

URBAN **TIMBER**

a resilient timber architecture in the city and a vision for mass customization

Anna Esbjörnsson | James Ford | Patrik Magnusson

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We are also very grateful for all of the suppliers who kindly donated materials for the prototype. Their contributions are further presented under chapter 02 | *design*.

keywords

- timber architecture
- cross laminated timber (CLT)
- massive timber
- mass customization
- CNC
- prefabrication
- bio-based/cellulose-based building
- life cycle assessment
- sustainable urban development

abstract

The severe and well-documented environmental impact of the construction industry demands systemic building innovations which responsibly manage resources from a life cycle perspective, and emerge as quality architecture in attractive and dynamic built environments.

This project presents an open-ended building system using CLT (cross laminated timber) for a versatile timber architecture in the city. It builds from a pervasive cellulose-based system measured by holistic design criteria with the aim to drastically reduce the environmental impact of construction and optimize performance over the lifespan of a building. Considering the architect's interface with CNC fabrication, we investigate the Swedish potential for mass customization and fine wood craft buildings within a practical economy of scale.

To prioritize a systemic approach and utilize our competence as a collaborative team we deal with a variety of aspects concerning timber architecture in a Swedish climate specifically related to a dense urban context. We examine principles in building physics and details concerning fire, moisture and sound to form a strategic concept that enables exposed timber on the interior and exterior as part of a diffusion-open building envelope. We also consider information management and fabrication specifics related to building tolerances and the current state of CNC fabrication in Sweden.

As architects we are motivated to influence early design decisions by expanding our knowledge toward a more informed design criteria which balances architectural quality and environmental aspects within economic realities of modern building production. Approaching our work both as researchers and designers we synthesize our findings in a potential next generation timber architecture for dense urban applications. As an economically viable, renewable, and carbon sequestering building material, CLT is put forward as a new standard option for architects and builders.

To relate our work to Swedish industry and current research, *Urban Timber* is carried out in collaboration with Martinsons and SP Wood Technology with consultation from Strombro Building Workshop. The output is presented through full-scale prototypes as well as a conceptual vision for a mass-customized timber city, presented in physical scale models. The project report is organized as an accessible information tool for anyone interested in CLT, timber building in general and resilient solutions for sustainable development.



THE TEAM

Patrik Magnusson has a bachelor in Architecture from Chalmers. In addition to his architecture studies at Chalmers he has also studied furniture design at Linnæus University in Växjö.

James Ford received his bachelor in Architecture from Georgia Tech in the USA where he also completed a bachelor in Civil Engineering.

Anna Esbjörnsson previously studied architecture at KTH from where she received her bachelor degree. She also studied painting at Umeå Academy of Fine Arts.

JOINT THESIS COLLABORATION

The work *Urban Timber* is a joint project by two master theses within the Design for Sustainable Development program at Chalmers School of Architecture. We set up this collaboration with a shared objective to take advantage of our diversity of skill and experience for mutual benefit and learning. We also anticipated that our individual ambitions would benefit from a group constellation, where more information is synthesized for a richer content and scope. We share a common priority for effective sustainable development and a fundamental interest in utilizing timber as an economically viable and renewable building material that sequesters carbon dioxide. Though all of us can speak for most parts of the project slightly different focus areas can be distinguished.

The subtitle of the project can be divided where *a resilient timber architecture in the city* refers to the main focus of Anna and Patrik's work, which deals with aspects of cellulose-based construction as a strategy to reduce the ecological footprint of the building industry. The work includes both the carbon assessment executed together with SP as well as the technical requirements of a prefab system in CLT, complemented with cellulose-based materials, for urban situations.

A vision for mass customization refers to the focus of James' work which deals with CNC fabrication as a new means for prefabrication and its implication for a customized architecture in the city. It also considers the interface with factory production and how architects can exploit emerging technology to empower the viability of CLT.

Along with an initial interest in creating a holistically resilient architecture for an urban context, the two theses meet at the deployment of the generic cellulose-based system, where they both contribute to give a sense of diversity in expressing a vision of timber in the city

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introduction

The topic of this thesis evolves around two basic questions: *What characterizes truly resilient building solutions and how can we manage high quality architecture while taking an active role toward a more sustainable building industry?*

Obviously these questions are complex in ways that make it difficult to give one complete answer. Effective solutions include knowledge from a wide range of fields, resulting in a web of technical and strategic innovations with potential to form new standards. Aware of the complexity of resilient building solutions we approach the topic through a study of emerging advancements in multistorey timber construction focusing on cross laminated timber (CLT), a construction method which has developed into a worldwide well-known and versatile building material (Brandner 2013, p. 1).

We narrow the scope to industrial building production in CLT, and the architectural possibilities and environmental advantages as a prefabricated timber product. We search for potential means of practical implementation of CLT construction practice in the Swedish building industry as part of a next generation urban architecture. Our aim is to study the whole production process, including the information management, material flow and the CNC interface of this particular fabrication process, all to widen our field of knowledge.

As architects we are intent on discovering possibilities for a crafted and customized quality architecture. While as individuals and professionals with a strong environmental interest we strive to think and operate holistically in order to cover the diverse aspects of constructing sustainable architecture. Ultimately we hope this work can inspire and support architects, contractors, property owners, students or anyone interested in timber and sustainable building solutions.

A VISION FOR TIMBER IN THE CITY

The performance-based fire regulations introduced in 1994 once again enabled legal construction of higher timber buildings and by 2012 15-20% of multi-family buildings in Sweden were built in timber, which is significant compared to 0% in 1994 (Gustafsson, Eriksson, Engström, Wik & Serrano 2013, p. 8). However, when we study these projects we find that timber is often used merely as a substitute for a steel or concrete structure without consideration for building physics or the architectural qualities and opportunities of the unique material and process.

Though we find some recent examples of multistorey timber projects in Sweden with exposed timber, the architecture is too often more or less reduced to an anonymous one-size-fits-all white gypsum surface where it's impossible to identify the timber building hidden underneath. We also question the development and character of standard systems for timber construction dominating the Swedish market, where increased use of volume elements (Höök 2008, p. 18) results in fast and cost effective construction but at the cost of a limited, static architecture and inefficient transport.

We recognize the importance of the ongoing trend of urbanization and in this context we support densification as a strategy of sustainable development. Even if multistorey timber structures have progressed from experiment to convention in recent years, most Swedish projects are built outside the urban grid. Few attempts have been made to fully reintroduce timber as part of a dense urban structure, probably due to persistent industry conventions and lack of knowledge and experience. In *Urban Timber* we investigate opportunities and obstacles as we work to evoke a vision for the modern Swedish timber city.

RESILIENT TIMBER ARCHITECTURE

Many multistorey timber buildings constructed since 1994 have been marketed as 'green' buildings made entirely of wood, when they actually contain many of the complementing materials found in most concrete buildings. It's correct to state that these buildings are environmentally advantageous relative to a standard concrete structure, but are they nearly as environmentally optimized as they could be? In fact about 50% of the carbon emissions from the production of an ordinary timber building in Sweden are derived from gypsum, mineral wool and plastics (Peñaloza, Norén & Eriksson 2013, p. 30),

It's still unconventional to advocate that many of these non-renewable complementing materials should be removed or replaced with cellulose-based alternatives, though current research indicates that wood fiber insulation has



Most multistorey timber buildings constructed since 1994 are detached from the urban grid. In addition they are often given facade materials that hide the fact that they are timber buildings. In Urban timber we envision timber architecture to once again become a natural part of dense urban structures where wood as a visible element among other facade materials gives a richer appearance.

Diagram: A generalized graphical representation of timber building since 1994 vs. *Urban Timber* vision.

several additional advantages in wooden construction due to its capacity to absorb and release moisture (Janols, Rönnelid, Wik, Brännström, Helling & Lövenvik 2013, p. 21).

The environmental impact of conventional timber and concrete systems are compared in the report *LCA of different building systems - The Wälluden Case Study*, released by SP Wood Technology in 2013 (Peñaloza, Norén & Eriksson 2013, p. 30). In their concluding chapter the authors express a desired continuation of the study where extensively cellulose-based building alternatives are presented and evaluated. This wish suited our initial interest and ambition so well that we contacted SP to suggest a collaboration for this thesis. SP accepted and generously assisted us in the environmental evaluation of the cellulose-based system we present under chapter 02 | *design*.

As part of any holistic approach to sustainable development the economic context is a crucial consideration. We make it a priority to understand the role of CNC and the factory production of CLT. We recognize it as a form of prefabrication and take this as an opportunity to make the case of a project delivery organization that competes with conventional industry methods, namely those of standard steel and concrete.



OUR ROLE AS ARCHITECTS

As a team of three we began the thesis with shared doubts concerning our expected role as architects in a time when strong economic interests are at odds with responsible building. For our profession we recognize the importance of taking a broad responsibility, to ensure the balance of cultural, social and environmental aspects of building. Aware of the severe environmental impacts of the construction industry we want to ensure our future efforts contribute to a more sustainable and resilient development. We search for an architecture of necessity and a language to express a unique identity for sustainable urban buildings.

Timber construction is today considered to be a cost effective and environmental building option (Gustafsson et al. 2013, p. 7). However, many architects and engineers don't feel confident suggesting timber in projects where other materials are still more conventional. (Roos, Woxblom & Mccluskey 2009:8, p. 1). The survey *Arkitekters och byggingenjörers inställning till trä i byggande* performed by Lantbruksuniversitetet in 2009 reveals that these two professional groups suffer a lack of knowledge and experience from timber construction. When architects don't bring forward economic and environmental arguments the builder or entrepreneur will be the one to influence the material choice.

To empower ourselves as architects we must expand our knowledge in material properties, production and construction as well as in building physics and economy of timber construction. This way we can have a stronger voice in the decision making for sustainable solutions to urban building production.

We engage massive timber experts like factory producer Martinsons and engineering firm Strombro Building Workshop to learn about the changing relationship between the architect and the factory, so that CLT buildings emerge from an efficient process of information management. As a proof of concept we have designed and conducted all steps until the actual production of a full scale prototype, imagined as a cut out piece of a building. This revealed both current limitations and future opportunities. By sharing our findings we hope to support architects within and outside Chalmers who favor working with timber and/or believe in its future as one of the solutions for a better and more sustainable architecture.

With the right knowledge our arguments can become influential and thereby strengthen our role as coordinators with a broad responsibility for the social, economic and environmental aspects in a project.

hypothesis

In *Urban Timber* we study current building production and emerging advancements in material and technology that can be feasibly applied toward a more environmentally responsible and intelligently managed building tradition. The following research question has guided our work:

How well can CLT and a cellulose-based building system respond to the architectural, economic and environmental demands of urban industrial building production?

The three hypotheses we have formulated somewhat correspond to the different focus areas of the thesis, the architectural and economical potential of CLT, the environmental potential of a cellulose-based system and the role of the architect in building production and fabrication.

- 1. The inherent qualities of CLT if fully utilized, can bring highly versatile and architecturally expressive building solutions, where the CLT acts as an honestly expressed load-bearing structure with refined quality and detail. An exposed CLT finish makes use of the hygroscopic and thermal advantages of massive timber.
- 2. A pervasive cellulose-based building system using CLT has the potential to outperform all conventional building systems for urban applications in Sweden today, considering the environmental impact of the production phase.
- 3. By integrating a more intelligent interface with the machining and production cycle, architects can take control of a customizable building method to express the innate design qualities of massive timber. As a CNC panel product, CLT stands to capitalize on the economic advantages of prefabrication and deliver mass customized urban architecture within a practical economy of scale.

DELIMITATIONS

This thesis investigates the implementation of an extensively cellulose-based building system in Sweden using cross laminated timber. We specifically consider the urban residential typology while focusing on aspects of environmental performance, architectural and structural possibilities, as well as economic feasibility connected to construction. We do not extend the cellulose-based alternatives for timber frame or post beam systems. We choose to work with CLT since it uses low quality timber in an advanced building product, enabling long-lasting carbon storage in a new assortment of wood. We speculate on the unique architectural implications of a rigid structural panel as a lightweight alternative to the reinforced concrete panel. We exemplify how massive timber might inform an urban aesthetic but without focusing on a specific program or design proposal.

CLT can be fabricated to a wide range of variable specifications that correspond to the limits of the factory infrastructure for each supplier. However, we choose to focus on the construction system relating to Martinson’s current system and production methods, as the only Swedish CLT producer and our main reference. Besides relating to the prerequisites of the Swedish timber industry the thesis primarily considers Swedish context and climate for intended implementation.

Two different types of LCA (life cycle assessment) are commonly used, the so called *attributional approach* considers flows within a certain system boundary and the *consequential approach* considers impact of different choices beyond the system boundary (Kuittinen, Ludvig & Weiss 2013, pp. 15-16). The environmental assessment presented in this report, based on the LCA-study of Wälludden, is delimited to an attributional approach where environmentally relevant physical flows related to a product are described in a cradle-to-grave system. The environmental impact categories included in the original Wälludden study are global warming-potential and primary energy demand assessed during the different stages of a building’s life cycle. This includes raw material extraction and material production processes, construction, heat and electricity production as well as supply for operation, demolition and end-of-life scenarios (Peñaloza, Norén & Eriksson 2013, p. 8). The assessment presented in this thesis is delimited to global warming potential of the production phase. This could be expanded to include the whole building life cycle, but we deliberately want to emphasize the importance of production (see *environmental impacts of architecture* in chapter 02 | *design*).

When considering the relationship between the architect and the factory, including the interface of CNC technology, we discuss a higher integration of information management which tries to digitally merge the architectural model with the fabrication model.



Image: Cross Laminated Timber (CLT) and Swedish climate and industry conditions are primarily considered in *Urban Timber*.

This has the potential to eliminate the translation between the two models, which is necessary in Sweden today. We describe how Martinsons might test current limits to produce our full scale prototype but we do not demonstrate the full extent of optimized information flow that might be possible in other factories or future upgrades. When speaking about CNC we principally refer to the 5-axis Hundegger PBA or similar machines of the same class.

Prefabrication is extended as far as a flatpack system and the premise of reducing the number of on-site connections and considering dimensional transportation limits. Associated economic advantages are implied but not fully evaluated. In considering mass customization, we specifically cite the implication in the ability to cut custom shapes from standard panels which brings a variability between projects.

METHODOLOGICAL CONSIDERATIONS

With *Urban Timber* we attempt to bridge the gap between academic studies and professional realities, with an ambition to reach for input outside the university and to learn from the experience of key actors in the field of timber construction. Establishing industry contacts and collaborating with both Martinsons, SP Wood Technology and Strombro Building Workshop has been essential in shaping our approach and perception of industry realities.

Through subject-focused research consisting of literature studies, study trips and discussions with experts in CLT construction, life cycle assessment and digital fabrication, we have considered existing research and experience in the field of cellulose-based construction while gathering basic knowledge in the details and constraints of CLT fabrication.

The physical output of our work consists of this report where we summarize and reflect on our findings for use by future researchers and design professionals, a smaller 1:1 wall section that demonstrates the cellulose-based system and a larger 1:1 prototype that elaborates on the system and showcases exposed CLT as part of our architectural concept. At current time of publication, the larger prototype is yet to be completed by Martinsons in Bygdsiljum.

We have strived for a balance between theoretical studies and practical work. We built the smaller 1:1 wall section ourselves in the workshop and explored the application of the system in a city environment through 1:25 scale models that start to reveal the architectural opportunities of CLT.

PROJECT START-UP

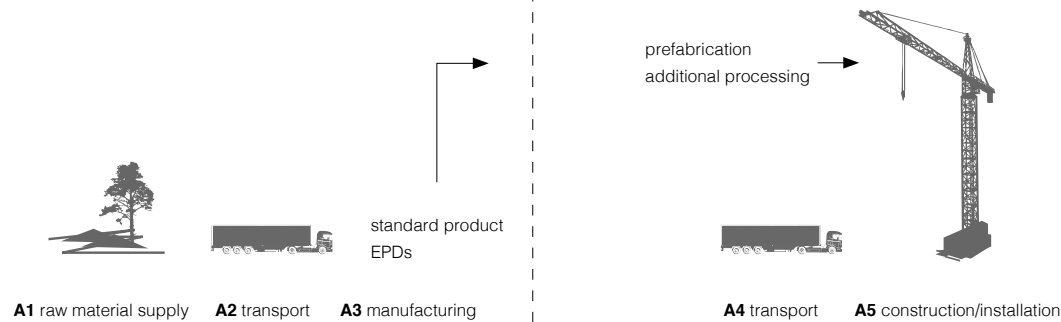
DESIGN



Life cycle approach,
a way to plan, a way to think,
a way to design!

- Where does the raw material come from?
- How is it produced?
- How to minimize waste?

- Factors with impact on transport emissions - weight, distance, volume?
- Energy on construction site?



FABRICATION

CONSTRUCTION

MODULE A1-3

production waste
↓
processed waste
(end-of-life state)

MODULE A4-5

construction waste

content overview

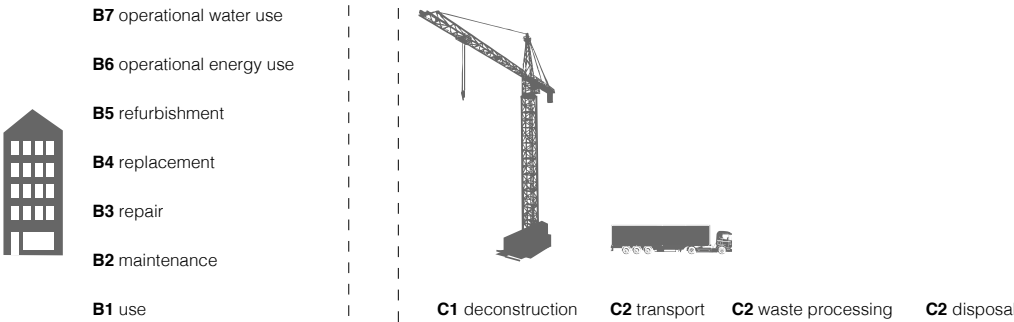
From idea to fabrication, use and afterlife. In *Urban Timber* we try to understand and problematize the different stages of the building process through a life cycle framework. The life cycle approach as a philosophical standpoint helps to align decisions with the effort to minimize environmental impact and create architectural qualities throughout a building's lifespan. We present our work in the chronological order of a building project from early decision making through fabrication, construction and beyond, with the ambition to compile our background research in an accessible output.

Diagram: The complete life cycle of the building process, standard ss-en 15978 Hållbarhet hos Byggnadsverk - Värdering av Byggnaders Miljöprestanda for standardized life cycle assessment (Svenskt Trä 2013:1, pp. 30-31).

Second life of materials?

- Energy efficiency?
- Life span of materials?
- Lifestyle?

- How to design for disassembly?
- How to minimize waste?
- What can be done with waste produced?



OPERATION & USE

END OF LIFE

MODULE B1-7

maintenance waste

MODULE C1-4

processed waste

D reuse/recycling



AFTERLIFE
beyond the system boundary

MODULE D

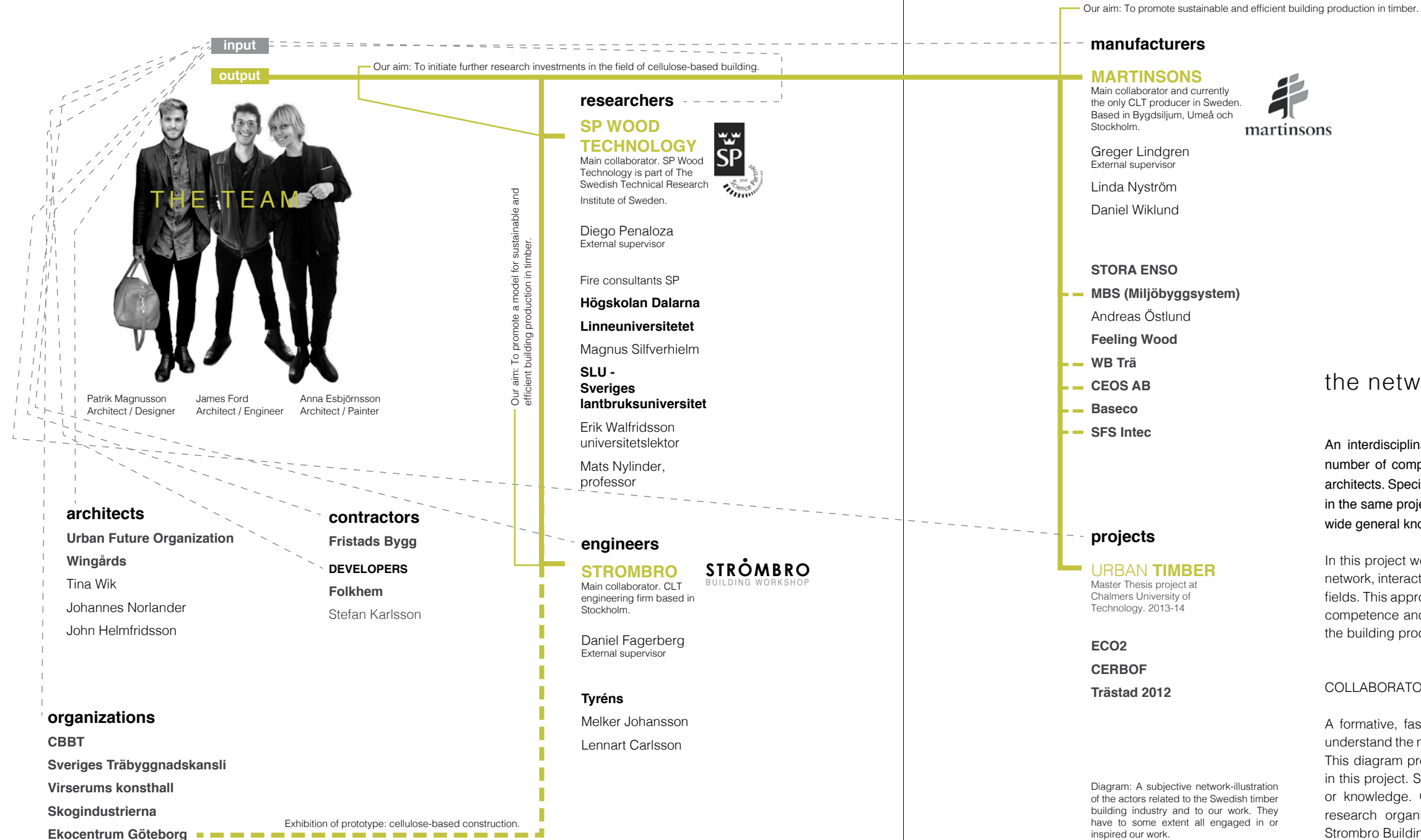


01

PROJECT START-UP

importance of early decisions

The building process is multi-phased and complex involving many actors. In early project stages crucial decisions are made that set the work direction for everyone involved. How can architects have a voice that more actively affects decision making? One way is to reclaim the traditional role as the client's confidant with greater responsibility for the building process and to present strong ecological, ethical and economical motives. The competence needed is not expected from one person but conceivable within a firm, or a network of specialists.



the network

An interdisciplinary network approach has become crucial to meet the large number of complex aspects of sustainability and to advance the relevance of architects. Specialists in different fields with a variety of competences get involved in the same projects, where the architect plays a coordinating role that exploits a wide general knowledge (Kieran & Timberlake 2004, p. 23).

In this project we try to place ourselves as architects within an interdisciplinary network, interacting with clients, manufacturers, builders and experts of different fields. This approach is meant to give us access to knowledge that will widen our competence and give us the capability to take larger responsibility throughout the building process.

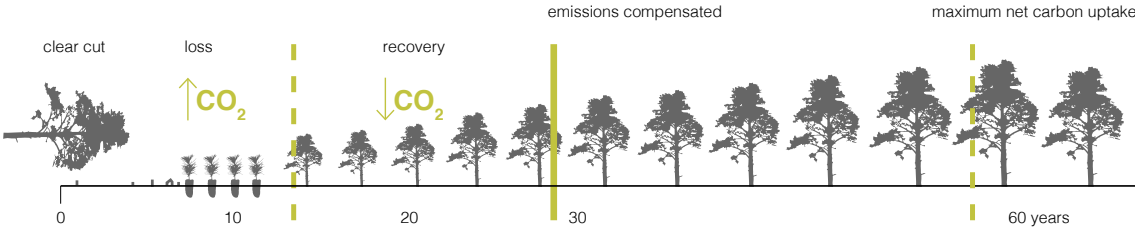
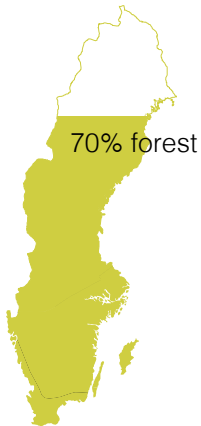
COLLABORATORS

A formative, fascinating and rewarding experience has been to identify and understand the network of actors related to the Swedish timber building industry. This diagram presents a graphical representation of the key actors taking part in this project. Some by contributing with valuable input, others with inspiration or knowledge. Our main collaborators are glulam-manufacturer Martinsons, research organization SP Wood Technology and massive timber experts, Strombro Building Workshop.

why timber

To consider a life cycle perspective and advocate timber we set out to better understand sustainable forestry. Despite a decent initial understanding of the environmental advantages of timber as a renewable and carbon-fixing structural material we were uncertain about environmental factors connected both to the short-term and long-term effects of forest management. In the following two chapters we briefly present our research connected to our main conclusions that support building with CLT.

Several aspects concerning sustainable forest management like soil, water and biodiversity are beyond the scope of this project. Instead we focus our investigations on carbon balance, considering the alarming effects of global warming. Additionally we speculate on the future of Swedish timber industry and the economical and environmental opportunities for CLT production.



AIMS FOR SUSTAINABLE FORESTRY

- 1. Protect old natural forests from deforestation
- 2. Replant forest to secure stable or growing volumes of biomass
- 3. Protect key biotopes to ensure biodiversity
- 4. Use wood for substitution of highly polluting materials and fuels
- 5. Use wood for storage of carbon in long lived products

Map: 70% of Sweden is covered with forest from the boreal belt dominated by softwood in the north and hardwood in the south. Natural forest is mainly found in nature reserves or protected areas and is estimated to account for less than 10% of the total forest land (Olsson 2011, p. 9). The total volume of biomass in Swedish forests has been growing since the beginning of the 20th century due to growth exceeding harvest (Skogsindustrierna 2013, p. 10).

Diagram: Net yield of GHG emissions between the ecosystem and the atmosphere in a clear-felled area (Olsson 2011, p. 36).

Text: Aims for sustainable forestry. Source: (Olsson 2011).

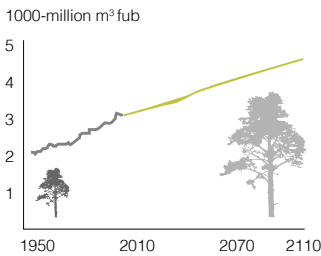
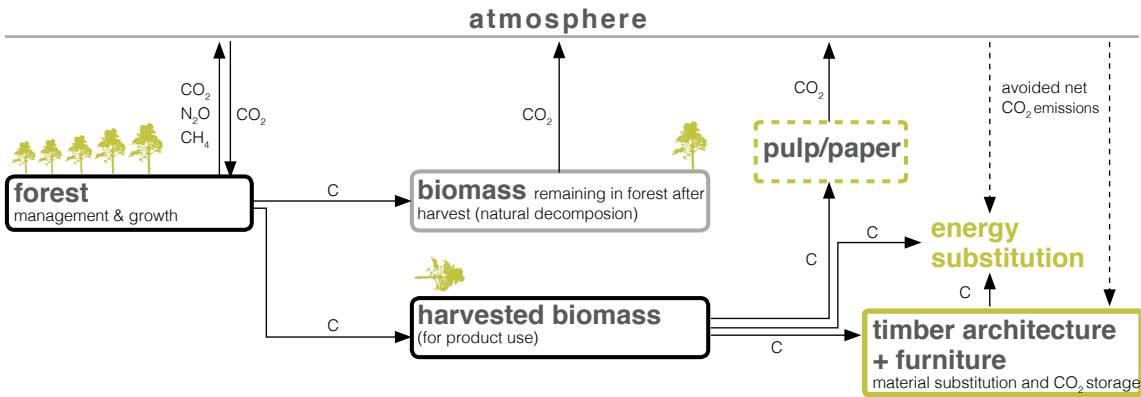


Diagram above: Historic and projected future standing stem volume on productive forest land in Sweden (Kuittinen, Ludvig & Weiss 2013, p. 27).

Diagram 2: Scheme of GHG flows and carbon stocks for forest products substituting non-forest products (Kuittinen, Ludvig & Weiss 2013, p. 25).

- 1. Autotrophic respiration = As biomass is produced by photosynthesis plants use some of the carbohydrates in the internal metabolism.
- 2. VOC = Volatile Organic Compounds are transformed into carbon dioxide in the atmosphere.
- 3. Heterotrophic respiration = Exhalation and decomposition of animals.

The boreal forests of the northern part of the globe constitute the largest carbon storage of all land ecosystems, storing twice as much carbon as the tropical forests (Olsson 2011, p. 14). Around 50% of the boreal forests have not been influenced by forestry or other human activities.

Since the growth rate declines in mature forests these trees might be close to or have reached the equilibrium where uptake and emission of carbon cancel each other out. However, in these old forests 90% of the carbon is stored in the ground and will be emitted to the atmosphere if the forest is cut down (Olsson 2011, p. 29), revealing how crucial it is to protect the remaining natural forests and conduct forestry in forests already under human influence.

CARBON SEQUESTRATION

A growing forest absorbs carbon dioxide from the air and stores it through photosynthesis when biomass is built up. It takes about 30-40 years for a replanted forest to compensate for the carbon dioxide that was released from the ground after harvest (Olsson 2011, pp. 35-36). The aged natural forest on the other hand has reached a balanced level, where uptake of carbon dioxide over longer periods of time equals the carbon released by autotrophic respiration [1], forest fires, VOC [2] emissions and heterotrophic respiration [3] (Olsson 2011, pp. 13-19). When harvesting the forest we extract biomass that would eventually have reached this dynamic equilibrium, with the amount of carbon taken up by new growth balanced by the carbon released by respiration and decay of old trees.



The potential to offset carbon emissions lies in using our forests to absorb carbon dioxide and then make use of the harvested timber as carbon storage. To achieve positive environmental effects the carbon emitting processes during manufacturing need to be minimized. In addition the products produced should have significantly long lifespans, otherwise the rate at which carbon dioxide is released back to the atmosphere does not amount to useful sequestration.

Timber used as a structural material in buildings is an obvious opportunity for longer-lasting carbon storage, which becomes meaningful through a positive substitution effect that avoids other high emitting building materials. Then taking advantage of residues from all timber processes in heating and power production as a substitution for fossil fuels can avoid introducing more carbon to the atmospheric balance.

USE OF SWEDISH FORESTS

With long-lasting carbon storage in mind we studied how our national forest volumes are distributed. Around 90 million cubic meters of forest material over the bark (m³sk) were removed from Swedish forests in 2011. This can be divided into three main flows, where 10% naturally goes to fuelwood, 45% to paper mills and 45% to sawmills. From sawing the timber about 30% of raw chips are produced, which was sold to paper mills. Additionally about 15% of chippings and shavings were generated and sent to power plants for heat and energy production.

Only around 25% of the yearly forest volume becomes sawn timber, of which 70% is exported. This leaves around 6% of the yearly forest volume to be used in Swedish timber products with some potential of local carbon storage. It is notable that out of the 6% one fifth goes to pallets and packaging, which are products with relatively short lifespans, and less than 0.1% of the timber biomass is being used in prefab timber building production with assured long-term and local carbon storage (Skogsindustrierna 2014; Eurostat Statistical Books 2011).

Diagram: A graphical representation of how Swedish forest volumes in 2011 were distributed in different fields of use, refinement and export (Skogsindustrierna 2014; Eurostat Statistical Books 2011).

m³sk = 100 % stem volume over the bark, treetop included.

m³fub = stem volume under bark, tree top excluded.

low-grade wood for a high quality product

Cross lamination of timber is a technique that was introduced in the early 1990s in Austria and Germany (Karacabeyli & Douglas 2013, p. 5). The multi-layer wooden panel is made from low grade lumber and gives use for the sapwood of a tree trunk. Mis-colouring, knots and even vermin damaged wood can be used in production of CLT (Martinsons n.d.). In order to use short wood dimensions, planks are spliced with finger joints. Each plank layer is placed perpendicular to the adjacent layers for increased rigidity and dimensional stability.

FROM PAPER TO CLT ?

The unique attribute of CLT as a structural timber building material is that it uses low grade lumber, particularly in the mid-layers of the panel. This raised the question if some of the Swedish timber currently used in short lifespan applications can be diverted to applications with long-lasting carbon storage. From brief discussions with industry contacts we found that some currently earmarked pulpwood, including timber from forest thinnings and crude grade timber, could theoretically be well suited for CLT production.

A clear obstacle is the relatively low demand for CLT, since the production volumes are vanishingly small compared to the large volumes for pulp and paper production. It's currently too costly to sort out and saw young trees from forests thinnings.



"It may be that we are facing a possible timber surplus in Sweden. Previously, we have been concerned about the opposite. Now we need a new use of our forest resources and the businesses have to survive until we find the next big volume product."

Maria Hollander, CEO for Paper Province (Englund 2013).

Shifting to CLT production, together with a higher demand for massive timber in construction, could potentially constitute a new volume product for the Swedish timber industry. Such a scenario would generate great environmental benefits considering both the carbon storage opportunities and the substitution effect of building in timber (Olsson 2011).

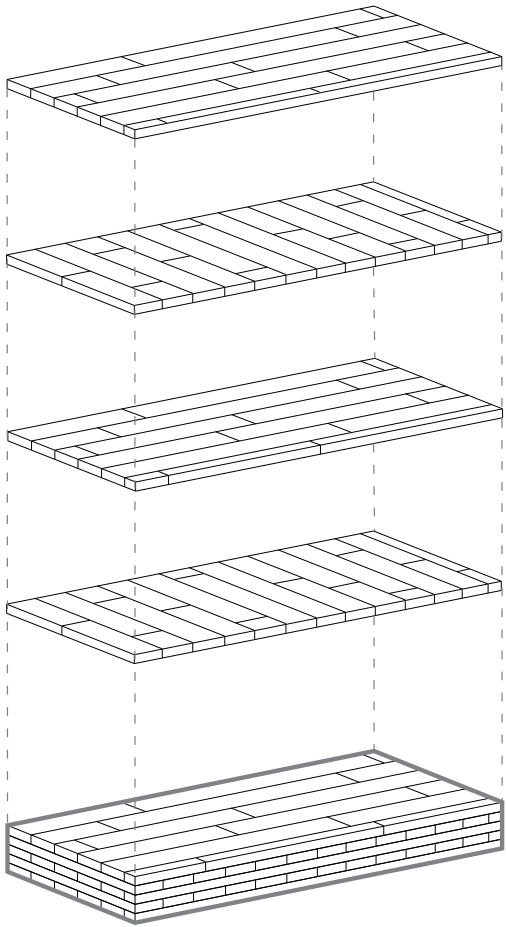


Diagram: Cross laminated timber: A structural panel made from the gluing of plank layers in opposing directions.

Image: (HYBRiD Build Solutions 2013)

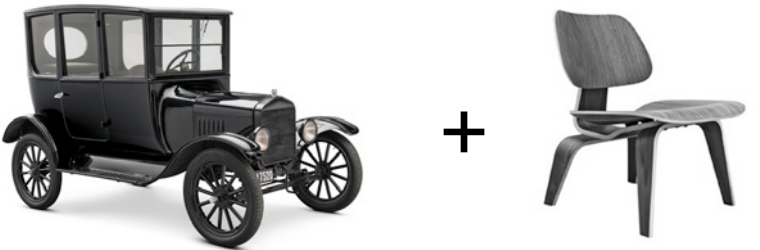
However, the demand for pulpwood has decreased in recent years which has gradually resulted in smaller sawn lumber dimensions. If the demand for CLT largely increases, a future scenario could potentially be that a new assortment of timber is sorted out from thinnings as an economically viable branch of the industry. Additionally some of the crude timber currently used in pallets and packaging could also divert to a more meaningful carbon storage, such as CLT in buildings.

Read about the possibilities for creating paper products out of down-cycled CLT under chapter 06 | *afterlife*.

prefab: a context for massive timber

The industrial economic context for building production today demands that practical architecture is built quickly, with low material cost and at a large scale to address the daunting task of housing growing populations.

Prefabrication is the idea that buildings are produced as assemblies after the manner of automobiles or aircraft, and are shipped from the factory as packaged parts or modules to be completed on site. The theoretical advantages are well documented and in some cases successful at reducing material cost, labor, construction time and waste while maintaining quality. At the same time, the outcomes have often resulted in a repetitive architecture and a uniformity of design that lacks interest and human sensibility. Along with other societal failures connected to the Swedish *Million Program*, prefabrication has earned negative associations in the public eye.



**prefab mass production =
interchangeability
component standardization**



the failed dream...

Prefabrication can in some ways be called a failed dream. A dream which tried to extend architecture from the Fordist notion of a quality product delivered cheaply and quickly to the common people as well as the Eames ideal of good design for the masses.

Image 1: (Henry Ford Museum 2013)

Image 2: (Berkshire Fine Arts 2011)

Image 3: (Fastighet och Bostadsrätt 2011)

...and a new vision

Mass customization is a concept that combines the low unit costs of mass production processes with the flexibility of individual customization. This might become possible by use of flexible computer-aided manufacturing systems, like a CNC machine. Could this be a means to a new dream for prefabrication?



CLT is an industrial product poised to take advantage of a mass production method of building construction while being mass customized through a computer driven process of CNC that allows for architectural freedom within an industrial economy of scale. Quick, light-weight construction methods with easily transported elements assembled in difficult urban situations makes for a convincing urban production strategy. Unique as a carbon-fixing structural material and volume product, CLT could become especially competitive in a future with carbon emissions taxes (Karacabeyli & Douglas 2013, p. 461). Together with emerging software environments that facilitate intelligent translation from idea to built form, massive timber is posited as an advanced building alternative for architects that choose to combine good design with economic and sustainable building in the city.

FLEXIBLE PRE-EXISTING FACTORY INFRASTRUCTURE

Some of the prohibitive aspects of prefabrication as an alternative to on-site construction come from the need to set up a factory infrastructure that is particular to each project (Smith 2010, p. 83). In many modular construction examples, factories are set up with the express purpose of fabricating modules for a specific project. In a typical prefab concrete project standard molds are built for casting each unique concrete panel. In the case for CLT, several of the primary prohibitive drawbacks of traditionally practiced prefab can be sidestepped owing mainly to the use of CNC, computer numeric control. The CNC machine can produce all range of parts defined by the designer, while the factory conditions remain the same from project to project. Factories can theoretically produce for multiple projects of totally different character simultaneously. This is a crucial cost advantage of massive timber (Smith 2010, p. 148).

**CNC mass customization =
information management
component uniqueness at no extra cost**



02

DESIGN

a systemic approach to architecture

From the pre-conditions set in the project start-up we move on to the design phase, the most common ground for architects. A systemic approach demands thoughtful design criterias, as each design decision affects the environmental footprint of a project through all coming phases of its lifecycle. In this chapter we preface some first steps for implementing an extensively cellulose-based building system by creating a vision for massive timber as a new architecture in the city. We explore the architectural expressions and soft values of massive timber with an ambition to inspire.

The Swedish building sector accounts for...



Source: Toller, Wadeskog & Finnveden 2009, p. 30, 41.

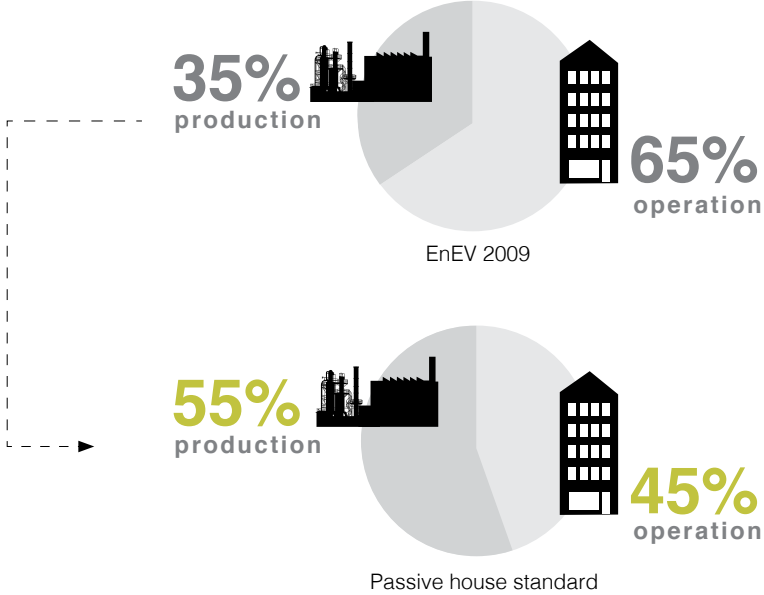
Photo: P. Magnusson 2013

TOTAL ENVIRONMENTAL FOOTPRINT DIVISION

EnEV is the German Energy Saving Ordinance (Energieeinsparverordnung) and includes standard requirements for efficient operation in energy, heating and hot water demand. It applies to residential buildings, office buildings and some industrial buildings.

Passive House Standard refers to a rigorous, voluntary standard for energy efficiency in a building, reducing its ecological footprint. The German Passivhaus standard is the origin of the Swedish version and allows not more than 15 kWh/m² per year in annual heating and cooling demand, or a peak heat load of 10W/m² (Passive House Institute 2013, p. 1).

Diagram: Illustration of the increased importance of production impacts when buildings become more energy efficient in operation (Kuittinen et al. 2013 p. 72).



environmental impact of architecture

The building sector accounts for up to 30% of the annual greenhouse gas emissions worldwide (UNEP 2009, p. 3). In Sweden 20% of the national greenhouse gas emissions can be traced to the building industry, from which only 4% derives from the operation and the remaining 16% from production (Toller, Wadeskog & Finnveden 2009, p. 30).

OPERATION VS. CONSTRUCTION

Following the energy crisis in the 1970s regulations concerning energy efficiency have gradually become more stringent yielding environmental benefits. As the energy efficiency of buildings has improved, and environmental impact of operation has decreased, a larger share of a building's total environmental impact is addressed to its production; including manufacturing of building materials, transport and construction methods (Kuittinen, Ludvig & Weiss 2013, p. 14). The environmental impact of construction is often a direct consequence of the design decisions we make as architects, and choosing local building materials with low environmental impact is the next step towards a more sustainable building industry.

PROJECT START-UP

DESIGN



Life cycle approach,
a way to plan, a way to think,
a way to design!

- Where does the raw material come from?
- How is it produced?
- How to minimize waste?

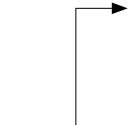
- Factors with impact on transport emissions - weight, distance, volume?
- Energy on construction site?



A1 raw material supply



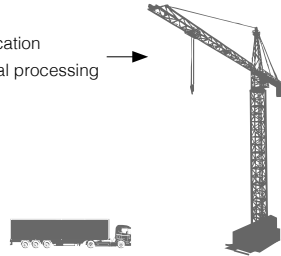
A2 transport



standard product
EPDs

A3 manufacturing

prefabrication
additional processing



A4 transport

A5 construction/installation

FABRICATION

MODULE A1-3

CONSTRUCTION

MODULE A4-5

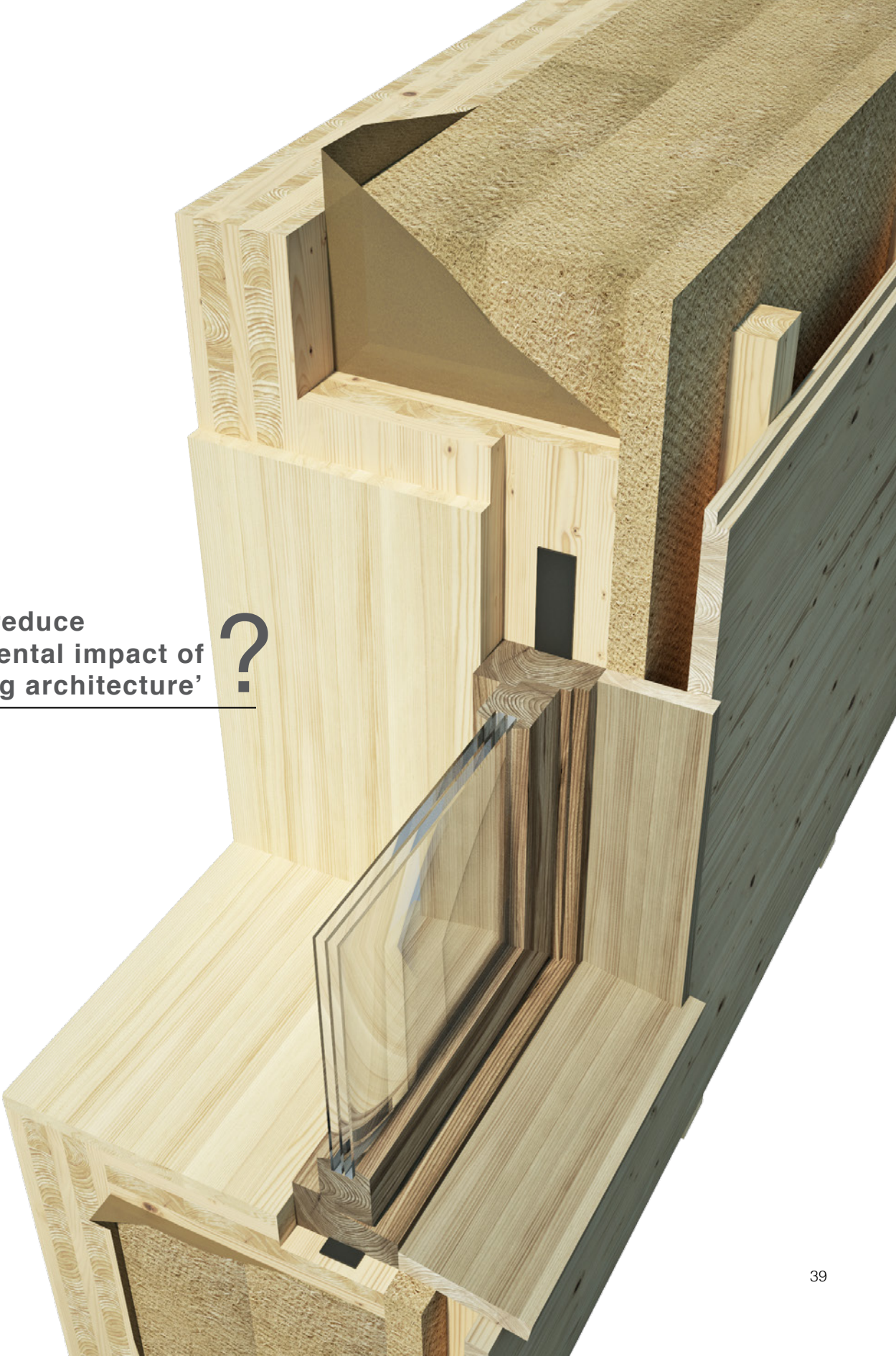
a cellulose-based building system

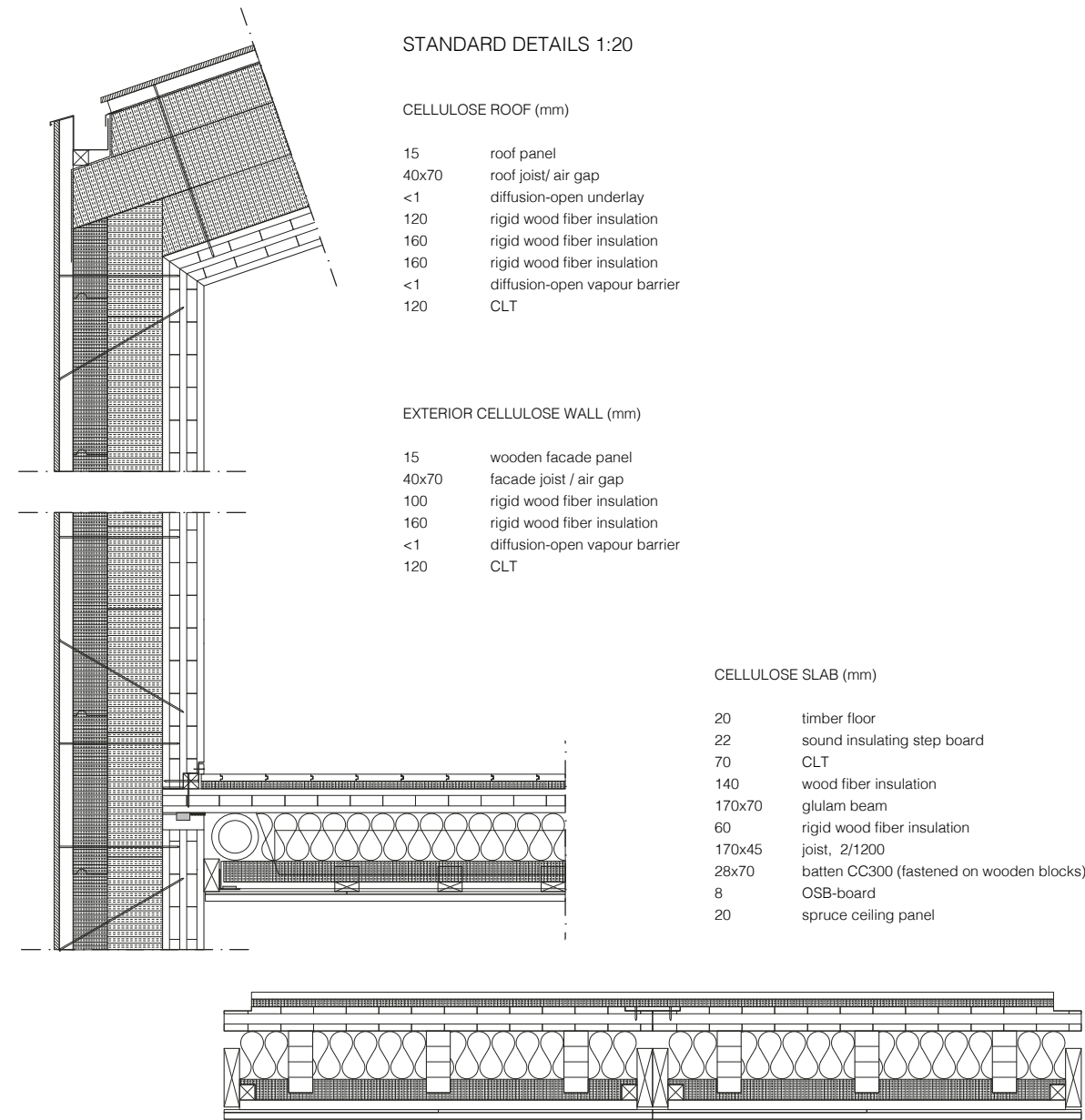
A holistic approach invites us to look at buildings at a system level. We investigate opportunities for a new building tradition focused on using renewable forest products and advocate a cellulose-based building system, using structural massive timber, where the composition of materials actively perform to create a sound and well functioning whole. A primary strategy has been to ensure that this system provides a healthy, comfortable and stable indoor climate, but also reduces the environmental impact of 'producing' architecture.

Diagram: Considerations for the environmental impact in early stages of a building's lifecycle.

Image (next page): Cellulose-based wall section using structural timber, paper sheets, wood fiber insulation, and timber cladding.

a way to reduce
environmental impact of
'producing architecture' ?





OPEN-ENDED SYSTEM

The cellulose-based building system constitutes generic construction details which comprise build-ups of wall, floor and roof. The components are designed to provide a platform which enables and encourages a diverse architecture, leaving the architect free to interpret and design with an unlimited number of detailed solutions and finished outcomes, as the point of an open-ended construction system. The rigid base of the system grows from principles of life cycle thinking that considers the composition of bio-based materials, building physics properties, minimized environmental impact and not at least the architecture of exposed massive timber.

CURRENT TIMBER ARCHITECTURE: A MIX OF MATERIALS

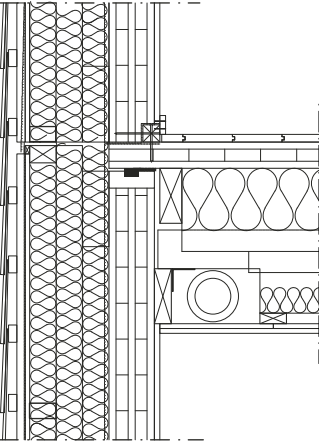
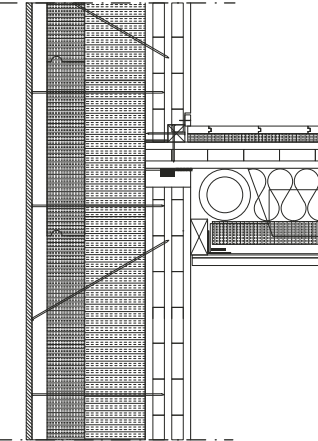
The multistorey timber projects we have encountered and studied during our research are mainly built in Sweden after 1994, due to the changed fire regulations that once again enable higher buildings in timber. Besides the structural frames these projects use several non-renewable and non-organic materials to complete the building shell and interior surfaces, more or less leaving the timber structure as a replacement for reinforced concrete. Mixing organic and non-organic materials not only gives these systems a larger environmental footprint, but also generates unnecessarily complicated and sometimes fragile solutions where the specific material properties are not considered or utilized. Plastic sheets are used to achieve airtightness in constructions that become vulnerable to ageing and mechanical damage (Janols et al. 2012, p. 7), with risks of trapped condensation and moisture causing mold to grow.

EXPOSED TIMBER IN A DIFFUSION-OPEN BUILDING ENVELOPE

The combined features of massive timber offer essentially the same thermal properties as a heavy concrete structure (Simonson, Salonvaara & Ojanen 2001). However, the good properties of massive timber aren't fully utilized when covered with gypsum. All wood-based products in the cellulose-based system offer hygroscopic properties which allow them to absorb and release moisture. Diffusion-open vapor barriers can be used to ensure airtightness, but the principle is to let the building envelope breathe by taking up, storing and releasing moisture. This gives a pleasant indoor climate and better air quality. Read more about thermal properties connected to energy and indoor climate under chapter 05 | operation & use.

Drawings (previous page): Standard details of the cellulose based building system 1:20.


Photo: Cellulose-based wall build-up (P. Magnusson 2014).

REFERENCE WALL		CELLULOSE-BASED WALL	
			
(mm)		(mm)	
3-10	shingles of cedar	15	wooden facade panel
22	batten / air gap	40	facade batten / air gap
22	batten / air gap	100	rigid wood fiber insulation
<1	weather shielding sheet	160	rigid wood fiber insulation
12	plywood	<1	diffusion-open vapor barrier
70	mineral wool / joist c-c 600	120	CLT
140	mineral wool / joist c-c 600		
<1	plastic sheet		
120	CLT		
15	fire protecting gypsum		

STEP-BY-STEP COMPARISON

The generic details of the system are formed through the design criteria described above. This step-by-step wall comparison to the reference system used in *Strandparken* will further describe the build up and principle behind the cellulose-based system.

1. Using massive timber as a structural material gives the opportunity to remove the gypsum leaving the exposed timber as the finished internal surface. This requires a visible timber quality and a higher level of precision. Read more about the consequences of fire protection under chapter 05 | *operation & use*.

 Building materials part of conventional timber buildings that are not renewable (bio-based).

Drawings: Wall sections of reference wall and *Urban Timber* cellulose-based wall 1:20.



In October 2013 we made a study visit to Strandparken in Sundbyberg and met with a representative from Folkhem, who is the commissioner of this housing project designed by Wingårdhs. Strandparken is the latest massive timber housing project of Martinsons, who delivers the whole structural system.

Building in massive timber is still a construction method under development and each new project makes room for further investigations and improvements. In several ways Strandparken is a forefront multi-storey massive timber project with fine architectural details and exposed timber in facade, entrance and stairwells.

Folkhem has a clear environmental profile, so the natural next step would be to carefully choose complementary materials, like those proposed in the cellulose-based system.

Photo: A. Esbjörnsson 2013

2. With higher precision assembly the plastic sheet behind the CLT can be removed, since the massive timber panel is airtight itself (Janols et al. 2012, p. 7). Good element meetings further act to keep air out of the building. However, cracks in the CLT may occur over time and a diffusion-open sheet can be used to secure an airtight construction. More on airtightness and energy under chapter 05 | *operation & use*.

3. The insulating mineral wool in the reference system is replaced with rigid wood fiber insulation. In Strandparken a framework of wooden joists, almost strong enough to work as the load bearing structure alone, are used to keep the insulation in place and hold the facade. This is not necessary with the rigid wood fiber insulation boards since long screws hold the facade, by being put through the facade battens and through the rigid insulation into the CLT. The screws are put along the vertical facade battens every 300 mm. The screws at the top and on the bottom of each batten are longer since they are fastened at an angle to achieve rigidity and optimize load-carrying.

4. Mineral wool has weak hygroscopic performance and doesn't buffer moisture. (Simonson, Salonvaara & Ojanen 2001, p. 98). Therefore, a proper weather protection is needed to ensure that water does not penetrate the construction and accumulate locally which may result in mold growth. In this case, an impregnated plywood and a weather shielding sheet is used. The wood fiber insulation on the other hand has very good hygroscopic capabilities, which means that water is absorbed and released in balance with the moisture level of the surroundings (Simonson, Salonvaara & Ojanen 2001, p. 98). The outer layer of wood fiber board is waxed to provide the needed weather protection.

5. Both systems feature tasteful examples of timber cladding, which acts nicely to declare the timber architecture beneath.

LCA: life cycle assessment

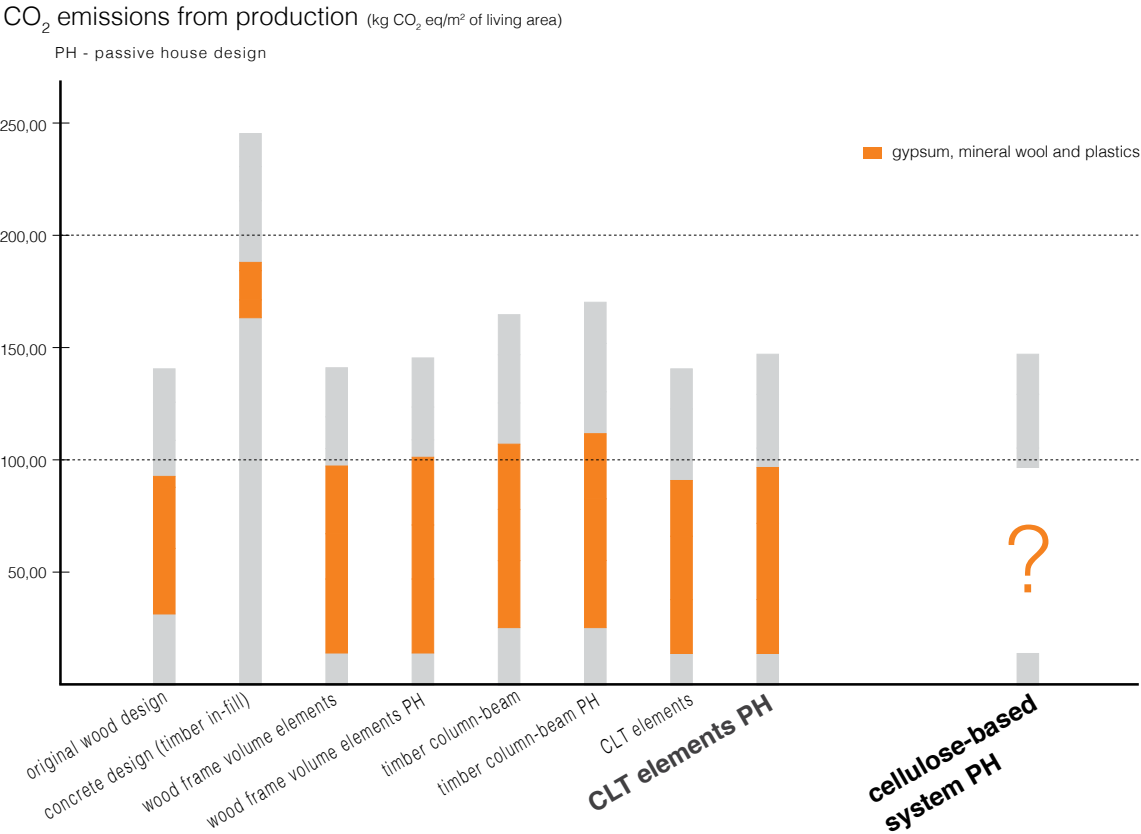
To demonstrate the relevance of the cellulose-based system and support it with concrete arguments we sought to perform calculations and comparisons that would assess how well it performs from an environmental point of view. The comparative study presented here is performed in collaboration with SP Wood Technology (Technical Research Institute of Sweden) and is based on their previous research. It presents carbon emissions from production alone to bring light to the importance of material selection. This chapter also introduces LCA as a future design tool and possible means for architects and other disciplines to make conscious design decisions that can reduce the negative impacts of construction.

LCA AS AN ASSESSMENT TOOL

Life Cycle Assessment (LCA) is standardized in the 14000 series of environmental management standards published by the ISO, International Organization for Standardization (König, Kohler, Kreissig & Lützkendorf 2010, p. 39). The standardization enables comparable studies over projects and nations. An LCA can be performed for every product and service, or for combinations of them, where a systematic analysis describes the resources drawn from nature and the environmental effects over their entire lifespans. In the past only local effects of manufacturing were considered, whereas the intellectual principles behind LCA indicate a more informed and holistic consideration in products and services. A brief survey revealed that very few architectural offices in Sweden currently integrate LCA in their daily design work.

THE WÄLLUDDEN CASE STUDY

SP Wood Technology released the publication *Life Cycle Assessment of Different Building Systems: The Wälludden Case Study* in may 2013. SP Wood Technology is also part of the European project *ECO2* and the Wälludden study is partly presented in the book *Wood in carbon efficient construction - tools methods & applications* (2013). The original study is a complete life cycle analysis of various building systems theoretically applied to an existing building in Växjö, built in 1995. The study compares the original light wood frame design to a concrete structure with exterior wood-frame infill walls, which was initially considered when the building was constructed. These two are compared with three other systems in timber; a volume element system, a flat element system in CLT and a column beam system with LVL and glulam beams. Passive house alternatives for all these three systems were also evaluated.



ORIGINAL STUDY OBSERVATIONS

When we initially started to distinguish the impact of the different materials used in the evaluated systems we found that the timber products have relatively small impact in all systems. The concrete system clearly has the largest environmental footprint and if the in-fill walls had been in lightweight steel, instead of timber, the estimated total carbon emissions would have further increased. All timber systems have significantly lower impact than the concrete system, but show small differences among themselves. What is most astonishing is the fact that the non-renewable and non-organic materials; mineral wool, gypsum and plastics account for around 50% of the environmental impact in all timber systems (Peñaloza, Norén & Eriksson 2013, p.30). Another interesting point is that the extra materials needed to achieve passive house-standard do not greatly increase the total carbon footprint of the building, leaving good arguments for highly insulated buildings.



Diagram: Environmental impact from production of the different building systems evaluated in the Wälludden study (Peñaloza, Norén & Eriksson 2013, p.30).

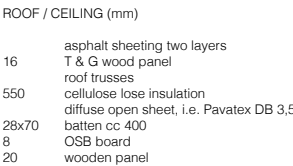
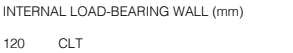
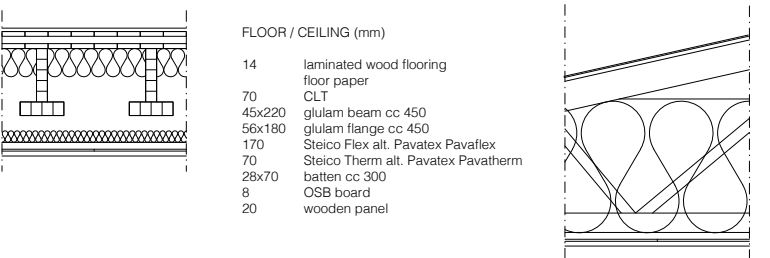
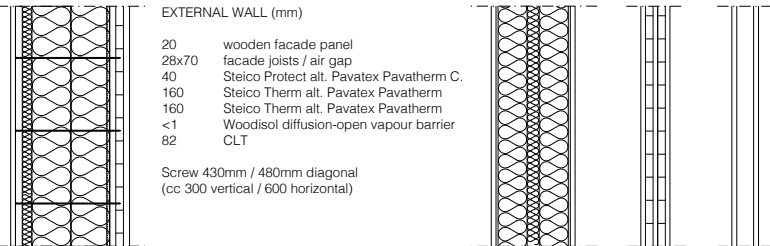
Photo: (RM Fönster 2013).

NEW STUDY DELIMITATIONS

SP's original study covers the carbon footprint as well as the primary energy requirements of all the processes involved in the life cycle of the studied building during normal operation. The graphs shown here present only carbon emissions from the production phase which include manufacturing of building materials, transport, and construction emissions. This type of environmental impact is often referred to as the 'embodied energy' of a building. Notice that the carbon stored in the timber is not considered in this study, which would otherwise further compensate for the environmental impact of the timber systems.

NEW STUDY EXECUTION

We contacted Diego Peñaloza, environmental engineer at SP Wood Technology, who would assist and guide us through the process of complementing the original study by assessing the cellulose-based system. We visited SP's office in Stockholm and Diego demonstrated their material database and the principles behind the Wälluden case study.

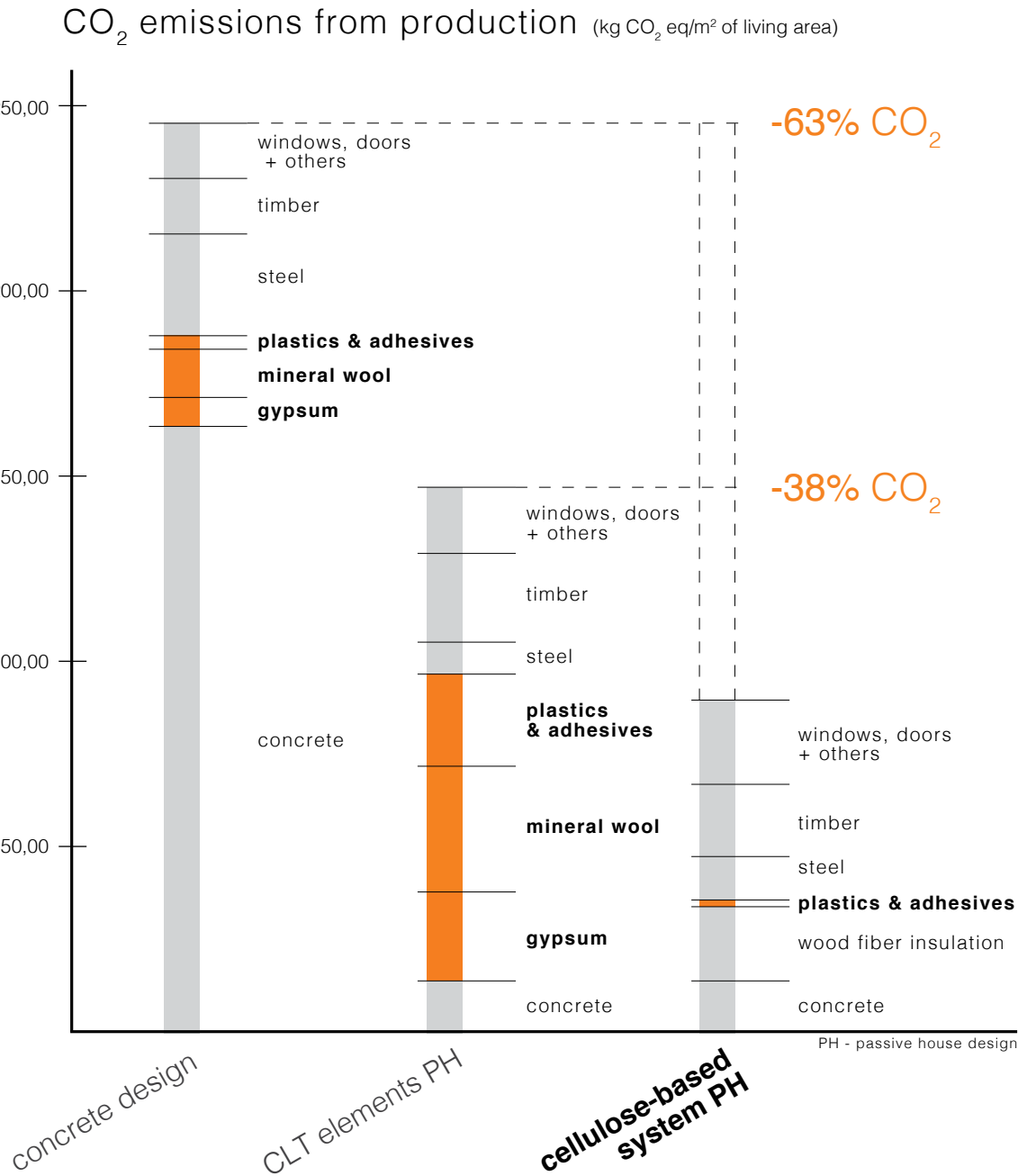


KOMPONENT	PRODUKT/MATERIAL	TJOCKLEK (mm)	BREDD (mm)	ANTAL/m²	DENSITET (kg/m³)	Fuktkvot (%)	EPD	MASSA (kg/m²)
Bärande yttervägg area YV2: 1070 m²	massive wooden board, spruce	20		1	450			9
	screw for fastening of facade board			10				0,0652
	wooden batten	28	95	1,67	427	18		1,89
	screw for fastening of insulation and batten CC300/600			6				0,8244
	comments: all the EPDs for the pavatex products are in the info sheets, help?	100		1	180			19
	Rigid wood fibre insulation, Pavatex Pavatherm plus	100		1	140			14
	Rigid wood fibre insulation, Pavatex Pavatherm	160		1	140			22,4
	Polypropen textile, wind stopper, Pavatex LDB 0,02	0,72		1				0,18
	CLT	82		1	400	10-12		32,8
	wooden batten	45	70			18		0,45
Lägenhetsskiljande vägg area LSV: 527 m²	massive wooden board, spruce	20		1	450			9
	OSB (dont know the name for this)	8		1	650			5,2
	wooden batten CC 600	45	120	1,67	427	18		3,84
	Rigid wood fibre insulation, Pavatherm Pavaflex	120		1	55			6,58
	Rigid wood fibre insulation, Pavatherm Pavaflex	50		1	55			2,74
	Rigid wood fibre insulation, Pavatherm Pavaflex	120		1	55			6,58
	wooden batten C 600	45	120	1,67	427	18		3,84
	OSB	8		1	650			5,2
	massive wooden board, spruce	20		35	450			9
	screw for OSB			35				0,05
Innervägg Area: 195 m²	CLT	120			400	10-12		48
	Övrig innervägg, icke bärande	20			450			9
	wooden batten	45	70	1,67	427	18		2,24
	Rigid wood fibre insulation, Pavatherm Pavaflex	70	560	1,65	55			3,5574
	massive wooden board, spruce	20		35	450			9
	screw for massive wooden board							0,1
	nail			3,64				0,03
	wooden joists	45	70	0,8	427	18		1,08
Slab 1 area: 857 m²	laminated wooden floor	14		1				8
	Lurppapp, (dont know the eng name, but cellulose based paper)	0,8		1				0,4
	CLT	70		1	400			28
	wooden joist LK20 CC 450	45	220	2,5	450	18		11,1375
	wooden joist L40 CC 450	56	180	2,5	450	18		11,34
	Plywood	12	158	0,45	500			0,45
	wooden joist	45	220	1,6639	427	18		7,0338
	Rigid wood fibre insulation, Pavatex pavaflex	140		1	55			7,68
	Rigid wood fibre insulation, Pavatex Pavaboard	60		1	220			12,59
	wooden batten	28	70	2,5	427	18		2,0923
Slab 2, staircase Area: 75 m²	OSB	8		1	650			5,2
	massive wooden board, spruce	20		13,2	450			9
	screw for OSB			13,2				0,01992
	screw for massive wooden board							0,02772
	CLT	120		1	400			48
	wooden joist	45	220	1,6639	427	18		7,0338
	wooden batten	28	70	2,5	427	18		2,0923
	OSB	8		1	650			5,2
	massive wooden board, spruce	20		13,2	450			9
	screw for OSB			13,2				0,01992
Roof element, Takbjälklag Area: 300 m²	Yttrapp + underlagspapp							7,525
	wooden joists							13,0769
	wooden batten							16,1383
	gluelam beams							7,78927
	Kerto, type of gluelam							0,11667
	steel plates for nailing							1,81973
	Bestag steel							0,46453
	Bult, stålskåring, steel							0,21313
	nail							0,448243
	wooden batten	28	70	2,5	427			2,0923
Complementing material walls	Rigid wood fibre insulation, Pavatex Pavaflex	550	1	1	55			30,25
	Polypropen fabric with							
	polyolefin-copolymer covering Pavatex DB 3,5	0,48		1				0,11
	MDF	16	390	1,32	750			
	Steel, gängstäng	25	40					
	Sylomer	12	158					
	Steel sound device	45	70					
	Plywood							
	wooden batten							
	wooden batten							
Roof element, Takbjälklag Area: 300 m²	glutningsände, steel							
	CLT balcony							
	gluelam							
	MDF							

Drawings (previous page): Cellulose-based system applied to Wälludden.

Spreadsheet: Template from Wälludden study with the integrated numbers generating impact of each material used in the cellulose-based building system.

To assess the cellulose-based system in a context comparable to the original study we drew detailed drawings of partition walls, slab and roof applied to the construction details for Wälludden. We used EPDs (Environmental Product Declarations) for each product and quantified the mass of each material per square meter. These numbers were sent to Diego who integrated them into the template for Wälludden and sent us new detailed diagrams showing the impact of every material in the cellulose-based system.



DETAILS

1. Both systems have the same amount of concrete in the foundations.
2. In the cellulose-based system the gypsum is removed and the plastic usage is minimized.
3. The wood fiber insulation has much less environmental impact than the mineral wool, but due to the higher density in the rigid wood fiber insulation more mass per square meter is used.
4. The impact from steel is a little higher in the cellulose-based system due to the long screws, but receives an overall reduction due to the removed timber frame. Also a sprinkler system, necessary when exposing timber, accounts for some additional steel impact.

a way to reduce environmental impact of 'producing architecture'



THE RESULTS

The CLT system in the study was originally provided by Martinsons and has basically the same features as the system used in Strandparken. To maintain comparability within the study both the CLT system and the cellulose-based system are represented with passive house design.

The results, a 63% reduction of CO₂ compared to the concrete alternative and a 38% reduction of CO₂ compared to the reference CLT wall, reveals that this study can potentially be of great importance for the future discourse of sustainable construction. Hopefully these findings together with our presented arguments can contribute to a new way of looking at timber architecture in Sweden and lead to further research.

Diagram (previous page): The Carbon assessment of the concrete system and conventional CLT system of the Wälludden study complemented with the cellulose-based system.

Image: Cellulose-based wall section using structural timber, paper sheets, wood fiber insulation, and timber cladding.

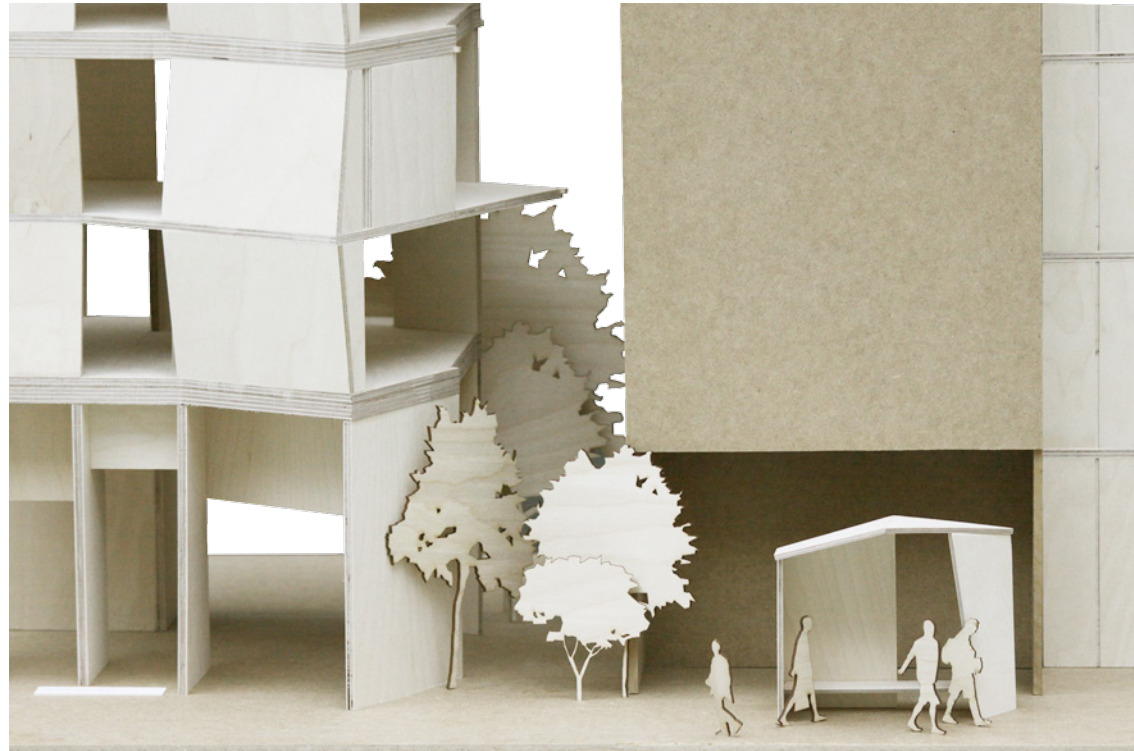


massive timber: toward an architecture

This chapter exemplifies how technology meets craftsmanship to yield high quality detailing within a practical economy of scale, taking advantage of the customization made possible by CNC technology. The cellulose-based system is intended as a design platform where low impact materials are used to achieve a versatile architecture that expresses the quality of massive timber. The designs presented in this chapter hint at the diverse aesthetic identity which could grow into an urban architecture that re-introduces timber in the city.

CLT is often touted as a competitor or replacement for concrete, and in many of the existing examples of multistorey massive timber buildings it is not obvious that the structural material is wood. This is one way to transition to a new structural system but it does not exploit or demonstrate the nature of the material structurally or architecturally.

Before engaging in the opportunities for architectural expression using CLT, we go through some essential principles that guide the design ideas presented in this thesis. At the core of a pervasive cellulose-based building system and a systemic approach to urban development, we imagine an architecture that can become a common mode of building that accounts for ease of assembly and efficient use of material in balance with basic environmental and building physics performance.

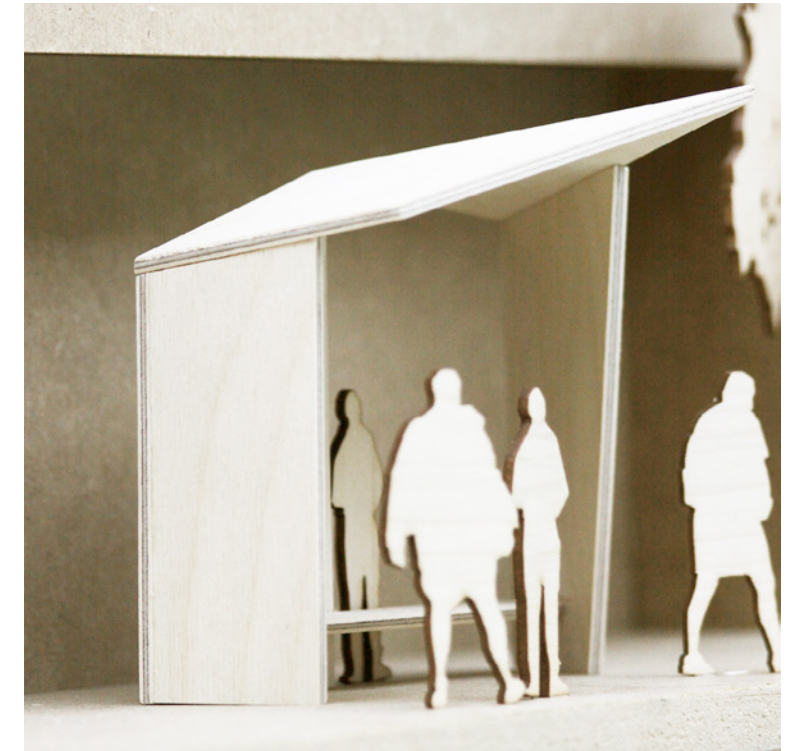


THE RIGID PLATE

A plate that performs both in tension and compression is considered 'rigid'. A common example is a steel reinforced concrete slab which was invented to meet a demand for structural performance that allowed for flat floor slabs and walls meant for a common pragmatic architecture. The reinforcement of steel liberates concrete from having to perform only in compression as it does in arches and domes. Therefore it is easy to miss the point about how naturally cross laminated timber in itself solves the problem of the flat slab. With similar structural properties but nearly 1/5 the density of steel reinforced concrete (Karacabeyli & Douglas 2013, p. 532), cross laminated timber is a unique product with its own implications for structural performance and expression as a lightweight structure. Concrete structures rely on their dead weight for stability while the structural thicknesses of tall CLT buildings are driven more by sound and deflection considerations than by strength capacity (Karacabeyli & Douglas 2013, p. 108).

Images on the following pages are photos of models that we built in scale 1:25. The models were part of an architectural exploration and presented in the master thesis exhibition at Chalmers Architecture.

Also urban furniture (e.g. bus stops, benches, bike parking and garden roofs) can be made fully or partly out of CLT. The picture on the next page shows a model of an urban bus stop in massive timber.



LANGUAGE OF CLT

It is important to realize that massive timber is a class of timber building decidedly different from existing timber frame and common notions of what a timber building should be. It is not enough to replace concrete with massive timber placeholders but to realize the potential of a material as it emerges to form a new building tradition. As a subtractive volumetric panel, CLT is different from traditional timber structures employing ribs, beams or trusses.

To explore the rigid CLT plate as an architectural element we strive to use its structural and architectural qualities, which follow from the conditions of the production. The diagrams presented on the next spread demonstrate some qualities of CLT that we believe could be part of expressing the language of massive timber.



SURFACE & EDGE

Interior walls can be built from a single CLT panel. The exposed wooden surfaces and the uncovered edges enhance the notion of mass and the homogeneity of the wall.



CLT + GLULAM

Where more openness is desired the CLT system could preferably be combined with glulam beams that could either be hung on steel hangers on the wall or be placed in cut outs made by the CNC machine.



THE RIGID PLATE I

Cross lamination makes the CLT panel stiff enough to resist tension, compression, and shear forces in multiple directions which allows a rigid timber slab to be hung from the ceiling without additional beams or bracing.



WALL CUT-OUT I

Irregular and even organically shaped wall openings are easy to make in the CNC machine, creating interesting transitions between rooms.



WALL CUT-OUT II

With the same principle as wall cut outs, window openings are simply made in the CNC. Also here the cuts could be straight or organic to fit any type of window. Angled cuts could be made to let more light in.



THE RIGID PLATE II

The stiffness of the plate also gives the possibility of large horizontal spans to create wide unbroken panoramic views.

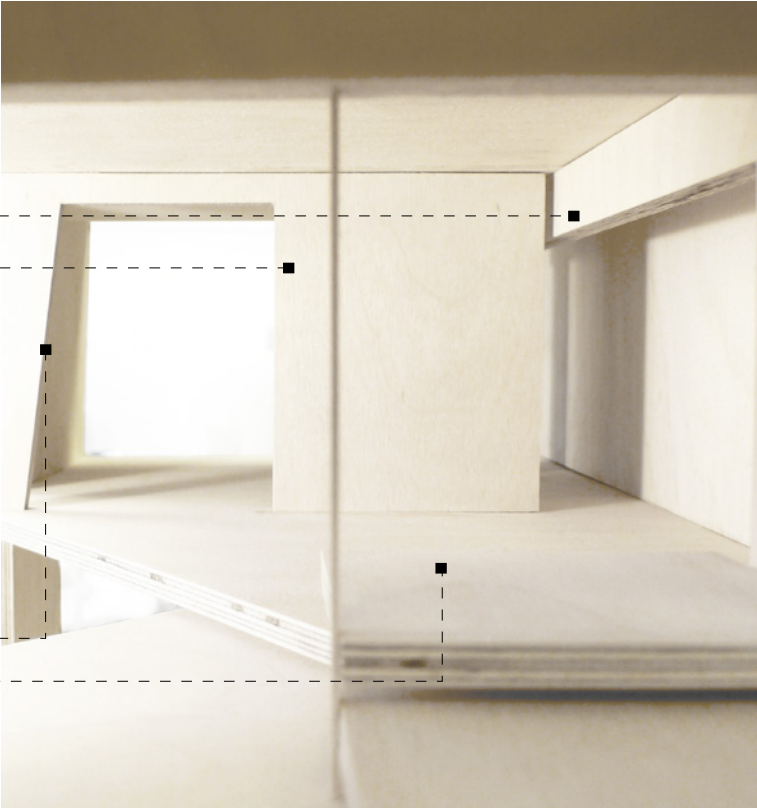
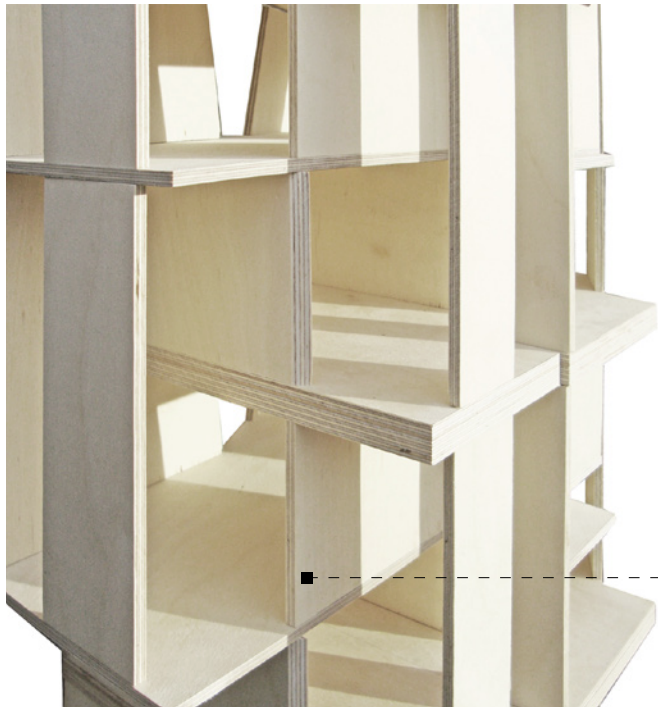


Image: Model of apartment exemplifying the structural properties and architectural opportunities of massive timber.



FLOATING VOLUMES

Floating volumes are suggested by an alternation between solids and voids, lights and darks, possibly made by a misalignment of vertical walls between floors as a quality of the dimensionally stable rigid plate more simply achieved with CLT than concrete.

ARTICULATING MASSIVE TIMBER IN BUILDINGS I

In a deployment of the cellulose-based system as a structural prefab panel the architecture envisioned makes an aesthetic point of the flat-pack prefab plate as an economic means and necessity, but in customized configurations that exploit the inherent lightness of the material. Most often, tall lightweight structures are structurally driven by wind load considerations as they are at risk of overturning. The structural strategy becomes more about restraining the building and stiffening its shear wall action (Falk 2005, p. 96).

In this conceptual model the lightness of the timber is exemplified in a way that tries to be honest about the structural action by making a point of the tension cables holding the building to the ground. Since floor slabs are structurally driven more by service considerations like sound and vibration we propose alternating walls between stories so that the rigid plate can come into play as it works in bending and shear, giving a lightness and depth which comes from an aesthetic of alternating solid and void. Cantilevers take advantage of the inherent rigidity and offer a flexibility of architectural expression.

ANGLED WALLS

Obliquely angled walls can break the uniformity of a flat panelized facade adding depth and contrasting angles of light reflection to affect an alternation between dark and light.

EDGES

Edges articulated as gaps create organizing boundaries for the components in the facade and allow a dramatic light permeability and a sense of order and tectonics.

TENSION CORDS

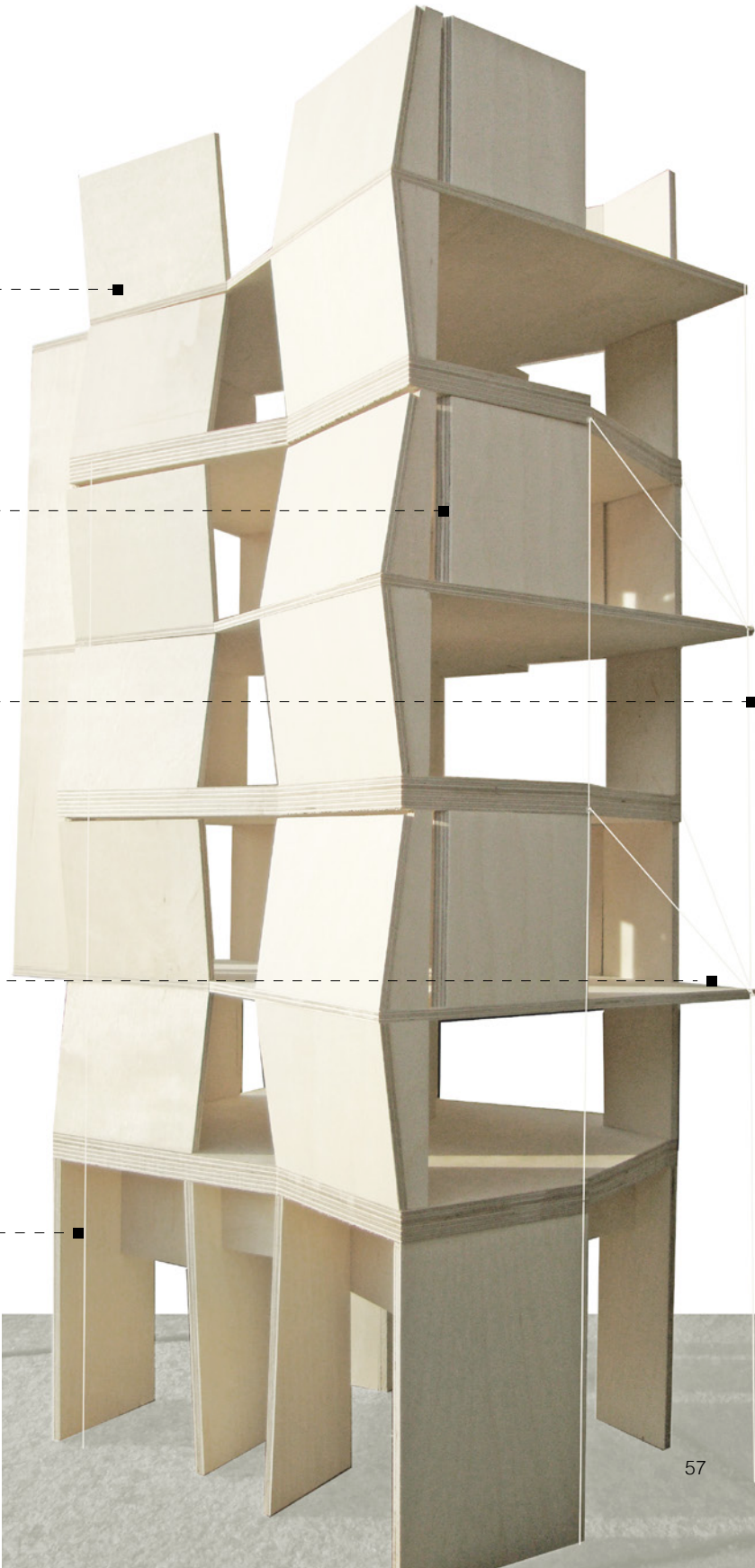
Tall lightweight structures are structurally governed by wind & uplift stability. The cables demonstrate the structural action of tensile resistance and come forward as an aesthetic of lightness.

CANTILEVER

Some wall panels are primarily in tension and depend on the rigidity of the floor slab to evoke the notion of a floating volume.

STREETSCAPE

At the ground floor the panel turns 90deg to make a permeable street front which directs focus through the plane of the facade and maintains a structural cross section allowing the mass above to appear lighter.





' PANEL

It's a point to articulate the rigid prefab plate to give the impression of an ordered assembly that might drive a massive timber identity that's more than a mere substitution for monolithic concrete architecture.

' CLADDING

A plywood panel gives a timber face toward the city, extends the aesthetic of a panelized system, is low cost and easy to replace.

WEDGE OF LIGHT

The acute angle is an opportunity to make a natural wedge from the meeting of right-angled plates and funnel light over the exposed wooden surface of the interior.

Images: A structural concept for rigid plates and a timber facade in the city.



ARTICULATING MASSIVE TIMBER IN BUILDINGS II

Preferably the nature of the material as a structural panel comes forward as an aesthetic that brings character and identity. In this model we aim to articulate the rigid prefab plate and give the impression of an ordered assembly of smaller panels in varied proportions. This gives a sense of how it is put together and carries the signature of the technology used in fabrication. It's a point to use the different available thicknesses of CLT in a gradient that expands all the way to the panelized cladding. In this way the panel adapts to various tasks of architecture.

Taking some inspiration from vernacular building traditions, an architecture is imagined that makes straight-forward use of the rigid plate in a way that expresses a unique pattern language that isn't distinctive in the sense it can be viewed as an object but that it feels like part of a system and a process. Vernacular architecture bears a truth about how it was made and what it's made of and this is always directly linked to economic, technological, and material conditions that evolve over time.



ARTICULATING MASSIVE TIMBER IN BUILDINGS III

One way to create dense urban environments is to build on top of existing structures. In this model we demonstrate deployment of the cellulose-based system as a four storey row house added to an existing building; find more information under chapter 04 | *construction*. Designing additions to existing buildings demands a careful approach. However, the addition doesn't necessarily have to resemble what has already been built. Contrasting with the existing structure and changing the proportions can mark the addition for its unique time and context and help to create a diverse and dynamic cityscape.

Images: The model of the four story row-house was built to show how easily elements can be mounted in a dense urban area. The model is a step by step visualization of a building under construction.





TEXTURES AND TREATMENTS

Facades and interior surfaces affect us with their appearance and sensitivity. We experience these materials both from up close and far away, like background scenes of our everyday lives. We believe in exposing timber and letting it generate architectural qualities. The shades, fibers and grains of the organically grown material evoke warmth and resemble life.

"Generally, my opinion is that wood should not be painted, it is a Swedish perception created by the paint industry. There are no painted houses in Austria and Switzerland. Painted facades require expensive maintenance and are mostly perceived as completely apart in the landscape."

(Johannes Norlander, architect and owner of Johannes Norlander Arkitektur AB, mail correspondence about timber and treatments, 2014-01-09).

EXTERNAL USE OF TIMBER

The current Swedish building code requires residential sprinklers to enable a free use of timber cladding in residential buildings with more than two floors (Tråtek 2007, p. 41). More fire-related aspects are found under chapter 05 | operation & use. Using timber as a cladding material is a relatively cheap investment, but in multistorey applications maintenance can be difficult if the timber is painted (3).

Some species of wood, like cedar (2) have naturally resistant properties and protection from outer mold growth and rotting. Swedish pine or spruce could benefit from protective treatments, without losing the wooden expression. Toxic impregnations should be avoided and replaced with environmental alternatives. Heat treatment (4) is a process that alters the cellular structure and artificially ages the timber to become more resistant. Wood tar (5) is produced through dry distillation of dead pine trees and stumps and is a traditional, well-tested wood protection often used for boats.

Visualization: We envision that timber in various forms can be a naturally visible element in the urban structure.

Photos (next page):

- 1. (Atelier des Granges 2012)
- 2. (A. Esbjörnsson 2013)
- 3. (private photographer)
- 4. (Thermowood Das original n.d.)
- 5 & 6. (Photographer R. Norlander)



1.



2.



3.



4.



5.



6.



INTERNAL USE OF TIMBER

Building with CLT automatically gives the opportunity to leave an exposed timber surface internally. This requires a visible wood quality and a higher standard of detailing that leaves the exposed joints of wall elements well designed or hidden.

It's common for residents of a newly constructed building to decide wallpaper or wall color. In the case of a building constructed with the cellulose-based system the residents should be able to choose an untreated wooden surface. The expression can of course be toned down by wood stain, lasures or even covered with paint or wallpaper. Combinations of materials and textures from tiles, patterned wallpapers can possibly generate more interesting and dynamic interiors.

Visualization: Exposed CLT combined with other wall finishes.

Image: Close-up photo of the prototype that was built in scale 1:1 for the master thesis exhibition. The staircase is an experimental showcase for creating fixed furniture using CLT.





Image: Visualization of the interior from the add-on row house seen in *ARTICULATING MASSIVE TIMBER IN BUILDINGS III*.

full scale prototypes

To summarize our project and the suggested improvements we envision for mass housing we designed two full-scale prototypes, a 3 meter high apartment cutout and a smaller wall section. The large prototype was an exercise in design and project delivery toward the manufacturer, it is yet to be produced and will be owned by Martinsons. The small wall section we built ourselves for the exhibition, as a practical and tangible exercise.



Visualization: The interior part of the large prototype.



Image 1: Plywood cladding in the small prototype is treated with a natural tar mixed with turpentine and black pigment.

Image 2: The double layer of rigid cellulose insulation is visible here together with separating battens.

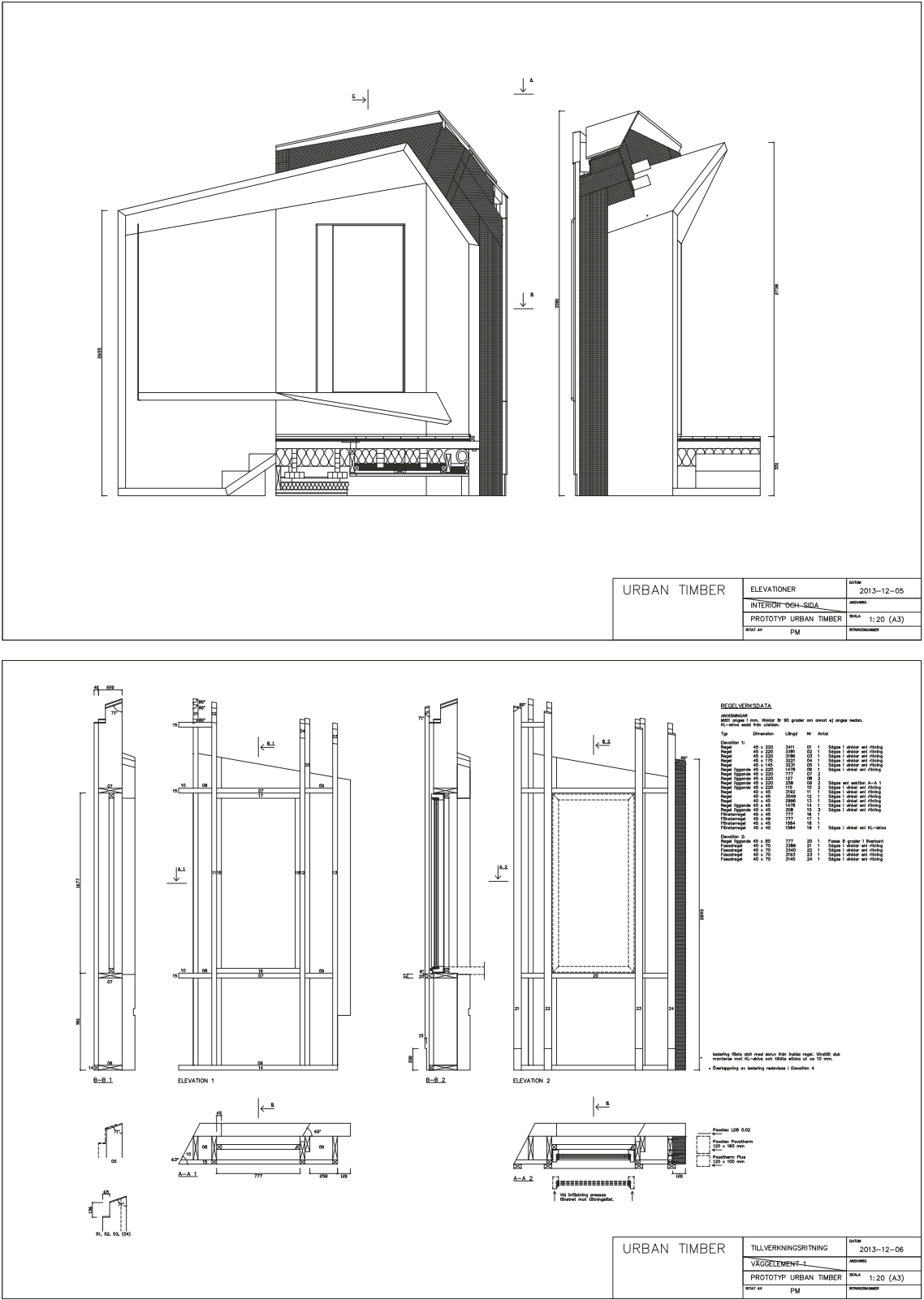
Photos: P. Magnusson 2014

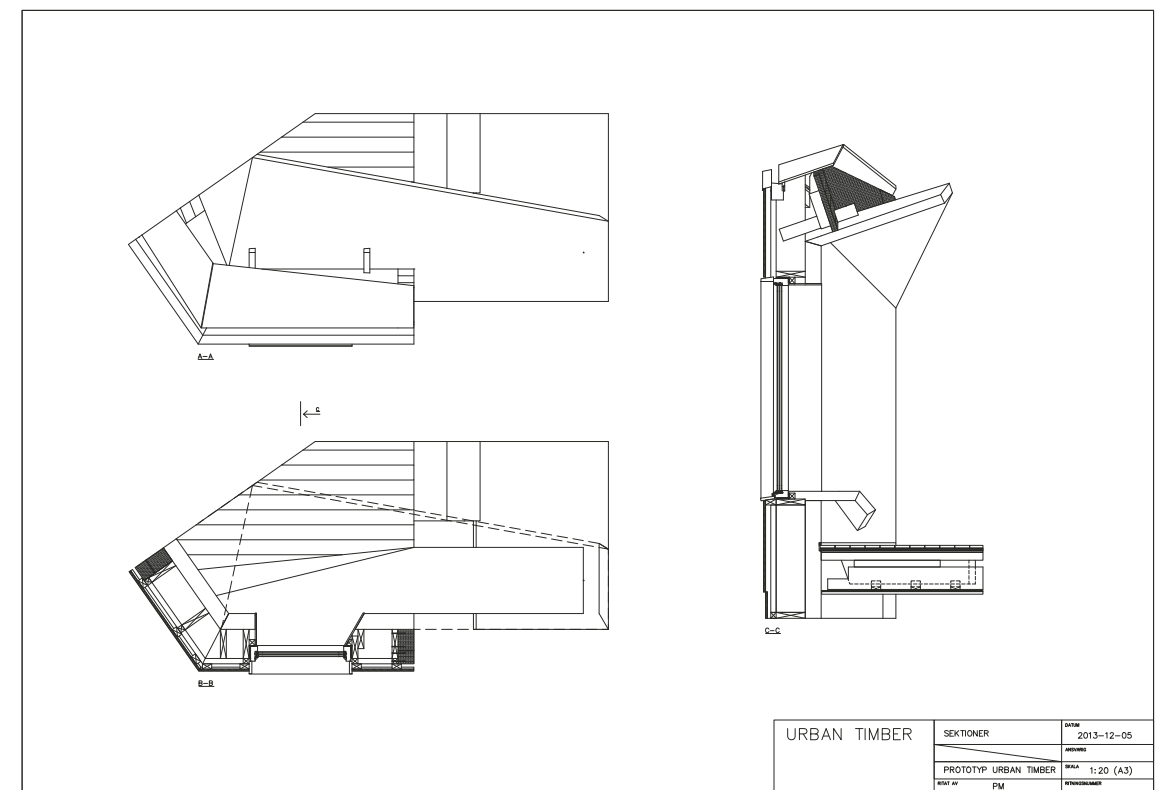
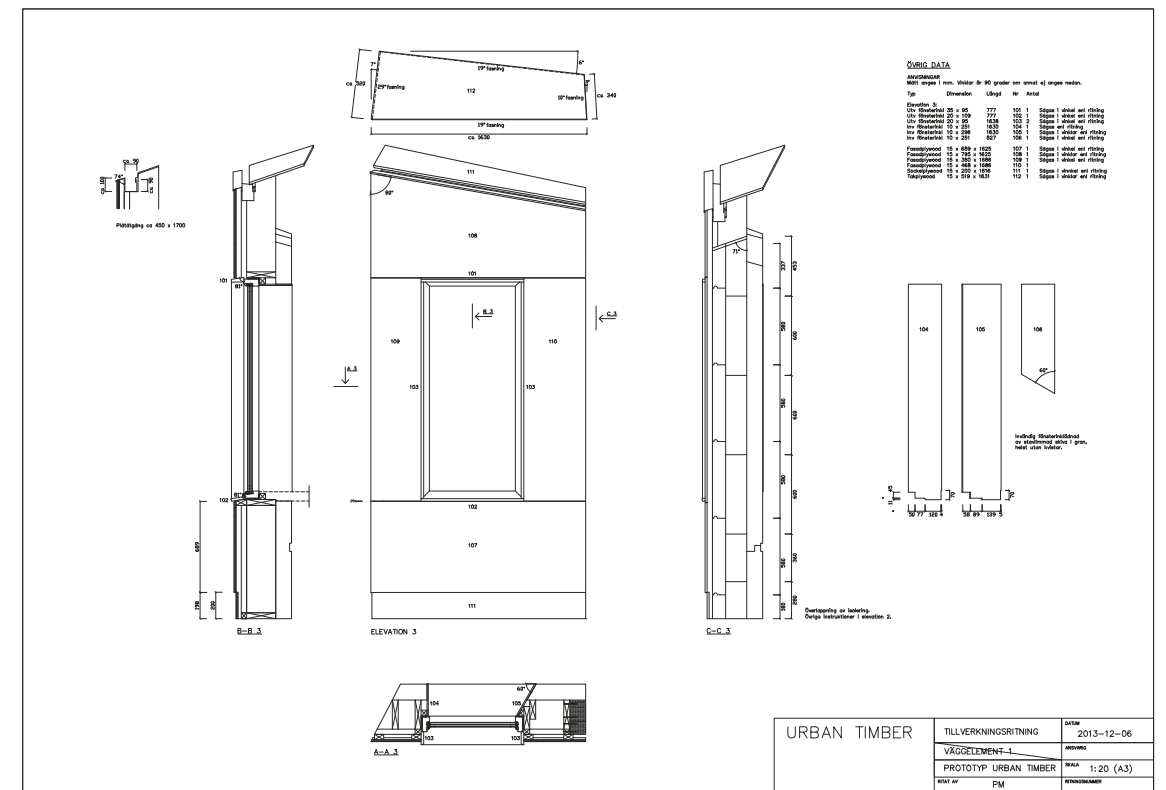
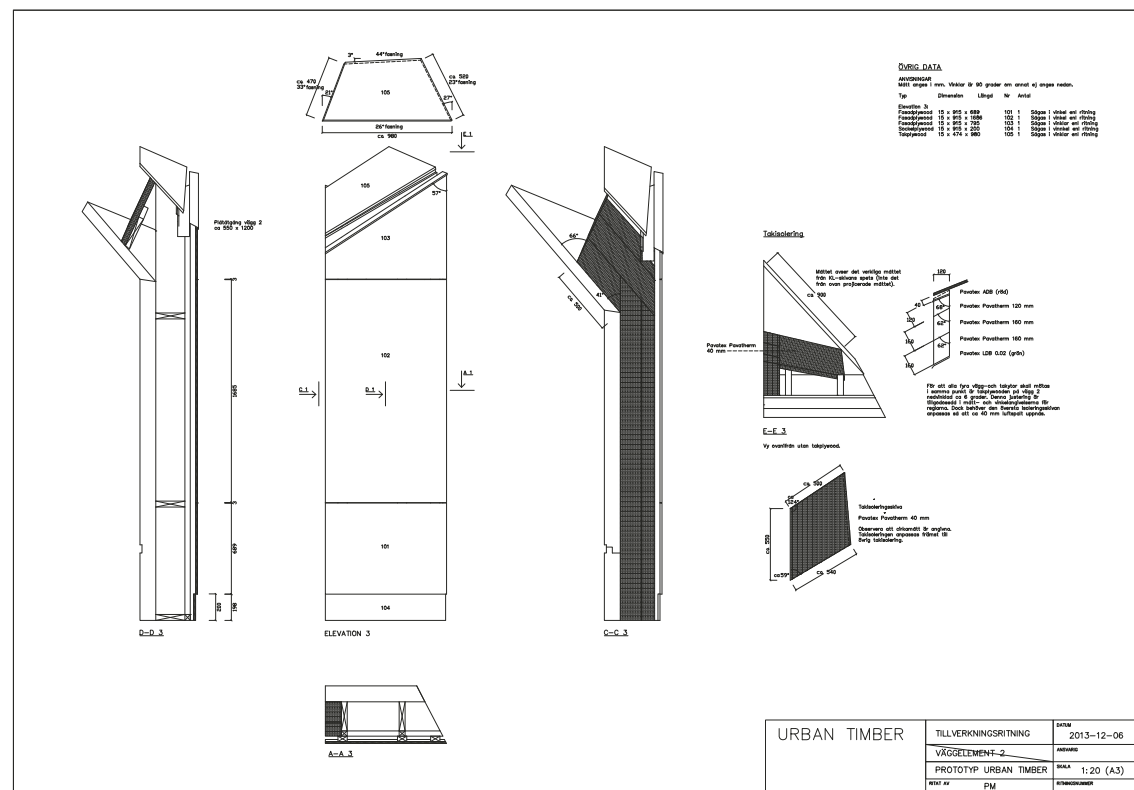
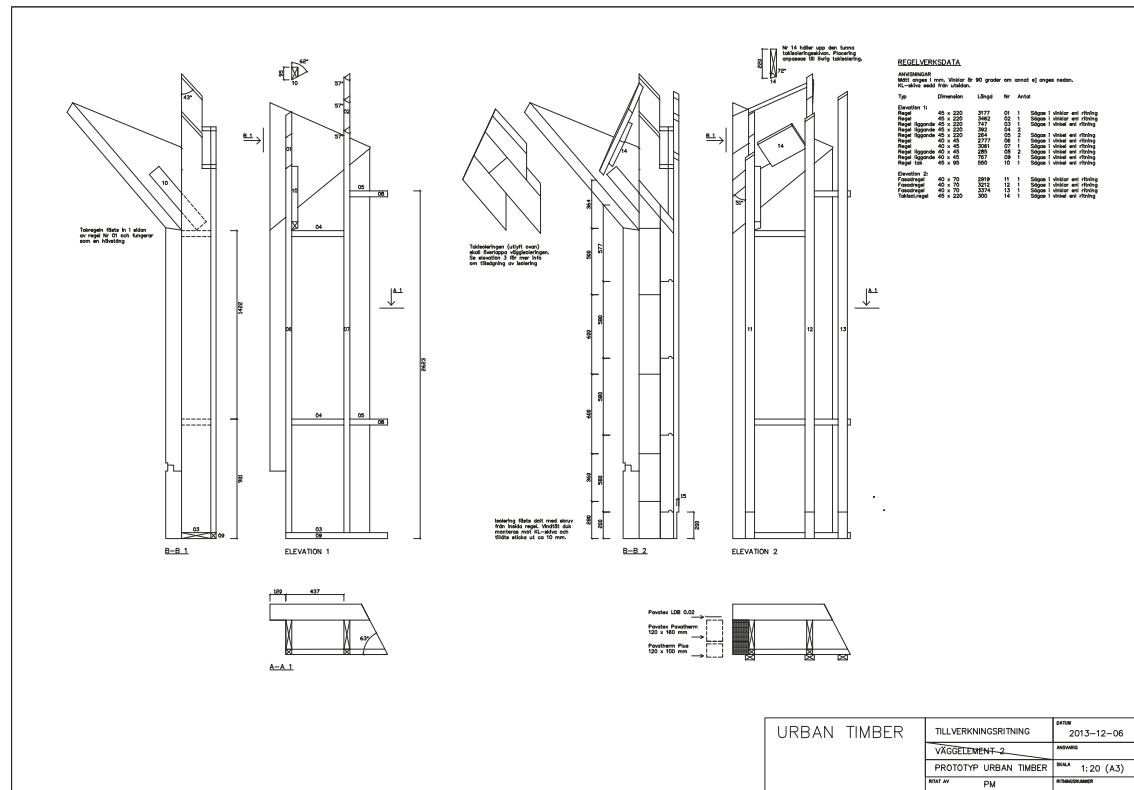
The large prototype presents the cellulose-based system in the section cuts of the wall, floor and roof. It also presents designed interior detailing of exposed timber connected to CNC technology. We have been balancing the fact that it has to be a relevant and interesting showcase both for our project and its future use for Martinsons. Our ambition has been to create an inviting space that people are intrigued to approach, pause to study details, and experience texture and smells. By presenting Martinsons' current slab system next to the thinner slab we propose in Urban Timber, we aim to emphasize the importance of research in this field as means to further strengthen timber construction in urban applications. Read more under chapter 04 | construction.

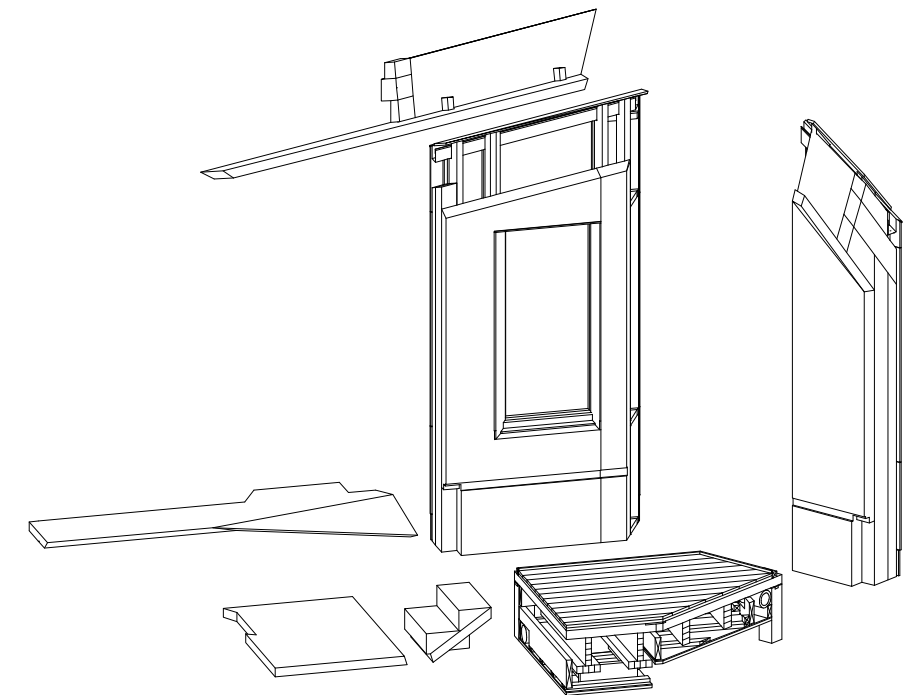
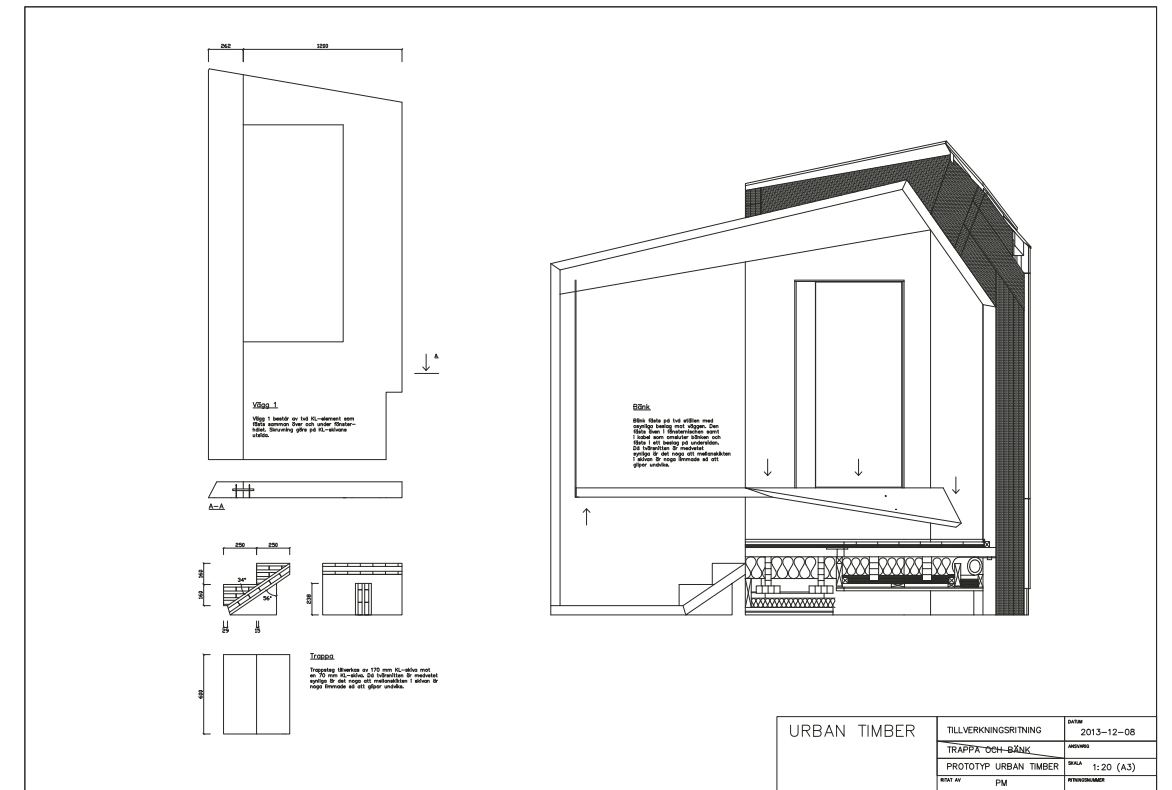
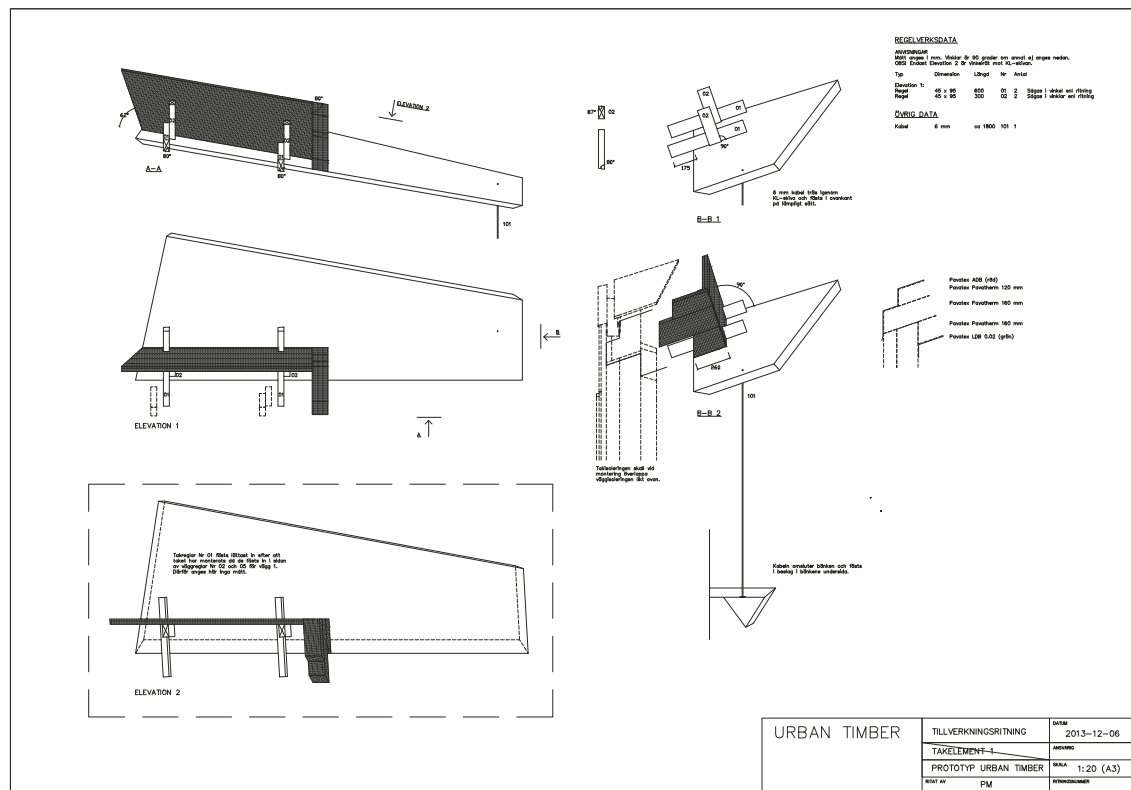
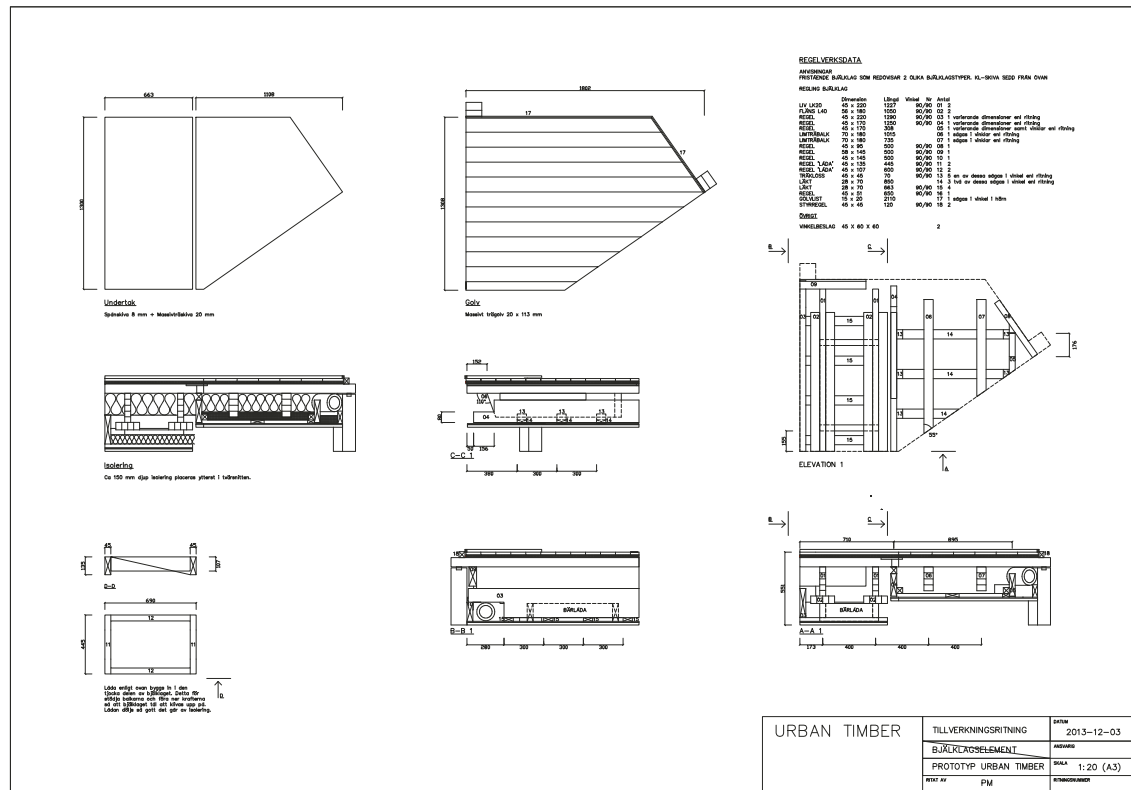
As a proof of concept for empowering our position as architects we hoped to be able to produce the actual machine files driving the CNC machine to cut the CLT pieces (read more under chapter 03 | fabrication), but finally found this too time consuming to execute within the timeframe of the thesis. A lot of time and effort has gone into design, producing construction drawings, assembly strategies, communicating with Martinsons, finding sponsors and ordering materials.



Visualization: The exterior of the prototype.
Drawings (page 73-76): Montage drawings for the prototype.







Drawing: Exploded axonometric drawing of all prototype parts.



EXHIBITING AT EKOCENTRUM

In addition to the large full scale prototype we decided to build a smaller piece ourselves to exhibit at the master thesis exhibition. A simple wall section connected to a part of a staircase, all in full scale, was constructed in the Chalmers workshop. It was satisfying to work in full scale since it gives a realistic idea of the material, weight and practical assembly methods.

Photos: Process of building the smaller 1:1 prototype in the Chalmers workshop. The experience of cutting CLT by hand gave a good sense for the mass of the material.



Image: After the master exhibition we remounted the smaller prototype at Ekocentrum, Gothenburg. We received a nice backdrop from Gothenburg City's poster promoting 'the sustainable city'.

Above are the logos of the collaborators and sponsors involved in *Urban Timber*.



During the semester we participated in the seminar *Hållbart Byggande och Materialval* at Ekocentrum, an independent foundation for techniques and methods supporting sustainable development. The theme of the seminar was strongly connected to our subject and after the Chalmers exhibition the small prototype was integrated in Ekocentrum's exhibition. At the time of writing, the prototype can be found at Aschebergsgatan 44 in Gothenburg.

SPONSORS

Urban Timber has been conducted in close collaboration with several actors and manufacturers in the Swedish timber building industry and we are most grateful for all the valuable input and sponsorships we have received.

Martinsons is one of our main collaborators and in addition to continuous discussions on construction details they have sponsored us with CLT and wall studs for the small exhibition piece as well as for the coming full scale prototype. Miljöbyggsystem MBS AB has been very helpful in the discussions concerning diffusion-open construction and they have kindly sponsored wood fiber insulation from Pavatex for both prototypes. SFS intec AB has sponsored us with the long screws that support the facade and insulation. WB Trä, situated in Burträsk, manufactured and kindly sponsored the prototype window and wooden frames from the best pine found in Norrland. Ceos sponsored pine-plywood for cladding as well as the wood fiberboard used in the ceiling of the slab. Baseco, also situated in northern Sweden, sponsored the massive timber floor.



03

FABRICATION

mass customization & responsible material use

As a relatively new factory produced building method CLT invites a new expertise, since most architects and builders are still inexperienced with the process and its possibilities. In this chapter we illustrate the steps and methods of CLT production and investigate the notion of mass customization as an economic competitor to mass production of standard parts. We discover how information management and software integration is central to the economic resilience of a CNC model of building production.



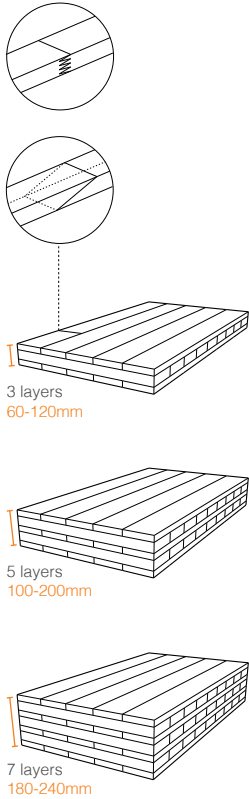
on the factory floor

To begin, we visited the Martinsons factory in Bygdsiljum where we established a background knowledge of the factory processes involved in CLT production. It was important for us to bear in mind the conditions and ordered steps that drive the character and economy of the material.

At the start of the CLT panel production line, we first find the delivery of sawn timber planks which together with glue, comprise the essential elements of the cross laminated panel. Because of the redundancy in perpendicular layers, low quality timber can be diverted from short lifespan applications and incorporated in a structural building material. The layers can comprise different grades or species so that an exposed side can be finished with a higher quality wood for desirable effects (Stora Enso 2012, p. 8).

The ends of these planks are cut by a machine to create finger joints so that they can be spliced together with glue to yield a standard length which governs the dimensions of the finished panel. The spliced planks move immediately to a stage where they are stacked neatly in rows. This stage is in some factories and also at Martinsons' directed manually so the precision of the spacing and alignment of the planks can be driven by the attention of the human operator. In the case where CLT is left exposed, it becomes more important to make sure that this step is carefully executed to avoid unsightly gaps between planks. Some factories have equipment that automates this process which is a way toward a more consistent quality.

Image 1-3 (spread): Study visit at Martinsons, Factory 4, in Bygdsiljum 2013. Photos: A. Esbjörnsson 2013



Massive timber panels are most typically produced in varieties of 3, 5 & 7 layers (always an odd number) (Karacabeyli E & Douglas 2013, p. 19).

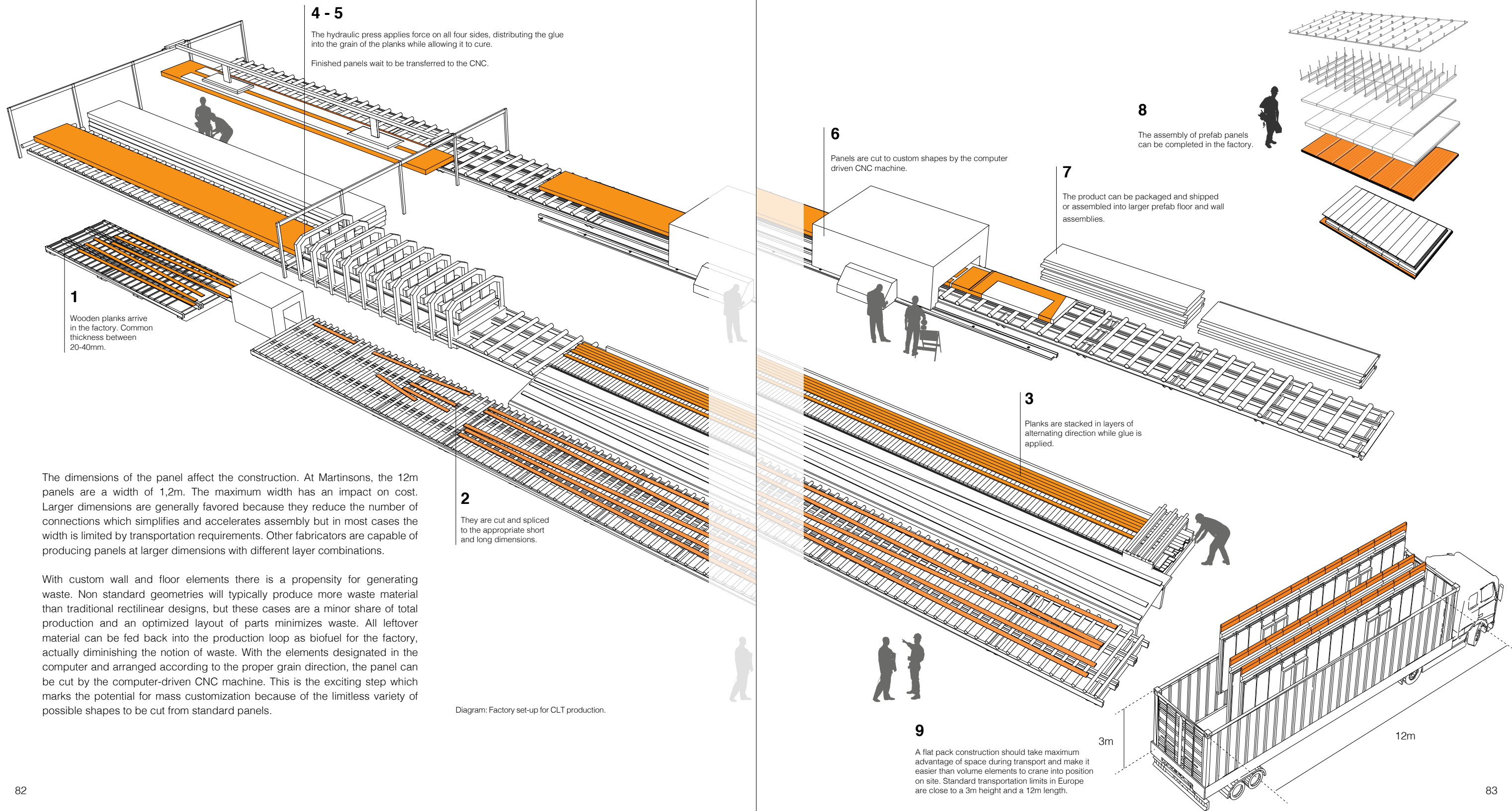
The plank layers themselves come in a variety of dimensions and grades to serve specified performance and aesthetic quality. Even shorter lengths from young trees can be used when spliced together with finger joints or scarf joints to create longer segments.

Unused portions of the panel are inevitable and often result from cutting out windows and doors, use of non-standard shapes or panel-length leftovers from long, narrow panels. The waste material is reclaimed as biofuel and used to power the factory. To the right, features a possible layout for the prototype. The remainder of the half-used panel could actually become part of a different project.

After each perpendicular layer, glue is applied by a machine. CLT panels always contain an odd number of layers giving the panel a symmetry in grain direction about both sides and accords the panel a primary direction of bending resistance. There are different varieties of glue which vary in cure time, chemical composition, and performance. The desirable adhesive system should not contain VOCs like formaldehyde or water-soluble ingredients that can pollute the environment.

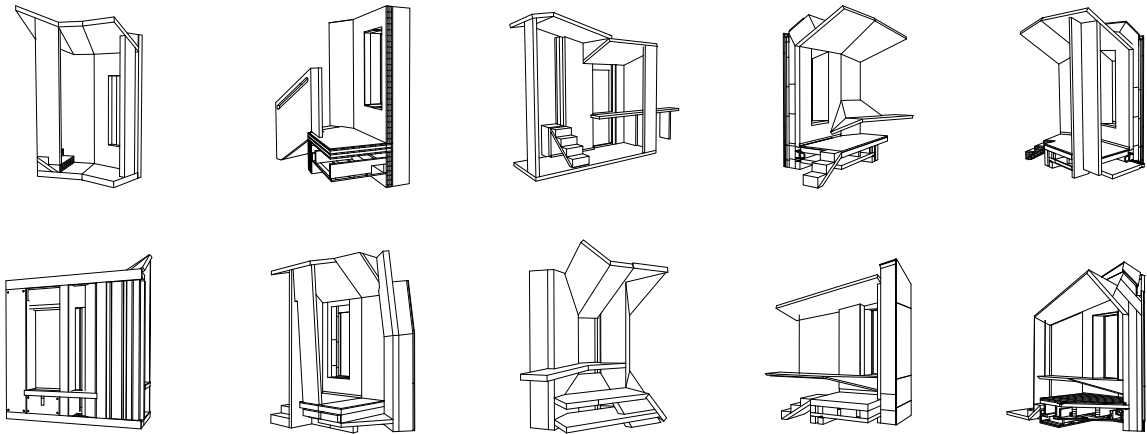
From here the panel is ready for the hydraulic press which will evenly distribute pressure on all four sides along the length of the panel forcing the glue into the grain where it cures to form a finished structural panel. The time it takes to complete this step depends on the type of glue being used and the specifications of the machine. At Martinsons it takes 400 seconds to press a 12 meter panel. After this stage the panel surface is sanded and the product is ready for the CNC. At this time it can either be packaged and shipped to another facility for cutting or it can be fully processed in the same factory.





The dimensions of the panel affect the construction. At Martinsons, the 12m panels are a width of 1,2m. The maximum width has an impact on cost. Larger dimensions are generally favored because they reduce the number of connections which simplifies and accelerates assembly but in most cases the width is limited by transportation requirements. Other fabricators are capable of producing panels at larger dimensions with different layer combinations.

With custom wall and floor elements there is a propensity for generating waste. Non standard geometries will typically produce more waste material than traditional rectilinear designs, but these cases are a minor share of total production and an optimized layout of parts minimizes waste. All leftover material can be fed back into the production loop as biofuel for the factory, actually diminishing the notion of waste. With the elements designated in the computer and arranged according to the proper grain direction, the panel can be cut by the computer-driven CNC machine. This is the exciting step which marks the potential for mass customization because of the limitless variety of possible shapes to be cut from standard panels.



mass customization

Mass customization is something of a modern buzzword which situates itself as a replacement for the familiar term mass production. It implies all the promises of widespread material distribution (mass) with the personal particularity of pre-industrial products (customization).

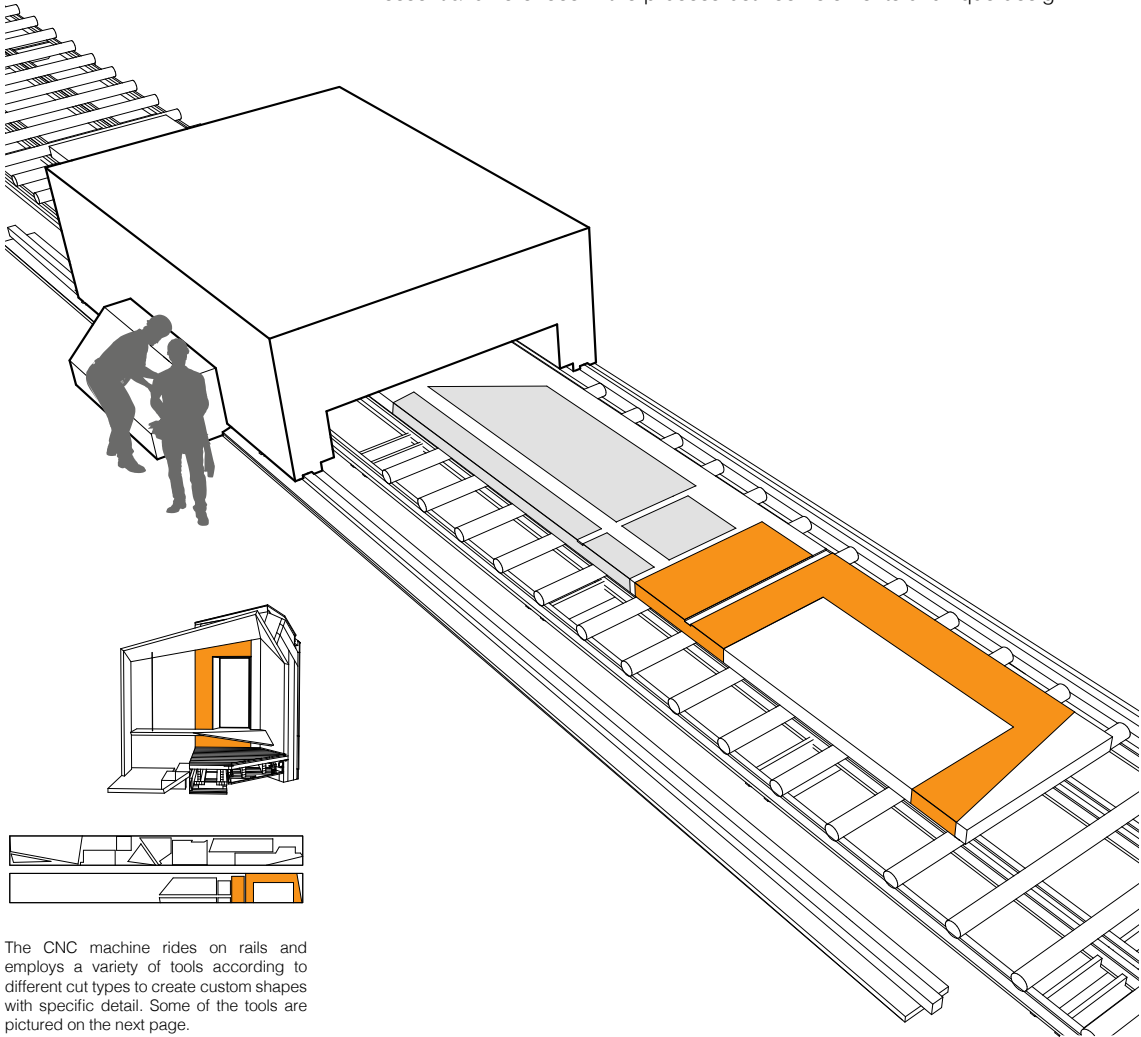
How is it possible to produce buildings at a scale that can meet mass volume while remaining site-specific and adaptable to complex and varied conditions? The necessary standardization and interchangeability that makes mass production an economic success has often delivered a uniform architecture. The difficulty to customize prefab buildings while confined to standard interchangeable parts has been a recurring hindrance to the supposed economic advantage of prefabricated buildings because of the need to adapt to unique user demands and site conditions (Smith 2010, p. 90).

In some places this has earned prefab a reputation for dull forms or cheap mass housing. In the case of CLT, the CNC machine cuts desired custom shapes out of a standard panel in a process that does not change between unique elements. Can industrial mass housing become personal and specialized and break some of the conventional limits of prefabrication while remaining as economically successful? With a CNC mode of production we imagine there is an opportunity for mass customization at an industrial scale and a new tool for the architect.

The prototype is partly meant as a trial of the customization process and an example of architectural possibility that also becomes a point of learning about communication between the designer and the fabricator.

COMPUTER NUMERIC CONTROL (CNC)

CNC machines exist as several types but are generally understood as computer-controlled machines that cut shapes out of flat panels. Today CNC machines are often controlled from a visual CAD-CAM interface that allows the user to define geometries as cut paths for the machine to follow. The cut paths define standard operations like a saw cutting at an angle or a router cutting a window out of a panel. Standard operations like this can give a variety of outcomes without essential differences in the process between elements of unique design.



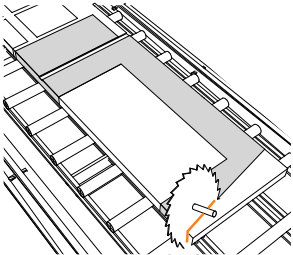
The CNC machine rides on rails and employs a variety of tools according to different cut types to create custom shapes with specific detail. Some of the tools are pictured on the next page.

Common structural systems like concrete construction and steel frame are not able to take advantage of CNC technology because they are not built up from board materials as in the case of metal sheets or wooden panels. Cross laminated timber on the other hand is a structural panel cut by CNC and a customizable prefabricated building option.

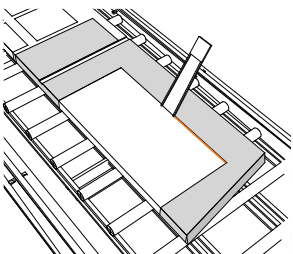
THE MACHINE

The most common CNC machine used for CLT is the Hundegger PBA panel cutting machine. It is a five axis CNC able to perform a set of standard operations that determine the variety and complexity of the customized product. It controls different tools which must be swapped out when the machine is ready to perform a new operation. Some of these tools include a chainsaw and a circular saw for cutting along straight contours. Router drills cut curved contours and most tools can be tilted to cut at angles. From these standard operations, a great architectural variety is possible.

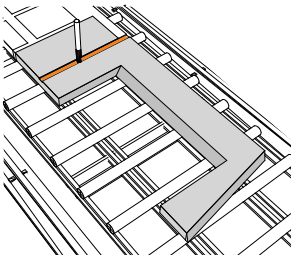
In our discussions with Martinsons concerning their current factory conditions we discovered some important constraints of the fabrication process that govern the possibilities for the CNC product. Precise right angle cut-outs are only approximated at the corners because the roundness of the router drill leaves all interior corners with a small radial fillet. The corners can be cut as true square angles using the chainsaw which can enter and exit the panel anywhere along its cut path. Unfortunately it will leave a less clean, less precise cut. Wherever possible it is preferable to use the circular saw as it cuts efficiently and gives a clean edge allowing the product to be exposed. Sometimes it is difficult to cut small shapes or curved geometries from the center of a panel where the router or chainsaw is more appropriate. Typically they prefer to minimize the variety of tools and especially avoid switching back and forth between tools within the course of a cut queue because of the extra time these changes add to fabrication.



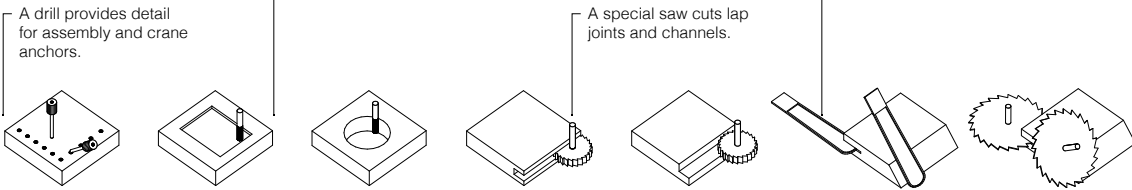
A circular saw is best for clean cuts especially on panel edges.



A chain saw is best for rough cuts when it is necessary for the blade to enter and exit the panel in the middle at custom angles.

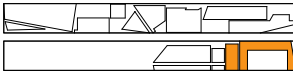
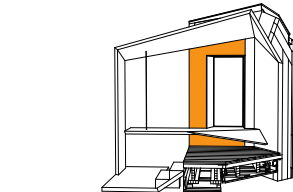


A router engraves surfaces and cuts curved geometry from the center of panels.



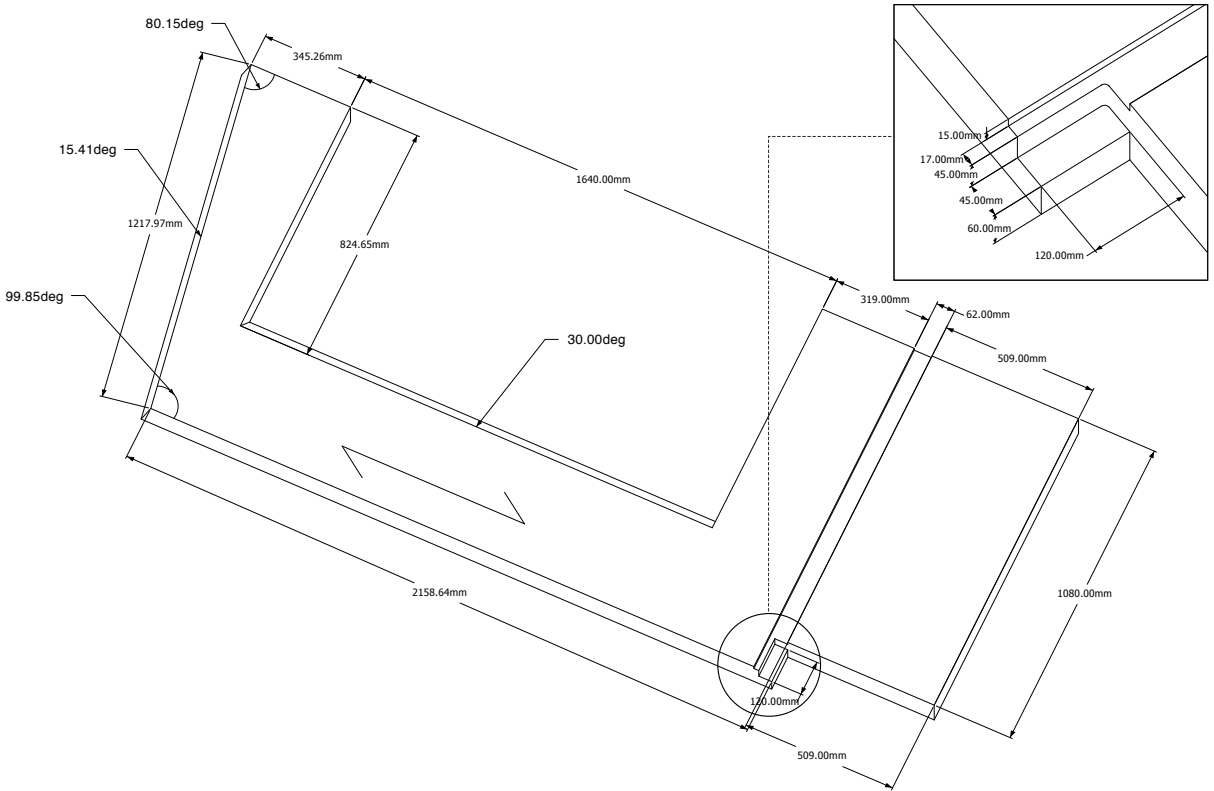
A drill provides detail for assembly and crane anchors.

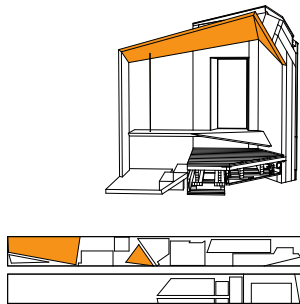
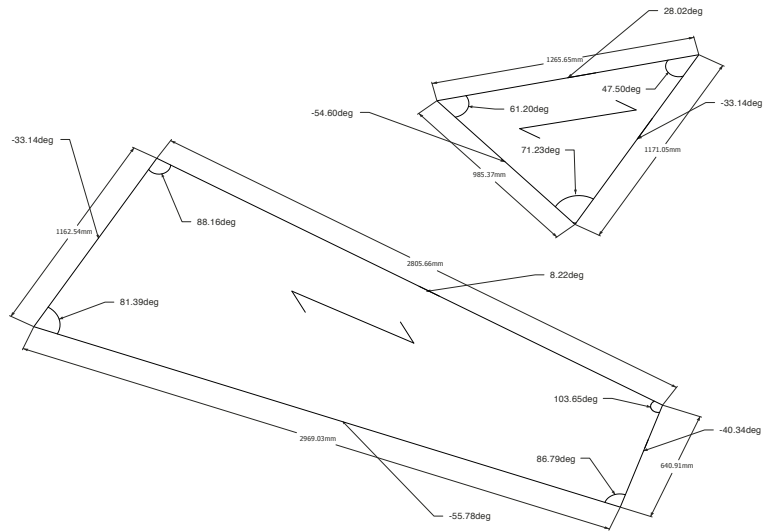
A special saw cuts lap joints and channels.



PROTOTYPE

The prototype serves as a proof of concept that showcases some of the custom details given by the CNC in relatively advanced factory conditions. It tries to set up the opportunity to use a variety of the available tools including routers and the circular saw for clean straight cuts. We learned that the chain saw is great for quick cutting inside the panel and along the edges but leaves a jagged edge not suitable for visible CLT. We also learned that the precision of the machine does not always correspond to a precision of construction as transportation and on-site assembly make low-tolerance joints very difficult. Interlocking joints and such details that are suggested by such a workable material actually could become prohibitively difficult to assemble in real situations. Therefore, steel screw connections with butt-end meetings or shallow lap joints between elements are typically the most cost effective.





Where edges meet at oblique angles we specify a mitered joint that requires an angled bevel and takes advantage of the 5-axis machine to express an architectural flexibility. To add a detail around the window we have designed a beveled vertical edge which occurs on the inside of the panel and requires that the cutting tool enter at an angle, withdraw diagonally and re-enter at a new angle. The router will come into play where we have added details at the meeting between the wall and floor so that the piece rests in a groove when assembled.

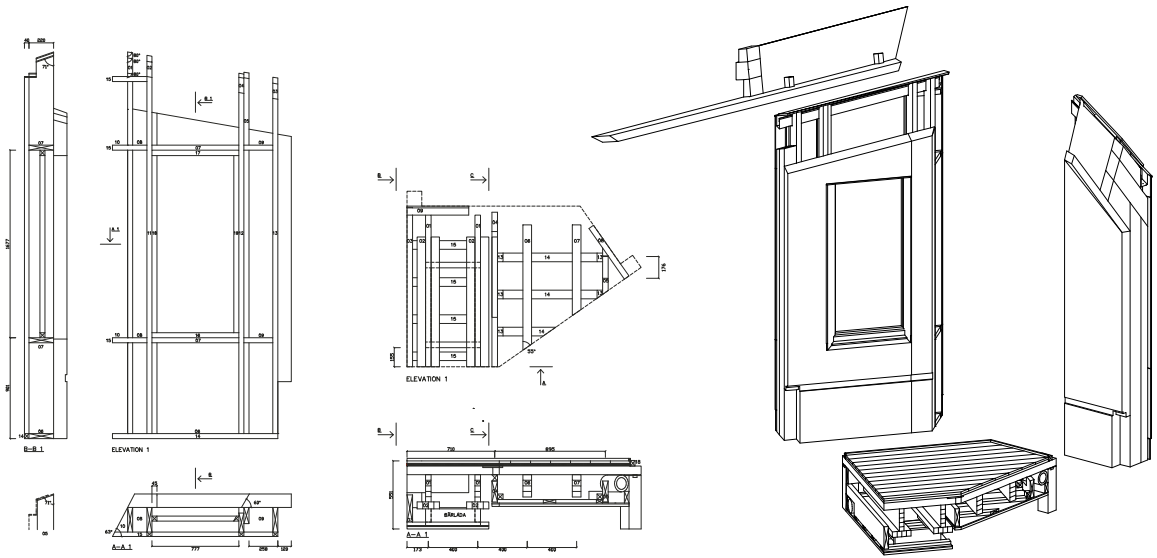
INTERFACING WITH THE MACHINE

The currently conventional path from idea to fabrication requires that the architect submit design drawings which the fabrication engineer resolves into separate parts that the machine can fabricate and standard trucks can transport.

To experiment with the knowledge gained from our factory experience we wanted to take this step ourselves with the production of the prototype. Therefore we designed the CLT elements and precisely specified their geometry and connection detail. We produced descriptive drawings of the elements where each cut of the element is drawn and dimensioned with its cut angle indicated. This way the fabrication engineer can set the angle of the blade and the order of operations. We also specify the angle between adjacent sides making sure to include the principal grain direction and which side is meant to be visible.

Drawings (here and on the previous page): Martinsons will use these drawings to digitally rebuild the prototype with a software that breaks the elements down into a series of operations that direct the machine to cut the custom parts.

Drawings: Some examples of production drawings that were made for the prototype, here is the large wall piece and the slab presented as well as the finished prefabricated single components before being assembled.



ASSEMBLY

An important final stage of the factory phase in a possible project is the assembly of prefabricated elements in the factory before shipment. The prototype is also meant as a trial for this phase and is designed for shipment and on site assembly. After the CLT elements are fabricated they must be assembled together with the remaining building components. In the case of our prototype, this includes the wood fiber insulation, separating battens secured with self tapping screws, plywood cladding, wooden flooring, and the installation of a window.

Describing the specifics of assembly for the fabricator is a complex additional step of prefabrication and demands careful communication between the architect and the fabricator. During this process we had continuous contact with Martinsons regarding questions of feasibility, timeline, and construction details.

Using the CNC we see how we can employ an industrial process for a custom architectural product which is something of an economic novelty but we also learned that a lot of time, energy and thought must go into the communication and cooperation between the architect and the fabricator and that the steps between idea and finished building are more complex than the simplistic *mass production* notion of standard products made in volume. Customization demands efficient information management if it hopes to become *mass customization*.

a new role for the architect:
producing machine drawings

In a conventional building process the architect is expected to translate ideas and design into construction documents for builders to interpret and execute. However, In a prefabricated CNC project the architectural drawings must be translated into part drawings, machine cut files, and assembly drawings.

Taking the example of an architect unaware of the CLT fabrication process, the factory engineer must interpret the architect's model and rebuild it in pieces that fit the constraints of machining and shipping. This involves that the walls and floors are cut into sections and made into separate part drawings for setting up each job in the machine, a time consuming process. In the case of our prototype, we have produced the part drawings and assembly drawings so that Martinsons will only translate the drawings into the model that drives the CNC. According to our consultations with Strombro, the engineer spends 4-6 hours per element preparing the machine drawings. The fact that the building is essentially redrawn several times makes it apparent that complex and custom elements require extra work, which is why simple elements are favored for fast manufacturing. It thus becomes questionable whether CNC is in fact a form of *mass customization* or if this system can really act as a successor to mass production. The software integration needs to advance if the factory is to become a natural platform for the designer.

Some developers are spearheading the effort to move control of the tools closer to the designer. A clear way to empower designers is through software applications that more directly bridge between model and machine so that architects receive feedback on their designs, and avoid problems by keeping factory constraints in mind (Smith 2004, p. 254). Timely feedback of information like total cut time, material waste, and cost can be very useful to designers trying to make decisions earlier in the process.

Furthermore, as the relationship stands today, the architect is often isolated from the fabrication process and the opportunity to develop design solutions that take full advantage of the technology. When the architect is unaware of the process, arguments cannot be made for solutions that depend on fabrication conditions. If more architects take control of machine file generation and become acquainted with factory constraints, a new convention may form around this responsibility and give energy to technology integration that has been slow to develop in this field (Kieran & Timberlake 2004, pp. 30-31).

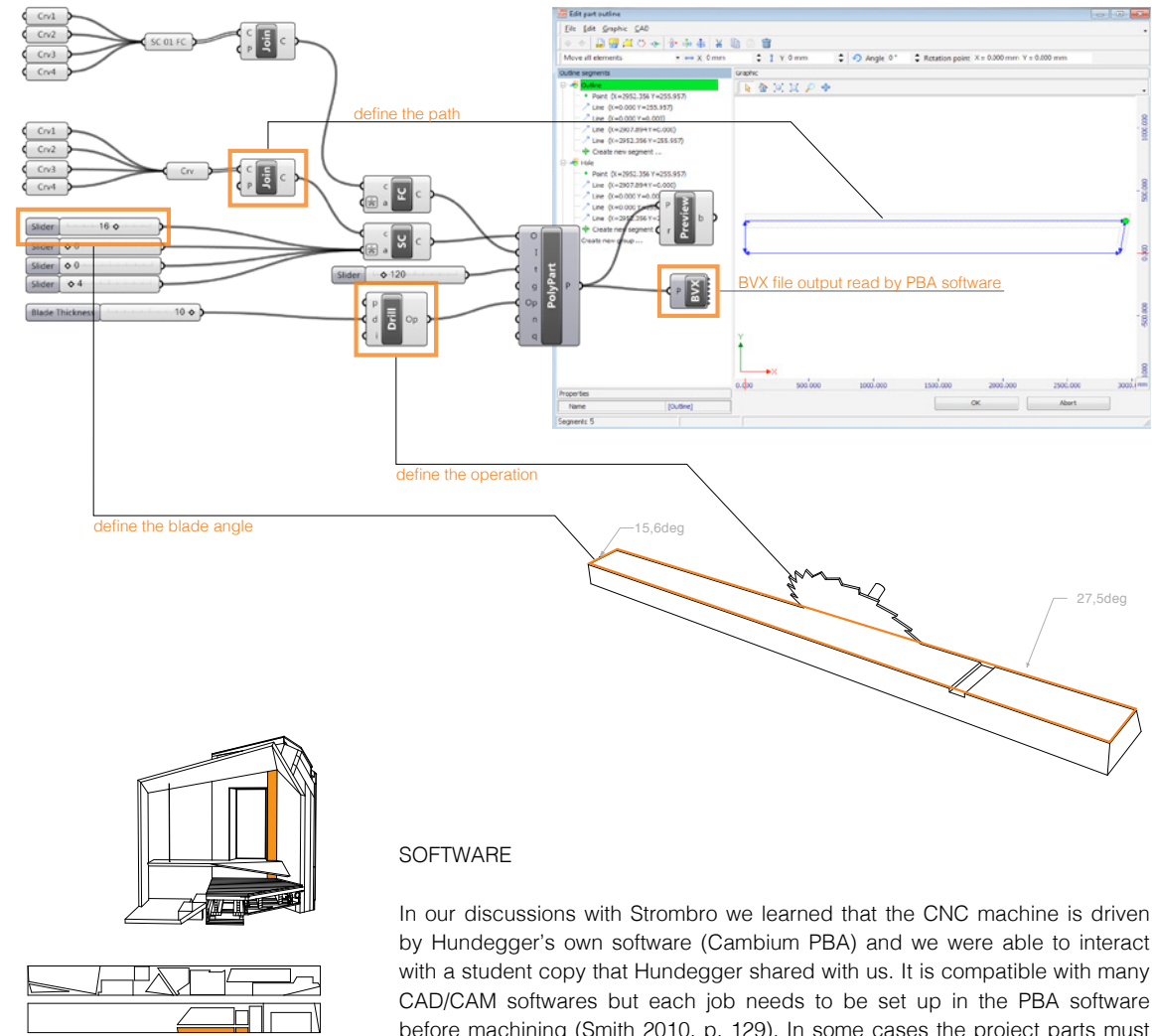
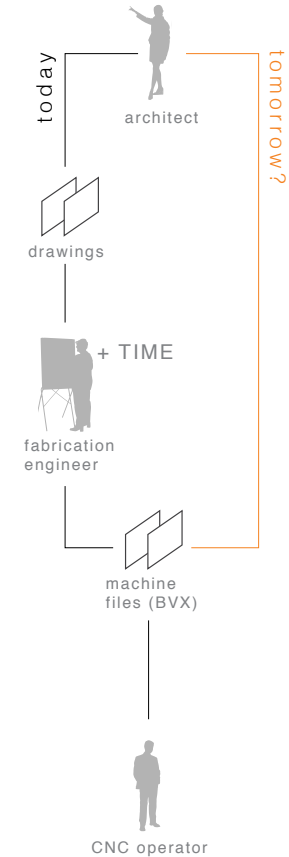
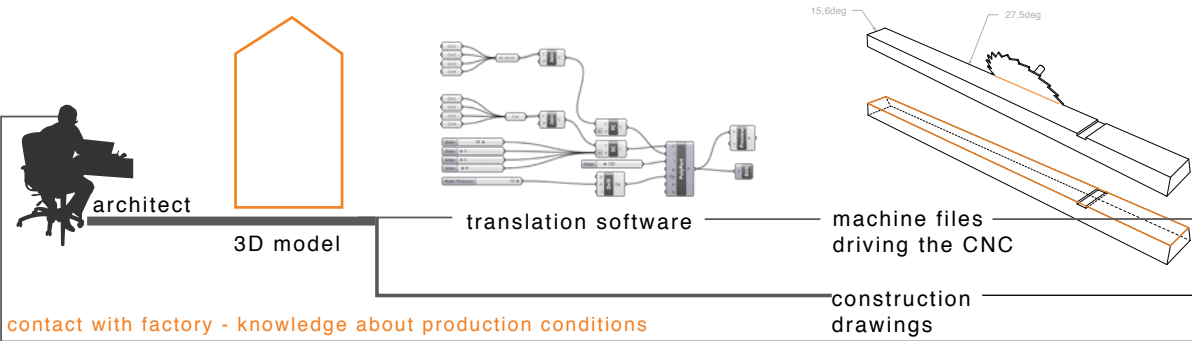


Illustration: Using Beaver, an add-on for Grasshopper we are able to create the instructions for the CNC machine and test it in the Hundegger PBA software. Here we see how a part of the prototype can be translated from a digital model in Rhino.

SOFTWARE

In our discussions with Strombro we learned that the CNC machine is driven by Hundegger's own software (Cambium PBA) and we were able to interact with a student copy that Hundegger shared with us. It is compatible with many CAD/CAM softwares but each job needs to be set up in the PBA software before machining (Smith 2010, p. 129). In some cases the project parts must be redrawn in the PBA environment. The operator must input the contours which define the cutting path and specify the order of the cuts. The bevel angles, tool changes, xyz coordinates and dimensions will need to be entered and checked. The direction of the grain and the visible side of the finished panel must be understood before the operator can create the machine file. This software is not designed for architects or typically available to users outside the factory.



This inaccessibility and the architect's distance from specifics of factory production can become problematic when arguing for applications of CLT in a building project. Without the knowledge of what is possible or the relative difficulty certain operations might mean for the production line architects must default to the operator's word when it comes to deciding what is physically and economically feasible.

GRASSHOPPER

Grasshopper is an intuitive Rhino plugin that gives design minded users the ability to interface with the power of script-based operations for automation and parametric design. An add-on to this environment called Beaver, currently in development, is able to generate PBA compatible bxv files from Rhino geometry. Further development looks promising and a next generation interface for CNC machining could take a form similar to this.

Strombro Building Workshop in Stockholm has developed a plugin for Sketchup called PAQAM which uses a 3d model of CLT elements to directly export to bxv. This means that the intuitive modeling environment of Sketchup can be extended directly to a set of instructions that drive the CNC machine. Promising developments like these bring the architect closer to the factory and advance the viability of CLT as an industry alternative.

TOWARD THE FUTURE

Currently, the steps between the architect and the product slow down the prefabrication process. Every drawing, translation, interpretation, and redundant model is a risk for costly errors. Compressing this process could offer great

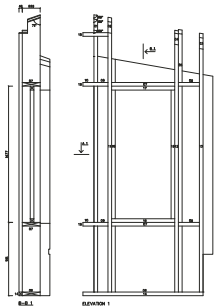
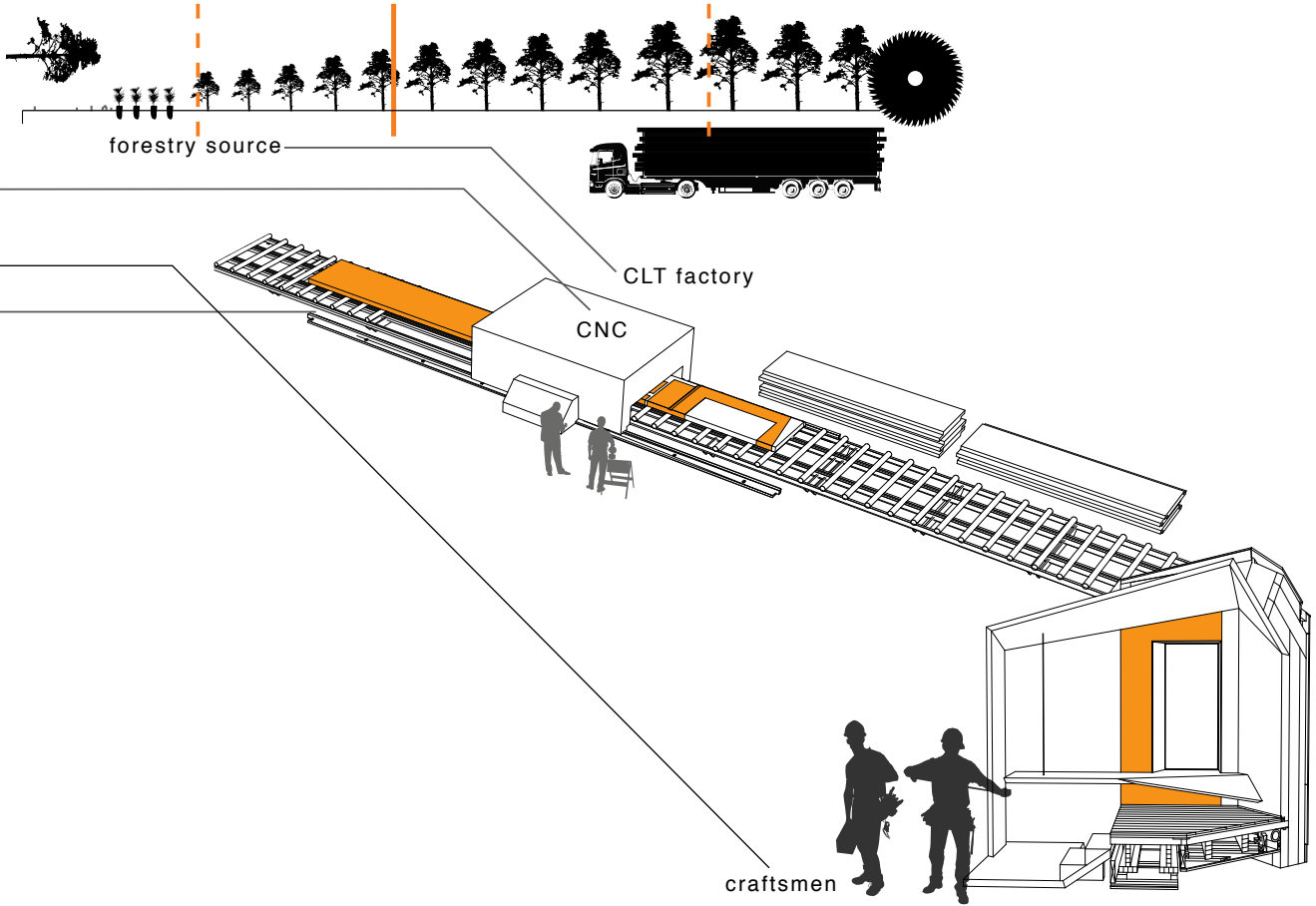


Diagram: Imagining a future information flow from the architect to the final product.



leverage to architects arguing for timber. Realizing a fully integrated information flow is not a clear and simple achievement but once in place it can become a powerful tool to support the economic feasibility of bringing customized volume architecture to the city. Architects and CNC operators work with separate digital models of the same project. Merging them is an obvious way forward and though this challenge is technical it also depends on interest and communication. Architects have the power to drive innovation with an interest in taking design decisions all the way to the factory floor and exploiting the new software opportunities and information models that are beginning to emerge. A means to mass customized industrial building may be a matter of time.



04

CONSTRUCTION

fast, safe and cost effective

When the prefabricated building elements are ready to be shipped we move on to construction, where considerations for weight and size of elements impact both transportation costs, emissions, and speed of assembly. These factors can in turn affect insurance costs. Design of connections is crucial to ensure efficient mounting and a well functioning, airtight and energy efficient building. This chapter presents how the success of the cellulose-based system with exposed timber depends on precision and carefulness in construction. It also discusses the economic competitiveness of timber as a structural material for urban applications.

timber construction in the city

As stated in the introduction of this report, timber is rarely considered as a structural material when densifying existing city structures nor for development of dense new urban quarters. Convention and building traditions perpetuated by large construction companies can be a strong obstacle to innovation when combined with a general lack of knowledge, but new multistorey timber buildings highly integrated within an urban context have full potential to be realized.

Timber is due to its lightness especially well suited for deployment in dense urban areas and for additional superstructures to existing buildings. The lightness of the material gives economic benefits due to a rapid construction and because a safer working environment can lower insurance costs (Crespell & Gagnon 2010, p. 11). It's additionally advantageous in areas with poor ground conditions since the costly foundation work is reduced (Stehn, Rask, Nygren & Östman 2008, p. 7). In *Urban Timber* we focus on prefab construction as a key to fast mounting, minimal disturbance on site and low construction costs. Prefabrication makes it possible to pre-assemble larger building elements and their various services in the controlled environment of the factory. Since connections require special care and attention, having fewer on-site connections speeds up construction time while ensuring an airtight and energy efficient building (Smith 2010, p. 184).

SUSTAINABLE URBAN DEVELOPMENT

The trend of urbanization is established and ongoing and by 2030 6 out of 10 people are expected to live in cities opposed to only 2 out of 10 people a century back (World Health Organization 2014). Cities today are often associated with consumption and traffic congestion resulting in large emissions of greenhouse gases.

There is an urgent need for new planning strategies that reverse the trend of our cities toward becoming heavy sources of pollution. Although this thesis does not expand on planning principles we recognize urbanization as an important aspect of a sustainable future. Creating preconditions that enable and encourage people to live closer together can reduce the environmental impact by having them share resources, functions and means of transportation. A city structure dense with a diverse mix of qualities and functions encourages transportation by foot, bicycle or public transport since daily life necessities are within reach. Such urban environments are often considered attractive to live in, something that has to go hand in hand with high environmental ambitions.

TRANSPORTATION

Timber prefab elements can be either flat or finished volumetric modules constructed in the factory. The advantage of flat elements includes efficient packing in trucks that avoids transport of air resulting in reduced emissions and transportation costs. The economic and ecological advantages of timber over concrete construction is even more apparent. The weight of massive timber is about one fifth of precast concrete, which gives lighter and fewer deliveries to the construction site (Gustafsson et al. 2013, p. 21).

One architectural restriction is the size of elements that fit on a standard truck, which is around 3 meters high and 12 meters long. The elements could either be one story high and span the whole length of an apartment or be rotated 90 degrees to cover multiple storeys vertically.

MOUNTING ADVANTAGES AND DESIGNED CONNECTIONS

On site the light prefabricated wall and floor elements are easy to lift in place with smaller and less costly cranes than the large ones needed to lift heavy concrete panels (Crespell & Gagnon 2010, p. 13). As soon as the slabs are laid out the building services contractors can start their work, which speeds up the building process significantly as there are no wet trades that depend on cure time (Crespell & Gagnon 2010, p. 11).

Illustration: A flat pack system fits efficiently on a standard truck. When the first floor elements are mounted the service contractors can start working in a dry and safe environment.





Concrete construction is often done under open sky which in the Swedish climate demands long desiccation time with the help of fans, increasing costs and energy use on site. Higher prefab timber buildings in Sweden are often constructed under a tent to ensure a dry and safe working environment. Martinsons' own system is called Extoler and is raised efficiently with each floor. The need for much simpler tools in a case of unexpected alterations further explains why timber construction sites are considered to be safer and more cost effective than most building sites.

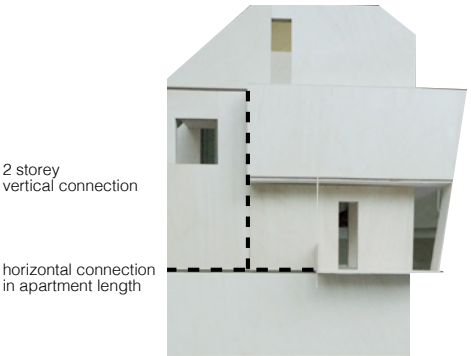
The energy performance of a prefab building relies on the quality of its connections. The conventional method to ensure airtightness is to overlap a plastic foil and tape all meeting points between the elements. This time consuming and costly work is often done with no thought of leaving an exposed CLT surface and the functional result depends a lot on the workmanship (Janols et al. 2013, p. 7). The cellulose-based system however is built on the idea of exposed CLT, which demands much greater care in handling of elements on the building site. When connections are made chipped edges must be avoided and obviously taping can not be made inside. The coming pages will further explain the principles of assembly and strategy for long term airtightness inherent in the cellulose-based system.

A smaller crane appropriate for prefab timber construction costs, 700-1000 SEK/day compared to 700-1000 SEK/hour, which is the cost for a large crane needed at the concrete construction site (Stehn et al. 2008, p. 8).

principles of assembly

In the following pages we present our process and assumptions about designing airtight element connections appropriate for exposing CLT.

The building elements are prefabricated from inside to out and consist of the loadbearing CLT complemented with a rigid wood fiber insulation and facade structure. At the connection points complementary and overlapping insulation is added after mounting. This assembly method enables the CLT panels to be screwed together from outside, leaving the internally exposed surface clean and protected. Airtightness is crucial for energy efficiency, and as explored in the Cerbof project report (*Slutrapport Passiva Massivträhus, Cerbof-projekt nr 76*), all CLT meeting points are cut to form an S-curve coupled with expanding strips, which are placed in between the elements and pressed together by the screws. The overlapping insulation layers detailed with S-curve joints, constitute a second air barrier and further help to prevent air leaks.



In *Urban Timber* we aim to see the massive timber panel both as a structural and architectural material, where the CLT is used as the finished internal surface. This demands high precision and skilled builders. The effort to tape all element meetings is costly, time consuming and is not aligned with the idea of exposing timber interiorly.

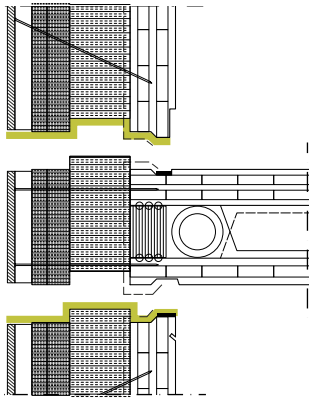
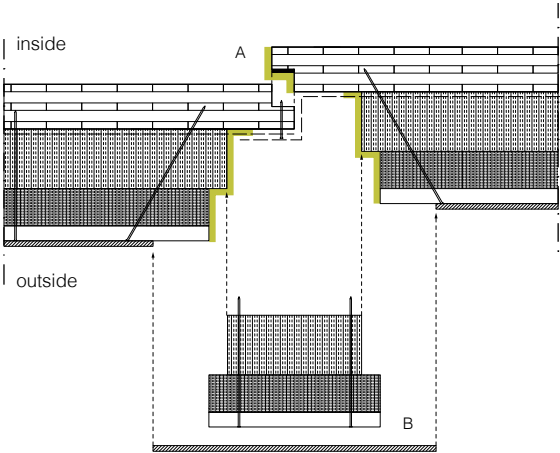
Photos: A. Esbjörnsson 2013

INVESTIGATIONS IN OPTIMIZING CONNECTIONS

As a part of our research and process we speculated on connections that would maximize the level of prefabrication and take advantage of the CNC in pre cut s-curves, which in turn would achieve desired air tightness and help direct the element to the right place when assembled. We learned through discussions with Martinsons that precision might depend on varying exactness among CNC machines and that building tolerances on site call for a flexible design that allows for minor adjustments. The current conditions on most building sites in Sweden do not reach the high precision needed.

WALL-WALL CONNECTION

Below we present designed assembly connections that ensure energy efficiency while expressing fine detail architecture of exposed wood. Where wall elements are joined the CLT is cut to form a lap joint. This partly ensures air tightness but also helps to steer the elements in the right position while mounting.



WALL-WALL CONNECTION
(HORIZONTAL SECTION)

[A] FIRST AIR BARRIER (FROM INSIDE)

CLT 120 mm cut in lap joint 60/60
expanding strips for air tightness
screws (perpendicular and diagonal)
optional; diffusion-open vapor barrier

[B] SECOND AIR BARRIER (from inside)

160 mm rigid wood fiber insulation
100 mm waxed rigid wood fiber insulation
facade batten / 400 & 250 mm screws
facade board

WALL-SLAB CONNECTION

Where the wall element lands on the floor slab an s-curve is achieved by cutting a groove in the CLT of the wall piece. Here the wall element is fixed to a steering batten, a detail that allows for small adjustments on site since the batten is screwed to the floor slab after the slab is mounted. Expanding strips are placed on both sides of the CLT in the floor slab, compressed by the weight of the elements. This is done both to ensure air tightness but also to prevent sound and vibrations from being transferred through the structure.

Drawing 1: Vertical section through wall and slab in element meeting point 1:20.
Test of optimized connection.

Drawing 2: Horizontal section through element meeting of the cellulose-based wall 1:20.

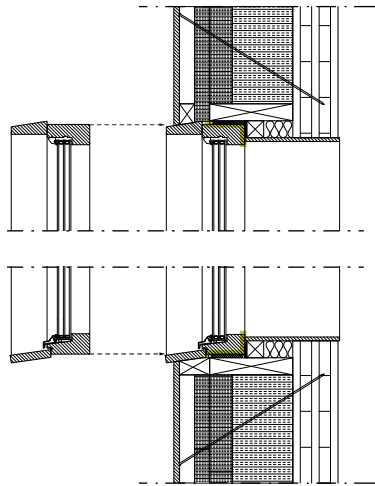
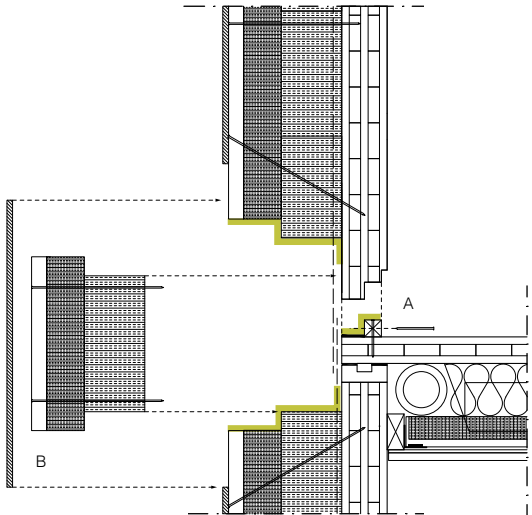
WALL-SLAB CONNECTION

[A] FIRST AIR BARRIER
(from inside)

CLT 120 mm cut in lap joint 60/60
(+ cut for hidden base board)
steering batten fixed to floor slab
expanding strip for air tightness
optional; diffusion-open vapor barrier

[B] SECOND AIR BARRIER
(from inside)

160 mm rigid wood fiber insulation
100 mm waxed rigid wood fiber insul.
facade batten/ 400 & 250 mm screws
facade board



WINDOW / DOOR CONNECTION

Windows and doors are mounted from outside and pressed against an air sealing strip. This ensures an airtight connection and a construction that can be easily dismantled and recycled.

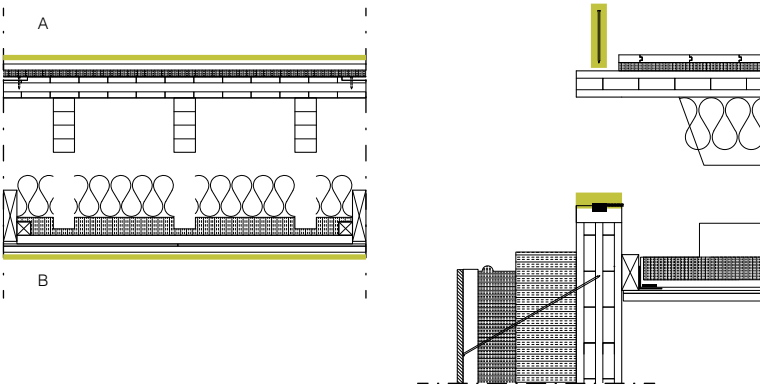
Drawing 1: Vertical section through wall and slab in element meeting point 1:20.

Drawing 2: Vertical section through the cellulose-based wall with mounted window 1:20.

timber slab systems for urban application

Often local development plans in urban areas stipulate a maximum height, considering the conventional thickness of a concrete slab or simply the previously lower acoustic requirements. To become a truly competitive alternative to concrete and steel in urban applications, currently used timber slab systems must become thinner to avoid time consuming modifications of the local development plans.

The difference in height between concrete slabs and timber slabs is currently so significant that the risk of losing an entire floor can appear in areas with certain height limits. This could be prohibitively costly for most clients and builders even if timber systems could be beneficial for other reasons. The thickness of timber slabs relates to the lightness of the material, which brings obstacles with resonance and flank transmissions, where sound and vibrations travel through floors and walls. To learn more about the acoustic principles of timber slabs we have had several discussions and mail conversations with acoustic experts, read more under chapter 05 | operation & use.



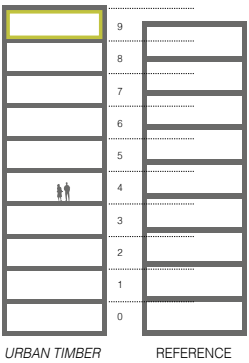
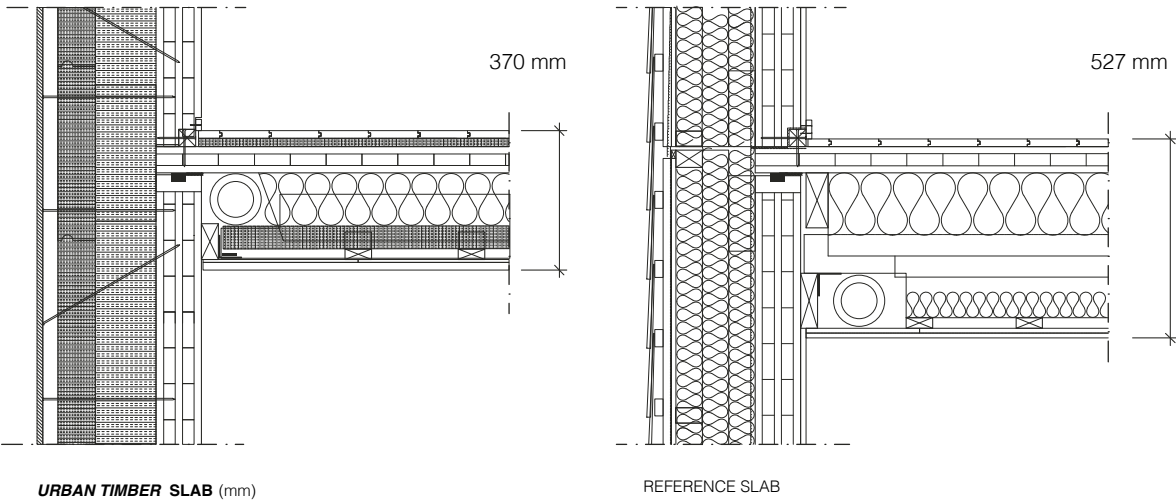
[A] CROSS SECTION UPPER SLAB PART
The structural parts of the slab consist of a 70 mm CLT panel combined with glulam beams. This upper part is placed on top of the loadbearing walls.

[B] CROSS SECTION LOWER SLAB PART
The ceiling consists of beams and battens that hold up the ceiling board, in this case a wooden panel. This part is hung on the inside of the walls.

HOW TO DESIGN A THIN TIMBER SLAB

As architects we are interested in the design of a thinner slab for several reasons. Beside the issue of height limits, it also becomes desirable to maximize ceiling heights for the spatial quality it brings. A double-layered slab system which has two separated structural parts is a common strategy to handle acoustic issues, where the upper and lower sections meet only in a few minor points. Insulation with different density is used in between the two layers to block a range of different sound frequencies.

The flexible connection between the CLT elements is achieved by placing a rubber strip in between the elements and using a rubber coated screw to fasten the slab.



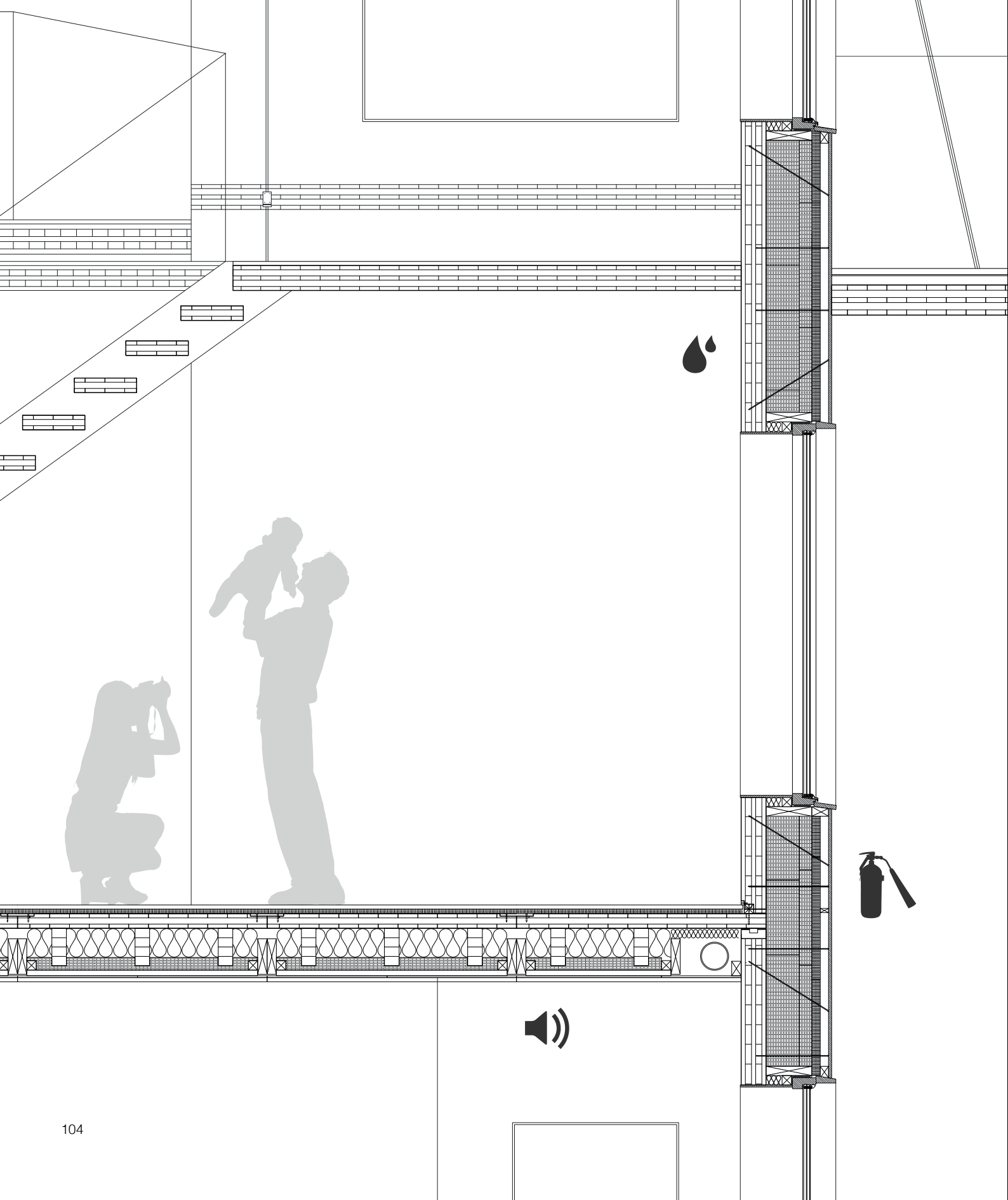
Drawings and illustration: The *Urban Timber* slab tries to emulate the properties of a heavy structure by adding high density boards of wood fiber insulation together with a sound insulating step board under the floor. The ambition is to avoid the risk of losing an entire floor where local development plans are set to a maximum height.

Some systems add gravel to better deal with vibrations and at the same time add necessary weight. The connection where the slab meets the wall is also crucial, and needs to be flexible to avoid sound bridging.

A HYPOTHETICAL SLAB

To bring new ideas to the discourse we set out to propose a thinner slab system, based on the Martinsons system and inspired by solutions advocated by Strombro Building Workshop. The design principle tries to emulate the properties of a heavy structure by adding high density boards of wood fiber insulation. These boards are placed in between the load bearing upper slab and the free hanging ceiling. Complemented with a low density wood fiber insulation the different sound insulating properties are meant to contribute to a comprehensive solution.

Under the flooring a sound insulating step board of high density is crucial to minimize transmission of footfall. Installations can be fitted in between the glulam beams or perpendicular along the walls where the beams are cut to leave space for plumbing. According to Martinsons, accurate evaluation of the exact performance of new slab systems is difficult to achieve with the available software simulations. A system has to be built in full-scale and tested accordingly in a lab, which of course brings additional expenses and impedes development.

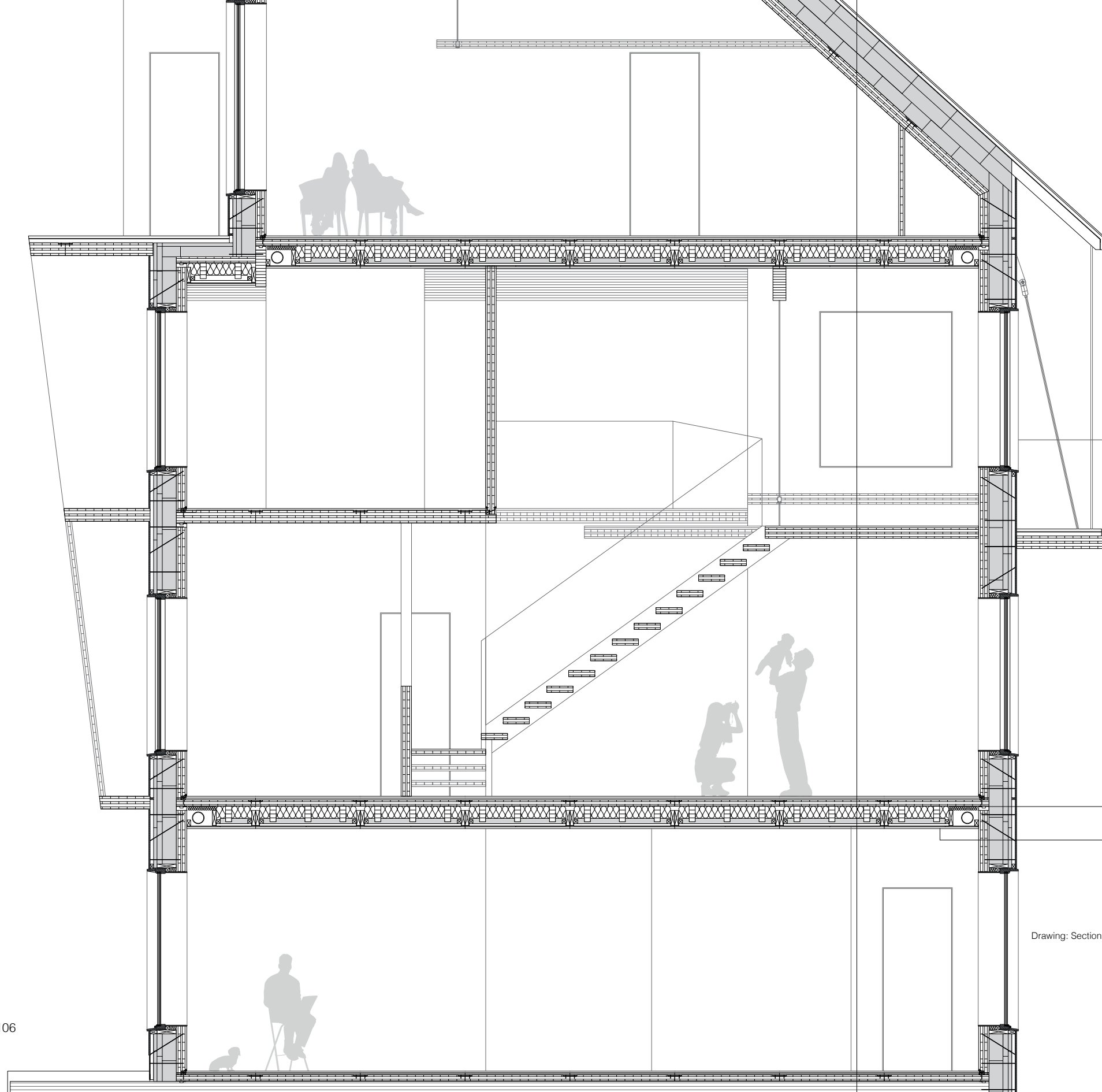


05

OPERATION & USE

maintenance, comfort and health benefits

This chapter exemplifies the operation of a residential timber building built on the cellulose-based system and placed in a dense urban area, where relevant aspects of building physics are considered and related to the specific construction details we have studied and applied. Builders, engineers, clients as well as residents all have their preconceptions. Fire is an instinctive primary concern when speaking of timber buildings, but this concern is most often unwarranted and inferior to the obstacle of acoustics. We will in this chapter expand on some of the properties of timber that relate to indoor climate, health, energy efficiency, and refurbishment costs.





sound, fire, moisture

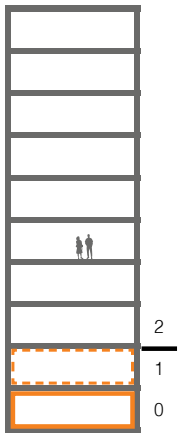
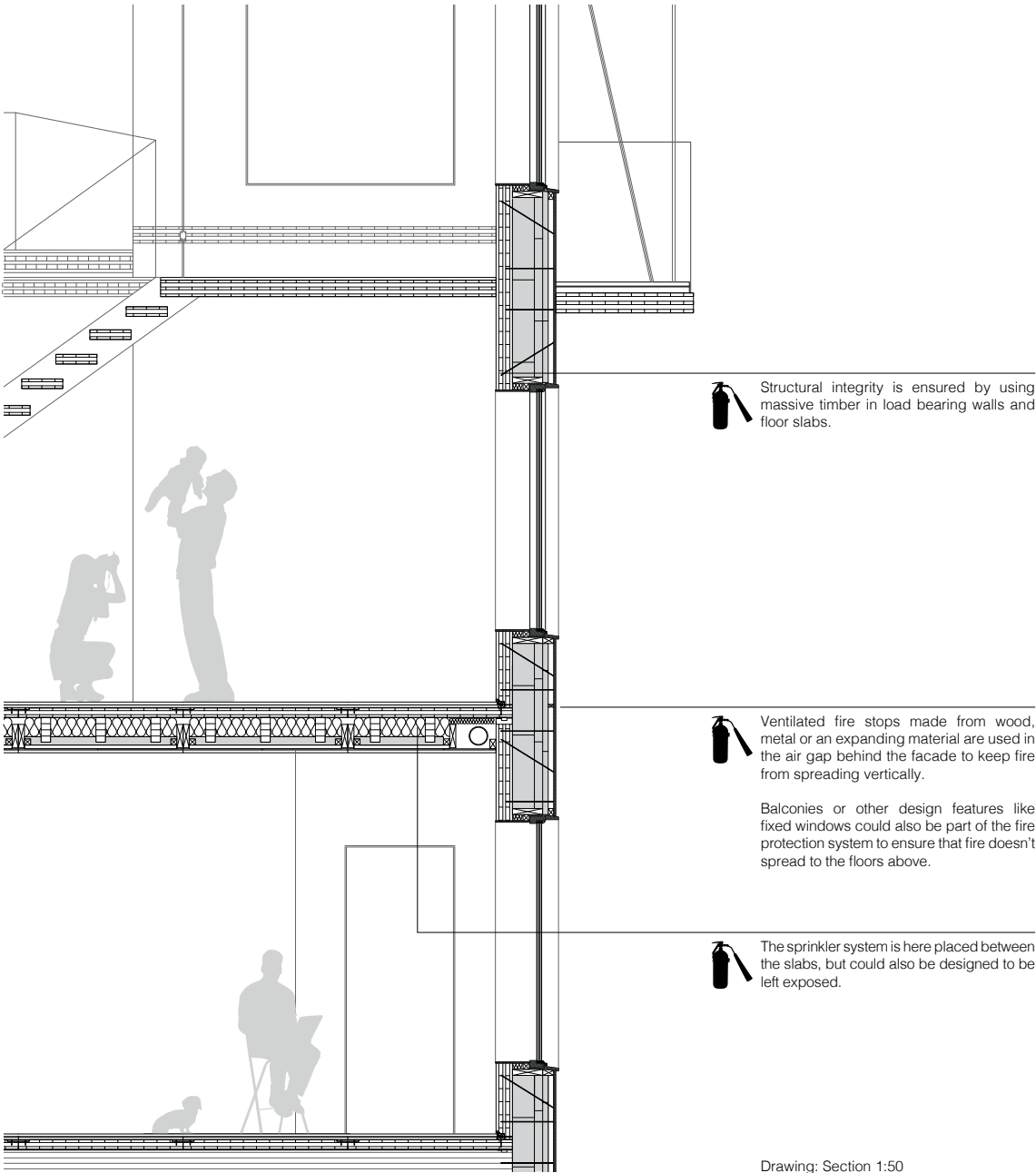
Industry competitors often proclaim timber buildings to burn, get moldy and leave a noisy indoor environment. Working with organic materials of course demands precautions and adapted methods that when considered result in robust, safe and long lasting buildings. A residential timber building differs in many aspects from conventional concrete buildings but is more similar than one would expect. To be able to investigate and illustrate the implications of the cellulose-based system we present drawings of a design for a four storey row house imagined as an add-on to an existing building in a dense urban context. See more of the design of standard details under chapter 02 | design.

TIMBER SINGS, BUT SOFTLY

Acoustic comfort is an important aspect of our well being and how we experience living in our home. Related concerns were discussed already in the previous chapter as well as the construction principles necessary to provide good sound insulation between floors. The lightweight material does not compare well with the sound damping advantage of the heavy concrete why a careful design is crucial to avoid unwanted sound bridging. The biggest challenges for timber structures are vibrations from foot step and flank transmissions as well as airborne low frequency noise in the frequency range 20 to 200 Hz. Connection details that isolate adjacent elements between apartments can however largely diminish the problems. There is in the time of writing still no authenticated calculation methods or accurate acoustic simulations available for designing timber structures, but built objects have shown that requirements can be fulfilled. This field will undoubtedly be the subject for research in the years to come (Gustafsson et al. 2013, p. 34). In the section of the hypothetical building a double layered floor slab is used in between apartments, while a single width of CLT is enough for the mezzanine floor of the double height apartment. The well-insulated walls efficiently block noise coming from outside.

-  Elastic dampers, like sylomer strips, are placed in between wall and floor elements. The connection is sealed with special screws, clad in rubber, to prevent flank transmissions through the connection. See construction details under chapter 04 | construction.
-  The apartment separating slab consists of a two layered floor slab with separated upper and a lower elements, which are screwed together in the factory for ease of transportation. After assembly they are separated again and the free hanging ceiling is lowered to rest on fasteners in between the loadbearing walls.

Drawing: Section of sample building 1:50



Vertical fire spread through a window from a flashover apartment is according to fire regulations acceptable up to one story above the source. Firestops, sprinklers or balconies should stop fire spread to the floors above.

Todays fire safety requirements do not consider furnishing which usually give rise to fires, if only indirectly (Trätek 2007, p. 45). This can be considered contradictory to the firm requirements of surface materials. Sprinkler systems have proven to save many lives and hinder fire progression but is not yet required in new multistorey residential buildings up to five floors (SP Sveriges Tekniska Forskningsinstitut 2012, p. 19), although a lot of people advocate its necessity regardless structural system.

Image: During a fire, the exterior layers of wood will char, creating a layer of insulation that prevents the interior from burning. Thus, the structural integrity is maintained (Archi-tectural Record 2013).

TIMBER BURNS, BUT SLOWLY

All of us have encountered wood burning in a bonfire or a fireplace and are aware of its combustibility. Fire safety is always to be considered in taller buildings, especially if built densely, but timber structures are actually as safe as any other structural systems.

The new performance-based fire regulations do not restrict specific materials, but consider general principles of evacuation, structural integrity for certain amount of time, spread of fire and smoke (SP Sveriges Tekniska Forskningsinstitut 2012, p. 11). Fire safety can in principle be achieved in two different ways, by a passive or an active system - or a combination of the two. A passive system includes sectioning of fire cell boundaries, dimensioning of structural elements and incombustible surface layers etc. To further enhance fire safety or maintain the same security level with smaller deviations from the passive system, active systems like sprinklers can be added (Gustafsson et al. 2013, p. 32).

A sprinkler system can in the case of the cellulose-based building system enable usage of exposed timber both externally and internally. An authorized fire consultant has to consider all aspects of fire safety in an analytical evaluation, a simplified evaluation is not adequate, before deciding if the fire requirements are fulfilled in a specific building design (Trätek 2007, p. 45).

Steel is hard to analyze for fire safety since its structural integrity fails gradually at high temperatures, whereas timber maintains structural integrity while burning in a predictable course. The density of massive timber ensures a slow and steady burn that chars the outer surface, leaving the structural core unharmed and the structural integrity between fire cells intact (BTY Group et al. 2012, p. ii).





🔹 The simple composition of wood-based materials makes a robust wall build up where the specific properties work together creating a sound and well functioning whole.

The wood fiber insulation in the diffusion-open wall absorb and emit humidity in equilibrium with the humidity of the surrounding environment, thereby preventing moisture from accumulating locally and causing mold growth.

TIMBER GETS WET, BUT DRIES

Timber buildings last as long as any other when properly detailed to keep the timber dry (AITC 2002, p 1). The Swedish convention of using plastic foil in modern building derives not only from air tightness and energy efficiency, but a fear of mold and rot. We have a tendency to mix organic materials like timber together with non-organic materials such as mineral wool that lacks hygroscopic properties. The obvious risk is that leaks in the plastic layer and a slight overpressure in the building presses vapor into the wall where it gets trapped locally between the mineral wool and the wooden beams (Gustafsson et al. 2013, p. 10).

Several European countries with traditions of timber construction, similar to ours in Scandinavia, have better adapted their modern timber building techniques to the inherent properties of timber. Wood is a hygroscopic material that buffers moisture naturally by absorbing and releasing water vapor. The wall of the cellulose-based system is inspired by European pioneers and intended as an airtight but diffusion-open building envelope that self-regulates, much like human skin absorbing and releasing moisture. This organic wall interacts with the surrounding environment to balance humidity. When tested in the Cerbof project nr 76, the wall maintained distinctly more stable humidity levels over time when compared to those found for mineral wool (Janols et al. 2013, p. 23). Read more about the details of the cellulose-based system under chapter 02 | design.

Image 1 : (HYBRiD Build Solutions 2013)

Image 2 : (Baulinks 2013)

Photo: Wall section of the cellulose-based building system. (A.Esbjörnsson)



Image: Walls and floors in massive timber buffer moisture and store heat, contributing to a comfortable living environment with even humidity and temperature levels over the day. Additionally building materials free from toxic emissions assure a healthy indoor environment.

living with timber

Does it matter to our health and well being what the walls and floors in our living spaces are made of? A good ventilation system is necessary in modern building. Current ventilation standards however are not set to ensure proper oxygen levels but to remove bad smells and excessive moisture levels. Another important aspect is to remove harmful emissions derived both from building materials and other artefacts brought into our homes (Boverket 2011, p. 63).

HEALTHY INDOOR ENVIRONMENT + ENERGY EFFICIENCY

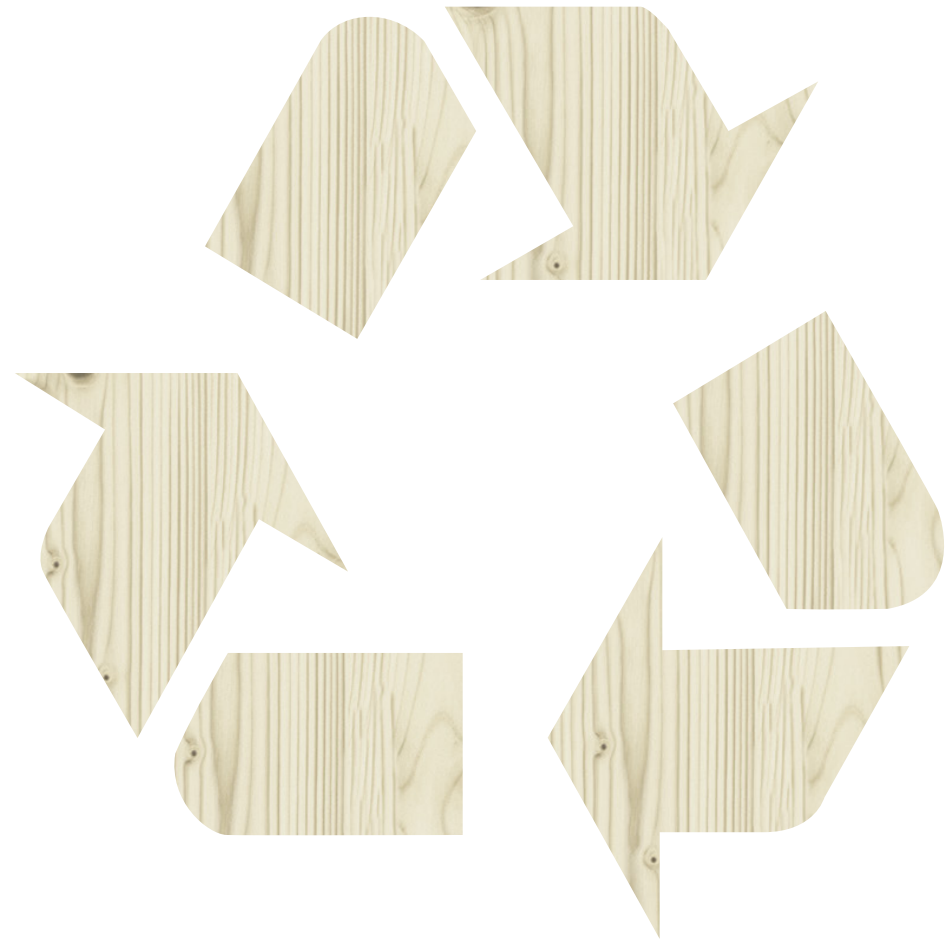
The moisture buffering ability of the components in the cellulose-based system gives a natural breathability that creates a comfortable indoor climate as humidity levels are equalized over the day (Simonson et al. 2001, p. 172). Comfort is additionally enhanced by exposed wooden surfaces that are perceived as warm and comfortable. Touching a wooden surface and a glass, concrete or stone surface in the same room gives different experiences, where the wood feels warmer due to its good insulating properties. The air temperature can therefore be lowered to yield energy savings, without confining comfort.

Furthermore, massive timber carries a capacity for useful heat storage called thermal mass where the interiorly exposed wall surface takes up and stores heat from solar radiation during the day providing a thermal inertia that lessens the need for active heating (Simonson et al. 2001, p. 179). The massive timber wall actually has similar performance to a heavy concrete wall, when taking all its features in consideration. While the heat capacity of timber is lower than in concrete, timber compensates with higher insulation capacity due to lower thermal conductivity. These inherent advantages of a massive timber structure are fully utilized in the cellulose-based system and could possibly further constitute energy savings.

Another promising but hypothetical possibility of a wholly cellulose wall section is the reduction of chemicals that contribute to the toxification of indoor environments. We only speculate on what an indoor environment free from harmful emissions would mean for current ventilation requirements. Such a scenario would have to include the clothes we wear and the furniture and devices we own. Heat is lost especially in wintertime due to ventilation, often leaving a dry and uncomfortable indoor air. We don't claim that we must ventilate less, but simply question building solutions that rely on and compensate with installation technology. Like advocated through the cellulose-based system we believe the future lies in healthy materials and robust building technology solutions, which hopefully bring both ecological and economical benefits.

An important aspect of sustainable building is the ability to change use or adapt to new living standards. Generality of a floorplan or flexibility of structural elements are aspects that can ease changeability, which although has to be weighed against the specific purpose a new building is designed and constructed for.

Considering smaller maintenance related changes property owners, managers and housing associations benefit from having walls of massive timber. Rental apartments often host several different tenants during the life of the building, why low conversion costs can become a long-term competitive advantage. The tenants themselves benefit from the ease of putting up shelves, frames and other furniture on the walls without the need for hammer drills and plugs. The small holes are easily fixed with putty, which can resemble light wood if the wall is untreated.



06

AFTERLIFE

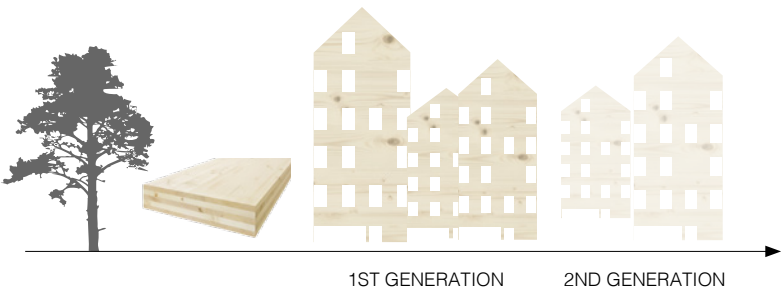
disassembly and re-use

The life of a CLT building has the potential to extend as far as any corresponding building in concrete or steel, but all buildings are eventually decommissioned and their materials become part of the next stage in a cycle. In the case of timber, we find that the ease of a lightweight construction implies a simplicity of disassembly for a non-invasive demolition, particularly advantageous in the city. Used timber panels can either be reused, down-cycled to paper products and biofuels or combusted for heating. Either way is better than landfill, as the fate of concrete, or the energy intensive processes of recycling steel.

design for disassembly

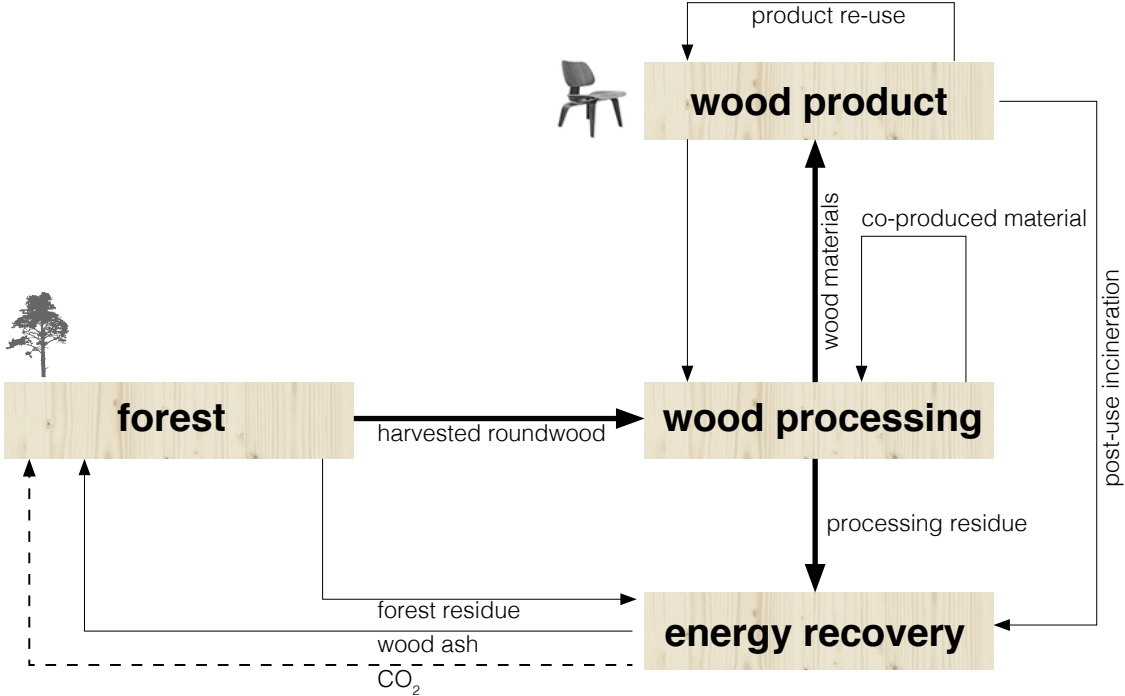
Part of a holistic approach is ‘designing for disassembly’ as a strategy to enable material separation, reuse and recycling of building parts. The total cost and energy use of a building should according to an LCA-perspective include the expenses of deconstruction and removal, aspects rarely considered in new construction (European Union 2010, p. iv). Dismounting a building with the cellulose-based system would be similar to the fast construction but performed in reverse.

Demountability once was part of the Swedish culture as timber dwellings and stables were moved both short and long distances. Although this level of mobility is not often expected of modern buildings, it could both facilitate reuse and recycling of building parts. It would also generate large savings in a scenario similar to the one in northern Sweden where the entire city of Kiruna is being moved to a different location due to the mining industry. Who knows, a future with extreme weather conditions and rising sea levels could unwillingly reform our idea of mobility and housing.



RE-USING MASSIVE TIMBER

The smallest ecological footprint is achieved when the impact of producing new building materials and other products can be avoided. Timber is a workable building material in the sense that it has great potential to be further processed and reused in new building applications. Naturally it's beneficial to have the carbon fixed in the built environment as long as possible, but there are also several environmentally viable options for down-cycling timber worth mentioning. Through mail correspondence with glue manufacturer Purbond, a theoretical opportunity for down-cycling CLT to paper pulp was revealed. At least their product, claimed to be free from VOCs and constituting less than 1% of a finished CLT panel, would according to Gabriel¹ not create any restrictions, besides possible legal opposition.



This means CLT has the potential to become a variety of useful paper products also after fulfilling its purpose as a building material. Another down-cycling opportunity is letting the fixed carbon in biomass be converted into convenient energy and used as biofuels. The biomass conversion can result in fuel in solid, liquid, or gas form. Biofuels have increased in popularity because of rising oil prices and the need for energy security (Worldwatch Institute 2011).

Ultimately whether the timber has been reused several times or not at all, the material has the unique potential of direct energy recovery through combustion, which is a perfectly brilliant way to serve the economy and ecology after the building life, especially if replacing non-renewable and polluting energy sources.

The fundamental idea behind the cellulose-based system is to have a building system where a prominent portion of the materials derive from renewable resources of a biological cycle. Both the wood fiber insulation and timber cladding naturally share many of the 'afterlife' opportunities as CLT. The long screws and other steel components can be removed and saved for optional reuse in new buildings, alternatively recycled and converted to new steel components in an eternal technical cycle.

Diagram: The no-waste circle of timber product manufacturing (Kuitinen, Ludvig & Weiss 2013, p. 27).

¹ Dr. Joseph Gabriel Technical Director Purbond, mail correspondence 2013-11-03



concluding remarks

Through these chapters we've presented the Master thesis project *Urban Timber* by stepping through the typical phases of an imagined urban residential project with the aim to minimize environmental impact and to create an architecture of high quality that meets human needs. This holistic mindset takes a possible form in an open-ended building system using cross laminated timber as the structural base. Together with a model of CNC production and prefabrication we point toward viable solutions for the next generation of building as an economic opportunity both for the Swedish construction industry as well as the timber industry. We discuss future means and possibilities extending from where the industry is today and visualize a new potential direction through drawings, scale models, and a full scale prototype that hopes to communicate a vision of a mass customized urban timber architecture.

SYSTEMIC SOLUTIONS

To be holistic and effective we aim to formulate systemic solutions that apply in a variety of urban situations with a range of architectural resolutions. Bearing this in mind we investigated the viability of a cellulose-based building system which replaces traditional materials like gypsum, mineral wool and plastic with bio-based alternatives. The output of this approach has taken form as generic building details, that highlight various meetings between wall elements and floors so that practical construction can be solved within the existing industry infrastructure, and shared with architects and industry actors as an open-ended system to be further developed.

ENVIRONMENTAL IMPACT: LCA

The purpose of investigating a cellulose-based system was to as far as possible enhance the positive environmental performance of a renewable, low-emissions resource. To evaluate its impact we performed an extension of the Wälludden case study (Peñaloza, Norén & Eriksson 2013), through a collaboration with SP Wood Technology, which uses a Life Cycle Analysis (LCA) to compare the carbon impact of one concrete system and three different systems with timber as a structural frame. From the original study we found that the timber systems perform a lot better than the concrete alternative but also that gypsum, mineral wool and plastics alone account for a large share of the environmental impact in all these timber systems. The extended study is limited to carbon emissions during production and shows that a cellulose-based system reduces the impact by about 37% compared to the conventional CLT system and up to 67% compared with the concrete system. These figures exclude the carbon that is sequestered by the timber itself, which only strengthens the argument for the cellulose-based system.

ECONOMIC VIABILITY

With an ambition to address the realities of an industrial economy we explored how to optimize a factory production process for mass customization and tie this together with a vision for a customized prefab architecture that is both architecturally rich and economically practical.

Early in the process we visited the Martinsons CLT factory in Bygdsiljum and began discussions around the state of CLT building today, the obstacles and opportunities, and how they can develop in the future. In chapter 3 | fabrication we explore information management and the interface between the architect and the CNC machine. The current state of the information flow hinders the economic competitiveness of CLT, due to the time consuming process between design and fabrication, where multiple translations of digital models and formats occur. We also learned from several of our industry contacts that it is in reality very difficult to put ideas like BIM and other organizing structures of project management into practice. The industry is slow to integrate new methods and technology because it is difficult to coordinate standards between the different actors. Nevertheless, software developments promise to offer a chance to more closely tie designers to the factory process, streamline the steps between, and bring meaning to the notion of mass customization.

Despite the obstacles of information management CLT buildings are currently of comparable cost to concrete equivalents, due to the lightweight prefab system in CLT being more effectively and safely installed compared to a site-cast or prefab concrete system. Lighter cranes allow for a less invasive urban installation and are aided further by a shorter construction time as builders do not have to accommodate the cure time of concrete when beginning the next story of a tall urban building. We deliberately focused on developing a flatpack prefab system instead of a volume element system, both due to more efficient transportation and because it allows a larger architectural freedom and more customized solutions that can be inserted into a dense urban site.

FIRE, SOUND, & MOISTURE

We also pursued environmental and economically viable solutions to the issues of fire, sound & moisture that can enable building of dense urban blocks entirely of timber. The shift to a performance-based fire code in 1994 once again enabled higher buildings in timber in Sweden and opened the door to exposed timber surfaces both on the interior and exterior of buildings, as long as they can perform at the required level of safety. This is often approved by consciously integrating smart passive solutions with an active system, like sprinklers. To use the cellulose-based system to its full extent in a project demands an authorized

fire consultant to execute an analytical evaluation for the specific design. We investigated the obstacle of sound bridging connected to a lightweight structure and learned that careful design and smart connection details are keys to ensure acoustic comfort. However, conventional sound protecting strategies often dictate an uncommonly thick floor slab, while a CLT project stands to lose a whole floor compared to a concrete equivalent when conforming to height limitations. Acoustic performance of timber structures is hard to simulate but we see exciting potential in new combinations of insulation types and layer build-ups that are opportunities for future research. The proposed floor slab part of the cellulose-based system is merely a contribution to this debate to emphasize the importance of research and development of new thinner timber floor slabs.

Fears surrounding the risk of molds and related moisture problems connected to building with organic materials have in recent decades resulted in fragile building solutions. Addressing building physics properties the cellulose-based system has a carefully considered composition of materials that makes a robust wall build up where the specific properties of every material work together to create a sound and well functioning whole. The need for plastic sheets and gypsum is sidestepped by having the hygroscopic materials actively perform to create a comfortable and healthy indoor climate with a natural breathability.

Another interesting aspect of the cellulose-based system is the effect of a non-toxic indoor environment, that potentially can bring both health benefits and energy savings. Each point described above offers further opportunities for future innovation.

FULL-SCALE PROTOTYPES

To summarize our project and the suggested improvements we envision for mass housing we designed two full-scale prototypes, a 3 m high apartment cutout and a smaller wall section. The large prototype was an exercise in design and project delivery through the factory, also constituting a practical example when testing the boundaries of mass customization in Sweden today.

We built the small wall section ourselves for the exhibition as a practical and tangible exercise that gave a realistic idea of the material, weight and practical assembly methods.

TOWARD AN ARCHITECTURE

With all practical considerations we have hoped to understand and convey a starting point for the implementation of an urban timber architecture. The prototype together with the models imply a design philosophy and method that might characterize an urban aesthetic that extends from the cellulose-based system. Not an aesthetic in the sense that it dictates certain rules, but one that gives room for an extensive use of wood. This together with prefabrication and the structural opportunities of a lightweight rigid plate we imagine a new medium for future architects to find architectural qualities and expression in massive timber. Ultimately, we hope our work will inspire a vision for timber architecture that also provides architects and researchers with a practical foundation and the arguments necessary to influence a future of sustainable development.

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