amount of joint the need to be tightened before finishing the building
PO-Lab: the aim is to have a as low as possible on-site assembly time. The assembly time should be considerably lower than conventional prefab building methods. (has to be specified later)

End-of-life

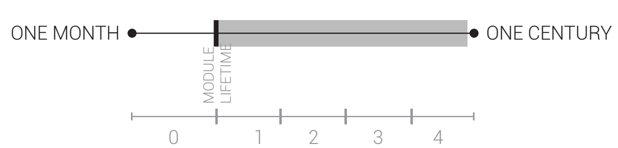
End-of-life activity

The level of possible end-of-life activity (landfill, combustion, recycle, re-manufacture, reuse) of the module elements and the modules as a whole.
PO-Lab: aim for maximum reuse of modules and module elements, minimum requirement is recycling.



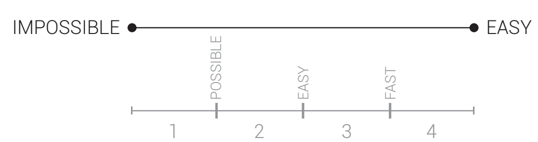
Lifespan

The lifespan of the elements relative to the complete module lifespan.
PO-Lab: modules and module elements should be able to survive at least one building lifespan. If the lifespan of single elements exceeds that of the module that it is part of, easy disassembly is desireable.



Disassembly ease

The ease, speed and possibility of disassembly of the modules from the complete building as well as of disassembly of the modules itself.
PO-Lab: possibility to reuse elements that have not reached end-of-life yet and ability to separate different materials for reuse or recycling.



Costs

Costs

The overall estimated cost of the whole. The cost is further elaborated when a more detailed designs are available. Then the costs can be listed by costs per phase (e.g. labour, energy, material, etc.)

APPENDIX D WEIGHT

	Freedom of design	Aesthetic	Environmental imp.	Batch Size	Process time	Component assemb.	Am. of elements	Nesting	Weight	Vulnerabilty	Loading efficiency	Adaptability	Accessability	Building speed	Building ease	Am. of components	EoL activity	Lifespan	Disassembly	Costs	SCORE	WEIGHT
Freedom of design		1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	0	1	0	1	14	3
Aesthetic	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
Environmental imp.	1	1		1	0	1	1	0	1	1	1	0	1	0	0	1	0	1	0	0	11	2
Batch Size	0	1	0		0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1
Milling time	0	1	1	1		1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	8	2
Assembly complex.	0	1	0	1	0		1	0	1	0	0	0	0	0	0	0	0	0	0	0	4	1
Am. of elements	0	1	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0	0	2	1
Nesting efficiency	1	1	1	1	1	1	1		1	1	1	0	1	1	1	1	0	0	0	0	14	3
Weight	0	1	0	1	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	2	1
Vulnerabilty	0	1	0	1	0	1	1	0	1		0	0	1	0	0	0	0	1	0	0	7	1
Loading efficiency	0	1	0	1	1	1	1	0	1	1		0	1	0	1	0	0	0	0	0	9	2
Adaptability	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	0	1	1	1	18	3
Accessability	0	1	0	1	0	1	1	0	1	0	0	0		0	0	0	0	0	0	0	5	1
Am. of joints	0	1	1	1	1	1	1	0	1	1	1	0	1		0	1	0	0	0	0	11	2
Ergonomics	0	1	1	1	1	1	1	0	1	1	0	0	1	1		1	0	0	0	0	11	2
Am. of components	0	1	0	1	1	1	1	0	1	1	1	0	1	0	0		0	1	0	0	10	2
EoL activity	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	0	1	18	3
Lifespan	0	1	0	1	1	1	1	1	1	0	1	0	1	1	1	0	0		0	0	11	2
Disassembly	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1		0	17	3
Costs	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1		16	3