SENSIBLE STRAW

EXPLORING INDUSTRIALIZATION OF STRAW BALE BUILDING IN SWEDEN

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& Isabelle Sjöberg

Master´s thesis at Chalmers Architecture
Design for Sustainable Development
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CHALMERS
UNIVERSITY OF TECHNOLOGY

Changing the world, one straw at a time

Picture 2.

PREFACE

A seed was planted some years ago to look closer at straw bale construction. Attending a practical course in straw bale construction, at Slöjd & Byggnadsvård in the spring of 2014, was a large stepping stone for the realization and the formation of this master's thesis.

This master's thesis would not be possible without the help from skilled individuals and companies, and therefore we want to thank everyone who has contributed to our work. Special thanks to our supervisor John Helmfridsson, Liljewall arkitekter, for supporting us along this journey. Furthermore appreciations to our examiner Lena Falkheden, Director of master's programme Design for Sustainable Development/MPDSD, at the department of Architecture, Chalmers University of Technology.

Acknowledgements to Torbjörn Svensson at Becohus and representatives from PEAB and NCC. Further thanks to Thomas Henrikson at Malmömässan and Marius Tarvydas at Ecococon. Appreciations to Miljöbyggsystem for providing material for the psychical model of the "*Sensible Straw*" wall element. Thanks to other architects around the world for sharing their thoughts about the straw bale building technique.

Finally, special acknowledgements to ModCell® and Finlay White for welcoming us and sharing thoughts and ideas throughout the process of this master's thesis.

We hope that this work will inspire people to continue to question the conventional and exploring other alternatives.

Picture 3.

SAMMANFATTNING

Intresset för hållbara byggtekniker och framför allt hur byggnadsmaterial kan bidra till hållbar utveckling har varit utgångspunkten för detta examensarbete. Arbetet fokuserar på att utforska potentialen av halm som byggnadsmaterial. Mer specifikt undersöks hur byggandet med halm kan anpassas och utvecklas till det industriella byggandet i Sverige. Än så länge har halmhusbygget i Sverige till största delen realiserats i form av självbyggeri. Detta examensarbete riktar sig därför främst till byggindustrin, i hopp om att inspirera och påverka.

Som många andra områden i dagens samhälle, är byggbranschen ekonomiskt driven. En önskan om att hitta billigare, snabbare och mer effektiva sätt att bygga kommer alltid att existera. Detta är en av anledningarna till att halmbalsbyggandet ännu inte har gjort entré på den kommersiella byggmarknaden. Byggindustrin har även haft en mentalitet där *"vi gör som vi har alltid gjort"*. Det finns svårigheter att ändra detta synsätt eftersom det ofta finns en rad förutfattade meningar, i synnerhet om halm.

Prefabricerade byggelement används i stor utsträckning av byggindustrin i dagens konstruktioner. För att halm ska bli ett konventionellt och accepterat byggnadsmaterial kan prefabricerade väggelement av halm därför vara en lösning. Det huvudsakliga resultatet i detta examensarbete är därför ett förslag på prefabricerade halmbalsmoduler som är anpassade till svenska förhållanden. För att till fullo förstå och testa modulernas potential, har ett förslag till utformning av en förskola som utnyttjar dessa prefabmoduler tagits fram, i Ale kommun i västra Sverige.

Nyckelord: halm, halmhusbygge, prefabricering, väggelement, förskola

Picture 4.

ABSTRACT

As many other things in today's society, the building industry is economically driven. There is always the desire of finding cheaper, faster and more efficient ways of building. New techniques and methods need to be developed in order to both suit and appeal to this way of building, and at the same time not exhaust non-renewable resources. Yet, the building industry has a long cultural history and seems to be stuck in the mentality of doing "*what we've always done*". Changing this paradigm is hard since there is a lot of preconception about straw in particular. This is one of the reasons that straw bale building techniques has not yet entered the commercial building market.

The point of departure for this master's thesis has been the interest in how sustainable materials can contribute to sustainable development. The aim is to explore the potential of straw as a building material, and specifically how the technique can be adapted to an industrial way of building. So far, most straw bale buildings in Sweden have been owner-built. This master's thesis is therefore primarily aimed at the building industry, in hopes to influence it towards making more sustainable choices.

Prefabricated building elements are frequently used in constructions nowadays. Prefabricated straw wall elements could therefore be a solution to make straw a conventional and an accepted building material, as well as a step towards a more sustainable future. The main result is therefore a proposal of prefabricated straw bale modules, adapted to Swedish conditions. In order to fully understand and test the potential of the modules, an implementation example has also been designed. This implementation is a preschool set in the municipality of Ale in the west of Sweden.

Key words: straw, straw bale building, prefabrication, wall module, preschool

Picture 5.

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Picture 4.

INTRODUCTION

BACKGROUND

Our world is facing difficult challenges in the nearby future and the need for sustainable solutions is growing more and more with each passing day. A number of studies show that humans and our activities have contributed to global warming and the deterioration of the environment and the planet. The intergovernmental panel on Climate Change, IPCC, states that it is extremely likely (95 % certainty) that human activity is the main cause for global warming since the mid-20th century (IPCC, 2013). And since we are the cause of the problem, we have the responsibility as well as a possibility to do something about it, and turn it around for the better.

The modern day societies and technological advancements have led to the development of building materials that in many cases do more harm than good. Today, most conventional building materials have high embodied energy, and some are even toxic and wasteful. The built environment accounts for approximately 40 % of the world's total primary energy consumption and contributes to up to 30 % of global annual greenhouse gas emissions (Lemmet, 2009). This needs to stop, or ways of recycling and reusing waste and pollution needs to be developed. Buildings need to do more good than harm.

To move away from the wastefulness of conventional construction can imply extra research, costs and additional time to create a wholesome design with other sustainable solutions incorporated. Most sustainable methods and materials are hardly the norm within construction, even though they are no longer either alternative or experimental (Paschich & Zimmerman, 2001).

The building industry is, as many other things in society, economically driven. The desire of finding cheaper, faster and more efficient ways of building will always exist. This is one of the reasons that many sustainable building techniques have not yet entered the commercial building industry. Making a profit is another reason for this. If a sustainable alternative does not yield a higher profit than the already existing one, the probability of exchanging these are almost zero.

Mankind has slowly begun to realize that earth's resources are not endless and that we have to think before extracting raw materials. The growing will of using toxic-free and renewable materials and the strive for constructing energy efficient buildings have made people reevaluate old building techniques (Bävernäs, 2012).

Sustainable building techniques and above all; sustainable materials, is one important aspect to how the building industry can contribute towards creating a sustainable society for generations to come. It is essential to choose materials that have beneficial environmental properties, such as:

- Derived from renewable resources

- Be biodegradable

- Serve as a carbon storage

- Be within a reasonable shipping distance

- Does not require extraction from the ground

- Come from an abundant resource

- Have low embodied energy

- Be non-toxic

Picture 6.

PURPOSE

The main purpose of this master's thesis is to explore how sustainable materials, such as straw, can be adapted to and enter the industrial way of building in Sweden. Therefore, the potential of an efficient and modular construction system is explored, which should be able to realistically compete with conventional materials and methods, and at the same time be derived from local and environmentally friendly materials.

The development of straw bale construction in Sweden has more or less stood still since the technique was introduced in our country. However, the development has come further in other parts of the world. Prefabricated systems have for example been developed in some countries. These solutions will serve as inspiration for this thesis to help develop a solution adapted to Swedish conditions.

Existing straw bale buildings in Sweden are quite small and have been owner-built. There is a gap between the main methods employed in straw bale building today, and the main methods employed by the building industry. This master's thesis hopes to bridge this gap by developing a prefabricated modular straw bale system. Further showing that straw bale construction does not only work in single-family houses but also in larger public buildings. Since there is a growing interest in eco-schools, and environmental friendly buildings overall, the implementation design for this thesis is a proposal of a new preschool. Preschools often serve as role models, sometimes influencing entire new surrounding neighborhoods to be built more sustainably, following the preschool's example.

The key stakeholders are naturally the building industry but also architects, contractors and producers. Convincing them is not an easy thing to do. Showing how the proposed modules work and how they can be implemented is therefore an important and necessary part of this thesis.

The intention of this master's thesis is to shed some new light and innovation on this new/old building technique, this as an attempt to reach out to others and show how this relatively simple and genuine building method can be developed and adapted to the building industry. In the nearby future maybe this method will become the new normal and be a conventional option.

Picture 7. A "truth window", showing that the wall is insulated with straw.

RESEARCH QUESTIONS

The master's thesis aims at exploring, and reflect upon, how straw bale building can be industrialized in Sweden, and how it can enter the industrial building market. It is important to reflect upon whether the suggested industrial construction method is a good solution for straw, and how this potentially will affect the building industry.

The sub-questions in this thesis will concern the flexibility and the possibilities of straw as a building material.

"How can straw become a part of the industrial way of building?"

- *What are the properties, benefits and drawbacks of straw, both as a material and a building technique?*

- *What has already been done in the field of industrializing straw bale building, and how do these prefabricated solutions work?*

- *Is prefabrication a good solution for straw?*

Topics that also will be touched upon is how the building industry can accept new and more sustainable alternatives when it comes to building materials, and what is needed in order for them to do so.

The research has led to a specific focus on investigating prefabrication methods and to the development of a potential prefabricated modular system with straw. The questions concerning the design of the suggested modules, and the implementation of these, is related to how thermal bridging can be minimized, and how the modules can be built and assembled as easily and fast as possible. Which materials are preferable to use in combination with straw, and how much of the construction should be prefabricated?

Picture 8. Before rebaling a straw bale at the straw bale building course in 2014.

DELIMITATIONS

This thesis will primarily focus on adapting the straw bale building technique to Sweden and our specific conditions. It will therefore not consider techniques and materials that cannot be derived from a national resource. Smaller owner-built buildings will not be further developed, since that is currently being built in Sweden. Neither will private building cooperatives be discussed further. It is most likely not in this way of building that straw could gain the most ground. Instead, the challenge lies within creating a bigger area of use for straw in buildings, and convincing the industrial building industry to invest in this type of technique.

Since straw is a natural material, it makes sense to use sustainable materials, to furthest extent possible, in the other parts of construction. This can create construction limits in terms of shape and height etc. depending on the choice of material. However, it is a fine balance between not being so visionary or different that it discourages the building industry. In the chapter "*Choosing materials*" structural material options is not assessed, neither are exterior cladding or the main insulation, straw. The chosen materials are not thoroughly assessed and does not consider all aspects. Only a brief exposition is carried out in this section to show more sustainable and environmentally friendly options. Conventional materials such as concrete and mineral wool are instead described in the chapter "*Conventional building materials*".

In the chapter "*Laws and regulations*", a brief description of existing laws and regulations is made. Only energy requirements and fire protection are discussed since these affect the modules and the implementation task, the most.

In the design phase of this master's thesis, the proposed straw bale modules are wall elements. This choice has been based upon the conviction that this building method needs to gradually be introduced to the building sector in a familiar concept that suits the industrial way of building today, with for example infill walls and double walls. Roof and ground details are presented as principal solutions in order to make the wall element as flexible as possible.

The implementation, in the form of a preschool design, should be seen as just one example of how the modules can be put together in a finished building design. Other aspects associated with sustainable construction such as technical installations and waste management will therefore not be developed in detail. In spite of this, some energy calculation are done in order to ensure Passive House Standard. If the Passive House Standard is a good standard or not is up to one's own interpretation. It has been presented only to prove that it is possible to achieve this standard when using straw. Further, a number or rules and guidelines have been set up to facilitate the design of the preschool. Some of these rules should therefore not be evaluated, since these are just based on personal thoughts and ideals, and not on scientific research.

The preschool has also been designed according to the existing comprehensive plan, an illustrated master plan over the site (see picture 44, p. 119), and other related documentations by the municipality of Ale, where the site is located.

METHODS

To address the questions asked in this master's thesis, relevant literature studies, courses, interviews and field trips have been an essential part of creating a thorough knowledge base. The research is based on literature regarding straw bale construction but also how industrial construction worked historically and today. It has been important to continuously analyze the gathered information, and the result has been based upon these reflections.

A comparison between materials that are commonly used in the industrial way of building today and sustainable alternatives has been carried out Carbon emissions, insulation properties, costs and the locality of the source and production of the material are some aspects that have been taken into consideration and weighed against one another.

An important part of this master's thesis has been to visit pioneers within the field of straw bale building. These people have great knowledge, in different ways, about the building technique. For example, the architect Conny Jerer have many years of experience in building with straw, and Frans Yzermans and Lena Falkheden were one of the first people to construct a straw bale building in Sweden.

A field trip to England, to visit the founder of ModCell® was done, since they are in the forefront when it comes to the development of straw bale construction. ModCell® produces prefabricated straw bale elements, and it was therefore important to visit them in order to get a greater understanding of this type of building technique. ModCell® are not the only company that produces prefabricated straw bale elements. In order to properly investigate the potential of a prefabricated straw bale module, other solutions and companies have been analyzed. A meeting with the company Ecococon was made possible since they were represented at Malmömässan in 2015. Other prefabricated solutions have been studied online and through mail contact. All of which has served as inspiration to the creation of a modular system adapted to Swedish conditions.

A picture of how the building industry works today have been given through personal contact with construction companies, mainly with representatives from PEAB and NCC. An important input concerning this aspect was a study visit to the prefabrication factory of Becohus, in Falkenberg. All of these inputs have made it possible to receive feedback directly from the industry. Feedback has also been given by other experienced people such as for example carpenters, architects, structural engineers and fire experts.

Outlines, sketches, models and drawings have been a large part of the creative process. The designed implementation example is an important part of this thesis to demonstrate and assess the potential and credibility of the modules. Existing plans and documentations from the municipality of Ale, together with material provided by Liljewall Arkitekter, have been studied to create a realistic design proposal. Aditionally, a document published by the municipality of Umeå has been useful, "*Funktionsprogram förskola*" from 2010. It states the specific functions needed in a preschool. Furthermore, a study visit to Vommedalens förskola, in Kållered was carried out in order to discuss thoughts and ideas regarding the preschool design of this thesis.

Picture 9-10

IMPLEMENTATION SITE

Working with an existing site, for the preschool design, has been important in order to create a realistic and credible project. This is of course also to show that straw constructions can work on most any site, and therefore could be an alternative conventional building material and method.

The site was provided to this master's thesis, by Liljewall Arkitekter through John Helmfridsson. The site is situated in the municipality of Ale, in Nödinge, along Norra Kilandavägen.

Nödinge was a former church village, which began to grow in the end of the 1960s, due to the shortage of housing in the Gothenburg region. Therefore several dwellings were built in just a few years (Ale Kommun, 2007). Today the municipality of Ale nearly has 30 000 inhabitants, of which around 5 600 live in Nödinge (SCB, 2014).

Nödinge has two elementary schools, Nödinge School, Kyrkby School. There are three preschools, and some additional temporary pavilions. The number of children in the preschools is expected to grow, from about 1600 to somewhere around 2050 children in 2020. Therefore there is a need for both new preschools and refurbishment of the already existing ones, to manage the increasing demand (Ale Kommun, 2007).

In 2010, the municipal council of Ale decided to build a new school in Nödinge along Norra Kilandavägen (Ale Kommun, 2012). Different kinds of investigations concerning the site have been carried out, for instance; geotechnical, storm water, traffic and noise investigations. Liljewall Arkitekter then designed a proposal for this site. However, the realization of this project never happened, but the preparatory work for this project has been helpful when designing the fictional proposal in this thesis.

Picture 11. An aerial photograph over Nödinge, highlighting the implementation site, in the municipality of Ale.

0 250 m

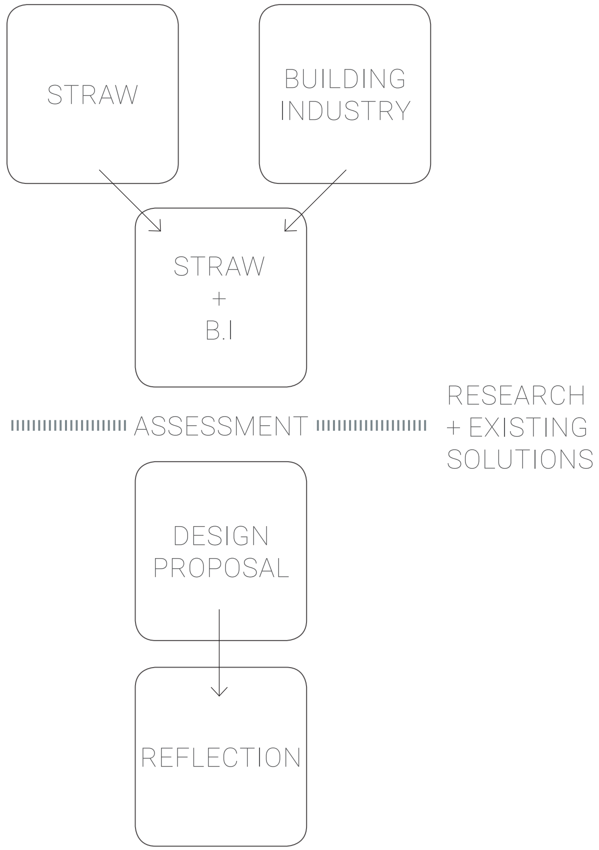
STRUCTURE OF THE THESIS

This master's thesis primarily consists of three main parts; a theoretical investigation, the design of straw bale modules and finally how the modules can be implemented in a building design. None of the parts are completely freestanding. The design has been enriched and based upon the research, and likewise the research has been enriched during the design process.

The thesis ends with a reflection on how the proposed straw bale modules potentially will affect the building industry and the built environment. The reflection also addressess whether prefabrication is a good solution for straw and possible future research concerning this topic.

On the next page, each chapter is presented briefly to get an overview of their content.

The illustration shows the key features needed in order to realize this master's thesis. The structure of this report follow the same pattern.



STRAW AS A BUILDING MATERIAL
This chapter presents straw as a building material; its properties, how mankind has used it historically and how straw bale building techniques are carried out today.

THE BUILDING INDUSTRY
This part briefly explains the building industry in Sweden. Its history and ways of working today is outlined, as well as a presentation of the big developers on the market. Their methods and commonly used materials are also laid out.

STRAW AND THE BUILDING INDUSTRY
This chapter investigates how straw can become part of an industrial way of building. An assessment of already existing prefabricated systems, with straw incorporated, is carried out. The comparison between these, have laid the foundation for the development of how to industrialize straw bale building in Sweden.

INDUSTRIALIZING STRAW BALE BUILDING IN SWEDEN
In the first part of this chapter a framework is set through a brief description of the national considerations; the climate and Swedish laws and regulations.

The last part aims at unfolding the challenges with prefabrication and the introduction of straw into the industrial way of building. The sections; *"Challenges with prefabrication"* and *"Weighing the options"* are based on previous chapters and thoughts generated from these.

STRAW BALE MODULES – A VISION FOR SWEDEN
A method of how to introduce straw into the building industry is presented in the initial part of this chapter, followed by a design of straw wall elements adapted to Swedish conditions. Other alternative designs and options are also described.

IMPLEMENTATION
The designed straw wall elements are presented in a full building design, to test and evaluate the modules.

CONCLUSIONS AND DISCUSSION
The results and conclusions of the master's thesis is discussed here, as well as the working process and suggestions for possible future research.

APPENDIX
The study visits and the model construction made during the process of the thesis is presented in the first appendix. The following appendix presents the passive house calculation.

STRAW AS A BUILDING MATERIAL

Picture 3.

WHY STRAW?

A sustainable and renewable material that has been used in vernacular architecture, since the beginning of humanity, is straw. It is a sustainable construction material that does not require extraction of raw materials from the ground and does not produce any toxins or pollutions while it is being produced (Lacinski & Bergeron, 2000).

There are plenty of good reasons to move towards using straw for construction purposes, even if this abundant renewable resource held no particular advantage over other materials. Building with straw can lighten the load on the environment and straw bale buildings can actually outperform buildings with other materials (Magwood & Mack, 2000). It is the significantly lower environmental impact that makes many people grow attached to straw. As the following chapters will show, there are no reasons that it cannot become a standard part in construction, the problem stems from economics, politics and from a conservative industry in general. The challenge lies in convincing politicians, the building industry and particularity the developers and builders to move towards using materials that have low environmental impact.

Straw is the leftover stems of cereals after the grains are removed in the process of harvesting. It is mainly used as bedding and food for animals. Sometimes straw is chopped directly behind the harvester and incorporated back to the soil by ploughing. Government subsidy has however contributed to the increasing amount of straw being burnt for heat and electricity (Atkinson, 2011).

There are few regions that are not within a reasonable shipping distance from a straw supply (Magwood, 2005). And while modern agricultural practices are far from perfect, it does makes sense to use some of the excess straw that it produces for construction. Every year a great amount of straw is grown around the world, enough to build millions of houses (Lacinski & Bergeron, 2000). In the US alone, around 200 million tons of waste straw is produced every year (Paschich & Zimmerman, 2001).

Already in the field, straw is a building material ready to be used. This is unique for a building material.

All constructions today produce waste of some sort, most of which ends up in landfills. However, the waste straw on a straw bale construction site can either be composted or used for animal bedding. There is also no need for landfill when a natural building, such as a straw baled one, has served its purpose; it can simply be exposed to the elements allowing it to biodegrade (Atkinson, 2011).

Insulation is, and always has been, an important issue in construction. Up to 40 % of the energy required for the heating and cooling of buildings is caused by air leakages. These leakages can occasionally consume additional energy in order to maintain a constant ideal indoor temperature. The use of proper insulation can eliminate 30 % of this energy (Attmann, 2010). Straw bales have enormous potential as a construction material in cold climates, thanks to their insulation properties (Lacinski & Bergeron, 2000).

Considering all the benefits, it makes it difficult to understand why the use of straw, as a building material, has not become as widely spread in Sweden as it has in other countries. This chapter provides a greater understanding of straw as a material and the technical information needed to further develop this technique and adapt it to the Swedish building industry.

“Once people try this type of construction, they absorb it and agree with it, and begin to recognize it as a concept, as a psychological departure from the idea that industry is somehow more sophisticated than nature. It brings the left and the right together; it functions as a stepping block into an ecological way of building and living. People begin to ask, ‘How can I put this to work in the rest of my life?”

- Bruce Millard (Lacinski & Bergeron, 2000, 4).

Picture 12. Pilgrim Holiness Church in Arthur, Nebraska USA. The church was built out of straw bales in 1928 .

HISTORY OF STRAW BALE CONSTRUCTION

Straw, and other natural fibers, have been used for different kinds of purposes since the beginning of humanity (Atkinson, 2010). Straw has traditionally been used for animal bedding, craft objects, roofing and occasionally as mattress stuffing. Archaeological finds indicate that thatched roofs were used as early as 1000 BC in northern Europe. In Sweden, it is believed to have existed from 500 BC. Thatched roofs were even the most common roofing in the south of Sweden during the 19th century. Later on, straw on roofs came to be replaced by reed, mostly due to new harvesting methods and the pursuit for fireproof materials (Grey, 2013).

However, construction with straw bales was first used in the late 1800s with the invention of the baling machine in the Sand Hills region of Nebraska, United States. When settlers began to move here in the 1880s, wood for construction was scarce which quickly made lumber for building an expensive commodity. A common way of conserving wood was to use wide strips of turf to build up a wall of a house. However, the loose Sand Hill soil produced a turf of poor quality for construction in some places. Many of these sod houses collapsed before a farmer came up with the idea of stacking the product of the newly invented baler for shelter. These early shelters of grass bales were, according to oral history, only plastered on the inside. This because they supposedly were meant as temporary homes until they could build a "*real house*", but they typically came to realize, within a few years, that they not only had a real house but a house that also was comfortably warm in the winter and cool in the summer. The exterior plaster was then applied, creating a permanent home. It took a couple of years for the original bale builders to accept the idea that bales and plaster could from the walls of a house. But a couple of years is almost nothing compared to the hundreds of years it has taken for the same idea to reach a wider crowd (Lacinski & Bergeron, 2000).

The knowledge unfortunately died out during the 1940s, due to a combination of war and the increasing use of Portland cement (Atkinson, 2011). The technique may have died out forever were it not for a group of pioneers inspired by an article by

Roger Welsch, in *Shelter*, in the 1970s. In Sweden the first straw bale house was built in 1976 by Klas Anselm. The house was a part of the Ararat exhibition at Moderna Museet, which was an experimental exhibition of a future ecological society (Jacobsen 1999). Jon Hammond in California was another, among a handful of people, who began experimenting with this technique. After an article on Hammond's straw bale studio was published, in *Fine Homebuilding*, in 1983, more interest evoked for straw bale building in the 80s. By the late 80s a group of people began to explore the wider implications of straw bale constructions for grassland regions (Lacinski & Bergeron, 2000).

The early re-discoverers of straw bale construction usually had the same reasons as the Sand Hill settlers for choosing straw bales; they needed to make a place to live with what was lying around, more or less. With the publication of the book, *A Straw Bale Primer*, by Steve MacDonald in 1991, straw bale construction became available to a much wider crowd. He and his wife decided to share what they had learned from their experiments in the 80s after being inspired by Jon Hammond (Lacinski & Bergeron, 2000).

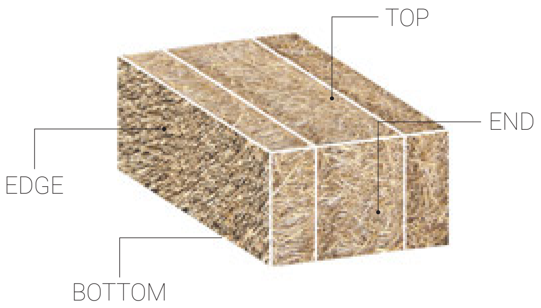
Since the early efforts of these pioneers, straw bale construction has come a long way. Hundreds of articles, books and videos have been published regarding the subject. As the understanding of straw, and how a straw bale wall works, has become more sophisticated, new methods and ideas has emerged. Bales have been incorporated in many different types of houses and also combined with different materials. One could say that the original system has traveled as far in ideas as it has done across continents (Lacinski & Bergeron, 2000).

Picture 13. Picture of the article by Roger Welsch in Shelter.

Picture 14. The straw bale house of Maja Lindstedt and Jesper Zander in Bohuslän.

BENEFITS AND DRAWBACKS

We all remember the story about *the three little pigs* and how the first little pig's house made of straw is blown down by the big bad wolf. There are a lot of negative preconceptions against building with straw which many of us have heard throughout our childhoods (Lacinski & Bergeron, 2000). Negative thoughts and doubts regarding straw bale buildings are mainly due to lack of knowledge and an irrational fear of the new and unknown (Minke & Mahlke, 2005).



INSULATION AND INDOOR CLIMATE

Straw makes a good insulation material since heat is transported slowly through the straw (Atkinson, 2011). Insulation is often rated in U-values, or in R-values* which is commonly used in US. Tests performed in 1998 by Oak Ridge National Laboratory in Tennessee found that the R-value of a bale wall laid flat measured at 1,45 per inch. The California Energy Commissions found, however, that a bale wall laid on edge measured at 2.06 per inch. This means that a two-stringed bale on edge has an R-value of 26, R-33.5 for a three-stringed bale laid flat, and R-33 for a three-stringed bale on edge. Another factor to include is that a straw bale wall is continuous and is not interrupted by less insulative material, as is the case with conventional construction. Thermal bridging through studs can substantially decrease the overall R-value. The performance of conventional walls can also be reduced by imperfections in the installation of the insulation material, to the point where the effective R-value is not much more than half that of a bale wall (Lacinski & Bergeron, 2000).

Thermal mass also influences the actual performance of a straw bale wall, both of the bales and the plaster. This has significant effect on the walls ability to store heat and thus maintain a constant temperature. This also seems related to the rate at which heat flows through the wall. The tests at Oak Ridge showed that it took almost 2 weeks before the wall started to lose heat at a consistent rate, when one side was heated to 21 °C and the other side chilled to -18 °C. As the heat moved through the

**U-values are the inverse of R-values (U = 1/R), meaning that the higher the R-value, the lower the U-value, the better the insulation is at resisting heat transfer.*

wall, some portion of it was stored within the mass and it was presumably only after the temperature had stabilized that the heat began to flow through at a consistent rate. Real life conditions, however, in most cold climates are very unlikely to bring a constant two-week temperature difference that high. For example do temperatures usually swing between day and night. These swings are flattened by the combination of mass and the uninterrupted insulation in a plastered straw bale wall, providing even greater energy savings and comfort than the rated R-value would imply (Lacinski & Bergeron, 2000).

In Sweden it is recommended, by Energimyndigheten, that new buildings should have an insulation thickness in the exterior walls that provides a U-value of less than 0,18 W/m²K (Grey, 2013). The U-value, or overall heat transfer coefficient, is a measurement for heat transfer in building elements. It describes how much heat goes out per square meter at one degree difference between the indoor and outdoor temperature (Energimyndigheten, 2013). A straw bale wall with a 475 mm wide bale and with 25 mm plaster on each sides has a U-value of 0,123 W/m²K, thus lies well below the recommendations (Atkinson, 2010). The width a timber or brick/block wall would need to match this insulation value is shown below (Table 1).

One thing to bear in mind is that the insulation value is not the only criteria. A brick/block wall with this width would have trouble with stability and a timber wall would have issues with lack of thermal mass and air leakage. Fully filled insulation,

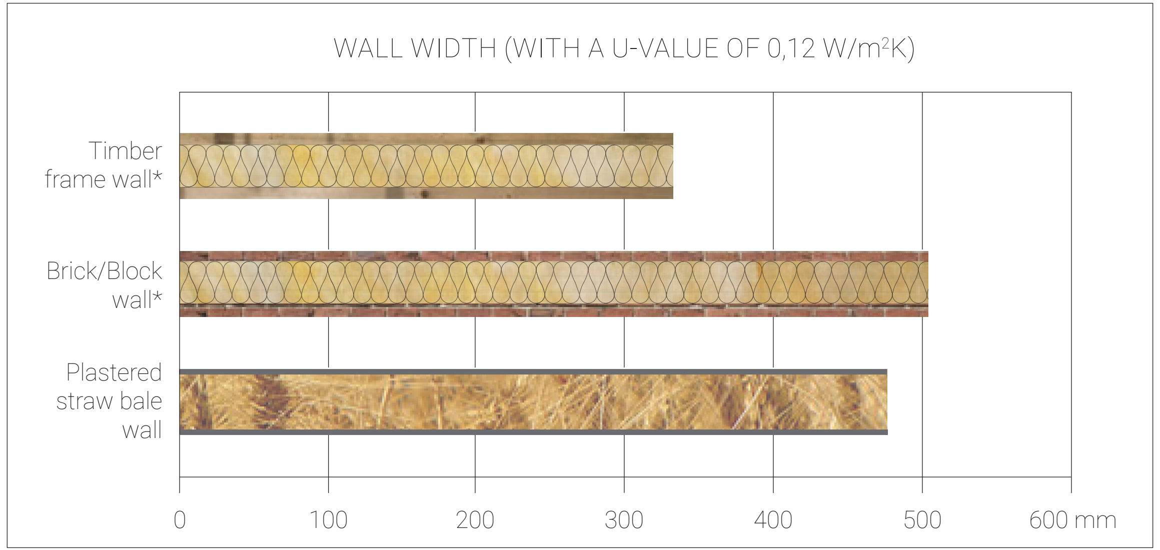


Table 1. The width different wall constructions would need to achieve a U-value of 0,12 W/m²K. Note that the timber wall is a frame construction insulated with glass wool. The brick/block solution is also insulated with glass wool in between. The straw wall is constructed with a 475 mm wide bale and a 25 mm layer of plaster on both sides (Atkinson, 2011). (The table is illustrated based upon source).

which is important to minimize convection in the wall, would be difficult for both of them to ensure (Atkinson, 2010).

The company Isover, who manufactures and distributes building materials, have developed construction solutions for exterior walls suitable for passive houses. They have a U-value of 0,10 W/m²K and are 468 mm wide, and are therefore comparable with a plastered straw bale wall (Grey, 2013).

However, straw bales creates very thick walls without consuming the quantity of resources frequently used to make equally thick walls of wood, glass fiber or other materials. If any conventional building method was used to build walls with the same thickness as a straw bale wall, they would provide the same levels of performance, but at a both higher environmental and economic cost (Magwood & Mack, 2000).

EMISSIONS AND ENERGY

Unlike many manufactured building products, bales are a natural material. They are chemically stable and do not contain any toxic ingredients that might be released into the finished building in form of off-gassing. They will also not emit poisonous fumes in case of fire (Lacinski & Bergeron, 2000). Organically grown straw is of course preferable to ensure that pesticides are not incorporated in buildings, though these should neither affect the performance nor the people.

Most conventional building materials have high embodied energy, which is the total energy required for producing it; for extracting, processing, transporting etc. Straw, on the other hand, has very low embodied energy (Atkinson, 2011). The production and transport to the building site of straw bales consumes very little energy in comparison, thus this construction method has minimal impact on the environment. Straw actually has lower embodied energy than wood, since timber requires much more energy for the production and processing. Timber also produces much more carbon dioxide in the production and processing compared with straw bales. Another comparison that can be made is mineral wool which consumes 77 times more energy to produce per cubic meter than straw (Minke & Mahlke, 2005).

However, one should bear in mind that embodied energy figures varies depending on what is included in that figure. For example, some figures could include the energy from the material extraction while others perhaps exclude this. Some also does not consider what happens after the material is

The energy needed to produce conventional insulation for one house would be enough to produce 35 houses insulated with straw (Snel, 2014).

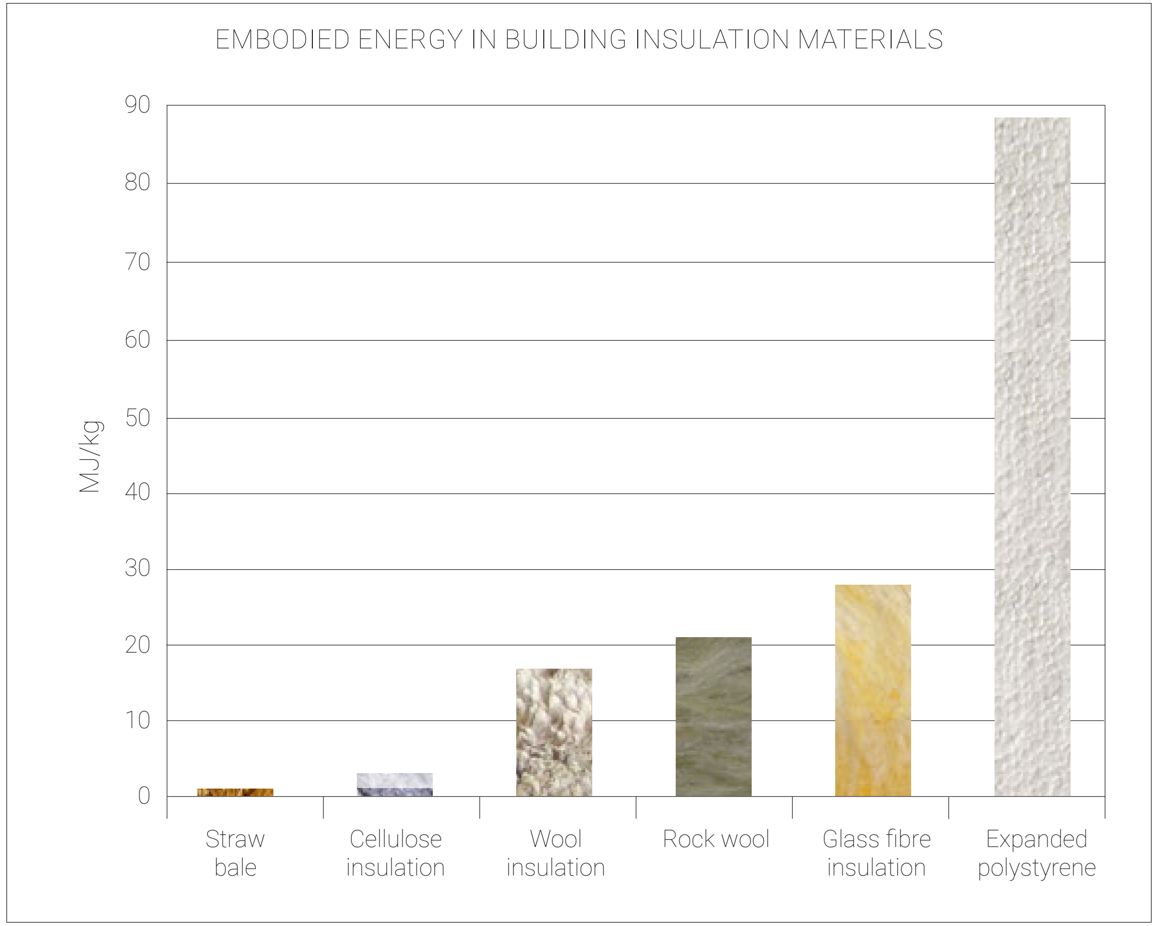


Table 2. The table shows the embodied energy of building materials with the use of figures from the Sustainable Energy Research Team (SERT) at the University of BATH. Embodied energy is here defined as the total primary energy consumed during all activities from material extraction, manufacturing, transport until the finished product is ready to leave the final factory. The value for cellulose insulation, vary between 0,94 - 3,3 MJ/kg (Anderson, n. d.). (The table is illustrated based upon source).

finished and does therefore not include the energy required for demolition and waste management. But no matter how the embodied energy is calculated, straw bales are one of the best materials in terms of embodied energy. A graph of embodied energy in different insulation materials can be seen to the left (Table 2).

Straw also acts as a carbon sink, absorbing and storing carbon dioxide during photosynthesis. The absorption of carbon dioxide is proportionally even higher than the carbon dioxide emissions during the production and transportation phase (Minke & Mahlke, 2005). Every 10 kg of straw absorbs nearly 15 kg of carbon dioxide and seals it in the walls for the lifetime of the building. Compared with straw, trees can capture almost 3 times the amount of carbon dioxide, 15 tons of carbon dioxide per hectare and year, thus timber might seem a better carbon storage. Even so, it can take 50 years to grow new trees for timber, whereas straw is produced every year with the cereal crops, not to mention that it can probably be grown within a one hour distance from even the most inaccessible place (Atkinson, 2011).

Straw bales alone are not enough to make an energy efficient or environmentally friendly building. There are few, if any, perfect materials. Compromises and trade-offs are necessary when contemporary houses are built with sustainable techniques. Appropriate choices concerning climate, geography and geology have to be made, and at the same time local laws and regulations should be met. Comparing solutions with conventional options is however always a good method to implement (Paschich & Zimmerman, 2001). The environmental impact of a building is also affected by how the larger scheme of things come together, from the groundwork to operational and maintenance aspects, and what happens with the materials after demolition (Bokalders, 1995).

ECONOMICS

There is no such thing as cheap, whether you are using bales or not. Building a house is always a costly affair (Magwood, 2005). However, straw is a very cheap insulation material, being an agricultural rather than a manufactured product. Though, one should be prepared to pay a little more than agricultural prices to ensure a good, tight, quality bale (Atkinson, 2011). Still, the cost of the walls is only a small part of the total building cost, typically around 10-15 %. Bale construction, in the industrial world, is getting more cost-competitive with good quality stick-framed construction. Whether the labor is volunteered or professional, every housing project is still unique with its own details and techniques. There have been simple straw bale utility buildings, constructed with reused materials, basically for free, but also straw bale buildings that have cost about 20 000 SEK per square meter. How the bales and the many other components fit into the larger issue of lifestyle choices and budget is what really affects the cost. Straw bale construction is still maturing and it is therefore likely that the cost of walls will continue to drop (Lacinski & Bergeron, 2000).

Building size also matters of course. Strictly speaking, one could say that the larger the building, the larger the costs. Though, one should keep in mind that buildings that expand inevitably leave a deep imprint. "*A million dollar house*" made of straw probably does not end up saving either energy or the planet.

Where one can save a lot of money is in labor costs. Straw is an ideal DIY (do it yourself) - construction method since it is a very forgiving material to work with. Most of the straw bale buildings in the world have been owner-built. However, the familiarity of professional contractors with conventional building techniques combined with the fact that straw construction is still an evolving discipline might offset this advantage of straw (Lacinski & Bergeron, 2000). Yet, one should remember that the real savings are long term ones. Proper and efficient insulation, such as straw, will reduce heating and cooling costs (Magwood, 2005). The long-term cost saving could be used as a sales argument to make sustainable architecture more attractive to developers.

MOISTURE

The major threat to straw bales is moisture, especially for straw bale constructions in colder climates. The bales need to be kept dry once inside the building, but they also need to be kept dry during transport and construction. Moisture damage can be a problem throughout the buildings lifetime. If straw does get wet and stays that way, it will start to decompose, though seems to last forever when kept dry. To protect the straw from water, and prevent moisture damage, it is sometimes said that a straw bale house should have high boots and a large hat, which translates to having large roof overhang, or porches and so on, and elevation from the ground. Around 20 cm above finished ground is a typical code minimum for biodegradable materials (Lacinski & Bergeron, 2000).

Plaster can be moisture sensitive. The northern side of a plastered straw bale wall can be critical, since there is little or no drying potential from the sun to this direction. This can of course be solved with larger overhangs or changing the finishing material to wood or some other type of more moisture resistant siding. Applying latex or oiled based paints is common in conventional home designs, but might not be suitable choice to combine with straw due to ecological reasons and personal beliefs (Magwood, 2005).

Bales of very wet straw can become dangerous if a specific mold, the *Stachybotrys atra*, is allowed to grow in it. This specific mold can also live in many other more common building materials such as water soaked wood, wall paneling, in-painted plaster board surfaces, ceiling tiles, cardboard boxes, cotton items and stacks of newspaper. The mold seems to prefer straw though, according to Canadian mold and fungal specialist Dr. David Miller (Lacinski & Bergeron, 2000). Mold cannot develop on dry straw however. Temperatures of 20-28 °C and a relative air humidity of more than 55 %, though some even claim 80-90 %, are ideal conditions for the development of molds. The most important thing is to make sure that the bales are kept dry. The bales moisture content should be lower than 15 % when constructing and there should be either a vapor barrier installed on the inside surface to prevent moisture entering the bales, or an exterior finish that is vapor permeable enough so that the potential condensate can diffuse out. During plastering, it is therefore important to make sure that the plaster dries out relativity fast so that the straw that has become moist during plastering can dry out. The earlier layers of plaster should always be dried out before layering the last one. On the contrary, the plaster should not dry out too quickly since this can cause cracks in the plaster (Minke & Mahlke, 2005). One should note that

if the walls get so wet that Stachybotrys atra begins to grow, there would be other problems far beyond the mold (Lacinski & Bergeron, 2000).

Damaging deterioration of straw has only been a result from direct water leakage into the wall or rising damp from the foundation. Tests suggests that straw may be able to withstand high levels of relative humidity, over 80 %, for longer periods of time without developing deleterious effects (Magwood & Mack, 2000). Regardless the material choice, moisture is always the enemy. Exposure to moisture consistently will also deteriorate wood, brick and even concrete.

FIRE RESISTANCE

When it comes to fire, bales are not a drawback. Plastered straw bale walls are very good at withstanding fire, something that usually surprises people. Plastered straw bales have actually outperformed wood-framed walls in fire tests. In 1993 the SHB Agra Engineering and Environmental Services Laboratory in Albuquerque, New Mexico, United States, performed small scale fire tests on straw bale wall assemblies. They performed tests on both bare and plastered bales. It took 34 minutes for the fire to work through the uncoated wall at a seam between two bales, where the maximum temperature applied was 921 °C. The second wall had been coated with gypsum plaster on the heated side and a cement stucco on the unheated side. The heated side reached a temperature of 1 060 °C, while the highest rise in temperature on the unheated side only was 12 °C after 2 hours of exposure. The charring in the straw was only about 5 cm deep, behind the cracks in the gypsum. Due to lack of funding, the final report of this test has unfortunately never been produced (Lacinski & Bergeron, 2000). Though, official testes done in Germany and Austria earned the construction a fire resistance rating of F90 (minutes that a barrier can withstand a fire before being consumed or before permitting passage of flame through the opening) (Minke & Mahlke, 2005). Straw is flammable though, especially in its loose form, but this varies and depends greatly on where and how it is used. Straw poses the greatest fire hazard when used as roof covering for example (Grey, 2013).

All the fire tests described above have either been carried out on plastered bales or uncoated ones. This makes one think of if there are other materials that can cover the bales, while at the same time perform as well as plastered bales when it comes to fire resistance. An option could be to cover the bales with some sort of wooden siding. Though, choosing wood can perhaps become a problem in terms of regulations that concern fire, and some might also want reassurance by tests carried out on the specific construction of the chosen wall.

Picture 15. Fire test carried out on a Compressed Straw Board on The One Show on BBC.

Regarding wood, fire resistance can be increased by using larger dimensions, but this can lead to a more expensive construction. Another well-tried alternative is to protect the wooden construction with gypsum. By either increasing the dimensions or covering the structure with gypsum, a wooden structure can obtain the same fire resistance as a steel structure that is covered with gypsum or with fire protecting paint (Ottosson, 2013).

When it comes to timber frames, there can be restrictions regarding height. In England, for example, an additional independent supporting structure is needed for buildings that are higher than tree stories (White, 2015). There are no restrictions in height when using a load-bearing wooden frame in Sweden on the other hand. Buildings have been built with both wooden structures and facades that have been up to eight stories high (Ottosson, 2013).

RODENTS AND INSECTS

Humans are not alone on this planet; it is shared with billions of other creatures, both large and small. One would be ignoring the persistence and intelligence of rodents and insects, to state that a particular house or construction style is pest proof (Magwood, 2005). However, straw itself is nutrient-poor, and is therefore not appealing to insects. Bale walls are highly resistant to damage from insects and rodents and insects when detailed correctly. The same details that protect the bales from moisture should keep out rodents for at least as long a period as in conventional constructions (Lacinski & Bergeron, 2000). Very few problems with insects and rodents in bale walls have been reported, but this does not mean that they will not inhabit other parts of the building such as the roof, floor or basement (Magwood, 2005).

The highly pressed straw in bales, with a density of 90 kg/m^3 or more, makes the bales strong enough to resist the onslaught of any rodent. Even so, one cannot claim that rodents will never get in since they are specialists of finding their way into any kind of walls. Cavities between bales that have not, or not sufficiently, been stuffed are potential risks. Plaster does typically provide reasonable protection against their entry. A mouse that has penetrated through a 3-6 cm strong layer of plaster has not yet been observed (Minke & Mahlke, 2005). Even if they were to get in somehow this will probably matter less than in a conventional wall with many cavities. Since they favor less dense horizontal runs, their movement in a dense bale is very limited (Lacinski & Bergeron, 2000). A ventilated facade could provide nesting opportunities for rodents, although this has also never been observed. These spaces are probably too cold in the winter and they are usually closed off with insect meshes, to also prevent wasps from nesting here (Minke & Mahlke, 2005).

Straw lying openly on the construction site, yet is not infested by either rodents or insects. The picture is from the straw bale building course by Slöjd och Byggnadsvård in 2014.

DESIGN LIMITATIONS AND POSSIBILITIES

Even though one might think straw bales are the ultimate sustainable material, they are not perfect for construction. There is a considerable set of design limitations due to their uneven and bulky size, their need to be kept dry and their unwillingness to hold nails, for apparent reasons. However, the technique is still evolving and is constantly getting better and better.

Picture 17-18. These images show a slightly exaggerated picture of the difference between hay and straw.

MANUFACTURING AND CHOOSING BALES

Straw is sometimes confused with hay, however these materials are very different. Hay is cut while it is still relatively green and can be any combination of field grasses. The grass is then baled and used to feed livestock when fresh grass is not available. Since it cut while it is relatively green, this also means that hay has a high moisture content which makes it more susceptible to rot and mold. Hay is also highly nutritious compared to straw, also making it more appealing to insects etc. Spontaneous combustion can also occur in a hay bale due to the significant microbial activity within them under extreme conditions of humidity, temperature and storage. However, straw bales do neither support nor create spontaneous combustions. Thus, hay is not a good building material and should not be confused with straw (Magwood, 2005).

Bales are sometimes not pure straw and have a mixture of straw and weeds. The few percent of green weeds have theoretically no detrimental effect on the performance of the bale. Green material is however less resistive to decay under severe moisture exposure, so the higher the content of straw, the healthier the walls will be (Lacinski & Bergeron, 2000).

There is often no such thing as an official verified source of construction quality bales. There are many types of bailing machines which result in many shapes and sizes (Atkinson, 2011). Personal contact with the farmer is the best way to ensure receiving the bales one wants. Good quality bales have to be uniform in size and weight (uniform in compactness), tightly strung and most importantly; they have to be dry (Lacinski & Bergeron, 2000). Yet, building with straw bales is technically approved in Germany since there is a company that certifies bales and approves them for construction. This is a national approval in Germany and does most likely not cover all EU-countries regulations (Kaesberg, 2015).

Bales are never perfectly consistent and the building design will have to accommodate some variation, especially in length. Dimension accuracy of the bales can be a real issue depending on the design. If the bales turn out to vary greatly, a lot of time can be wasted on retying them. Still, modern baling machines make a great percentage of uniform bales compared with older ones (Lacinski & Bergeron, 2000). The length of the straw can vary with the cereal growth, but the main thing is that they are not so short that they can be pulled out of the bale with relative ease. If that is the case, it will probably not be able to hold plaster satisfactory if that is the desired finish (Atkinson, 2011). In the past it was common that the same amount of cereal, in terms of weight, produced the same amount of straw. But today's straw has been grown shorter since it has been considered a by-product (Dock-Gustavsson, 2015). Yet, if straw construction were to take a stronger hold, it is likely that longer straw could be grown again.

Baling machines that create large, round bales have in recent years come into favor with many farmers. This can be one of the major drawbacks since it is hard to build with round shaped bales and rebaling these takes both time and consumes energy (Magwood, 2005).

It can sometimes be useful to know which type of cereal the straw has been harvested from, since these differ some in terms of their properties. Rice straw, and its glossy texture, is quite durable and highly fire resistant but can be tough on the hands when working with it. Barley resists moisture, and flax is thought to be the most rot resistant, but its high oil content also makes it more flammable than others (Lacinski & Bergeron, 2000).

The most common varieties of straw in northern climates are wheat, oat, barley and rye (Magwood & Mack, 2000), and in Sweden the most commonly grown cereal is wheat (Jordbruksverket, n.d.). Unfortunately there are no statistics or figures of the straw production in Sweden, partly because it is a by-product and therefore is not included in crop surveys that the Swedish board of agriculture performs. Though there has been a small sample survey, *Jordbruksekonomiska undersökningen* (JEU), carried out where the production and internal consumption and sales of straw were requested. The information concerning straw in the survey is of poor quality. There are perhaps many reasons for this, but the main reason probably being that the purpose of the survey is to get a more accurate picture of the participant's financial state, and straw has a limited economic value and is therefore, in many cases, overlooked. Additionally, only a 1000 out of 67 100 farm companies are represented in this survey, so it cannot be translated into a reliable national value (Hammarstrand, 2015). According to the crop statistics from the Swedish board of agriculture, over 3 million tons of wheat was produced in Sweden in 2014. One can therefore assume that the national straw production is slightly below this figure since, as mentioned earlier, today's straw is shorter and therefore no longer equals to the weight of the cereal produced.

To get a sense of how much straw is needed to construct a house one can turn to England, where 7 million tons of straw is annually produced from the production of wheat flour. About half of the straw is used for animal bedding and the remaining 3,8 million tons could be used to build more than 500 000 new single family houses. 7,2 tons is needed to build an average tree bedroom home (Lagerwall, 2015).

CONSTRUCTION

There are different kinds of construction methods when working with straw bales. The two most common ones are the original load-bearing construction, sometimes called the Nebraska style, and the non-loadbearing framed construction, sometimes called infill. The choice between the two is essentially one of design flexibility (Lacinski & Bergeron, 2000). The Nebraska style is the purest form of straw bale building in which stacked bales alone hold up the load of the roof, minimizing the use of timber (Atkinson, 2011). Still, Nebraska style buildings also come with a substantial set of design restrictions, limiting the range of situations over which they are practical. There are even some places that have building codes prohibiting straw bales alone in load-bearing walls, New Mexico in the US being one example (Paschich & Zimmerman, 2001). Making sure that the bales are kept dry during construction can be both hard and tiresome since the walls are built before the roof. The load-bearing technique also implies additional components such as top plates for the roof, and frames or boxes for the doors and windows.

A framed construction on the other hand removes the pressure to build under dry conditions by having the roof in place before stacking the bales, thus, making the framed approach better suited for cold climates. Load-bearing walls also need to stabilize before plastering can take place. Failures and cracks would occur as the straw settles by the weight of the roof. The straw bale walls should therefore be left unplastered for at least a week, ideally a month, before continuing the construction and plastering. This waiting period with load-bearing walls is not always practical (Magwood & Mack, 2000). It is also hard to achieve the proper configuration of the bales in the Nebraska style in order to properly support the roof, not to mention the issues that come with doors and windows, in this type of construction, and their ability to take excess loads from such things as snow for example. Some therefore recommend keeping the building quite small and only one story high when having load-bearing straw bale walls (Lacinski & Bergeron, 2000).

There is almost no limit in height when using the infill method. Here the height instead depends on which type of framed construction one uses. Several high straw bales buildings have been built in the Netherlands and France (Magwood & Mack, 2000).

Building high can also bring about other positive effects. Dividing the floor area into two levels instead of one, not only halves the roof and foundation size, but also halves the buildings footprint. Installations can also be easier to move around in a multistorey building.

Other types of construction methods, that are perhaps not that common today, include hybrids of the two styles (Atkinson, 2011). There is also a lot of development of prefabricated panels and walls, around the world. Some of these are presented in "*Aside from the bale*", p. 40.

Picture 19. The Strohhaus Braun-Dubuis by Werner Schmidt, situated in the Swiss Alps, is a load-bearing construction with jumbo bales that are 1,2 meters wide (Minke and Mahlke, 2005).

Picture 20. Infill straw bale construction in the spring of 2014. The house at Korpaberget in Alingsås, Sweden.

WALL THICKNESS

If one wants to have a straw bale house that insulates well and has a good U-value a straw bale wall does become quite thick, around 500 mm. However, this could be compared with the wall thickness of Isover's passive house construction solutions, mentioned earlier in chapter; "*Insulation and indoor climate*", that are 468 mm wide (Grey, 2013). The thickness allows different designs around doors and windows, and the deep window sills can give a sense of safety and quietness, as well as creating wide seats or benches.

Picture 21. Example of window sill in the house of Ingrid Fäldner.

Windows is an architectural and experientially very important part of a building. The thickness of straw walls can provide different light conditions depending on how the windows are designed. The massive feel to a straw bale wall can be compared with solidity of stone, but straw offers far more insulation value (Lacinski & Bergeron, 2000).

FLEXIBILITY

Straw, unlike many other materials, offers the possibility of creating spaces that are unique. It is a construction that can easily be adapted to a wide variety of configurations and designs that span from curved and round or other unusual designs to traditional straight and square (Magwood & Mack, 2000). This is one of the main attractions of building with straw. There are endless potentials for form and texture. Door and window sills can be designed in many different ways. Other design features such as ledges, shelves and niches can be incorporated in the house design (Magwood, 2005). It is however unlikely that free, round shapes would be the main attraction if straw would become an industrial building material. Yet, the sheer thickness of straw still provides flexibility around doors and windows.

As mentioned earlier, straw bales are not limited to smaller single family housing. They are versatile and can create many different structures; from small sheds to larger public buildings such as factories and schools.

Plaster is perhaps the most frequently used finishing material when it comes to straw bale walls. There are a number of available plasters; cement stucco, lime, earth and clay plasters or mixtures of these.

One should bear in mind that plaster is rather unwilling to hold nails and heavy objects for example. Even though it is highly recommended to seal the walls with at least one coat of plaster, it does not have to be the final finishing material. Any kind of siding is possible on both the interior and the exterior. Thin wooden strappings are usually used for fixing other forms of siding. However, a wall that does not have the first coat of plaster behind the siding, should at least have a well seal vapor and air barrier, and a borax treatment can be applied for fire protection. Bales loose some of their insulation value when they are exposed to moving air, and fire may be able to spread along the loose ends of the straw, even though the whole bales are likely to resist combustion (Magwood & Mack, 2000).

Picture 22. The house of Ingrid Fäldner with both plaster and wood siding. With wood paneling on the most weather-exposed side of the house.

MAINTENANCE

Most people look at building maintenance as a time-consuming drag and want maintenance free materials, which has had major implications on the choice of building materials. This has led to the development of materials that are unfortunately both toxic and wasteful. One example is the wide spread of vinyl siding in the world, which is stable in its solid form but is one of the most toxic materials produced in its gaseous and liquid form (Lacinski & Bergeron, 2000). One could put sidings on a straw bale house to reduce the amount of maintenance needed, nevertheless wood or any other kind of siding than vinyl is more suited to straw bales in terms of sustainability and toxins.

Straw bale constructions with plaster finish require a maintenance routine. The reason is that plaster cracks due to the shifting and settling that always goes on during a buildings life cycle. Also due to wind loads and the freeze and thaw cycles. With this in mind, no masonry finish can be trusted to remain waterproof forever, and since water is the main enemy of straw it is important to make sure that excessive moisture cannot enter and damage the bales. Rain water and condensed interior moisture need to be controlled. The maintenance routine required varies greatly with material choice and site, but also with how well the design responds to the site. Generally it involves applying lime wash or patching cracks a day or two each spring. Ones who cannot accept yearly maintenance should not consider a plastered straw bale house. If the plaster is maintained, historical evidence from around the world indicates that plastered bale constructions also works well in wet climates (Lacinski & Bergeron, 2000).

DURABILITY

The oldest straw bale building in Europe is a house located in France from 1921. There are several houses in the United States that are over one hundred years old (Atkinson, 2010). A testimony to the durability of straw bale constructions is that many old houses in Nebraska are still standing. The oldest straw bale house in the world, the Burke house, still stands in Nebraska and is from 1903 (King, 2006).

Even though the long term experience with straw bale constructions in cold climates is quite limited, much suggests that thoughtful design of new bale buildings, considering issues of heat loss, moisture control and air quality, along with some maintenance, will provide comfort to generations to come (Lacinski & Bergeron, 2000).

ASIDE FROM THE BALE

The growing popularity of straw bale houses is due to growing environmental awareness, making people search for alternatives to the conventional. The popularity is likely also connected to the increasing interest in other growing techniques with straw in its loose form. Cob, straw-clay, straw-board products and blocks are some examples that are gaining repute as alternatives to modern industrialized techniques and materials. Designers are also increasingly beginning to blend these methods into their straw bale houses as they look further back in history of straw in constructions (Lacinski & Bergeron, 2000).

The architect Bruce Millard, from Sandpoint, Idaho, once said that we will soon realize that straw is very valuable. Millard predicted that it would start going into boards and panels, and that it even might be mixed with wood fiber for paper production. The potential of straw is still being experimented with, and one should not treat experiments as a sure thing. There are still field tests and monitoring that needs to be carried out across many different geographical regions before local standards for straw bale construction can be established. When that happens straw bales may become the key material in a new type of local architecture more in harmony with the local environment (Lacinski & Bergeron, 2000).

Straw can be found in many different building elements. For example, straw has been used in different kinds of fiber boards, both in combination with other materials and independently. Four examples are briefly described here. Two more simple and traditional straw building techniques and two more modernized.

STRAW CLAY

Straw clay, or sometimes referred to as light clay from the German word leichtlehm, is a mixture of clay and straw. This mixture is usually stuffed between forms or studs in a timber frame structure. However, in Germany blocks of straw clay have been used for a long period of time (Lacinski & Bergeron, 2000).

COB

Simply put, cob is straw clay with sand, which is hand formed into lumps, or cobs. These are then stacked and tamped to form a wall. Variations of this technique can be found in vernacular architecture, all over the world. Due to the fact that this technique does not require a laid framework of any sort, it is perhaps the most flexible of straw building techniques and methods (Lacinski & Bergeron, 2000).

STRAW BOARD

One can find a number of different manufactured straw boards and panels on the market today. One company that has been active on the British construction market, for quite some time, is Stramit. Their partitioning interior walls from compressed straw forms the interior of over 300 000 homes in the UK. Worth mentioning is also that their boards and panels does not contain any glue. Instead, the boards are bounded by compounds which are exuded from straw under heat and pressure (Lacinski & Bergeron, 2000).

OSSB

The company Novofiber is the first company to manufacture Oriented Structural Straw Boards (OSSB). It was developed for the Asian market due to their lack of wood. The production of the panels is currently in China, but deliverance can be made anywhere in Europe. Though, there are hopes to invest in a facility in Europe when the market grows (Burgstaller, 2015).

The industrialization of straw is an ongoing process, even in the places where it currently exists. Industrializing straw is also a possibility in Sweden. Even so, the building industry etc. differs between countries, and it is therefore always important to understand the national situation in which a technique or method should be applied. These can then be adapted to best suit the local situation.

Picture 23-26. Pictures from the left show; straw clay, cob, a Compressed Straw Board and OSSB:s.

THE BUILDING INDUSTRY

Picture 2

The building industry is the world's single largest economic sector, with prefabrication as a massive sub-industry (Anderson & Anderson, 2007). The building sector is, and will always be, one of the pillars in society since there is always a need of new constructions and buildings that are in need of refurbishment.

The building industry is an economic sector that comprises all companies involved in construction. All people who contribute with resources to the construction of a building are included in the building sector. They can for example be building merchants, consultants, architects, distribution and transportation among others. All steps from financing, planning, designing, all the way to brokering and maintenance of the building is included within the construction process (Lutz & Gabrielsson, 2002).

As mentioned before, the built environment accounts for approximately 40 % of the world's total primary energy consumption and contributes to up to 30 % of global annual greenhouse gas emissions, and many building materials are extracted from non-renewable resources (Lemmet, 2009). Therefore the building industry and its methods, needs to change and evolve in many ways in order to ensure a sustainable society for the generations to come. The biggest problem is perhaps that there is always an economic interest to relate to. There appears to be an ongoing increase of speed within the building industry, where projects and construction times are continuously shortened. A short-term driving force is not the solution to ensure a sustainable built environment. construction costs usually ends up being higher than estimated price in the planning process. It is therefore important to work out how the final expenses will stay the same as the initial estimated costs, while at the same time finding ways of building with local materials that are not driven from non-renewable resources.

The building industry has a tendency to adopt new techniques fast. Though there is a paradox since the building industry also tends to deliver the same product in the same way that they have always done, mostly due to static competition in Sweden. Those who differ from the norm can easily be identified and rejected which makes it difficult for innovative companies to enter the market (Lutz & Gabrielsson, 2002). This means that the development in the building industry progresses quite slowly compare to other industries, such as the manufacturing industry, where the competition is higher. Another reason is that there are only a few major building contractors in Sweden, which more or less controls the market. (More information about these can be found in the chapter "*The big developers*" p. 52)

HISTORY

To get an understanding of why the building industry looks the way it does today, one needs to understand its history. The building industry has undergone many and major changes throughout history, and the built environment along with it.

When talking about the development of the building industry, one often points to the postwar period. Before this period of time, efforts were concentrated almost exclusively to methods of building on site. With time, the methods have evolved from manual construction, into more or less mechanized building, but they would change even more drastically after the Second World War (Östergren & Marmstål, 1992).

The shortage of housing was huge in Europe after the Second World War, and the large amount of refugees that came with it created even more pressure on the housing market (Adler, 2005). The housing shortage created an overwhelming task for the builders who still employed traditional building techniques, to a large extent. However, the postwar period was also filled with momentum, optimism and hope. For example, it only took two years for the housing market to double, mostly thanks to construction related unions who wanted to reduce the unemployment by stimulating construction (Östergren & Marmstål, 1992). Though, this was not

Picture 27. Carpenters and Masons, Frankford EL Construction in 1913. The building in the back was established in 1868.

Pictrue 28. How a construction site can appear today. This is "Star Apartments" in Los Angeles, 2013.

enough to erase the housing demand. It remained fairly extensive until the mid-70s, when the "*The Million Program*" was completed, where the goal was to build one million accommodations in just 10 years. At this time the building industry was changed drastically from manual, mechanized on-site building to industrialized, rationalized construction which was encouraged by the government through for example subventions and favorable loans (Adler, 2005). This made it possible even for smaller developers to enter the building industry. Grants were paid to apartments with a certain minimum size to prevent and reduce the crowded living situations that were typical in this period of time. The need for efficient and rational building methods became all the more urgent. Therefore it also became more customary to build with prefabricated building elements. There were some 50 prefabrication factories in production around Sweden during the intensive 60s and 70s (Östergren & Marmstål, 1992).

The Million Program never would have been possible if it were not for the development of

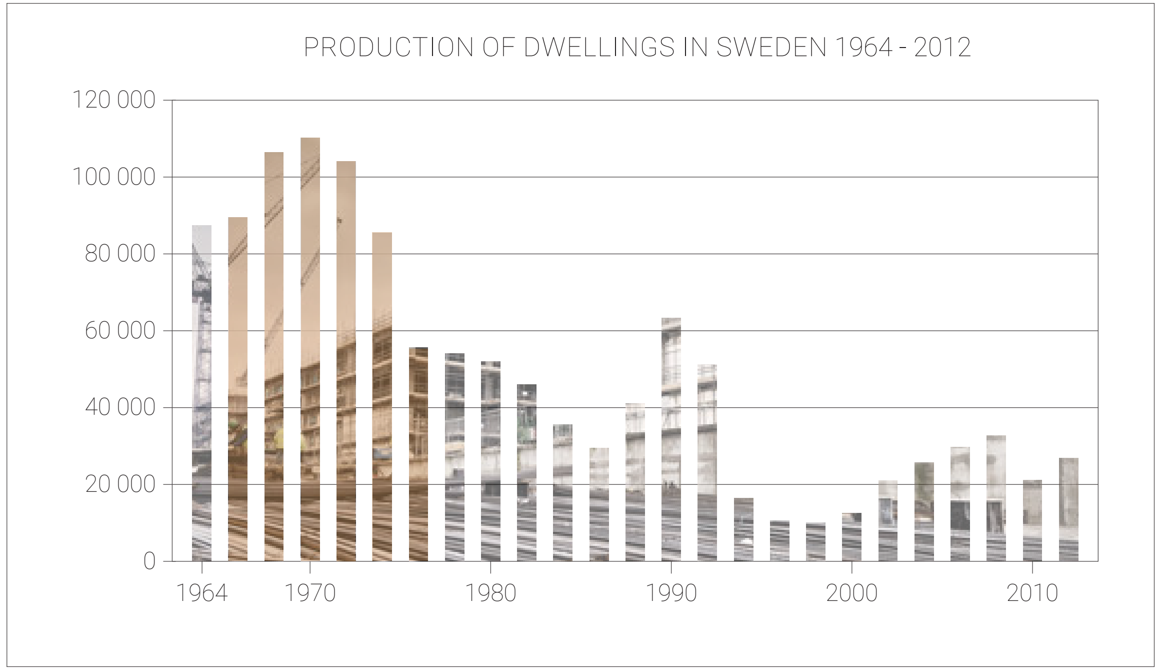


Table 3. The housing demand was quite low after The Million Program only to pick up again during the late 80s and 90s when the economic condition improved (Östergren & Marmstål, 1992). (The table is illustrated based upon figures from Statistiska Centralbyrån).

some new techniques and methods, of which the construction lifts and cranes perhaps were the most important ones. The construction lift became the largest selling building machines in the beginning of the 50s, and was also significant for the use of other new building materials such as lightweight concrete, that never would have suited being carried on the back of builders. Likewise, the use of cranes also grew explosively during the 50s. Imagining a modern construction site today without cranes is difficult, this was hard to imagine even in the 60s during The Million Program. The development in the building industry were also affected by the lack of bricklayers. More and more houses now had to be made with concrete, and since the casting molds were made of wood, the price for timber was conveniently raised. This led to a number of different ideas and developments, such as shuttering panels of plywood. The crane also made it possible to build with prefabricated wall elements and slabs. No other building method takes advantage of the possibilities and capacity of a building crane as well prefabrication (Östergren & Marmstål, 1992).

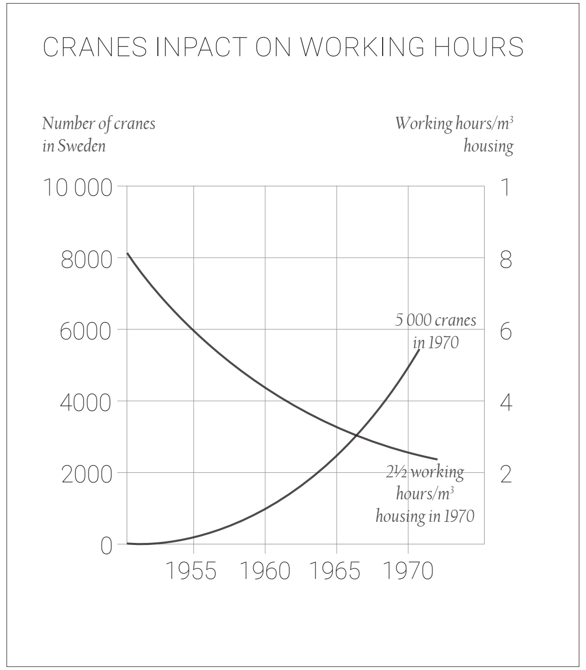


Table 4. Since cranes entered construction working hours per m³ where more than halved in just ten years, (Östergren & Marmstål, 1992). (The graph is illustrated based upon source).

PREFABRICATION OF BUILDINGS

To say that prefabrication of building components, and the later assembly on site, is exclusively associated with the industrial era would be wrong. On-site building was certainly over several thousands of years the most commonly practiced method. This gradually changed due to the new tools and aids that were developed. However, already among the oldest forms of construction, prefabricated parts existed, although they were not called prefabrication specifically. Brick is for example one of the oldest prefabricated building components. Thus, prefabrication and mass construction are not an invention of the industrial era (Adler, 2005).

Already during the 1920s - 30s the modernist was thinking about industrialization as an important idea. Thoughts of standardization and efficiency in order to achieving the lowest possible cost for a modern life, with great comfort, were widely spread. The realization of these came through the cottage and single family housing market (Adler, 2005), which later became a significant part in housing production. It is here the method of prefabrication actually has its roots (Östergren & Marmstål, 1992).

Industrial building means that a major quantity of the construction consists of prefabricated building parts. Prefabrication implies that the production of building elements takes place off-site, for instance in a factory, before these elements later are installed on site. Off-site construction is, and has been, an essential part of construction, since very early on in the building history, all over the world (Anderson & Anderson, 2008).

Today industrial prefabricated building materials play a significant role in nearly every project. The objective, among others, is to produce building parts in a more efficient and controlled work environment, where there is access to specialized skills and equipment. This means that both costs and time on site can be reduced and controlled, and at the same time quality and consistency can be ensured (Anderson & Anderson, 2007).

Picture 29. Prefabricated wall sections, insulated with cellulose, ready to be transported from the factory of Becohus, Falkenberg.

The phenomenon of prefabrication can be divided into subcategories depending on the degree of prefabrication. The subcategories range from structural framing elements to fully prefabricated modules and sometimes even complete box units.

Structural frames consist of vertical elements joint with horizontal floors, and are built according to three main systems; Cast on-site, combination of cast on-site and prefabricated units and prefabricated. Frames that are cast on-site take longer time to construct than prefabricated frames and elements, provided that the foundation is of good quality (Adler, 2005).

The degree of prefabrication is something that is discussed within the building sector. The higher the degree of prefabrication, the faster the progress of the construction, but often it is slightly more costly to work with prefabricated parts. This makes it important to way both cost and time savings into the calculations in order to get an acceptable overall economy for the construction (Appelberg, 2015). Many are convinced that it is better financially to use prefabrication, though no one has ever been able to prove it (Dahlman, 2015). Estimating the financial profit when using prefabrication compared with other methods, is very hard to do. Different sources state different things, and it always varies between projects and prefabrication method.

AN ASSESSMENT OF PREFABRICATION

The benefit with prefabrication is the increased quality gain when the production can be performed in the protected environment of a factory. Construction times are shortened, due to the minimized drying times inside, which also minimizes the potential of chemical reactions (Fernström & Kämpe, 1998). The elements become less weather-sensitive than traditional ones. Entire finished units, like bathrooms for example, can be put together in the factory, minimizing the time of weather exposure (Östergren & Marmstål, 1992). Some claim that the minimized weather exposure makes the buildings healthier since the risks for mold etc. therefore is reduced.

Today, the foundation is the only part of the building that still needs to be cast on site. The foundation need to be executed with great precision. If an error occurs in the foundation, this can lead to repeated adjustments on several floors above, especially if the rest of the building is prefabricated. The benefits with prefabrication can in that case immediately change and create problems, increasing the cost (Adler, 2005).

The result of excessive standardization, like in the former Soviet were concrete elements became a rule rather than an exception, can of course also be discussed. Industrial construction can in many cases be interpreted as monotonous and not well suited and adapted to the local environment in which it stands. For example there is a criticism to the standardized result of The Million Program in Sweden. However it is important to remember that it actually gave millions of people a home with higher standard.

Prefabricated building techniques should be flexible enough to be adapted to the urban planning and the local climate and topography, and at the same time have a high quality, both architecturally and environmentally.

S
strengths

minimized chemical reactions

shortened drying times

minimized weather exposure

minimizing mold / moisture damage

better working conditions and safety

increasing construction quality due to better working conditions

just-in-time delivery – no need for storage on site

fast assembly

W
weaknesses

design restrictions due to transport

no or little possibility to make changes or adjustments

expensive to correct faults late in the process

more middlemen

crane dependency

homogenization / look-alike buildings with no connection to the site

cutouts need to be executed within the framework of the elements

Reduction of choice and variety

O
opportunities

use sustainable materials

to choose several degrees of prefabrication

reduction in cost of the building

T
threats

no guaranties that assemblance is carried out thoroughly

dependency on supplier (delivery delays / logistics / bankruptcy)

choices in finishes may be limited, depending on the configuration of the element

SWOT analysis of prefabrication where strengths, weaknesses, opportunities and threats with the technique are identified.

THE BIG DEVELOPERS

It can be interesting to compare the Swedish construction market with England, which have some of the largest construction companies in the world, and yet also a working and growing market for prefabricated straw bale buildings.

Important to remember is that England did not experience the same financial crisis in the beginning of 1990s, as Sweden did. The middle sized companies in Sweden, were bankrupt, some of which were bought by the bigger ones. Even if twenty years have passed since the crisis, the middle sized companies have not yet recovered (Dahlman, 2015). Since construction companies in England operate regionally rather than nationally, and also have a larger share of smaller companies creating more competition, one can assume that it is easier for a new, small company to enter the market than it is in Sweden.

Today, the construction market in Sweden consists of a large number of small contractors and just a few big developers who operates nationwide (Lutz & Gabrielsson, 2002). The three major building contractors; NCC, Skanska and PEAB, accounts for 60 % of the construction market (Fernström & Kämpe, 1998). This has created a division within the market, where the smaller companies, to a large extent, is focusing on repairs, refurbishment and extensions on smaller buildings. Many small businesses are also lacking the resources or expertise to compete for larger projects (Lutz & Gabrielsson, 2002). One could therefore say that the market is divided into two parts with completely different competitive conditions. A balance between the larger, middle sized and smaller companies is probably the ideal situation to create a healthy competitive environment, which can result in more qualitative projects.

However, one arising problem is that there is a risk of getting lower quality and durability in the projects when the middle sized companies increase, since the bigger companies have had the time to develop routines and systems for their construction. In the same time, so called mega-projects are growing in number. Managing these projects can only be performed by companies with a large and stable economic asset. In addition, these projects often have high qualification criteria's (Dahlman, 2015).

Representatives from the larger companies in Sweden say that the building method changes depending on what type of building it is, mostly due to scale. Though, when it comes to facades, these are most often prefabricated. A high degree of prefabrication seems to be preferable since it gives better control on the quality, foremost for moisture (Appelberg, 2015).

THE 10 BIGGEST CONSTRUCTION COMPANIES BY TURNOVER IN SWEDEN

2013	Company	Turnover in million SEK in contracting			Number of Employees	
		Sweden	Abroad	Total	Sweden	Abroad
1	Peab	35 066	8 029	43 095	11 661	2 131
2	Skanska	33 567	102 921	136 488	10 462	46 643
3	NCC	30 547	27 276	57 823	9 988	8 372
4	JM	9 907	2 696	12 603	1 874	373
5	SVEVIA	7 180			2 113	
6	Veidekke Sverige	4 087			1 007	
7	INFRANORD	3 787			2 577	
8	Strabag Sverige	2 410			567	
9	Lemminkäinen	2 261			435	
10	Strukton Rail AB	1 987			848	

Table 5. The table shows the largest construction companies by turnover in Sweden. Notice the gap between the third and the fourth company, which differ a lot (Sveriges Byggindustrier, 2014). (The graph is illustrated based upon source).

CONVENTIONAL BUILDING MATERIALS

The construction and building industry consume the largest share of natural resources, both in terms of material extraction as well as land use. Buildings actually exploits 50 % of the world's raw materials and is responsible for 36 % of the waste generated worldwide (Attmann, 2010). Many conventional building materials are also derived from non-renewable resources and require a large amount of energy to produce, at the same time polluting the environment and generating solid waste during both the extraction and construction phase (Paschich & Zimmerman, 2001).

When construction became industrialized through the development of machines, both building methods and working conditions improved. However, the new production rate, which the machines brought with them, also led to new materials that have been proven not to be sufficient enough. Unfortunately some new methods were adopted far too hasty, like lightweight concrete for example, which can be toxic if it includes slate containing radon. Hundreds of homes in Sweden now have this toxic material incorporated in them (Östergren & Marmstål, 1992).

The most commonly used materials in constructions are cement, clay, rock, plaster, steel, iron, aluminum, plastic, wood and glass (Dahlman, 2015). In fact, these materials are to 99 % included in a finished building. The materials are for the most part merged together in larger units like reinforced concrete, leca, plywood, wood fiberboards, gypsum, insulation etc. Brick is for the most part only used as a facade material nowadays (Adler, 2005).

Materials with a noted increase in usages are gypsum, polystyrene (cellular plastic insulation), steel studs and joint compound. Today, heavy outer walls and foundations are almost always insulated with polystyrene, and in many cases also in intermediate floors. Floor structures are mainly carried out in concrete. Gypsum is increasingly being used in in-fill walls, and steel studs have replaced wooden studs, and are now being used in interior walls to a large extent. Wooden studs are still used in in-fill walls (Adler, 2005). When it comes to windows, aluminum-frames are used for the most part, since there often is a wish for maintenance free facades (Appelberg, 2015).

The building industry, especially the construction and demolition industry, has been identified as the major source of the waste producers in the world. It has been stated by the European Union Legislation, that the construction and demolition industry must prepare 70 % of the non-hazardous waste produced to either be reused, recycled or recovered by the year 2020 (Väntsi & Kärki, 2014). Increasing reuse in the building industry would of course have a number of direct benefits; less pollutions and extraction of

virgin raw materials, and it would also help reduce solid waste that is being disposed to both legal and illegal landfill sites. However, waste recycling has to be economically viable in order to make it a reality. It is dependent on a number of different factors such as virgin raw material prices as well as recycling, transportation and landfill costs. Every material has to be evaluated on a case to case basis.

One of the most energy consuming materials in the world is concrete. The most energy intensive component to produce is the cement, which comprises 10-20 % of the concrete. One ton of cement consumes around 6 million BTUs (British Thermal units) in production, which can roughly be translated into 1800 kWh (Paschich & Zimmerman, 2001). It has been estimated that 7-10 % of the world's CO_2 emissions is caused by the worldwide production of cement. For every ton of cement produced, one ton of CO_2 is emitted to the atmosphere (Magwood, 2005). In 1992 more than 11 million tons of CO_2 was generated during the production of 88 million tons of concrete in the US alone. This amount of concrete consumes more than 500 trillion BTUs and would be enough to build more than 120 *Hoover Dams* or to pave an 8-lane highway around the equator (Paschich & Zimmerman, 2001).

The yearly production of concrete in the US alone would be enough to construct an 8-lane highway around the equator (Paschich & Zimmerman, 2001).

Table 6. Waste levels from mineral wool are continually rising, and do not show any indication of stopping in the nearby future (Väntsi & Kärki). (The graph is illustrated based upon source).

When comparing straw with other materials, it is the most relevant to compare it with other types of insulations materials. About 60 % of the total insulation product market is accounted for by mineral wool, and there is a growing trend to both produce and use it. Today, mineral wool is widely used in buildings for heat insulation, cold and fire protection as well as noise insulation. Mineral wool is a general term which covers a variety of inorganic insulation materials such as rock wool, glass wool and slag wool. Glass wool accounts for approximately 30 % of the total mineral wool production, while rock wool accounts for as much as 70 %. It is stated, in the sector report for the mineral wool industry that was ordered by the European commission in 2009, that one ton of rock and slag wool consumes around 7 to 14 GJ in production. The production of glass wool, on the other hand, consumes about 9 to 20 GJ (Väntsi & Kärki, 2014).

Mineral wool has an average useful lifespan of 30 years and is often considered to be unrecyclable. It generates waste both in the processing and in the construction and demolition phase. Around 0,2 % of the waste from the construction and demolition industry is mineral wool waste (Väntsi & Kärki, 2014). The actual waste volume is extremely hard to estimate since there is little reliable data available.

SHIFTING TO SUSTAINABLE OPTIONS

Buildings can be more sustainable. The possibility of exchanging materials to more sustainable options is in theory likely if the customer feels that doing so will generate a greater value. Though, the materials still need to meet the requirement, for moisture, fire, strength, durability and function for example. It is important to use verified methods and materials. This means that new materials need to be tested and approved before they can be implemented (Dahlman, 2015).

When it comes to changing insulation material, the new alternative needs to meet the requirements for energy for example. Today the most common insulation material is mineral wool or cellular plastic, and it is becoming more common to use cellular plastic with a graphite mixture, which provides better insulation values (Appelberg, 2015).

The most important aspects to consider when introducing new materials on the market, is to prove that they work better, or as good as, existing ones. Likewise, the materials also need to be cheap and it should not inflict more work on the builders.

STRAW AND THE BUILDING INDUSTRY

Picture 4.

Straw bale construction has not yet been accepted or embraced by the building industry. This is probably most likely because straw offers limited opportunities for making a profit. Bales can neither be patented, nor would it be immediately feasible for a building supply company to go into straw bale production themselves. Advances in building technology mostly come from companies who both develop and test their products, later using the test results to get code approval, or even better code requirement. Considering this, straw bales has no, or very little, immediate chance of receiving the same high budget testing that big companies provide, nor receiving the promotional means that would convince contractors to use them. Contractors have no reason to invest in new equipment and retraining their workers for buildings that are no more costly than the ones that they already make. Investing in a new technology that does not yield a higher profit is simply not a good business move (Magwood, 2005).

Straw bale construction will remain a marginal percentage of new developments until consumers and politicians begin demanding environmentally responsible buildings, which are both highly efficient and sufficient in quality (Magwood, 2005).

If straw as a building material is to evolve from owner built buildings and enter a larger building market, it needs to be adapted to the industrial way of building. A way of combining straw with the building industry needs to be developed.

The concept of industrial construction is based upon resource efficient manufacturing. Since there is a growing demand for flexible and more energy efficient buildings, prefabrication can provide buildings that are reuse friendly and can easily be disassembled or demolished. In the production phase there is also a possibility of reducing waste (Fernström & Kämpe, 1998).

Prefabrication plays a significant role in nearly every project today, and it can help builders to build more quickly and efficiently. Incorporating straw in this way of building can perhaps give straw the repute it needs.

Picture 30. The Gateway building at the University of Nottingham, UK. Project by Make Architects. Each panel is 14 meters long and weighs two tons (Patterson, 2015).

STRAW IN PREFABRICATION

The usage of straw in prefabricated building elements is quite new. Some countries have come further developing this method, than others. In Germany straw bales are actually an approved building material. The company Baustroh certifies bales, ensuring that they are suited for construction (Kaesberg, 2015).

Projects with prefabricated straw elements built in field factories have been carried out in different parts of the world, while established manufacturing companies only exists in a few countries. The elements produced by some of these companies are investigated and compared next coming pages. A proper investigation of the French system by IsoPaille has not been possible due to limited information. The IsoPaille section is therefore based upon information coming from their website alone. In spite of that, it is still interesting to look at a French company, since France is in the forefront of straw bale building in Europe. Personal contact has been possible supporting the research of the other three systems.

Picture 31. Pre-fab strobouw huis in IJburg, Amsterdam in the Netherlands, by the sustainable building contractor and strawbuilder René Dalmeijer.

MODCELL®

ModCell® is a company that manufactures pre-fabricated straw bale elements, situated in Bristol, England. The company name stems from Modular Cellulose, and with the use of their panels they have built offices, schools, housing and commercial buildings in England (White, 2015).

The company was founded in 2005. However, the first panel was invented 14 years ago by the founder Craig White in one of his school projects. Since then the modules have evolved a lot from the initial one and they now offer different kinds of panels (White, 2015). ModCell® Core Passiv was recently put on the market. This panel system has been certified by the Passive House Institute (ModCell, 2015).

> *" We are delighted to have secured the world's first Passivhaus Component Certifications for straw bale construction [...] Our journey towards building a low-carbon, affordable and sustainable future just got easier "*

- Craig White, Director at White Design and ModCell® (ModCell, 2015).

The panels are usually manufactured in a certified factory, but so called Flying Factories™, close to the building site, have also been set up in specific projects. These factories do not comply with regulations but are good in terms of advertisement and involving the locals, creating a sense of community. Construction times can become longer when using Flying Factories™ since additional time is needed for training (White, 2015).

PANELS

ModCell® panels are built and adjusted to each individual project they are used in. However, the standard module is three bales wide, enclosed by a laminated timber frame box, making the general size 3 meters wide and 3,2 meters high, with a weight of 1,7 tons. The bales are stuffed into the box by hand and are sometimes cut in machines, or retied by hand, to ensure a perfect fit. Every ten bales are tested to ensure that they are good enough for construction (White, 2015).

Building the modules lying down makes it easier to build higher elements. Yet, if the elements are rendered with plaster, it can easily crack when raising them in place. Transportation affects the size, where the width is the most critical dimension (White, 2015).

The modules are load-bearing but building regulations in the United Kingdom only allow timber constructions up to three stories high due to fire. Beyond that an independent structural frame is needed. The panels arrive to the construction site as an enclosed unit, which is also necessary in order to meet the regulations. The panels are sealed during the transportation as well. ModCell® panels can be covered with almost any cladding, both on the interior and the exterior (White, 2015).

There have been a number of tests carried out on the ModCell® panels, mostly through the ongoing research program together with the University of Bath. The U-value of a ModCell® wall ranges from 0,11-0,19 W/m^2K, depending on the chosen type of panel. The ModCell® Core Passiv panel has a U-value of 0,11 W/m^2K (White, 2015).

Picture 32. Knowle West Media Center from , Bristol, UK. Completed February 2008.

ECOCOCON

The company Ecococon was founded in 2008 and is today building approximately 7 000 square meters of wall panels per year, which corresponds to about 40 houses. Ecococon operates in Lithuania but also exports to other European counties. Even though the panels are only produced in Lithuania, the company believes that it is important to have a local production and is therefore planning to expand when the demand of straw panels grows (Tarvydas, 2015).

Right now Ecococon uses 99 % renewable materials in their modules, and they are striving to achieve cradle-to-cradle buildings (Ecococon, n.d.), which briefly means waste should be looked upon as food, implying that everything is a nutrient to something else in the larger system of things. Therefore environmentally safe and healthy materials should be used, which later can be recycled and/or composted, creating a closed loop system. However, a 100 % cradle to cradle building does not yet exist (Braungart & Mulhall, 2010), perhaps due to the complexity of buildings themselves and perhaps due to the conservative building industry.

PANELS

The size of the panels vary between 0,4-1,2 meters wide and 0,4-3 meters high. Although, they can be designed and adjusted to each specific project, but are most often rectangular in their shape. Cutouts, like doors and windows, are not incorporated within the module; instead they are built around their planned position. Doors and windows are therefore installed later on the construction site. A team of three people can assemble around 100 m^2 of wall panels per day, and should be manageable for any skilled carpenter (Ecococon, n.d.).

Ecococon uses loose straw from round bales, rather than the more typical approach of using square or rectangular ones. They stuff the straw directly into the panel, which is a frame of wooden studs. The straw is compressed to a specific density to ensure a good insulation capacity. The straw is then trimmed around the edges of the panel to create a straight surface. The panels arrive to the construction site with the straw exposed, and when the panel is rendered and finished, an Ecococon wall has a U-value of about 0,11 W/m^{2}K. The panels are plastered on the interior, while the exterior is wrapped with a vapor permeable airtight layer. This layer needs to be covered with wood fiber boards, at least a 60 mm thick, which complies with the Passive House Standard´s demand for air tightness (Tarvydas, 2015).

There are options when it comes to facade materials, though the interior clay plaster is a set part of the Ecococon panels. Though, the clay plaster can be given a variety of different colors (Tarvydas, 2015).

Picture 33. The straw system by Ecococon. Malmömässan exhibition, in March 2015.

ENDEAVOUR

A prefabricated straw bale system has also been developed by Endeavour, in Ontario, Canada, through the founder and director, Chris Magwood and students. Endeavour Centre is an organization that teaches sustainable building techniques and design, working with a wide range of innovative materials and systems like for example straw bales, earthen plasters and hempcrete. Endeavour is continuously experimenting with sustainable building techniques and testing new methods. They have for instance tested round bales working as load-bearing columns in a building (Endeavour, 2011).

Endeavour Centre have used their panels to construct four buildings in collaboration with NatureBuilt, which is a company that no longer exists. Nevertheless, NatureBuilt built at least 12 buildings with this technique (Magwood, 2015).

Endeavor refers to others when it comes to proving straw as a building material and method. For example, they refer to a pressure test by Building Research Centre at the University of New South Wale, a compression test of plastered straw bale walls, at University of Colorado and a fire test at SHB Agra, New Mexico, USA, to mention a few (Endeavour, n.d.).

PANELS

The prefabricated straw wall system by Endeavour has similarities to both ModCell® and Ecococon. The panels consist of a temporary wooden box, with both studs and wooden boards, which encloses the bales. The boards are removed in the final stage, making the panel into a frame. The panels are commonly two bales wide and five to six bales high (Magwood, 2015).

Before stuffing the panels with straw bales, lime-cement plaster is put into the frame. Plaster is also applied on the bales before placing them into the frame, ensuring the connection between the plaster and the bales, also minimizing air pockets. The finished panel is a load-bearing straw box (Magwood, 2015).

Worth mentioning is that the panels have extra insulation both in the bottom and on the top. This seems to be unique. The additional insulation is fixed, like the straw, in a box which works as a structural beam (Magwood, 2015).

Windows and doors are not included within the panels. These are built on site with another type of wall construction, making the walls around them thinner. However, Endeavor have recently started constructing prefabricated sections above and below windows (Magwood, 2015), similar to Ecococon.

ISOPAILLE

IsoPaille is a research company situated in Cherré, France that manufactures, sells and assembles prefabricated straw bale buildings. They use different kinds of methods, including prefabrication. The prefabricated system is called Bloc ISOPAILLE® and contains solutions for prefabricated walls, floors and roofs. The production takes place in a factory, and under the manufacturing process the bales are continuously tested and controlled in terms of humidity, density and thermal conductivity (IsoPaille, n.d.).

IsoPaille have executed different kinds of projects, including both single-family houses, office buildings and a three story high school building for example (IsoPaille, n.d.).

PANELS

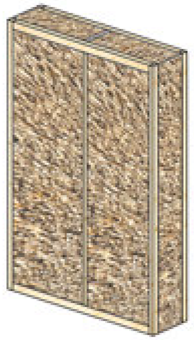
IsoPaille designs their straw modules for each specific project. The limit is though a maximum weight of three tons per panel, and the measurements must not exceed 10 meters in width and 3,60 meters in height. The U-value for the wall panels is 0,11 W/m^{2}K (IsoPaille, n.d.).

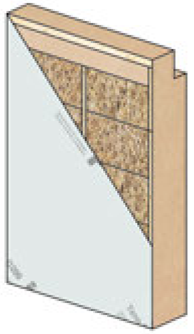
A wooden I-beam is constructed vertically on each side of the straw bale, with horizontal studs on the bottom and at the top, holding the I-beams together, creating a frame (IsoPaille, n.d.).

What makes the IsoPaille system unique is that their modules incorporate a landing for intermediate floors on top of the panels. The edge of this landing is however filled with another type of insulation. The same insulation is also used underneath the windows, where the wall thickness becomes thinner. Cutouts for windows and doors are made within the modules, and are also installed in the factory (IsoPaille, n.d.).

Depending on the project, modules either arrive to the site completely finished including exterior cladding, or the cladding is applied on site. Wooden facades seem to be frequently used in their projects (IsoPaille, n.d.).

COMPARISON BETWEEN THE SYSTEMS



MODCELL®:	ECOCOCON:	ENDEAVOUR:	ISOPAILLE:
Wooden box	Wooden frame	Wooden stud frame with a top and bottom plate	Wooden stud box with OSB and internal I-beams
Load-bearing	Load-bearing	Load-bearing but sometimes used as infill walls	Load-bearing
Closed system - Weather protected	Open system with exposed straw	Semi-closed system – open on the sides	Enclosed system
Intermediate floors are placed on top on the modules	Intermediate floors are hanging on the modules	Intermediate floors are placed on top on the modules	Intermediate floors are placed on the landing on the modules
Bales standing on edge	Loose straw is pressed into the modules	Bales standing on edge	Bales seem to be standing on edge
Cutouts for doors and windows within the modules	No cutouts for doors and windows within the modules	On-site constructed wall pieces where the windows are placed (these are not made out of straw)	Cutouts for doors and windows within the modules (but not insulated with straw around the cutouts)
Many options for the interior and the exterior finish	Plaster on interior side of the modules / Some options for exterior cladding	Lime-cement plaster on interior and on the exterior side, but wood occurs	Optional cladding on the interior. Wood facade on the exterior.
Vapor and airtight membrane on straw on interior side. (Though this differs between types of panels)	No vapor barrier on interior side Airtight layer on straw on exterior side	No vapor or airtight layers	Vapor barrier on OSB on interior side Airtight layer on OSB on exterior side

INDUSTRIALIZING STRAW BALE BUILDING IN SWEDEN

Picture 34.

When constructing any type of building, the local context is always an important aspect to consider. Overlooking such aspects can in some cases lead to undesirable outcomes, which can ultimately lead to demolition. In the 1990s when straw bale constructions started gaining more recognition, electronic communication also bloomed. Straw bale builders could now easily share ideas and keep each other informed about the latest experimentation (Lacinski & Bergeron, 2000). But while this has been useful for the most part one must remember that it is never a good idea to simply copy what works well on one location, no matter how tempting. Instead one must design and plan with the specific site and environment in mind, regardless of which construction method is being used.

The following pages in this chapter will lay out the national considerations for building construction in Sweden. Nevertheless, there are some characteristics that several green building certifications have formalized, which are aspects that can be obtained and used as a framework in all parts of the world;

Avoiding construction in ecologically fragile areas

Favoring techniques that restore rather than destroy the environment

Avoiding materials harmful to the health of humans and animals

Reducing air, water and soil waste pollution

Maximizing the use of building materials with recycled content

Using materials with low-environmental impact during the entire lifecycle. (Production, construction, long-term use and disposal)

Reducing and recycling construction waste

Using water-conserving plumbing fixtures

Incorporating rainwater harvesting or gray water techniques for irrigation

Controlling noise

Assessing long-range savings

Strengthening the local economy

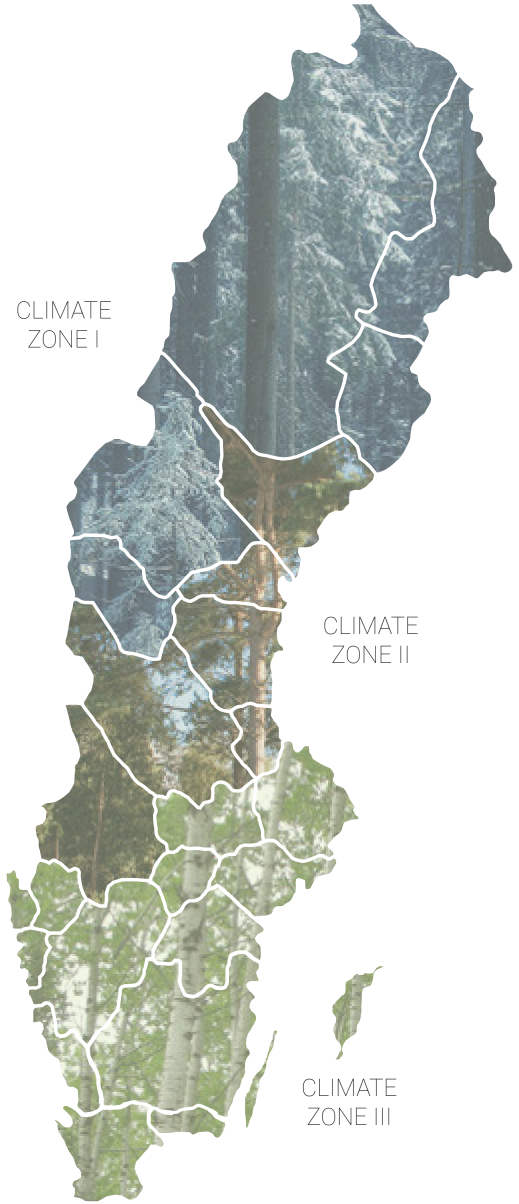
(Paschich & Zimmerman, 2001).

CLIMATE IN SWEDEN

Sweden is located in the northern Europe west of the Baltic Sea, and 15 % of Sweden lies north of the Arctic Circle (Wikipedia, 2015). The Atlantic Ocean and the prevailing winds give the country a mild temperate climate, despite the northern latitude. The low pressures also make the climate precipitation rich, with fallings throughout the year. Since low pressures mostly move in, across the country, from the west or southwest, the western part of the country receives the heaviest precipitation. The southern parts receive around 1 000-1 200 mm of rain fall per year. Relatively long dry periods can occur though, during high pressures. Most of the precipitation falls as snow during winter, with the exception of the southern coastlines. However, the snow cover in the mountain areas lies thick for about 6 to 8 months of the year. Deciduous forests dominate the warmer tempered south. Though, most of the country has a cold-tempered climate with coniferous forests as the primary natural vegetation and winters with heavy snowfalls (SMHI, 2014).

Sweden is divided into three climate zones. The energy requirements for new construction or refurbishments are dependent on the climate zone the building is situated in. The energy requirements in these zones are listed on p. 81.

Norrbotten, Västerbotten och Jämtland is included in climate zone I. Climate zone II accounts for Västernorrland, Gävleborg, Dalarna och Värmland. The last one, climate zone III, is Västra Götalands, Jönköpings, Kronobergs, Kalmar, Östergötlands, Södermanlands, Örebro, Västmanlands, Stockholms, Uppsala, Skåne, Hallands, Blekinge och Gotlands län (BFS 2011:26, 2011).



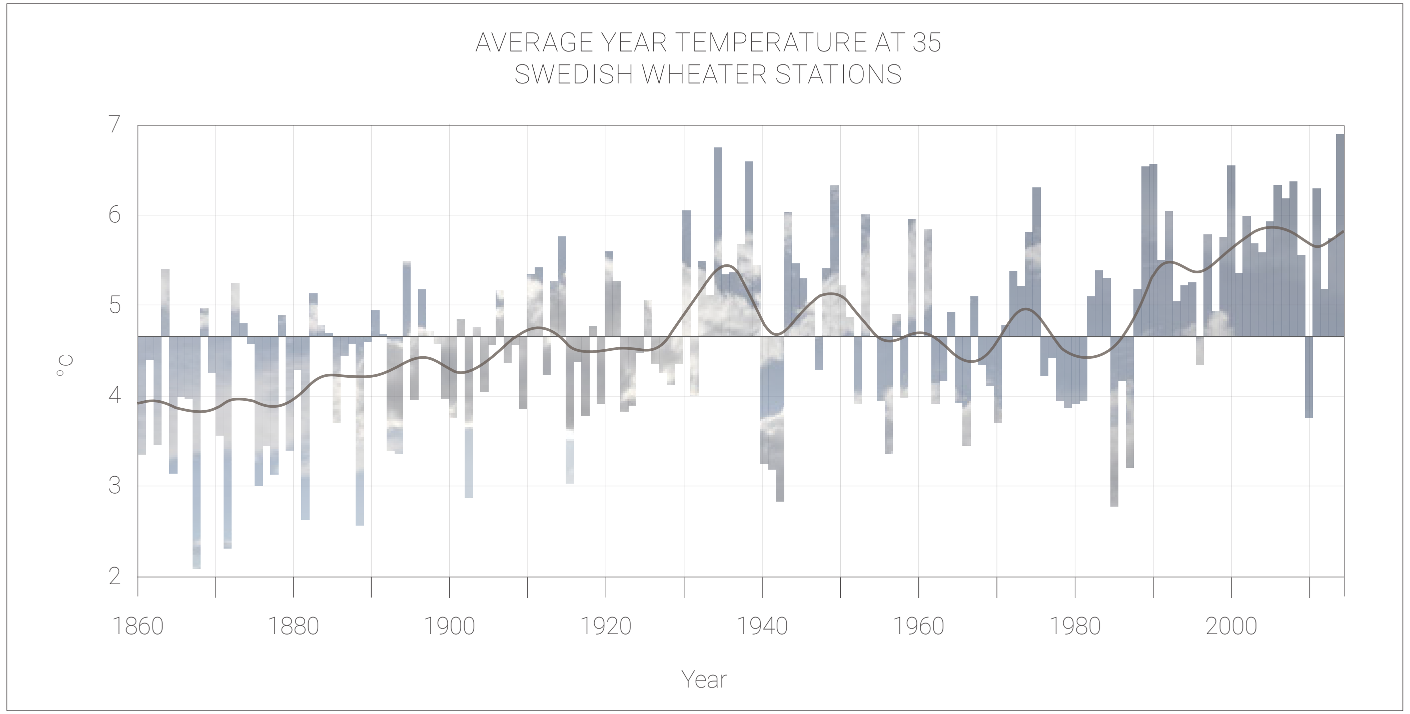


Table 7. The horizontal line shows the average temperature between 1961-1990. Since then, the average temperature has risen. The black curve represents the more leveled progression which has been calculated through 10-year averages (SMHI, 2015). (The table is illustrated based upon source).

FUTURE CLIMATE OF SWEDEN

Several signs indicates that the climate is changing beyond what can be considered as natural variations. The average global temperature has increased with about 0,7 degrees during the last hundred year period (from 1906-2005). This is considered to be a large and rapid increase. The reduction of the Arctic ice cover, rising sea levels and changes in rainfall patterns are other signs of climate change (SMHI, 2015).

The average global temperature is expected to increase between 0,5 to 5 degrees by the year 2100. I Sweden, the average temperature is even expected to rise above this, with an increase between 2 and up to 7 degrees during the same period of time. The temperature increase is estimated to be greater during the winter, at the end of the century. The changes will vary significantly between regions, where the northern part of the country will have the largest increase in temperature (SMHI, 2015).

Temperature zones will be affected by the increasing temperatures, each 1 degree increase corresponds to a north-south distance in Sweden of 150 km. An increase of 3 to 4 degrees would also imply that the tree line is moved 500 m vertically (SMHI, 2015).

Precipitation is estimated to increase with up to 40 % over the next century. Sea levels will most likely continue to rise for a long time in the future. Likewise, water levels in lakes can also be subject to change in future climate (SMHI, 2015).

All of the expected changes are something that society in general and the building industry needs to cope with in the future. Buildings need to withstand heavier precipitation and occasional flooding. Many of our old buildings might be subject to moisture damage in the nearby future. The rising temperatures, causing overheating, could also be a problem for buildings, but there is also an opportunity to design for more passive strategies, such as carefully designed solar shading which also takes advantages of solar gain in the winter. Natural materials combined with passive strategies are something that needs to be employed to a larger extent.

LAWS AND REGULATIONS

Already during the middle-ages there were rules about how buildings should be designed. Since then, the need for laws and regulations has grown together with society (Boverket, 2014). There are a lot of building laws and regulations in most countries around the world today. These regulations also exist on different levels, for examples some regulations can be international, coming from the European Union for example, while most only applies nationally. Some municipalities also have specific regulations and recommendations.

Laws and regulations have a tendency to over protect, simplify and narrowing options. Building sustainably and at the same time meeting the laws and regulations can therefore be two opposing ideals. With any luck, builders and building officials will begin to recognize the need for improving methods to allow for greater sustainability (Magwood & Mack, 2000). In Sweden, like many other countries, there are laws and regulations that need to be met, and there are a number of general recommendations and standards that are somewhat optional to follow. Some might claim that Sweden has rather liberal building regulations, making the options and the introduction of new ideas and techniques easier. But even though the binding laws are quite broad and general in Sweden, there are still function requirements that need to be met, which therefore can narrow the options.

In Sweden there is a building legislation called PBL (Plan- och Bygglagen), which states that a construction needs to have essential technical characteristics. This contains, among other things, energy conservation, thermal insulation, water conservation and waste. The requirements must be met in both new construction and refurbishment. With normal maintenance, during an economic and reasonable life-span, the building's technical characteristics need to be retained (SFS 2012:900, 2010).

The laws and regulations in the Nordic countries and Germany have in some aspects many things in common. They all have requirements concerning thermal insulation of the building envelope, as well as a maximum energy usage for the first year in new constructions. However, when closer examined, these regulations have as many variations as the number of countries they are applied in. When it comes to thermal insulation for example, which is indicated by U-values, the requirements can either be set on specific elements of the building or on the building as a whole. In Germany U-values etc. are specified for different elements in a reference building, which later should be compared with the actual building. This method was employed in Sweden in previous building regulations (Nybyggnadsregler 1988:18 NR 1 och BBR 1993:57) between 1989 and 1993. Rules based on reference buildings were considered to give and unacceptably wide spread of the actual energy consumption in buildings. This type of requirements often has a missing link between the calculated value and the actual result (Boverket, 2012).

The requirement for maximum energy usage per year is calculated, in the Nordic countries, by kWh/m^2. Calculating this is however carried out differently in the different countries. The requirement can for example depend on the used type of heating, or in which type of climate zone the building is situated in (Boverket, 2012). For premises in Sweden, this is set at 80 kWh/m^2/year, in climate zone III, 100 kWh/m^2/year, in climate zone II, and in climate zone I, 120 kWh/m^2/year. These numbers must be followed when heating methods other than electric heating are used. (BFS 2011:26, 2011). The requirements usually also varies between building types (housing, industries, commercial premises etc.). Norway has requirements for 13 different building types, whereas Sweden only distinguishes between housing and other facilities (Boverket, 2012). Energy calculations are carried out before construction starts in Sweden. These should show that the energy requirements are likely to be met in the finished building. A energy declaration

ENERGY DEMAND IN THE NORDIC COUNTRIES AND GERMANY

		Sweden	Danmark	Finland	Norway	Germany
U-values	Demand for specific elements	No	Yes	Yes	Yes	Yes
[W/m^2 och K]	Demand for building envelope	Yes	Yes	Yes	No	Yes
Specific energy	Demand on calculated value	No*	Yes	Yes	Yes	Yes
consumption	Demand on measured value	Yes	No	No	No	No
[kWh/m^2/year]	Reference building	No	No	Yes	No	Yes
	Demands vary with building size	No	Yes	Yes	No	-
	Demands vary with usage	Yes, 2 different	Yes, 2 different	Yes, 9 different	Yes, 12 different	-
	Demand on heat recovery	No	No	Yes	Yes	-

** A calculation of the specific energy, should be made in the planning process but is not a demand*

Table 8. Energy demand consideration by country (Boverket, 2012). (The table is illustrated based upon source).

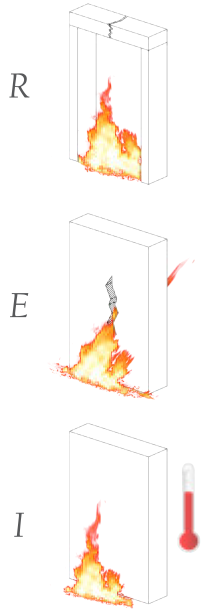
(energideklaration) is carried out two years after completion in order to see if the requirements actually have been met. It is satisfactory with just the estimated energy calculation made in the planning process in the other Nordic countries and in Germany. This implies that there are no restrictions or limits for the actual energy usage after the building has been put into use. Measuring the real energy usage was introduced in Sweden in 2006 and originates from directives from the European Union (Boverket, 2012).

Building regulations in Sweden state that every building should have fire protection, but the exact requirements vary depending on building type and activity. The protection should be planned and designed so that individual events or strains do not wipe out large parts or the entire system (BFS 2011:6, 2011).

Buildings should be planned and constructed to meet the requirements listed below, in case of fire;

- The load-bearing capacity should stay intact for a given amount of time
- The development and spread of smoke within the building should be limited
- Fire spreading to adjacent buildings should be limited
- People within the building should be able to leave or be rescued in another way
- The safety of rescue workers should be considered
(SP, 2012).

When it comes to fire proofing most countries also have restrictions for the use of wood in constructions. Methods for fire testing and rating systems have been harmonized in Europe, though the binding regulations are still national (SP, 2012). In Sweden, up to 1994, it was not allowed to have a load-bearing wooden construction for buildings more than two stories high. After this year, it became possible to build high buildings with wood when the ban for flammable materials was replaced with function based demands (Träguiden, 2014).



Picture 35. Structural elements must be able to withstand a fully developed fire and meet the functional requirements; load-bearing capacity (R), integrity/seclusion/tightness (E) and insulation (I). Constructions should be able to withstand fire exposure during a specific time period, for example 60 minutes, REI 60 or E60 for example (SP, 2012).

CERTIFICATIONS

Sustainable design gained more recognition in the 1990s with the creation of the first green building rating system in the UK, BREEAM (Building Research Establishment's Environmental Assessment Method). The US Green Building Council in the United States followed and developed the rating system LEED (Leadership in Energy and Environmental Design) for new constructions in 2000. Nowadays LEED also has rating systems for existing buildings and even entire neighborhoods. These early programs have influenced a number of additional rating systems around the world that have been tailored to national priorities and requirements. Some have even sought to go beyond the limits of current policies to address broader issues of sustainability and evolved concepts such as zero net energy or designs to model nature, often mentioned as biomimicry (Vierra, 2014).

There is now a vast spread of certifications, ratings and standards available to help designers and developers to deliver high-performance and sustainable buildings. Nearly 600 green product certifications are estimated to exist around the world today, and they are continuously increasing in number. Green building rating programs used globally often have some outlining conditions and optional credits, but vary in their approach. Consequently, determining which rating program, certification and standard is the most credible and applicable to a particular project can be both time consuming and challenging (Vierra 2014).

The table below shows an overview of some of the most widely recognized green building certifications in use today, with an emphasis on what they take into consideration.

COMPARISON BETWEEN GREEN CERTIFICATIONS

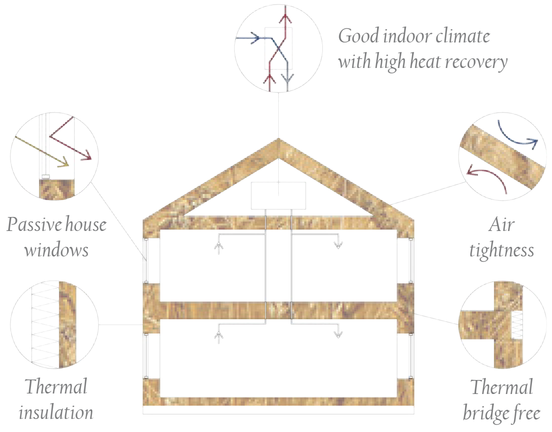
	LEED	BREEAM	GreenBuilding	Miljöbyggnad	Passivhaus
Energy	Yes	Yes	Yes	Yes	Yes
Indoor climate	Yes	Yes	No	Yes	Yes
Materials	Yes	Yes	No	Yes	No
Moisture managment	Yes	No*	No	Yes	No
Heating (microclimate)	Yes	No	No	No	No
Follow-up	Yes	Yes	Yes	Yes	Yes
Construction	Yes	Yes	No	No	Yes
Waste	Yes	Yes	No	No	No

Table 9. The five commonly used green certifications and their considerations (Skanska, n.d.). (The table is illustrated based upon source).
** Moisture management is considered in the national version of BREEAM in Sweden (BREEAM-SE).*

PASSIVE HOUSE STANDARD

One type of building certification that has grown and gained international repute is the Passive House Standard, originated from Germany. It is a standard for energy efficiency, which results in low energy buildings that require extremely little energy for heating and cooling (Passive House Institute, 2015). Later in the chapter "*Implementation*" this standard is set as a goal to achieve, since it also is a wish from the municipality.

There are five principles to a passive house; they should be free from thermal bridges, have superior windows, a ventilation system with heat recovery, have quality insulation and be air tight. Simplified, passive houses can be seen as a well-insulated building where heating and cooling is provided for through a fresh air supply. Though, only as much fresh air needed for creating an adequate air quality (Passive House Institute, 2015).



Picture 36. The five passive house principles.

The requirements a building must meet in order to be considered as a passive house, according to the international standard, are;

- The energy for heating must not exceed 15 kWh/m^2/year or 10 W/m^2 at the peak demand. (In areas were active cooling is required the figures are roughly the same, with some additional energy for dehumidification).

- The primary energy demand should be lower than 120 kWh/m^2 and year. (This is the total energy use for all applications in the building).

- The air tightness should be verified with an on-site pressure test, were the maximum of 0,6 air changes per hour at 50 Pa pressured is allowed.

- Thermal comfort should be met, both in summer and winter. Not more than 10 % of the hours, in a given year, should exceed 25 °C.

- The windows should have a U-value of 0.80 W/m^2K or less, and the insulation a U-value of 0.15 W/m^2K at the most.

- In the heat exchanger, at least 75 % of the heat from exhaust air should be recovered.

(Passive House Institute, 2015).

When designing passive houses in Sweden there is a greater focus on achieving the power (W) requirement, while the international standard focus on the energy (kWh) (Helmfridsson, 2014). The table to the right, (Table 10) shows the specific Swedish requirements. There are also different requirements for the different climate zones in Sweden (Eek, et al., 2007).

COMPARISON OF THE SWEDISH AND GERMAN CRITERIAS FOR PASSIVE HOUSES

	Swedish	International / German - PHI/PHPP
Heat demand at DUT	‹ 15 - 17 W/m^2 int load	‹ 10 W/m^2, or the energy criteria fulfilled
Dim. outdoor temp. (DUT)	SS 024310	PHI calculates two different DUT
Heat energy demand	-	15 kWh/m^2, or heat demand criteria
Vent. air flow (Build stand)	› 0,35 l/s, m^2	0,3 – 0,4 exchanges/h
Air tightness	0,30 l/s, m^2	0,6 exchanges/h
U-value window	0,80 W/K, m^2	0,8 W/K, m^2
Ventilation heat exchange	› 70% (recommended)	› 75% (PHI method)
"Primary energy"	63 - 73 kWh/m^2	120 kWh/m^2 (incl domestic electricity)

Table 10. Comparison between the Swedish and German criteras for passive houses. The requirements for the international standard is based on Erlandsson, et. al., 2009. The Swedish requirements are based on Erlandsson, et. al., 2012. The Swedish requirements change for buiding smaller than 400 m^2 (Erlandsson, et. al., 2012) (The table is illustrated based upon sources).

Picture 37. In the factory of Becohus, Falkenberg.

CHALLENGES WITH PREFABRICATION

There are a lot of aspects to consider when designing prefabricated elements in general. The intersections, fixings, transport and the working conditions for the builders etc., just to mention a few. When using straw, the combination with other materials also needs to be considered. The question of how general the modules should be in order to not have too many unique variations is also important to reflect upon. The same goes for the usage of materials. It is perhaps a good idea to use as little material as possible in order to lower the price, but also in order to make the modules less heavy for example. All off these, among other aspects, have affected the outcome and the design and the "*Sensible Straw*" bale modules.

When prefabricating building elements, a major aspect is to design for the delivery truck. This means that the size of the modules is limited if standard trucks are to be used. In order to get a sense of this limitation standards trucks usually allows a maximum height of 3,2 meters. An exception can be made if low suspended trucks are used, where there is a possibility for the modules to be up to 4,2 meters high. These low trucks are, however, limited in number, and can therefore be difficult to obtain. For this reason it is better to try not to exceed the first mentioned limit (Svensson, 2015).

There is a need to figure out how the working conditions for the builders should be as good as possible. This includes the handling of weight and other ergonomic aspects. It also includes that the materials and methods are easy to work with. To give an example one can look at how Becohus in Falkenberg are handling the insulation. The cellulose insulation is blown into the modules, with the help of a machine, until the desired density of the insulation is reached. If straw is to become a conventional building material it needs to be easy for the builders to handle.

On the next page some more specific questions and difficulties regarding prefabrication of straw bale modules are listed.

CUTOUTS FOR DOORS AND WINDOWS

If the modules are load-bearing, cutouts can be difficult. Cutouts for doors and windows need to be executed within the framework of the modules, which means, depending on the size of the modules, windows cannot increase in size indefinitely. Depending on window sizes and placement, lintels may also need to be incorporated within the modules.

There are mainly three alternatives when it comes to cutouts for doors and windows. Either the modules are built around the cutouts, or the cutouts are included within the modules. There is also the option of including and installing doors and windows already in the factory. However, these different alternatives lead to other kinds of difficulties. One crucial stage is the sealing of doors and windows. A sealing tape that expands is often used to get the construction airtight. The expansion of this tape needs to be controlled which imply that the installation only works properly in a defined span of temperature.

Bay windows and other protruding parts in the building are possible but are troublesome, especially if one wants them made with straw. The problem is that straw walls are thick which can make bay windows look less elegant or even clumsy. Having space for electrical wiring and other installations incorporated within the modules can for obvious reasons also be beneficial.

FOUNDATIONS

The foundation is perhaps the most critical connection. Improper intersections between different materials can result in moisture problems due to condensation, capillary suction and so forth. Organic materials may also have to be elevated from the ground to avoid moisture damage. An additional elevating structure can therefore be needed.

INTERSECTIONS AND CORNERS

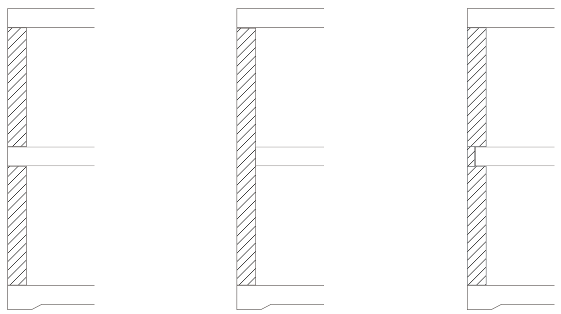
When assembling a modular system intersections and corners are especially difficult. It is essential to make sure there is no air leakage in the construction, both in terms of thermal comfort and moisture control. This could be done by creating a continuous layer by overlapping vapor barriers, which are either open to diffusion or completely closed. Another option when using straw is to create an airtight layer with plaster on site.

Another part that can be complicated is how and where to position the fixings, corners being the most difficult.

INTERMEDIATE FLOORS

Intermediate floors can be installed in three different ways; either they are placed on top of the wall elements, hanging inside the wall elements, or they are placed as a combination of the two. The first option is not a good option in terms of thermal bridging, and hanging the slab on the modules requires a greater control over sound and fire requirements. The combination of placing the slab on the element but leaving space for additional insulation is perhaps the best option.

Intermediate floors can easily grow in size due to spans, fire regulations and acoustics. The straw wall elements therefore need to handle a heavy load, if the modules are load-bearing.



The three main ways of connecting to intermediate floors.

WEIGHING THE OPTIONS

Both positive and negative aspects can be found in all of the existing prefabricated straw bale systems, described earlier. A comparison of the different options can be seen here.

**Points that are seen as crucial and more important for the development of the prefabricated straw wall element in Sweden.*

Wooden box	vs	Wooden frame
Easier to construct Easier to stack the bales Heavier		*Minimizing thermal bridging Less material for fixings in intersections

Entire volumes	vs	Wall sections
Reduced flexibility due to transport Need thorough planning Large and bulky to assemble Efficient - Shorter construction times on site		*More flexible More intersections *Less heavy and more manageable to assemble Can be more weather sensitive

Finished surfaces	vs	On-site completions
Can result in intersections with poor quality (mostly aesthetic) Can be less flexible (need of choosing what the producer has to offer) Efficient - Shorter construction times on site		Intersections better executed (mostly aesthetic) *More freedom and flexibility *Airtight layer and vapor barriers can be applied over intersections in larger sections

Exposed straw	vs	Closed modules
Promoting sustainability with the exposed straw (trade mark and advertising) Possibly less thermal bridges (straw against straw) Can be a bit messy on site and hard on the hands		Weatherproofed *Can perhaps be seen as more conventional and familiar to builders Straightforward *Can make intersections easier

Cutouts in module	vs	Modules around cutouts
*Weather tight building faster Increasing properly executed installation More sensitive during transport, if windows are installed in the factory Shorter construction times on site		Flexibility for windows in terms of size Easy construction in the factory Smaller elements – weight and size *Many intersections – more thermal bridges

Load bearing	vs	Infill
*More efficient to have the load-bearing structure embedded in the modules Can make modules larger and increase the wall thickness The load-bearing structure can lower the U-value and cause thermal bridging Potential height restrictions due to fire regulations (when using wood)		Requires independent structure and perhaps more material No height restrictions

Clay plaster	or	Not
Natural material Breathable (No airtight layer or vapor barriers needed) Gives thermal mass Improves indoor climate (Can hold and release moisture)		Moisture sensitive *Time consuming = expensive Heavy *Can crack during transportation Needs yearly maintenance *Internal plaster is not suited for hanging, for example shelves or other furnishings It is depended on experienced workers Non-renewable

STRAW BALE MODULES - A VISION FOR SWEDEN

Picture 38.

The desired outcome of this thesis is that straw will receive greater acceptance by the building sector. Achieving this realistically means that straw needs to be adapted to the major building methods employed today as a first step. As stated earlier, incorporating straw in prefabricated building elements can be a solution.

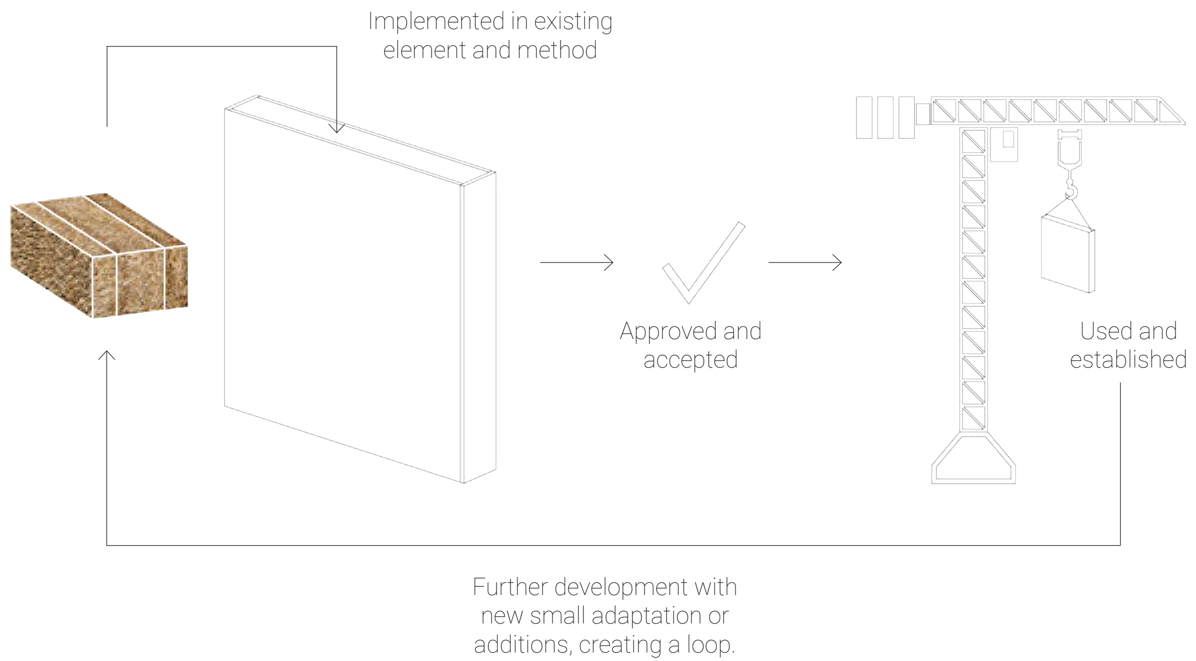
The main purpose of the design, construction and assembly of modular straw bale building components is to create an efficient, cost competitive and qualitative system. Preferably these components should easily be able to function with other components from different manufacturers. Together, these can then be integrated into a full design, without unnecessary complications or costly adjustments, either in the factory or on site.

The vision is that prefabricated straw systems are, in the future, a commonly used method when constructing buildings.

CONCEPT

The proposed straw wall system aims to become as accepted as any other conventional alternatives that exists on the construction market today. Since the larger construction companies more or less control the market, these have the greatest power to influence and develop the building industry in Sweden. Through contact with representatives from both the big developers and smaller companies, there seems to be a general view that the building industry is curious and not foreign to try new building techniques and methods. The problem lies within that it is easier to build as usual since there is a lot of existing knowledge. This familiarity also creates a sense of security. On that account, straw bale modules need to be carefully designed before introducing them to the construction market, with an emphasis on proving that they will work and perform as they are supposed to. Additionally, they need to be easier, or equally as easy, to manufacture, transport and assemble as existing systems and methods. Lastly, there obviously needs to be an economical gain in using them.

Therefore, the main concept is to gradually introduce sustainable material and technique on the market, starting with straw. Introducing the system in steps makes it more likely to get the building sector comfortable and familiar with using straw as insulation, starting with straw wall elements which can evolve with time. The key is that the modules should, in the first step, be as familiar and flexible as possible for a developer to feel comfortable in switching their existing modules to the "*Sensible Straw*" bale modules. When this has been accepted, the modules can evolve further stepwise with additional small changes, making them more sustainable with time, creating a development loop.



DESIGN CRITERIA'S

The research in the previous chapters has laid the foundation for the design criteria's for the proposed "*Sensible Straw*" bale modules in Sweden.

The design criteria's are mainly a summary of the two chapters "*Challenges with prefabrication*" and "*Weighing the options*".

- Structural system embedded within the modules
- Airtight system but open to diffusion
- As general modules as possible
- Flexible in terms of shape, size, cutouts and cladding
- To some degree on-site completion
- Weather protected straw
- Low U-value
- Module size suited to delivery trucks
- Use of sustainable materials to the furthest extent possible
- Easy assembly and installation

Picture 39. Some tools needed when building a straw bale house.

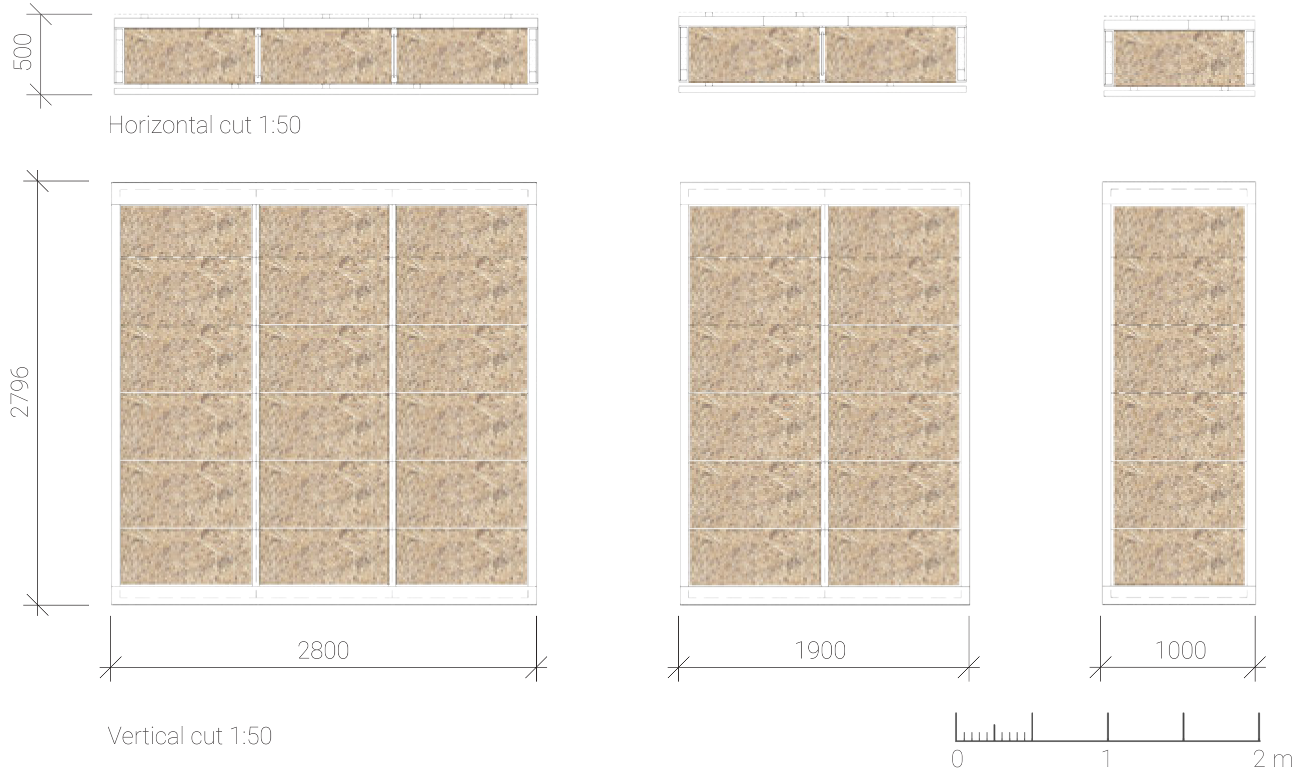
The proposed *"Sensible Straw"* wall elements are presented in this section. The following details show principle intersections with usual building elements such as foundation slab, intermediate floor and roof. These solutions therefore mainly show how the modules can be installed and work together with standard solutions as well as the structure and composition of the designed modules. The material choice is based on a number of different factors. An brief assessment of these can be found after the detail drawings.

Picture 40.

PROPOSAL

DETAILS

The *"Sensible Straw"* bale modules are constructed with wooden studs, creating a frame. Straw bales are stacked in the frame, between internal masonite I-beams. The standard wall element is just short of 2,8 meters high (equivalent to 6 bales on edge) and exactly 2,8 meters wide (three bales on edge). Wall elements with two or one bale are also used where they are preferable in the building design. Using larger modules implies fewer intersections. However, the modules are adapted to each project, and special solutions can be made.



A full scale mock-up model of the "*Sensible Straw*" wall element. To the left the exterior side of the module is shown, while the interior side is seen to the right. The exterior side of the module has been given a wooden facade to show an example. More pictures can be seen in *Appendix I*.

Picture 41.

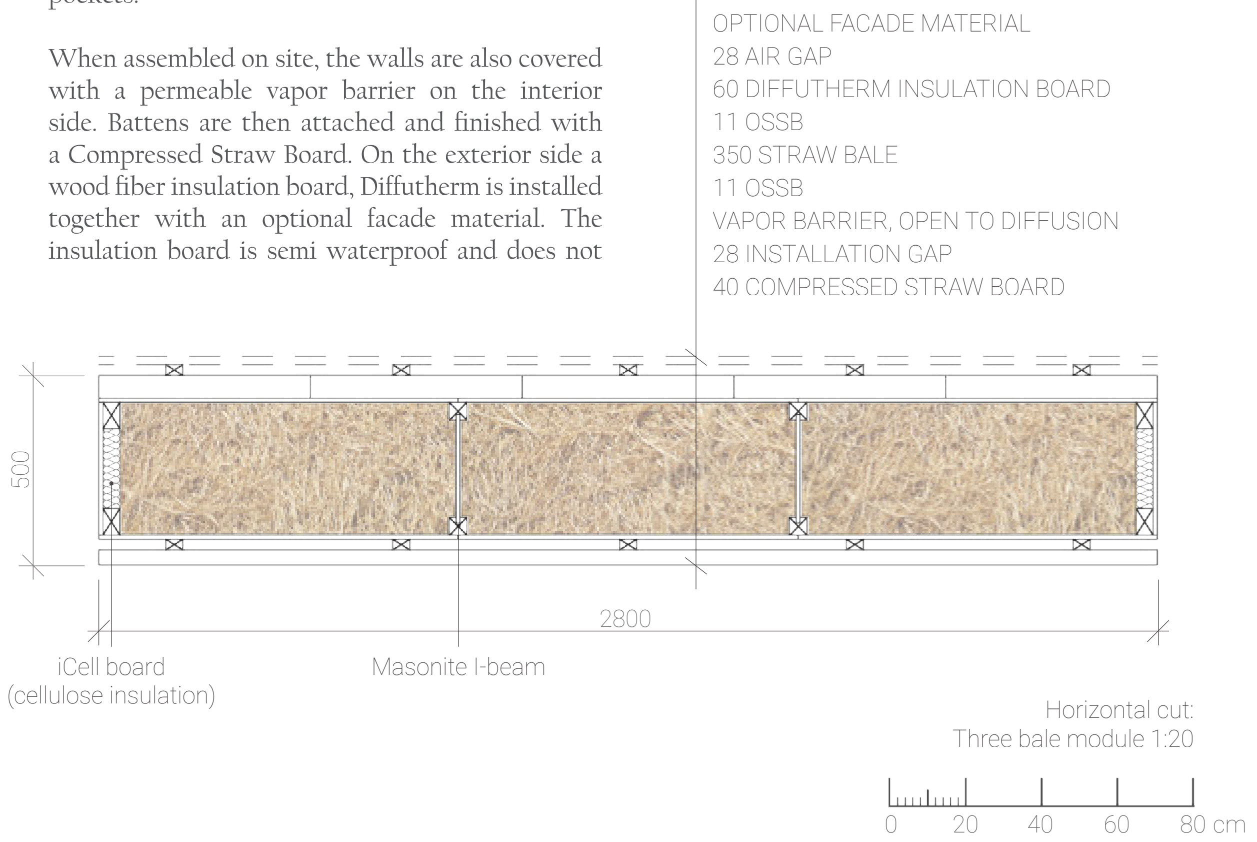
Cutouts are made in the factory where doors and windows are installed as well. Cutouts are preferably made according to bale size, but to deviate from this is not a big problem since cutouts are built with individual studs, and the bales are stacked around.

Figures are demonstrating cutouts within the modules which in the case of the window is following bale sizes. Halved bales are used for the space above and on the right side of the door opening.

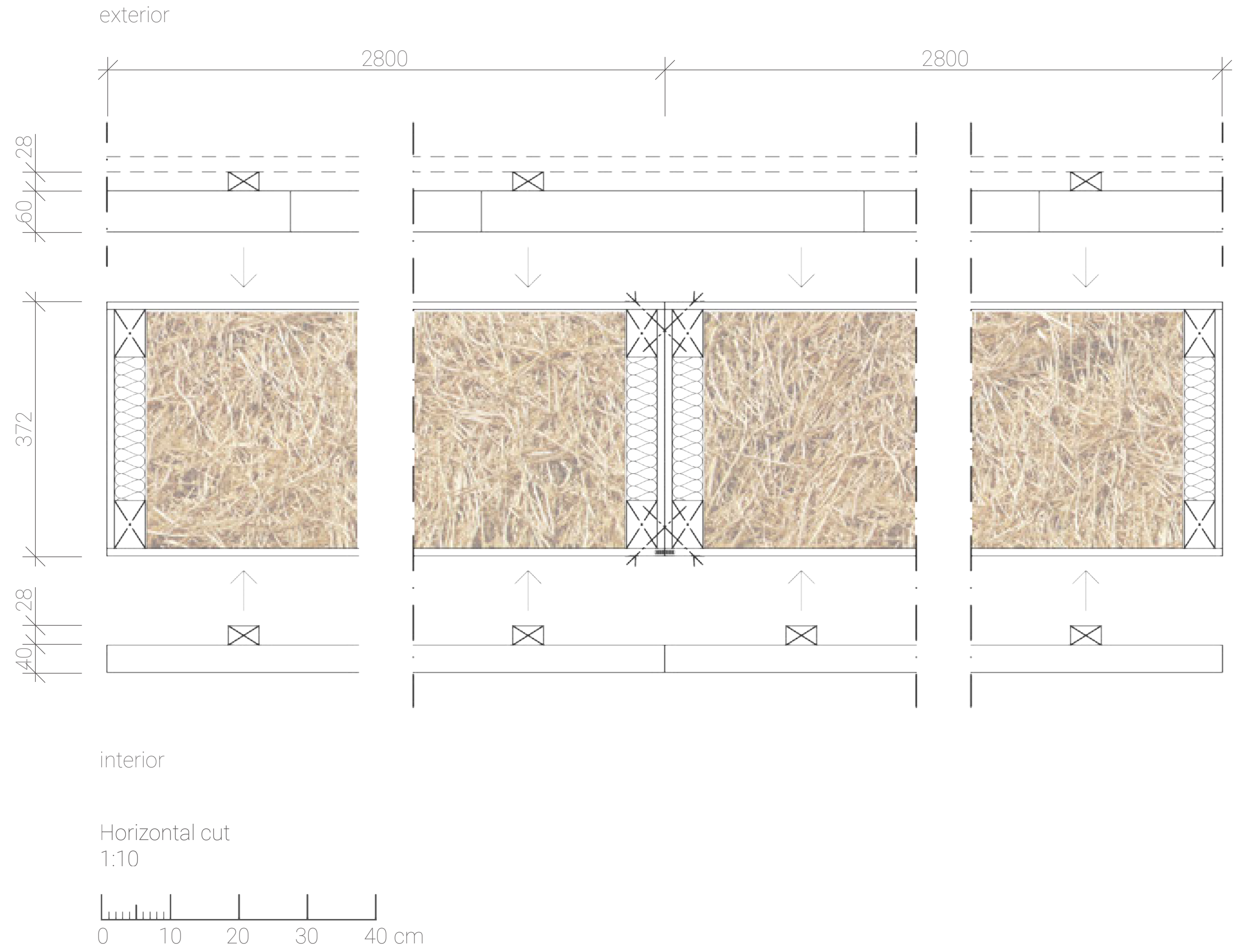
COMPOSITION AND ASSEMBLY

The prefabricated wall elements arrive to the construction site as an enclosed, weather protected, unit. The wooden studs and straw are enclosed with OSSB (Oriented Structural Straw Board) and cellulose insulation is used between studs to ensure a tight and compact construction with few air pockets.

When assembled on site, the walls are also covered with a permeable vapor barrier on the interior side. Battens are then attached and finished with a Compressed Straw Board. On the exterior side a wood fiber insulation board, Diffutherm is installed together with an optional facade material. The insulation board is semi waterproof and does not need any sheets or barriers before applying the finishing material. The insulation properties of Diffutherm also help lower the U-value. The U-value for the "*Sensible Straw*" module is calculated at 0,115 W/m²K. The calculation can be seen in *Appendix II*.

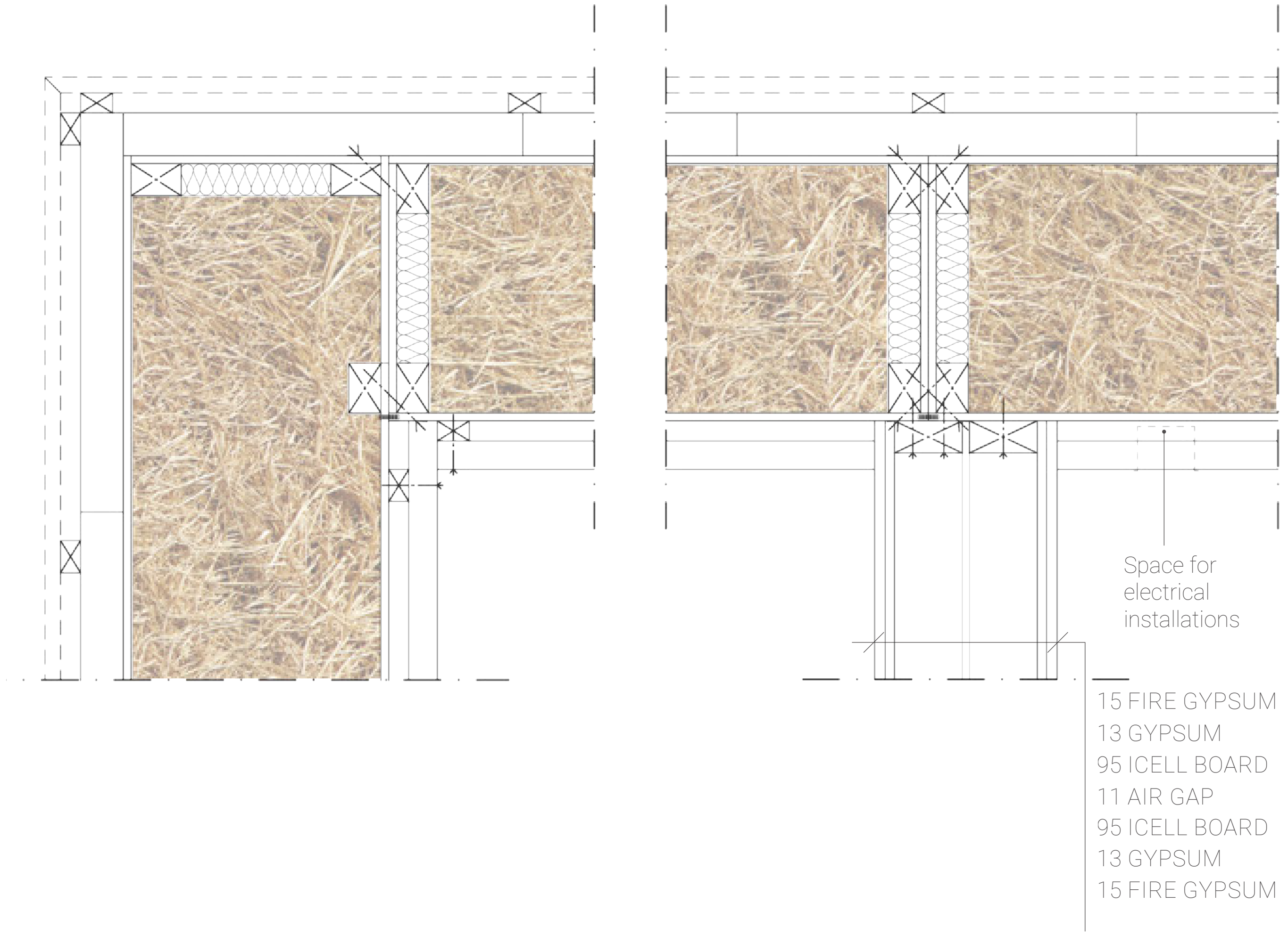


Horizontal cut:
Three bale module 1:20

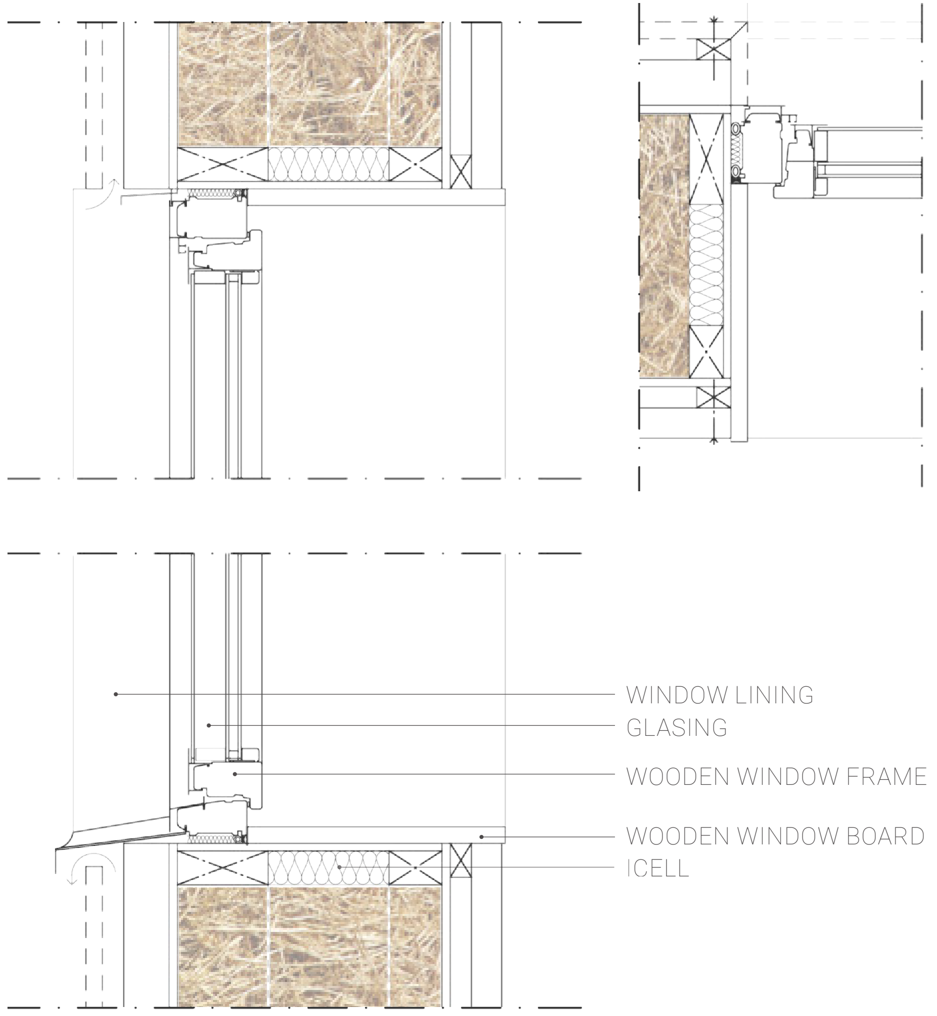


Horizontal cut
1:10

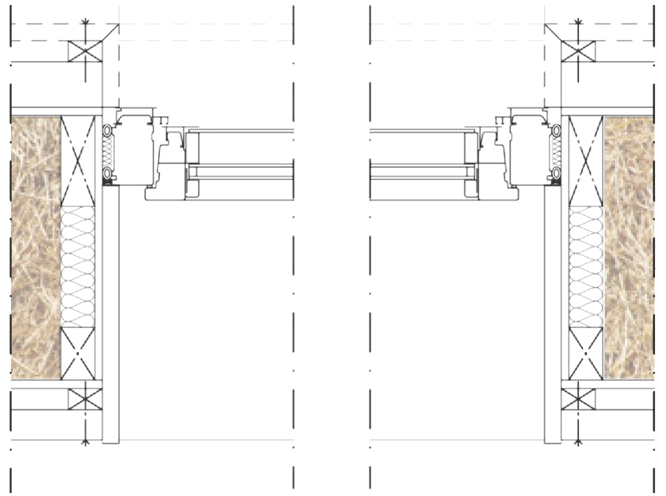
CORNERS, INTERIOR WALLS AND WINDOWS



Horizontal cut
1:10



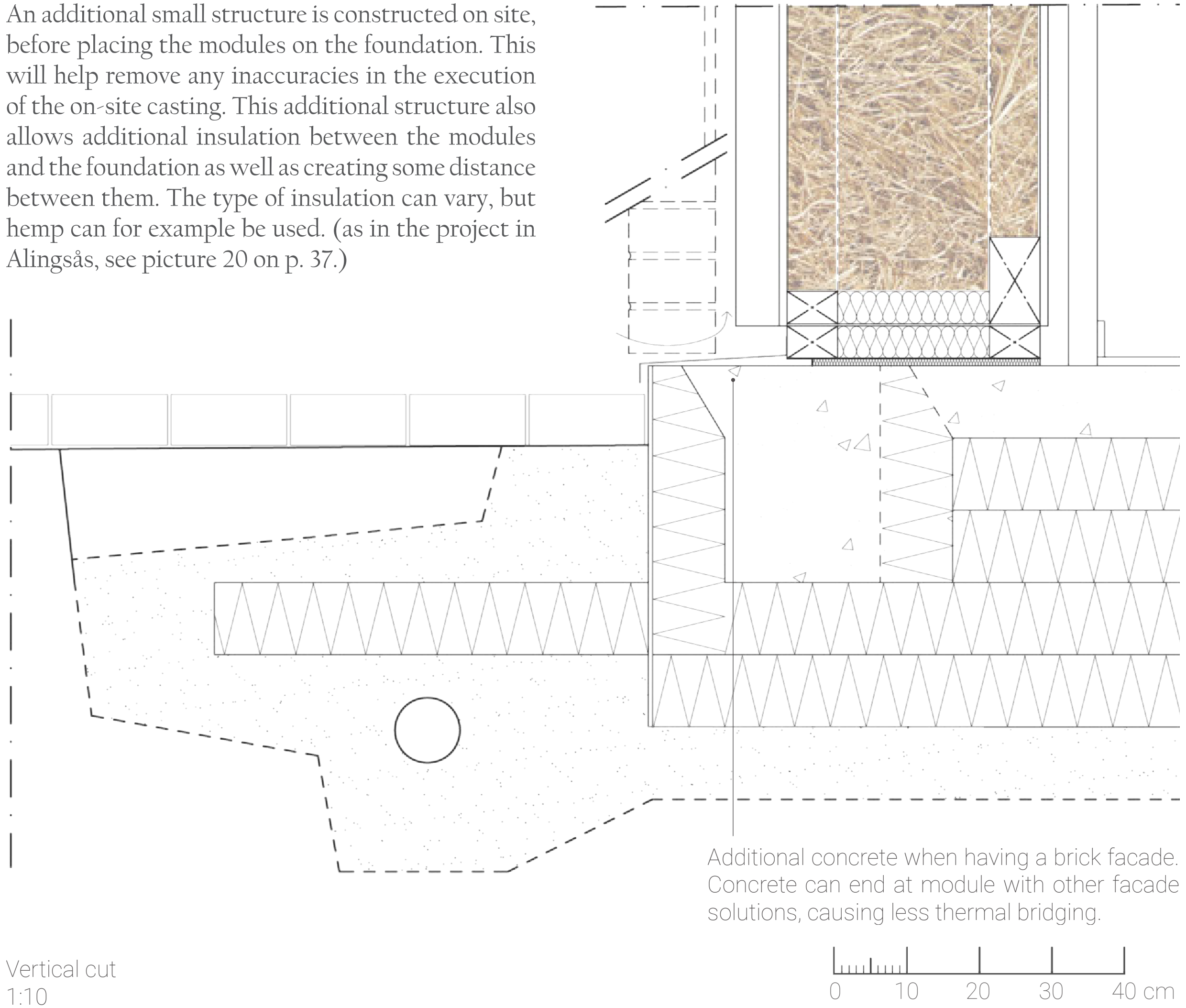
Vertical cut
1:10



Horizontal cut
1:10

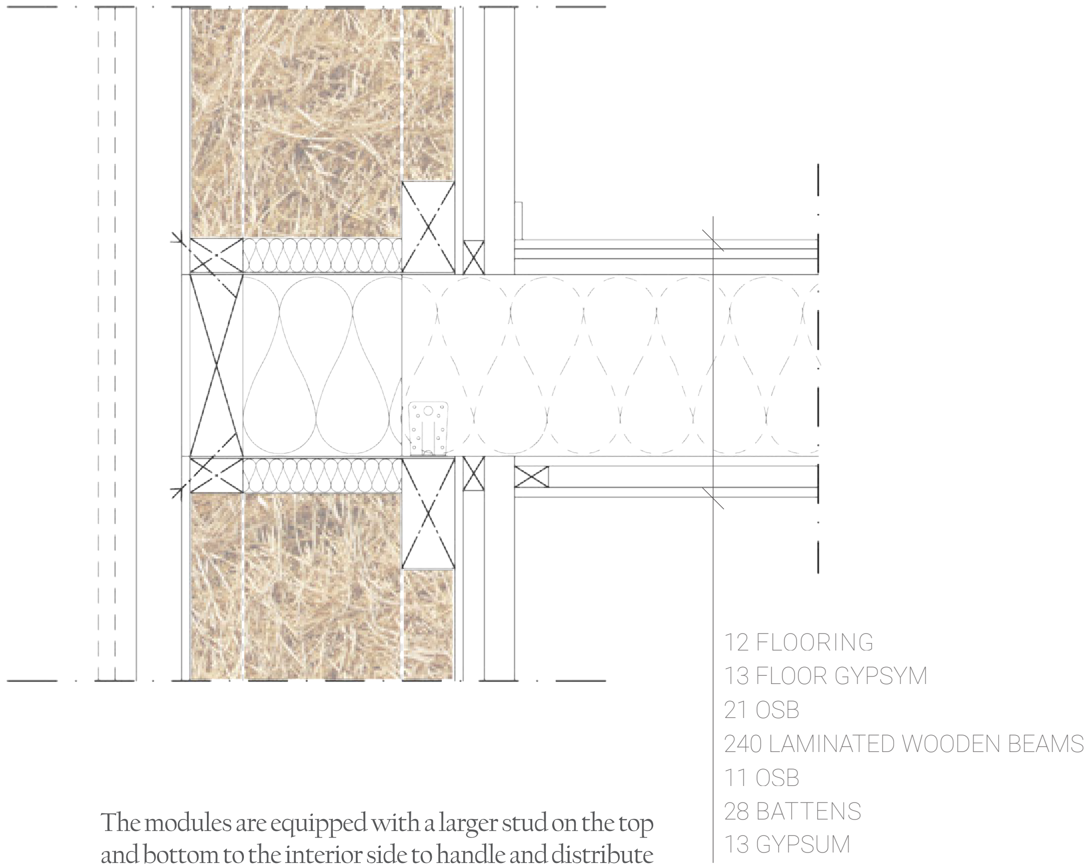
FOUNDATION

An additional small structure is constructed on site, before placing the modules on the foundation. This will help remove any inaccuracies in the execution of the on-site casting. This additional structure also allows additional insulation between the modules and the foundation as well as creating some distance between them. The type of insulation can vary, but hemp can for example be used. (as in the project in Alingsås, see picture 20 on p. 37.)



Vertical cut
1:10

INTERMEDIATE FLOOR

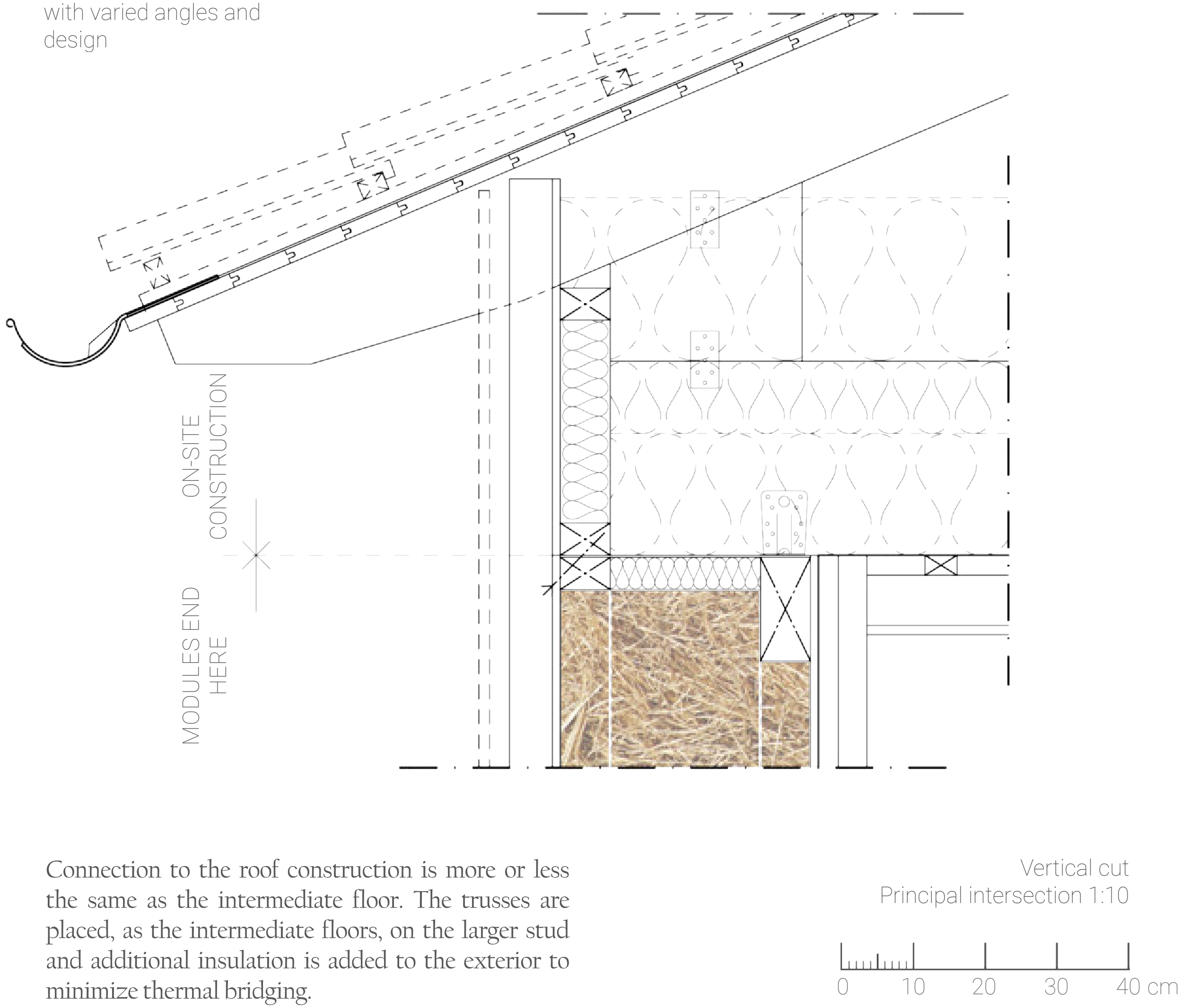


The modules are equipped with a larger stud on the top and bottom to the interior side to handle and distribute the load of overhead constructions. The intermediate floor is placed on top of the modules on the larger stud, and an edge beam in placed on the exterior stud. The gap between these is filled with additional insulation, and since the exterior facade material is applied on site this will not create any stripes in the finished facade.

Vertical cut
1:10

ROOF

Roof construction with varied angles and design



Vertical cut
Principal intersection 1:10

Connection to the roof construction is more or less the same as the intermediate floor. The trusses are placed, as the intermediate floors, on the larger stud and additional insulation is added to the exterior to minimize thermal bridging.

Picture 42. An example of a wooden roof, covering a piece of wall at the house of Ingrid Faldner.

CHOOSING MATERIALS

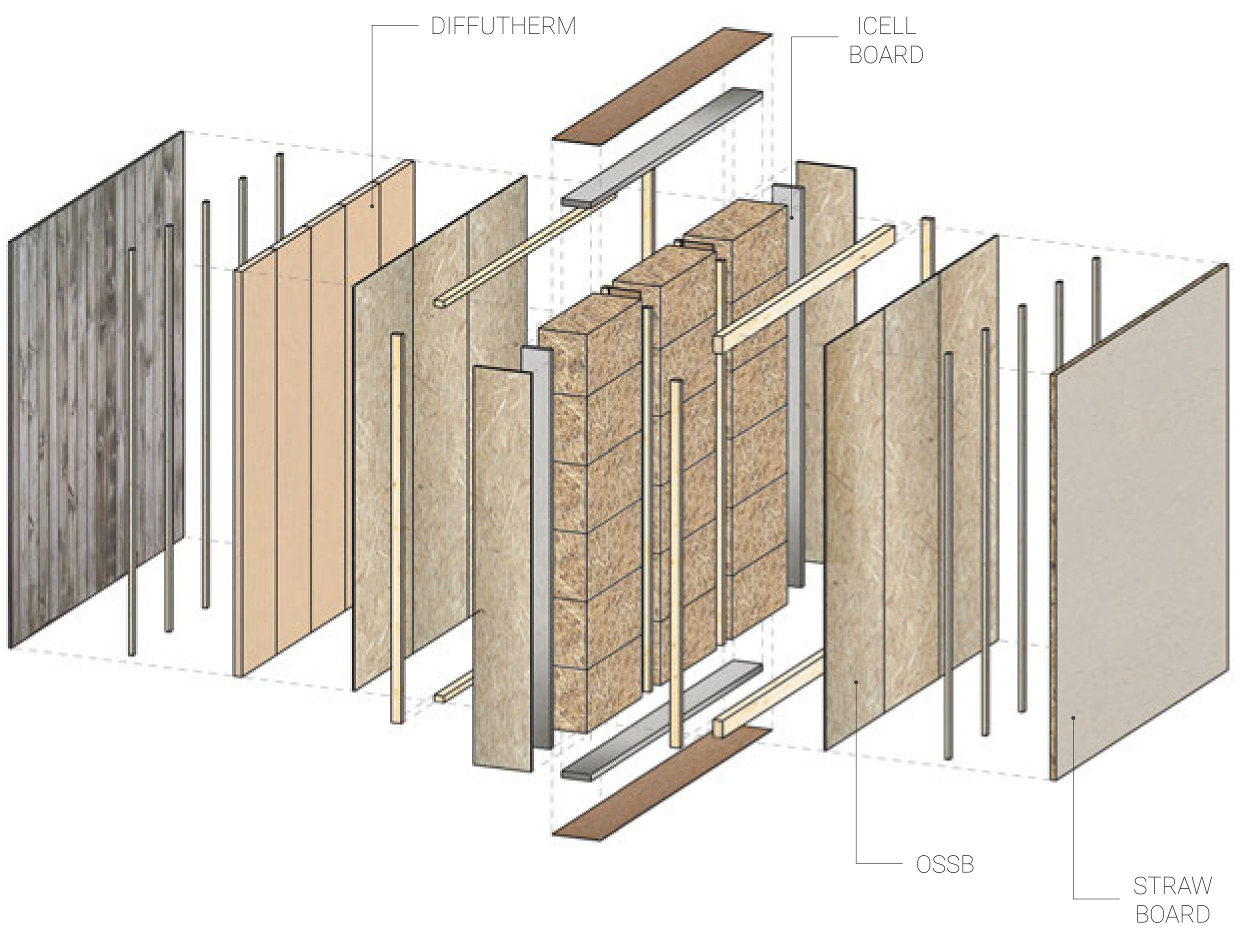
The choice of materials in general should be made based on a number of different aspects. In terms of sustainability, materials that consume the minimum amount of energy during all stages of its live cycle are preferable. In order to reduce energy consumption, emissions and transportation costs, the products should preferably also be produced locally. Though, there is always the need to consider other aspects, such as, availability, quality, economics and social values etc. rather than always choosing the most locally sourced material.

The load on landfills can also be reduced if constructions and products are easily disassembled. Other important aspects concerning materials are that they should be easy to maintain, suited to the local climate and they should also be durable. Durability is perhaps one of the most sustainable characteristics of materials, since it reduces the need to build in the first place.

Fire safety is an important aspect when choosing building materials. Many renewable and ecological materials are in many cases also flammable, like wood for example. Despite this, if properly used and executed they are as good as any other materials (SP, 2012).

Next, a comparison between conventional materials and more sustainable ones is carried out, focusing on some of the functions needed in the proposed straw wall system, (Additional insulation, bracing panels and interior cladding). Structural materials are excluded, since concrete or steel is not an alternative compared to wood. The same is true for the main insulation since straw is a given.

An exploded view over the composition of the proposed "Sensible Straw" modules, highlighting the chosen material alternatives.



	Additional insulation				Bracing panels				Interior cladding		
	Expanded polyesterene (EPS)	*Mineral wool*	*Cellulose insulation*	*Fiber board Diffutherm*	*Plywood*	*Masonite*	*OSB*	*OSSB*	*Plaster*	*Gypsum*	*Straw Board*
Renewable raw material[1]	-	-	x	x	x	x	x	x	-	-	x
Local production[2]	x	x	x	-	x	x	x	-	x	x	-
Embodied energy[3] (MJ/Kg)	88,6	16,8	0,94-3,3	-	15	16	15	-	1,8	6,75	-
CO^2 Emissions[3] (kg CO^2/kg)	2,55	1,05	-	-	1,07	1,05	0,96	-	0,12	0,38	-
Lambda value[4], λ (W/mK)	0,035	0,036	0,04	0,045	0,13	0,13	0,13	0,13?	0,7	0,21	0,119
Price[5] / m^2 + labor cost (SEK)	108	88	115	251	235	165	161	-	249	145	287 -327

[1] Since many of the products contain several components, this chart only assesses the main component.

[2] Local production means here that the material is manufactured nationally, in Sweden.

[3] Embodied energy and CO_2 emissions, based on figures from the Sustainable Energy Research Team (SERT) at the University of BATH (Anderson, w. d.). This type of research has probably not yet been carried out for Diffutherm fiber board, OSSB, or the Compressed Straw Board.

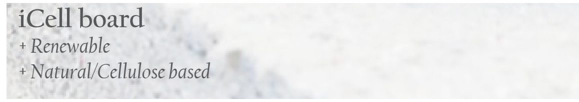
[4] Lambda values come from two different sources, "The ecology of building materials" (Berge, 2009), and from the Passive House Institute, trough Finlay White, ModCell® (White, 2015). Lambda value for Diffutherm fiber board is based upon a salesman at Miljöbyggsystem . Lambda value for OSSB could not be found. One can though assume that the lambda value for OSSB would be the same, or slightly lower than traditional OSB due to the insulative properties of straw.

[5] The numbers are based on general products in "Sektionsfakta NYB 14/15" (Wikells, 2014). These come from the 2012 price levels. The prices include labor costs.
The equation is (Price/m^2 + (working hours to assemble/install/place ∗ 180 SEK/h ∗ 3,53)) (The different presented materials have different working hours for how long it takes to install/assemble/place the material. Here these differ between 0,08 h - 0,3 h depending on material. Working cost per hour, set at 180 SEK/h. Additionally, a factor of 3,53 is multiplied which includes material waste, incurrences and potential errors etc.) (Wikells, 2014).

The prices are not completely reliable since they are dependent on the thickness of the material as well. Here, the thickness is based upon how much is needed to function in the designed modular system. Prices for OSSB could not be found, but one can assume that the price is quite high since these are currently only manufactured in China. ModCell® are still working on the final cost for the Compressed Straw Boards, so this price is not yet completely reliable either (White, 2015). Though, there is a company, iCell, which soon will launch a board made from cellulose (Larsson, 2015). These will probably cost less than the wood fiber boards, Diffutherm, and they are also going to be produced in Sweden.

The chosen materials for the straw bale modules, and their benefits, are listed below. They are alternatives to conventional options, and the choices are based on the aim for the modules to be as sustainable and natural as possible.

Cellulose insulation has been chosen as additional insulation, were needed, instead of mineral wool. This is mostly due to the fact that the cost and lambda value is more or less the same with the key difference that cellulose insulation both has far lower embodied energy and is renewable.

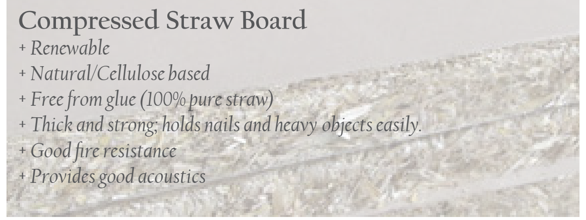


Another environmentally friendly board that also is very insulative, is a wood fiber board called Diffutherm. Diffutherm has a thermal conductivity (λ), of 0,045 W/mK, which is virtually the same as expanded polystyrene. It is unfortunately more expensive than both expanded polystyrene and mineral wool, but is instead both renewable, biodegradable, non-toxic and moisture controlling.

To show how versatile straw is, two other straw products have been chosen; OSSB and Compressed Straw Board. Since they are made almost exclusively from straw, they share the same benefits; abundant source as a by-product from the cereal harvest every year, they serve as carbon sinks etc. Nevertheless, they do have higher embodied energy than straw bales since these products are processed under heat and pressure.

These material alternatives, as seen in the table to the left, are however more expensive than the conventional options. For example, the OSSB is probably more expensive than traditional OSB due to the additional transportation cost from the production in China. Likewise, the Compressed Straw Boards are about twice as expensive than gypsum. In spite of this, the Compress Straw Board offers other values compared to gypsum. The compressed straw provides better acoustics for instance, and is cheaper than acoustic plaster boards, making them very competitive on that market.

Straw boards can also carry a lot of weight and hold heavy hanging objects. Installing a kitchen for example is therefore not a problem on straw boards, contrary to gypsum (White, 2015). This attribute is one of the reasons that Compressed Straw Boards are used as partitioning walls in the UK. Furthermore, both of the straw products are far more environmentally friendly options. Important to consider is also that the raw material, straw, is a by-product that can be sourced very locally, increasing the probability of national production when the demand grows.



IMPLEMENTATION

Picture 43.

This preschool proposal is mainly designed based upon the existing information and the previous work carried out by the municipality of Ale and Liljewall Architects for example. The choice was made not to stray away from the already made decisions in order to design a realistic proposal that suits the wishes of the municipality.

The site is located along Norra Kilandavägen, and is situated in a scenic location in the northern side of Nödinge in the municipality of Ale. It is a large site which suits a school or preschool well, since the children can have access to outdoor space. On the eastern part of the site there is a mixed forest in a slope. A stream is running through the site, which will be preserved and used for storm water management. There are no buildings on the site today, but a residential area is situated in the south. The site is also located quite near the city center, Göta älv and the train station. It takes about 15 minutes to travel into Gothenburg by train.

Ale Kommun suggest that the buildings should be situated in the eastern part of the site where the ground conditions are the best. Accessing the site should be done in the south, where a new roundabout is planned. The western part of the site consists of a school yard with a smaller sports field. Also worth mentioning is that the power lines running across the site today, will be buried underground (Ale Kommun, 2012).

Additionally, the municipality has stated that lowering energy consumption is important and that therefore the building should aim at reaching Passive House Standard (Ale Kommun, 2012). Achieving Passive House Standard is an important aspect to show the true potential of the straw bale modules presented in the previous chapter, as well as proving the potential of straw as a material.

To further show the potential of straw bale building and particularly the straw bale modules, it can be beneficial to think in a larger scale. A multi-story building is essential to show that it is possible to build both bigger and higher than the typical single-family home. A six department preschool will suit the aims for this implementation, due to the size of the building. Six departments will also mean a larger kitchen.

Creating an interesting shape of the building that challenges the modules has been regarded as important to assess the flexibility of them.

Designed based upon the existing information

Situated in the eastern part of the site

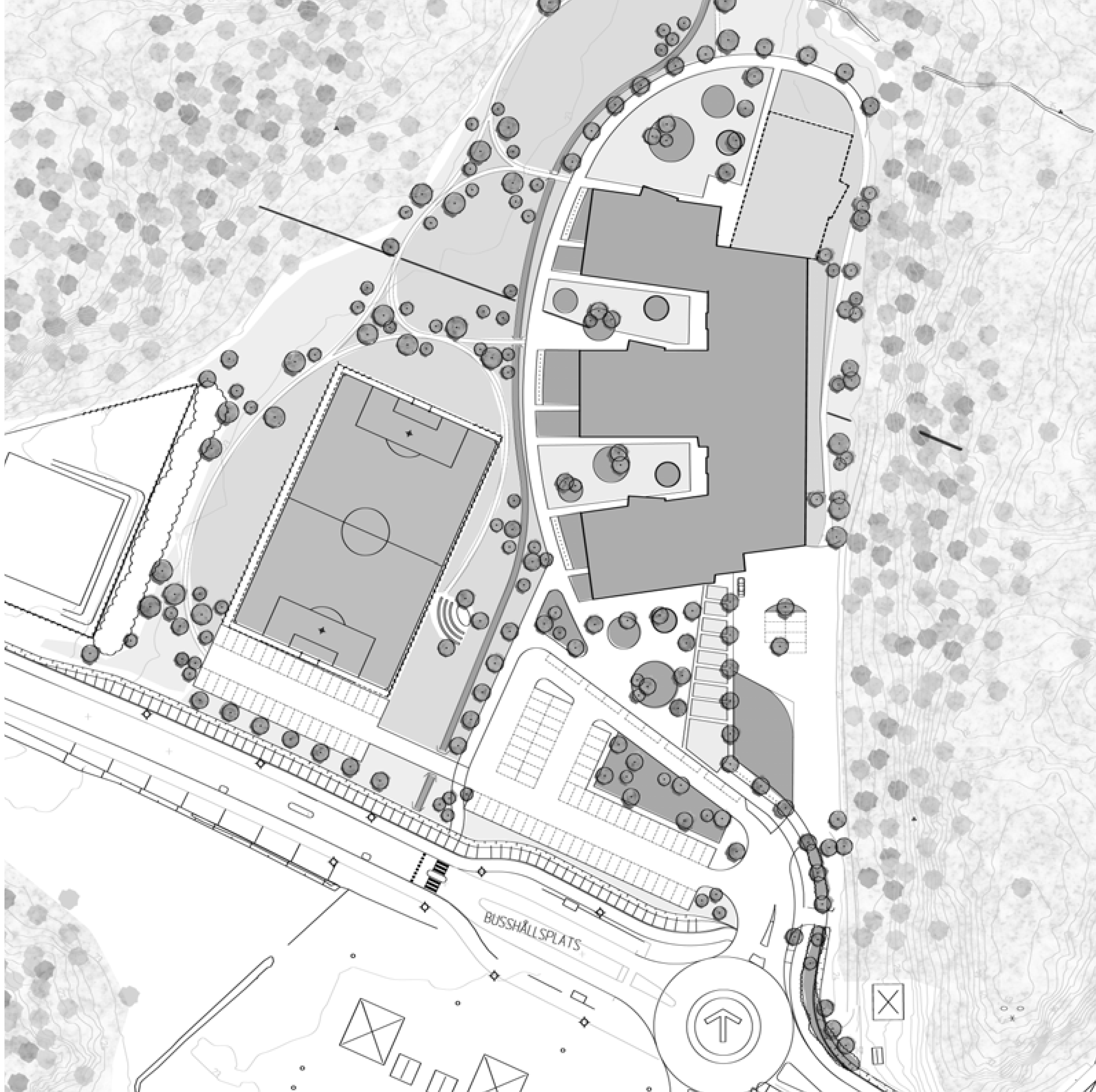
Passive House Standard

Multi-story building

A six department preschool

Challenging shape for the modules

Picture 44. The master plan of Norra Kilandavägen, by Liljewall Architects for the municipality of Ale, shows the intended school building that was not realized. The figure is not in scale.



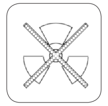
CONCEPT

The main idea is to create an open common ground floor with a central core, hosting the vertical communication. The core is therefore the link between the entrance floor and the calmer departments, one storey up. This vertical division forms a clear sectioning between the lively open areas and the safer home environment, where the children can feel a sense of belonging.

Incorporating straw in building designs meant for children is also a way of producing responsible and toxic-free environments for them to grow up in. Moreover, "*truth windows*" which expose the internal straw in the exterior walls can be educational and could hopefully inspirie future sustainable choices.

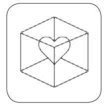
The next page shows an illustration of the figuration of functions divided by floor.

Picture 45. Picture showing the site, Norra Kilandavägen, Nödinge, in March 2015.



Toxic-free preschool

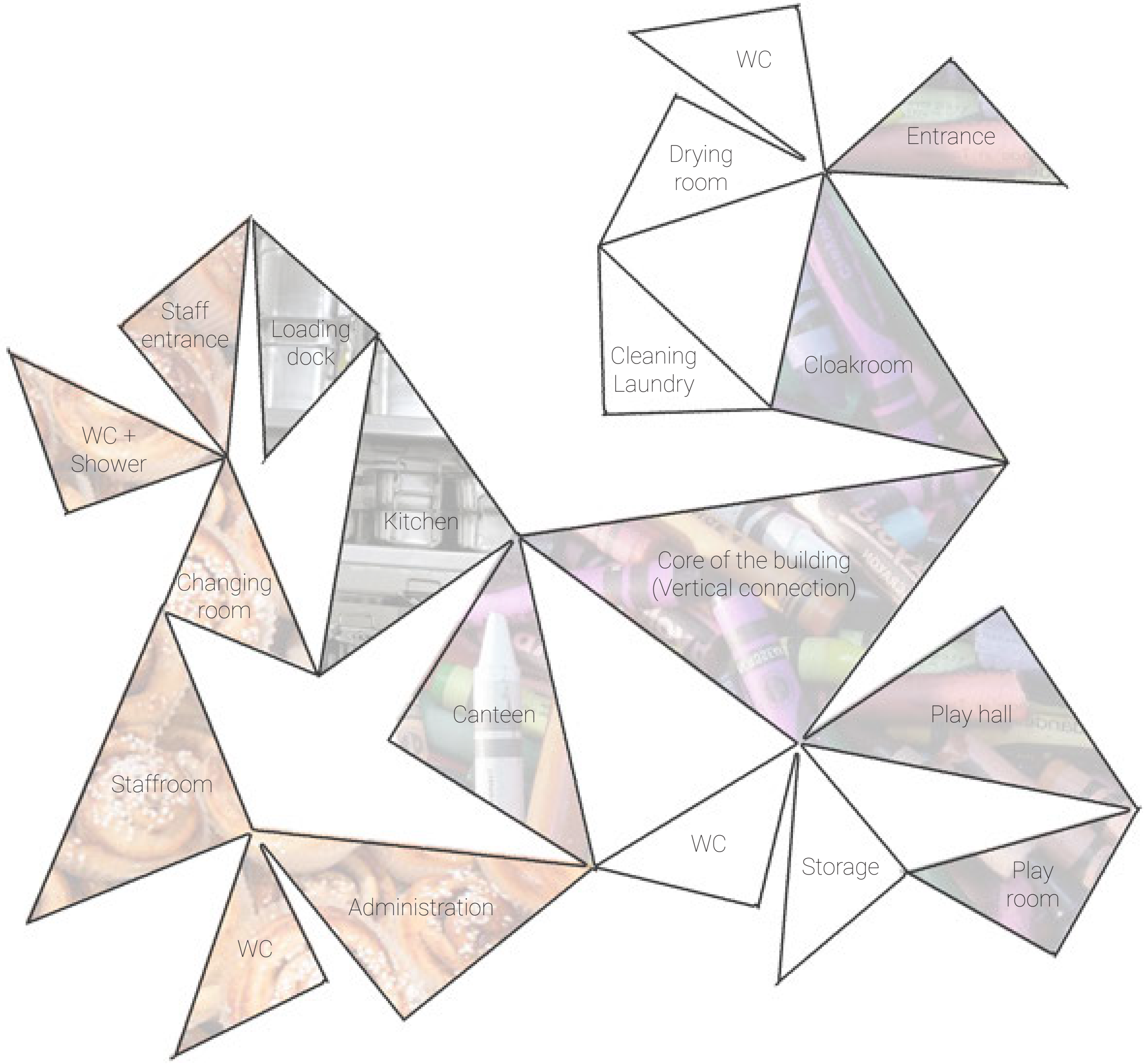
Educational preschool in terms of sustainability



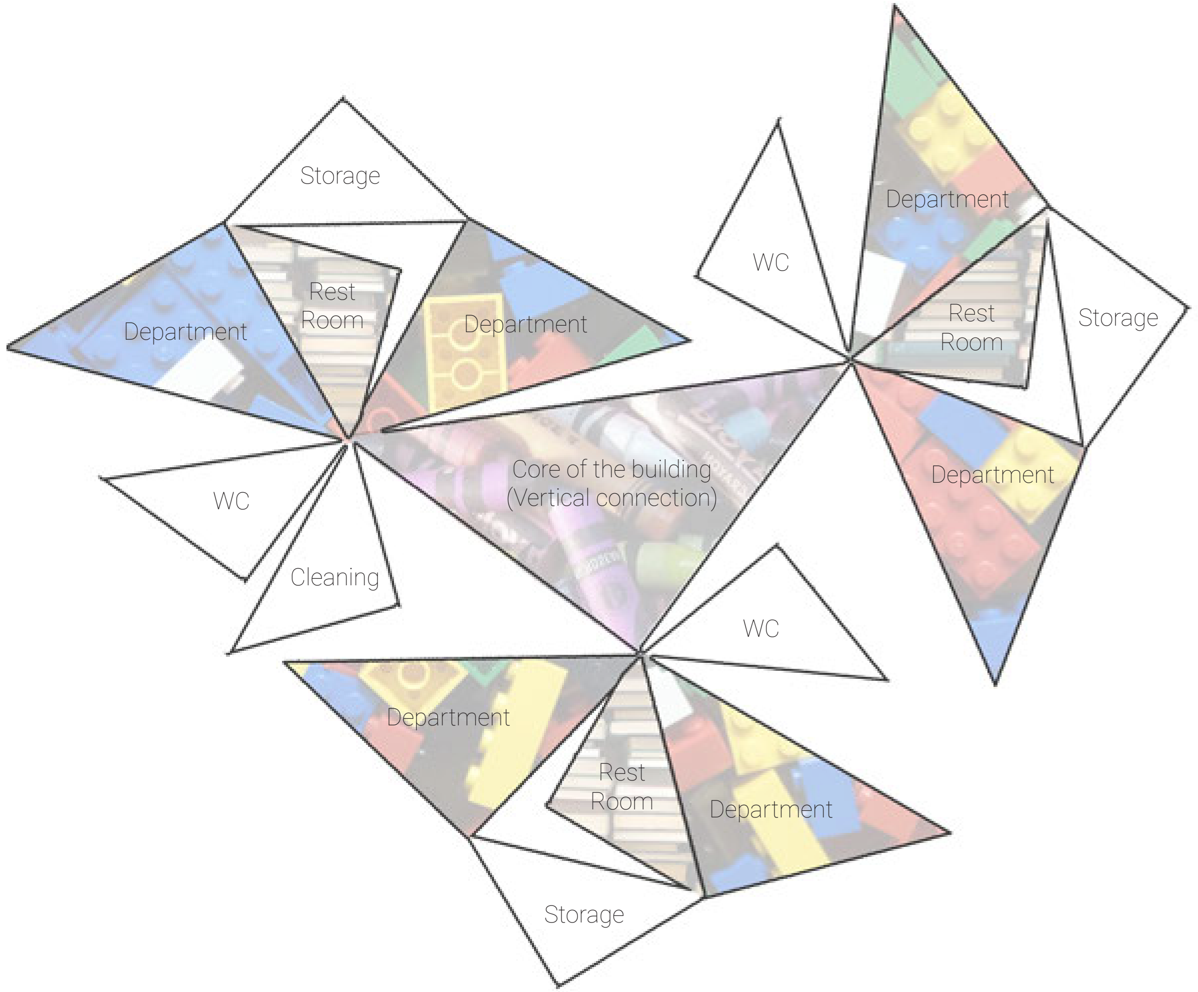
A public ground floor with a central common core

A calm second floor

FIGURATION OF FUNCTIONS

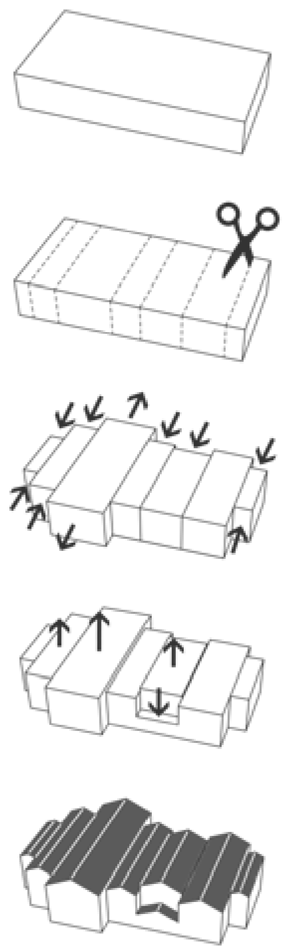


Function arrangement early in the process, for the first floor: The public floor with a central common core.



Function arrangement early in the process, for the second floor: The calm home environment.

PROPOSAL



The preschool has been separated from the larger main school building on the municipal plans. This is both to have more freedom in terms of shape but also to separate the older children from the smallest one, providing a sense of security.

As stated before, an interesting shape has been of importance to test the modules. This has been realized by pushing and pulling parts of the building. As always, the design should be adapted to the specific needs, conditions and use. By dividing the roof in several parts on different heights the design becomes more playful aimed at children.

The central core is the heat of the building. It serves as a common space where children and teachers can meet across departments. The canteen on the entrance floor is another space where this interaction takes place. The canteen is meant as a flexible space which can host other activities during the day when needed. The canteen also allows the departments to have their meals together which makes is possible for the teachers to assist each other.

The central core is directly connected to a larger common room on the second floor. This room has high ceiling height and skylight which makes is an ideal creative room for aesthetic activities. The remaining areas on the second floor are divided between the departments.

SECOND FLOOR

1. Entrance
2. Second entrance
3. Drying rooms
4. Cloak room
5. Common room
6. Office
7. Laundry
8. Expedition
9. Staff room
10. Archive
11. Changing room
12. Ventilation
13. Janitor storage
14. RTU
15. Tele/El
16. Changing room
17. Loading dock
18. Waste separation
19. Kitchen office
20. Kitchen
21. Dishwashing
22. Serving
23. Canteen
24. Play room
25. Department
26. Wash room
27. Calm room
28. Aesthetic room

SECTION PERSPECTIVE A-A

FACADES

The preschool has a wooden facade with different appearances according to their orientation. The east-western facades have a darker natural grey wooden panel, while the north-southern facades are painted white. These lighter facades also have window frames in playful colors. The darker panels continue up and become roof covering which gives the building the expression of an enclosed unit. The northern facade has a peep-window into the ventilation room for educational purposes.

Northern facade

Eastern facade

Scale 1:250

The solar shading shutters in the south are painted in the same colors as the window frames.

The shutters help reduce the risk of overheating in the warmer months of the year and also give the building a more playful expression. The windows have different sizes and are placed on different sill heights. Each department has windows on sill heights at floor level, at 450 mm (suited for sitting) and at 900 mm. The larger windows starting from the floor gives the smaller children a better view and connection to the outer environment.

A green house is located in the south connected to the kitchen and canteen, where the children can grow and learn about vegetables.

Western facade

Southern facade

Scale 1:250

MODULE COMPOSITION AND PASSIVE HOUSE CALCULATION

The illustration to the right shows the division and configuration of the straw bale modules in the preschool design.

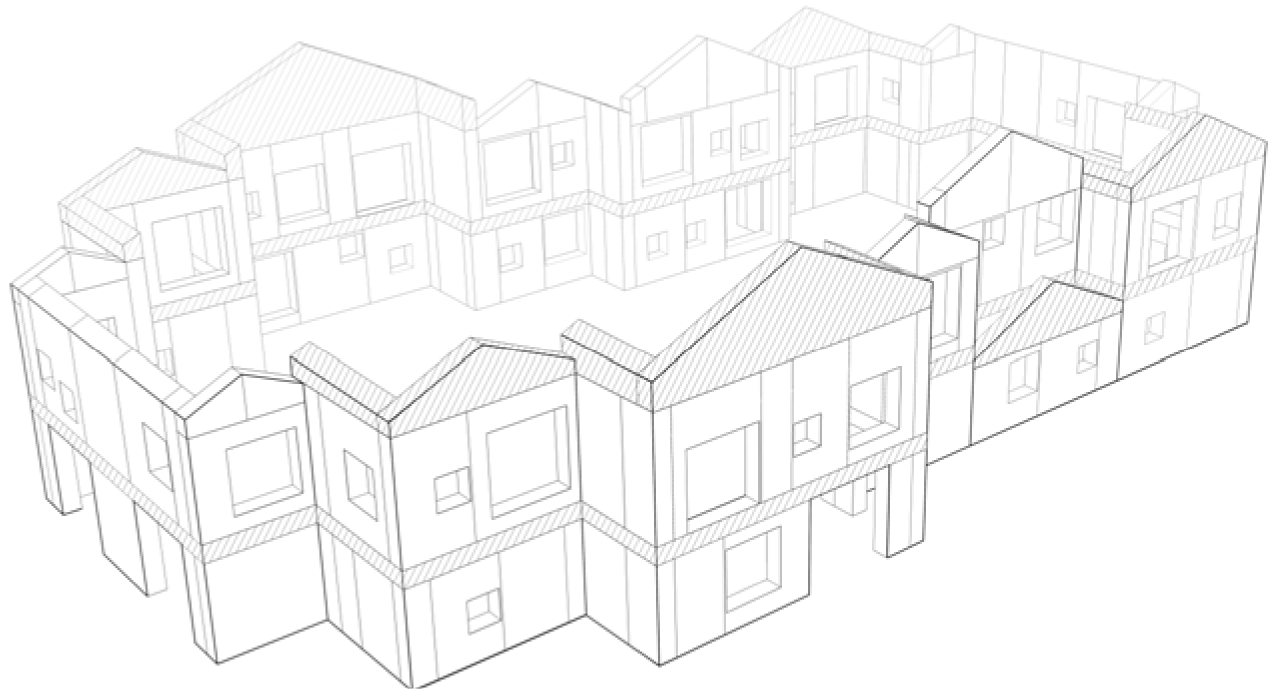
The shape of the preschool creates many corners which challenges the module assembly. An unusual shape is possible, but requires a greater amount of specialized and unique prefabricated elements. A more repetitive shape is of course preferable in many aspect; the simpler the shape, the simpler the assembly, the cheaper building in the end.

It is important to have cutouts for door and windows etc. in mind when designing projects with this modular system. Cutouts are most often not a problem in terms of size. Rather, the difficulty is the placement of them. If the larger standard size module is used to the furthest extent possible, it may become necessary to place windows for example, in the middle of an intersection, between two modules. This will then imply that one or two modules have to be produced in a custom size. However, any module that has a cutout incorporated in it is a customized module even if the standard length is used.

There are only a few places, in the designed preschool, where full ceiling heights are found. The remaining modules of the second floor, that do not have full ceiling height, have another structure and roof trusses on top of them, somewhat similar to the roof detail on p. 110. This is mainly because it is unnecessary and time consuming to produce modules with inclinations, since many straw bales need to be cut or rebaled in unusual shapes. Since the facade is applied on site, the overlaying structure of the modules is preferably also constructed on site, with prefabricated wood trusses. Modules with inclinations are produced for the part where full ceiling heights are desired. An evaluation of how easy or difficult these are to produce needs to be carried out in order to fully understand the potential of this modular system.

Even if there are some aspects that need further investigation, there are still many benefits which suggest that a prefabricated modular system with straw is a good solution. Incorporating sustainable materials in the main building methods and techniques employed today is one way of gradually moving towards a sustainable way of building. A prefabricated modular system with straw can also help straw bale building technique in Sweden to evolve beyond the owner-building movement that already exists.

Modular system also has the possibility of being replaced and/or reused, through having larger parts that can be disassembled. The "*Sensible Straw*" bale modules have screws, rather than nails, in intersections to facilitate this. Since there is additional layers applied on site, both on the exterior and interior side of the modules, these can be taken down and reused or recycled depending on the material. When a module finally has served its useful purpose the internal straw can go back to the soil through biodegradation.



On-site constructed building elements other than "Sensible straw" bale modules.

According to calculations, it is likely that the designed preschool building will reach Passive house standard, based on calculations from Energihuskalkyl.se. Below some metrics are presented from this calculation. Input data and the final report can be seen in the *Appendix II*.

The modules together with the other building components of the building have an average U-value of 0,17 W/m²K.

Heat loss: 12,1 W/m^2 A_{temp}

Building envelope Uaverage: 0,17 W/m^2 K

Electricity use: 15,3 kWh/m^2 A_{temp}

Hot water energy: 2,2 kWh/m^2 A_{temp}

Energy performance value: 33,1 kWh/m^2 A_{temp}

Balanced energy: 56 kWh/m^2 A_{temp}

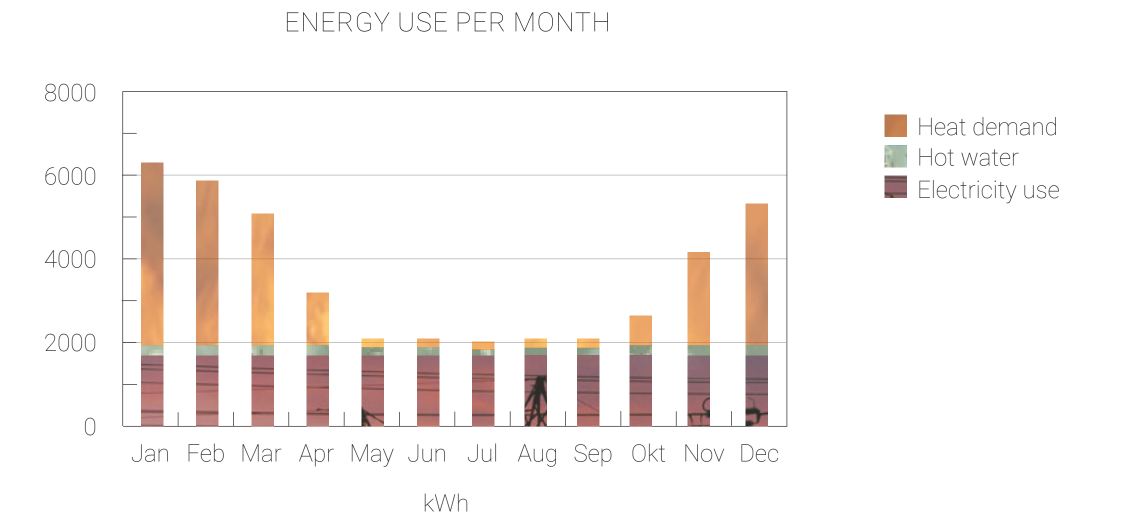


Table 11. In this table the heat includes losses from the hot water and its production system. The table is produced in the program Energihuskalkyl.se.

CONCLUSIONS AND DISCUSSION

Picture 40.

This master's thesis has very much been a learning process and a chance to go deeper into some parts while leaving others out, depending on personal interest or necessity for the credibility of the project. The investigation and learning process has been regarded to be more important than creating the most exiting architectural implementation proposal.

The main purpose was to investigate how straw as a building material can be adapted and enter the industrial construction market in Sweden, resulting in a prefabricated straw wall system. The process towards this result would not have been possible without study visits or interviews with informed and skilled individuals.

Hopefully "*Sensible Straw*" can inspire people to think more sustainably. A desirable outcome would also be that someone picks up where we left off, trying to realize a project of prefabricated straw walls in Sweden, that can trigger the demand and production of these more environmentally friendly building elements.

The master's thesis is based upon a series of research questions. The question it tries to answer are;

What are the properties, benefits and drawbacks of straw, both as a material and a building technique?

How can straw become a part of the industrial way of building? How can the building industry accept new and more sustainable alternatives when it comes to building materials, and what is needed in order for them to do so?

What has already been done in the field of industrializing straw bale building, and how do these prefabricated solutions work?

Is prefabrication a good solution for straw?

Which materials are preferable to use in combination with straw, and how much of the construction should be prefabricated?

CONCLUSIONS

THE PROPERTIES, BENEFITS AND DRAWBACKS OF STRAW

A thorough exploration of this question is carried out in the chapter "*Straw as a building material*", and as the research has shown, there are a number of benefits with straw; it is a renewable resource and a by-product from agricultural practices. Straw is biodegradable, has good thermal properties and low embodied energy compared to other building materials. Straw will also not emit poisonous fumes in case of fire. Additionally, straw is ready to be used as a building material already in the field where it grows, which is unique for any building material.

Some of the drawbacks with using straw as a building material is that it currently is an agricultural rather than a manufactured product, which can make it difficult to ensure that bales have high enough quality. The size and shape of these can therefore also be an issue. Additionally, straw needs to be kept dry, which is of importance for most building materials, especially for organic ones.

HOW STRAW CAN BECOME PART OF THE INDUSTRIAL WAY OF BUILDING

For any material to become accepted by the building industry and a part of the industrial way of building, they need to be better, or as good as, existing ones. Adapting new and more sustainable materials, such as straw, to the industrial way of building is therefore necessary. The research in the chapter "*The building industry*" has led to the specific focus on investigating prefabrication methods and ultimately to the design of a potential prefabricated modular system with straw. The design of the prefabricated straw system has been very much influenced by the personal contact with representatives from the big developers in Sweden, as well as the study visits. These experiences suggest that new materials need to be tested and approved before they can be implemented.

New materials need to meet local laws and regulations. A more detailed description of the national considerations can be found in the chapter "*National framework for industrializing straw*". In addition to compliance with the laws, the building industry is, as many other industries, very economically driven. As stated in the chapter "*Straw and the building industry*" straw alone offers limited opportunities for making a profit since it is not a manufactured product per se. If a new building technique or material implies more time and costs and does not yield a higher profit, it is most likely not going to be implemented, hence the need to adapt. Nevertheless, as seen in the chapter "*Straw in prefabrication*", straw can in fact yield a profit high enough for the foundation of companies in several countries, with straw as their niche. Companies that specialize in, and focus on, green and more sustainable techniques also have an opportunity to distinguish themselves from other alternatives on the market. This can in the best case scenario lead to an economical and ecological gain as well as creating a higher demand for more sustainable alternatives.

EXISTING PREFABRICATED STRAW SOLUTIONS

Prefabricated building elements with straw have already been realized in many parts of the world. There have been many individual custom-designed projects carried out, but the number of companies who both manufacturers and sell prefabricated straw building elements are fewer. This master's thesis has chosen to further look into four companies from different countries; ModCell, Ecococon, Endeavour and IsoPaille, all of which have a unique prefabricated wooden panel system with some similarities. For details of these systems see chapter "*Straw in prefabrication*".

IS PREFABRICATION A GOOD SOLUTION?

The studied examples from England, Lithuania, France and Canada have shown that prefabrication with straw can both work and increase the usage of straw in construction. A further elaboration on this question is carried out in the following discussion.

PREFERABLE MATERIAL COMBINATIONS AND DEGREE OF PREFABRICATION

Straw is a natural organic material and should therefore preferably be combined with other organic materials to the furthest extent possible. It is also desirable, in terms of sustainability, to have renewable and toxic-free materials to match the properties of straw.

The choice of designing prefabricated wall elements was mainly based on flexibility and the main prefabrication methods employed today. Wall elements are also less heavy than entire prefabricated building volumes. In order to further increase flexibility and improve the aesthetics, especially in intersections, the designed modules are not constructed with finishing materials. On-site completions will also make it possible to apply vapor barriers etc. over intersections in larger units, minimizing patching. Doors and windows are however included in the modules and installed in the factory, both to shorten the construction time to some extent, ensuring a weather protected construction faster, as well as ensuring proper installation of the items themselves, considering moisture and temperature swings which can be critical for some components such as expanding sealing tape, for example.

DISCUSSION

The research about straw, both as a material and a building technique, has strengthen the conviction that straw is a fairly untapped resource, with numerous benefits, that can become a versatile building material.

The suggested solution of integrating straw in prefabrication can, by some, be seen as contradictory. Mainly because of the view of mass production can be seen as unsustainable. Thus, some might think that the focus should instead be directed to develop the owner building movement. Nevertheless, this thesis has not been able to find any strong indications that prefabrication is not a good solution for straw. The question is whether it is the best solution. There are certainly other alternatives and solutions to investigate, making this an ongoing discussion.

It is sometimes not fair to put different building methods against each other. If the demand for prefabrication of straw wall elements, or even whole straw bale buildings, were to grow, it is not a certainty that the owner building movement would cease to exist. On the contrary, these two ways of building with straw could help strengthen each other. Some people are not suited, capable or willing to build themselves. The need for other alternatives is therefore important. There are no reasons not to use straw in the industrial way of building. No matter how you twist and turn it, it is still better to move away from many of the conventional building materials. There is always going to be a need for constructing larger buildings which are not suited to build with owner building methods. Industrialization of straw can therefore help bring about a larger spread of sustainability in the built environment.

Other countries have come further in the development of industrializing straw bale building, creating a larger market and building rate with straw incorporated. England and France have for example come quite far compared to Sweden. The question is why development has not progressed further here. There is not a simple or a single answer to this question. It is most likely due to several reasons, some of which could be that straw bale construction has not revived the same attention in media in Sweden compared to other countries, or the lack of evangelists who has dared and been able to further develop it. Another reason could be the static building competition that exists in Sweden, with a few large construction companies that more or less control the market. Large actors want tested and verified methods when finances are at stake, and are therefore not interested in experiments. The strive to be innovative does in many cases lead to that technological solutions are chosen automatically. Old solutions and methods are therefore often discarded and considered to be outdated. Several smaller enthusiastic actors are needed on the Swedish market. Smaller companies have a greater opportunity to specialize on a specific technique.

One needs to remember that new and controversial ideas are often discouraged and frowned upon. Therefore, the most reasonable solution would be to build upon common building methods employed today, through which then can enable a slow and steady change, both of methods and the building sector as a whole, towards a more sustainable way of building. Investors and advertisement is an aspect which should not be underestimated. This is most likely needed in order to popularize building with straw in Sweden. Nevertheless, changes and demands on a political level are most likely also needed to fully succeed.

When it comes to cost-competitiveness, the table on p. 114 in "*Choosing materials*" can be discussed. As this table shows, the designed modules will most likely not be cost competitive in the beginning since many chosen materials are more expensive than conventional ones. However, it is important to consider that new techniques and materials generally are more expensive before they get greater impact. Furthermore, the figures in the table are not as sufficient as one might have wanted them to be. Reliable sources for this type of research are hard to come across, especially for every material. A more thorough comparison between different building materials could perhaps be another research project. Still, one economic aspect worth repeating here is that the cost of the walls only amounts to a small part of the final building cost, typically only around 10-15 %. Paying a bit more for them to ensure a more environmentally friendly building is perhaps a price worth paying.

Even though there are still farmers who produce traditional rectangular straw bales, more and more farmers are using baling machines that create larger, round bales instead. The future growth and usage of the suggested straw bale modules can therefore perhaps be seen as unlikely since there supposedly could be a lack of rectangular bales in the future. However, a baling machine that makes rectangular bales could be incorporated within the prefabrication factory. There is a chance that some of the fibers could end up in an unfavorable direction when rebaling, though this should not affect the performance of the finished wall noticeably. It is also likely that it will be more economical for farmers to invest and go back to producing rectangular bales, if the use and production of prefabricated straw bale modules were to take hold. If that were to happen, the agricultural industry, as well as the forestry industry, would become one of the main suppliers to the building sector. This would imply a future potential for agricultural practices. Straw bales could be sold at a higher price to the building industry, creating a new financial market for the agricultural industry.

The flexibility of the designed "*Sensible Straw*" wall elements can perhaps be questioned. They are in some aspects flexible, mostly in terms of execution and appearance since finishing materials are optional and applied on site. Plaster can for example even be applied on the modules. The flexibility is somewhat limited to bale sizes though. The bales

can of course be rebaled and shaped as desired, but this means more time and effort for the builders. Cutouts for doors and windows are therefore also preferable to make in consideration to bale and module sizes, though they can be made in most any size and shape.

The walls also become quite thick in order to achieve a U-value that meets the passive house requirements. This can be regarded as both an asset and a hindrance. The deep window sills can become incorporated in the design and serve as benches etc., but the thickness also means that protruding parts in the building, such as bay windows for examples, can be difficult to make. However, the modules can be made thinner if that is an important desire of the client. The 60 mm external wood fiber board, Diffutherm, could be excluded, and the internal 40 mm straw board could be replaced with a conventional gypsum board. There is also the possibility of plastering both sides of the modules. Making the modules thinner will of course affect the U-value, making the construction worse at resisting heat transfer. The proposed materials in the "*Sensible Straw*" bale modules will achieve a better U-value while also being more sustainable than many other material alternatives.

Prefabricated straw wall elements will end up being thicker than conventional infill wall constructions with conventional insulation. Straw bale elements will most likely also weigh more which can perhaps be a disadvantage on the construction site. Even so, straw walls are comparable with passive house wall products, which are often also thick. The major difference is that prefabricated straw bale elements will provide thick, insulative walls without exhausting non-renewable resources.

Comparing the proposed "*Sensible Straw*" bale modules with existing straw wall solutions is harder to do. There are a number of different solutions on the market, and these are in certain aspects similar to each other. Even the four example studied in this master's thesis resembles each other in some aspects, making it difficult to state if one is better than the other. Yet, weather protecting the straw in an enclosed module can be a sensible choice in the Swedish climate. Leaving the choice of material finishes to the client is also an important aspect when the desire is to create a wide spread of industrialized building with straw.

Implementing the designed modules into a full architectural design has been a necessary part to both test and assess the modules. Though, the design and layout of the proposed preschool has not been the main priority in this master's thesis. The design is in many ways still in its infancy and can be debated. It is for example not preferable to design a preschool in two storeys, but this choice was made based on the need to evaluate the capacity of the modules, but also due to the site conditions and the municipal plans.

The preschool design tries to strike a balance between showing the possibility of an interesting shape while at the same time being rational and modular. The proposal has in many ways managed to achieve this. However, worth mentioning is that modular building is perhaps mostly suited to more rational building types such as offices or apartment buildings with repetitive and mirrored facades. The choice was made to design a preschool in order to show that straw bale building does not only apply to single-family houses, but also larger and public buildings. Increasing the area of use for straw bale building in Sweden will hopefully create more repute for straw in our country. Municipalities in Sweden are also more frequently requesting sustainable, toxic-free eco-preschools. This makes a preschool design more likely to be realized with straw bale modules, which perhaps can be seen as a bit controversial. Implementing them in for example a large apartment complex would therefore be more of a challenge. Nonetheless, industrialized building with straw is not limited solely to public buildings. As stated in the beginning of this master's thesis, straw is an abundant resource that is produced every year with the production of cereals all over the world, so much that it would be enough to build millions of homes. Incorporating straw in home construction could therefore be an answer to solve the housing demand for the growing population worldwide.

If straw were to enter the industrial construction market, it could accommodate the future need of constructions, while at the same time reduce emissions, store carbon, reduce waste and save both energy and non-renewable resources.

As mankind is beginning to take more responsibility for the environment, the awareness and need to establish a more sustainable building practice in general, will in all likelihood grow. With that said, straw bales alone are not enough to make an energy efficient or environmentally friendly building. There are no perfect materials. Many of the drawbacks have yet to be defined. There are still field test that needs to be carried out in different climates, and the designed modules in this master's thesis will also need to be tested extensively and verified if they are to be realized and be competitive on the commercial building market.

As this thesis has shown, there clearly is a potential for this new old building material, and not just in the form of bales. All over the world people are experimenting and inventing new techniques and materials. These alternatives also make more ecological sense than conventional ones. Perhaps in the future when one asks, *which is the most suitable material for this building?* The answer will be:

"Sensible Straw of course!"

FUTURE RESEARCH

A prefabricated straw wall element can, as this master's thesis has shown, be constructed and assembled in many different ways. They may also change in the course of time and look different in the future.

A main idea with modular building components is that they are supposed to be flexible, allowing an easy assembly both when the building is constructed but also when the building is going to be demolished. Intersections and fixings are done with screws rather than nails in the *"Sensible Straw"* bale modules to facilitate this better. In theory this would also allow replacements and reuse of the modules, facilitating future change of the building, for example an extension. However, future research is needed in order to test the true flexibility of the modules and the probability of dismantling and reuse. Studies on how to improve this aspect of the modules would also be desirable in conjunction with this study.

Despite the fact that it could be economically beneficial for farmers to go back to producing rectangular bales, future studies on the economic aspects for rebaling straw in the prefabrication factory could still be of interest. It could also be of interest to explore other alternatives and possibilities of using loose straw instead of bales. This would eliminate the dependency of which type of bales are produced in the field. Inspiration for this can be taken from the modular system of Ecococon, who stuffs their panels with loose straw from round bales.

Another approach is to draw inspiration from loose cellulose insulation. The cellulose insulation is put in a machine, which blows the insulation though a pipe, into the wall element. When the desired density is reached the machine turns off. Investigating the possibilities of grinding straw and using the same technique could be a future research assignment. This method will perhaps create a slightly worse U-value, but on the other hand it would create a more efficient and productive working environment for the builders. The probability of this idea obviously needs further and thorough research. Risk of subsidence in the grinded straw needs to be assessed, as well as the overall performance and the execution in the factory. Will the properties change concerning fire, insulation, mold, insects etc.? How finely should the straw be grinded? And which is the preferable density? These are just some of the questions that need to be investigated.

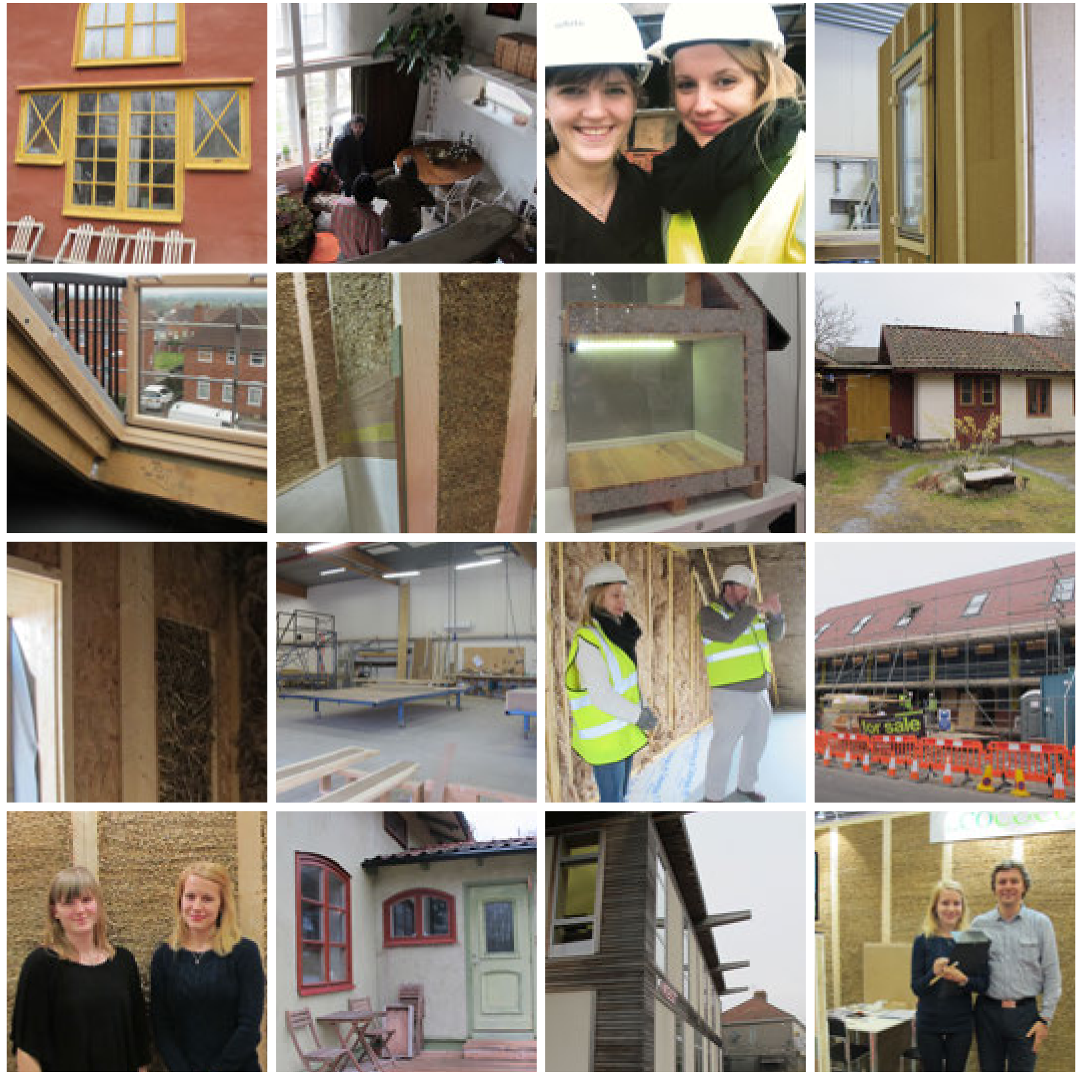
Picture 34.

APPENDIX I: REAL LIFE INVESTIGATIONS

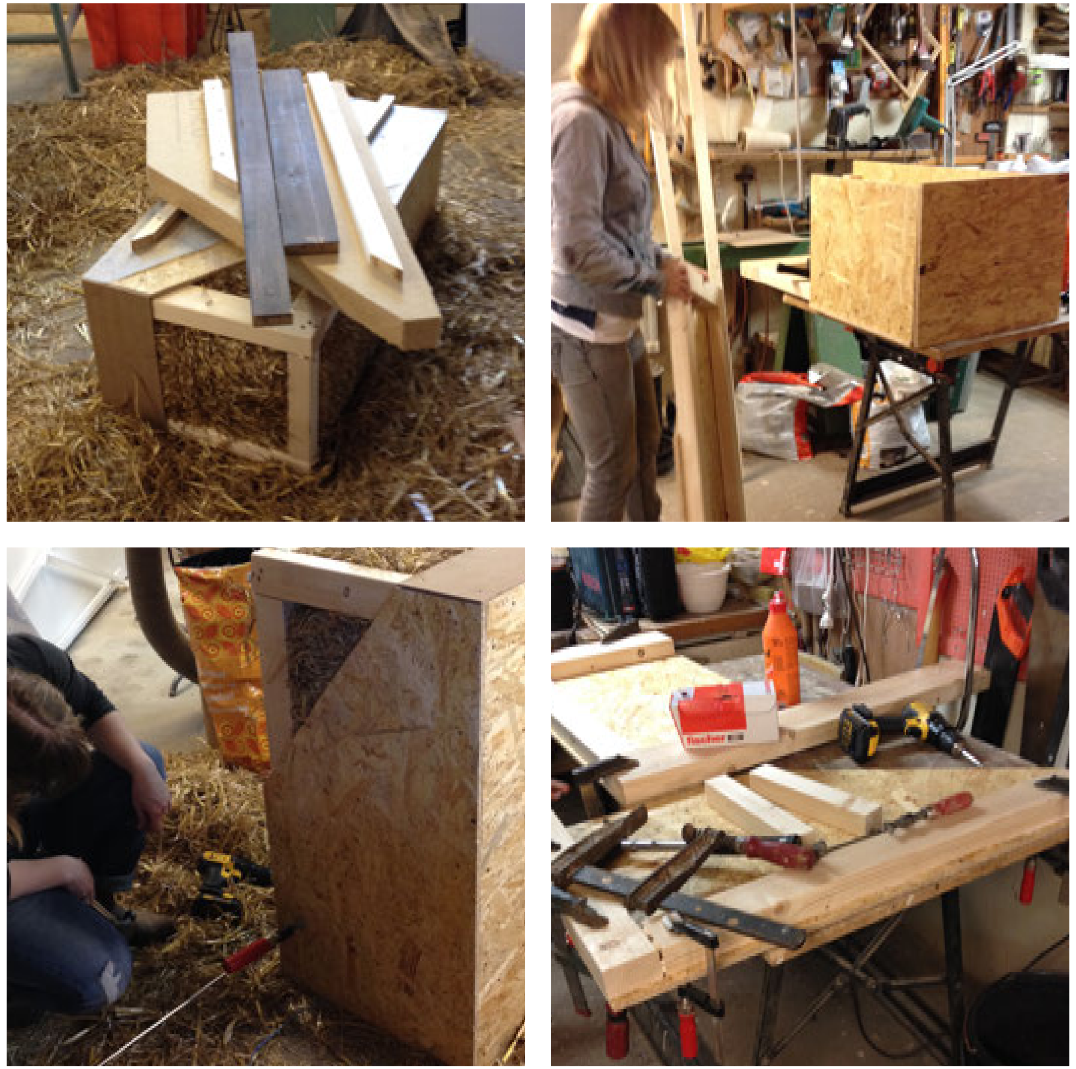
During this thesis a number of study visits have been made. Some pictures from these occasions can be seen on the following page. The pictures are from the day spent with ModCell® in Bristol, England, from Malmömässan where Ecococon exhibited, and the visit to the prefabrication factory in Falkenberg, Becohus. The pictures also include the study visit to Bottna in Bohuslän. The study visits to Vommedalens preschool in Kållered and the visit to Make Architects in London are not included.

An important part of the process was to test and investigate the proposed "*Sensible straw*" wall element further, by making a full scale prototype. The model became very stable in its construction, increasing the confidence in their durability. The hardest part of the construction of the model was placing the straw bale inside the frame, mainly because it was bigger than expected and not uniform in its shape. This will probably not be a problem when constructing larger sections, and when desired bale sizes and densities are ordered, or having the proper tools for rebaling them easily.

STUDY VISITS



BUILDING A PROTORYPE IN SCALE 1:1



Picture 38.

APPENDIX II: PASSIVE HOUSE CALCULATION

U-VALUE CALCULATION

MATERIAL
I VÄGG:

	%**	d (m)	λ *** (W/mk)
Diffutherm:		0,0600	0,045
OSSB:		0,0110	0,130
Halm*:	94,5	0,3306	0,052
Reglar:	2,2	0,0078	0,130
iCell:	2	0,0069	0,045
Masonitbalk:	0,5	0,0019	0,050
OSSB:	0,8	0,0028	0,130
OSSB:		0,0110	0,130
Straw Board:		0,04	0,119

TOT:		0,4720

* Halmen innehåller ett antal andra element. d, av dessa är därför beräknat i procent av halmens d. 100 % halm = d: 0,35 m.
** Källor på lamdavärden l, kan ses i "Choosing materials".
*** % beräknas genom att ta ett horisontellt snitt genom väggen, där totala areorna av respektive element, per meter vägglängd, har vägts samman.

R-VÄRDEN:

R:	d/ λ
Rsi****:	0,100
Diffutherm:	1,333
OSSB:	0,085
Halm:	6,359
Reglar:	0,060
iCell:	0,153
Masonitbalk:	0,037
OSSB:	0,022
OSSB:	0,085
Rse****:	0,130
Straw Board:	0,336

**** Rsi och Rse avser värden för luftspalter, interiört respektive exteriört.

U-VÄRDE:

U:	1 / R (tot)	
R (tot) :	8,70	m2K/W
U vägg: "Sensible Straw"	0,115	W/m2K

*PASSIVE HOUSE CALCULATION: INPUT DATA**

SPILLVÄRME:

Antal barn	Antal vuxna
15 avd	3 /avd
90 tot.	18 tot.

Personer:

Ant. i lokalen samtidigt:	63 st i snitt	14,4 st i snitt	Tot:	77,4 Antal pers
Värme gener. personer:	3150 W/antal pers	(pedag. + kökspers.) 620 W/antal pers	Tot:	3986 W/antal pers
		216 W/antal pers		

Spillvärme:	3,09 W/m2 LOA	Varmvatten:	0,18 m3/m2 LOA

Verksamhetsel:

	Scablonvärde elenergi	Verksamhets-tid / vecka	Övrig tid / vecka	m2 av Atemp		Elenergi /m2. av Atemp
Förskola:	15	60	108	1226		18394
Kök osv.:	25	45	123	65		1619
	(kWh/m2)	(h)	(h)	(m2)	Tot:	20013
					Tot/Atemp:	16
						(kWh)

Spillvärme drift:	**4,2** W/m2 LOA
Spillvärme övr. tid:	**0,4** W/m2 LOA

* Källor för indata och schablonvärden har hämtats från
- Blomsterberg, Å. et. al. (2012) "Kravspecifikation för nollenergihus, passivhus och minienergihus". FEBY 12
- Energihuskalkyl beräkningsprogram, värden i tidiga planeringsskeden.
- Konsultation med Eje Sandberg, ATON Teknikkonsult AB
- Handledning med John Helmfridsson arkitekt och miljösamordnare, Liljewall Arkitekter.

VENTILATION:

l/s, m2	Drifttid		Drifttid %	Antal pers.	Atemp	l/s, pers
0,35	60	h/vecka	0,36	77	1291	7
0,1	108	h/vecka	0,64	0	1291	7

	(Teoretiskt)					
	Kök			Antal port.		l/s port.
0	45	h/vecka	0,21	77	0	20

Snitt l/s	Snitt l/s, vecka
993,65	354,88
129,10	82,99
	Summa:
	437,87
	Inkl. kök:
1548,00	481,65

Pumpdrift:	
19,37	W
Fläkteffekt:	
722,48	W

AREOR:

Väggarea	LOA Plan 1	LOA Plan 2	Tak	
877,435	667	624	667	
(exkl. fönster och dörrar)			800	*

Atemp:	Aom:	Form Faktor	
1291	2211,435	1,71	
	2344,435	1,82	*

*Om full takhöjd utnyttjas

KÖLDBRYGGOR:

Grund	Mellanbjälkl.	Tak	Hörn	Håltagningar	
129,4	133,4	201,6	184,6	405,6	(m)

Tot köldbr.	
1054,6	(m)

FÖNSTER:

Antal fönster					
Fönstertyp	Norr	Söder	Öst	Väst	Tot.antal/typ:
A	11	8	2	2	23
B	2	4	1	3	10
C	3	5			8
D	7	4	1		12
E		1			1
F				2	2
G				2	2
Takfönster					3
Tot area/ väderstreck:	57,71	58,06	8,51	18,29	

Fönsterarea	Fönsterom.
0,81	3,6
1,8225	5
3,24	7,2
5,0625	9
7,84	11,2
2,8	7,6
2,8	7,6
2,25	6
m2	m

Tot. area/typ	Tot. Om./typ
18,63	82,8
18,225	50
25,92	57,6
60,75	108
7,84	11,2
5,6	15,2
5,6	15,2
6,75	18

Total fönsterarea:	Total fönsteromkr.:
142,565	358

GLASDÖRRAR:

Glasdörrtyp	Norr	Söder	Öst	Väst	Tot.antal/typ:
Antal glasdörrar					
Enkeldörr				1	1
Dubbeldörr			2		2

Dörrarea	Dörrom.
2,1	6,2
3,78	7,8

Tot. area/typ	Tot. Om./typ
2,1	6,2
7,56	15,6

Total dörrarea:	Total dörromkr.:
9,66	21,8

DÖRRAR:

Dörrtyp	Norr	Söder	Öst	Väst	Tot.antal/typ:
Antal dörrar					
Enkeldörr			3		3
Pardörr			1		1

Dörrarea	Dörrom.
2,1	6,2
3,15	7,2

Tot. area/typ	Tot. Om./typ
6,3	18,6
3,15	7,2

Total dörrarea:	Total dörromkr.:
9,45	25,8

RESULT: FEBY 12

Ort: ALE
Område: Ej definierat område **Kalkylnamn:** ALE - SENSIBLE STRAW
Kommentar: Examensarbete - Kalkylversion 2

Utskriven av: Emelie Sandmer
Senast ändrad: 2015-05-12

Egna indata
Utdata resultat
Låsta indata

Resultatsammanfattning

Värmeförlusttal (VFT)	12,1	W/m2 Atemp
Köpt energi:	33,1	kWh/m2 Atemp
-varav elenergi:	15,3	kWh/m2 Atemp
-varav fjärrkyla:	0	kWh/m2 Atemp
Köpt energi - BBR:	33,1	kWh/m2 Atemp

Tidskonstant:	8,9	dagar
Summa viktad energi:	56	kWh/m2 Atemp
Klimatskal Um:	0,17	W/m2K

viktningstal

El:	2,5	Fjärrvärme:	1	Biobränsle:	1
Naturgas:	1	Fjärrkyla:	0,4		

Värmeförlusteffekt (FEBY12)

Klimatdata dimensionerande

Klimatdata för ort	Göteborg	
Dimensionerande utetemperatur	-11,5	°C
Marktemperatur, dimensionerade	2,6	°C
Rumstemperatur	21	°C

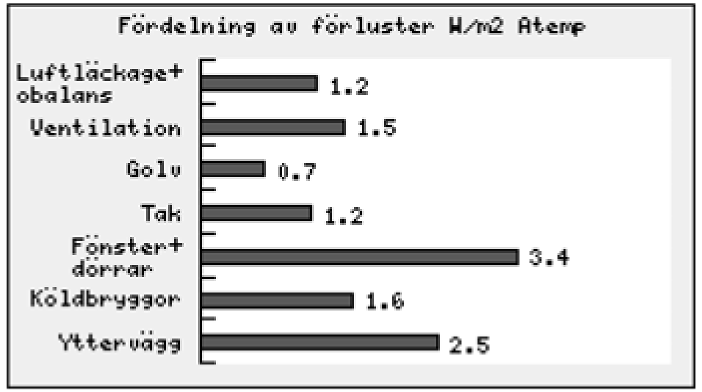
Spillvärme för lokalarean

Drifttid	60	h/vecka
Spillvärme personer	3,1	W/m2 LOA
Spillvärme drifttid	4,2	W/m2 LOA
Spillvärme övrig tid	0,4	W/m2 LOA

Byggnadskonstruktion

Byggnadstyp	Halvlätt	Atemp	1291	m2	Boarea BOA	0	m2
		Agarage	0	m2	Lokalarea LOA	1290	m2

Byggnadsdel	m2	W/(m2K)	K		Watt
Yttervägg	877	0,115	32,5	=	3278
Ytterdörr	9,4	1	32,5	=	306
Tak mot uteluft	667	0,07	32,5	=	1517
Terasstak	0	0	32,5	=	0
Golv mot platta på mark + krypgrund	667	0,09	18,4	=	890
Vägg mot mark	0	0	18,4	=	0
Köldbryggor mot mark	1	0	18,4	=	0
Köldbryggor mot uteluft	1	63,78	32,5	=	2073
Fönster	144,8	0,8	32,5	=	3765
Glasade altandörrar	9,7	0,9	32,5	=	284
Aom	2376	m2	Summa		12112



Köldbryggor	Längd L	Y	L*Y
	m	W/(mK)	W/K
Bottenbjälkslag	129,4	0,12	15,528
Fönster och dörrar	405,6	0,04	16,224
Mellanbjälkslag	133,4	0,05	6,67
Balkonginfästningar	0	0	0
Takfot	201,6	0,08	16,128
Ytter- och innerhörn	184,6	0,05	9,23
Summa mot luft			64
Köldbryggor mot mark	0	0	0
Punktköldbryggor mot mark	0	0	0
Summa mot mark			0
Köldbryggors andel av klimatskalets förluster			17 %

Fönster och glasade dörrar

	Syd	Väst	Norr	Öst	Summa	
Fönsterarea brutto (m2)	60	18,3	58	8,5	144,8	
Glasade dörrar (m2)	0	7,6	0	2,1	9,7	
				Fönsterandel (inkl. dörr)	12	%

Ventilationsdata Dimensionerade

Genomsnittligt frånluftsflöde (Vex)	485	(l/s)	Vindskyddskoefficient, e	0,06
Läckageflöde q50/Aom vid provtryckning	0,3	l/s, m2 Aom	Vindskyddskoefficient, f	15
Läckageflöde q50/Atemp vid provtryckning	0	l/s, m2 Atemp		

Värmeåtervinningsdata dimensionerande, placerad inom klimatskal

Tilluftsflöde	98	(% av Vex)
Värmeväxlarens återvinningsgrad, heff	80	%
Värmekonduktivitet uteluftkanal, Y	0,033	W/(mK)
Längd uteluftkanal	3	m
Värmekonduktivitet avluftkanal, heff	0,033	W/(mK)
Längd avluftkanal	15	m
Avfrostningstid vid DUT	1	(minuter per timme)
Jordvärmeväxlarens återvinningsgrad	60	% heff

Resultat effekt

Infiltration	40,9	l/s	Värmeväxlat luftflöde	475
Systemverkningsgrad	91	% heff	Oväxlat luftflöde	10
Summa förlustflöden Vf	91,3	l/s		
Effektbehov ventilation	**3561**	**Watt**		

Värmeförlusttal (VFT)

Värmeförlusttal (VFT)	12,1	Watt / m2

Schablonkalkyl för energianvändning

Följande energiresultat avser en typisk familj med typiskt beteende och varmvattenbehov, samt normala utetemperaturer och väderleksförhållanden. Hushållselanvändningen har antagits bli lägre än för genomsnittsvärden i Sverige, eftersom här finns krav på eleffektiva installationer. Att använda schablonvärden innebär att verkliga värden alltid kommer att avvika en del, men ger en bättre grund för jämförelser.

Resultat

Byggnadstyp	Lokaler			
Indata småhus/flerbostadshus			**Indata lokaler**	
Antal lägenheter	0			
Innetemperatur	21	°C		
Antal personer	0			
Effektiva varmvattenarmaturer	Nej		Nej	
Förd. mätning av, eller, eget varmvatten	Nej			
Varmvatten	0	m3 / år	0,04	m3/m2 LOA, år
Förluster VVC-ledning	0	W / lägenhet	0,2	W/m2 LOA
Stilleståndsförluster	0	W		
Evakuerande köksköpefläkt med VÅ / kolfilter	Nej			
Spiskåpa. Forcerat luftflöde per bostad	0	(l/s, lgh)		
Spillvärme från verksamhet och personer			2,9	W/m2 LOA (enligt effektkalkyl)

Indata driftel

Fläkteffekt normaldrift	730	W
Frånluftsfläktens placering i FTX	0	
Pumpdrift	20	W

Indata fastighetsel

	Area / antal	Effekt / enhet	Drifttid h / år	kWh/år	Spillvärmefaktor	Spillvärme kWh/år
Trapphusbelysning, grupp 1	4	20	45	3,6	70%	2,5
Trapphusbelysning, grupp 2	0	0	0	0	70%	0
Portal, utebelysning, antal	2	60	4000	480	0	0
Hisstyp bostad		0		0	70%	0
Hisstyp lokaler		0,5		645	70%	451,5
Hissbelysning, aktivitetsstyrd eller ej	1	48	1300	62,4	70%	43,7
Garagebelysning	0	0	0	0	0%	0
Garageventilation		0	0	0		0
Elvärmare utan spillvärme		0	0	0		0
Standby, DUC, etc.		0		0	100%	0
Fastighetsbelysning i LOA	250	15	2500	9375	70%	6562,5
Tvättstuga i byggnaden	Ja			0	20%	0
Oförutsett		2	kWh/m2	2582	20%	516,4
Summa				13148		7577

Verksamhetel

Komfortkyla / Fjärrkyla

Fjärrkyla för komfort i lokaler	0	kWh/m2 (LOA)
El till komfortkyla	0	kWh/m2 (LOA)

Utdata

Varmvattenenergi	2,2	kWh/m2 Atemp
Hushållsel exkl driftel	0	kWh/m2 Atemp
Driftel	15,3	kWh/m2 Atemp
Spillvärme medel/dygn	4	W/m2

Solenergi vinter och sommar

	Syd	Väst	Norr	Öst
Fönster brutto (m2)	60	18,3	58	8,5
Glasandel fönster, Fa	0,8	0,75	0,75	0,75
Altandörrar brutto (m2)	0	7,6	0	2,1
Glasandel altandörrar, Fa	0,7	0,7	0,7	0,7
Skuggfaktor, karm, mm	0,85	0,8	0,8	0,8
Horisontalvinkel (skuggningsfaktor)	0,2	0,2	0,67	0,67
Glasrutans g-värde	0,5	0,5	0,5	0,5
Sido- och överhängsavskärmning, sommarperiod	0,1	0,2	1	1
Rörliga solskydd vinter	0,85	0,85	0,85	0,85
Rörliga solskydd sommar	0,93	0,93	0,93	0,93
Produkt skuggning vinter	0,14	0,14	0,46	0,46

Reglersystemets verkningsgrad	93	%

Resultat värme netto	16	kWh/m2
Resultat värme + VV + driftel	33	kWh/m2
Solvärmefaktor (SVF)	1,7	%

Andel solvärme för varmvatten	0	%
Värmepump, V+VV	1	
Värmepump, endast V	1	
Värmepump, endast VV	1	

Fjärrvärmeansluting	Värme + Varmvatten
Bränsleanvändning	Nej
Pannverkningsgrad vid avsedd effekt	0,9

Viktad energi	56	kWh/m2
Obs, detta värde ska vara mindre än	63	kWh/m2

Denna information om kravgräns för viktad energi har bara relevans för byggnader med kombinerade energislag för värme- och varmvattensystem och där lokala energikrav ställts eller där energikrav enligt metodiken i FEBY12 tillämpas. Där energikrav enligt äldre kriterier ställs får resultatet räknas om enligt de viktningstal som då gällde.

För viktad energi har viktningsfaktorer använts.
Varje energislag har multiplicerats enligt följande:

El:	2,5
Fjärrvärme:	1
Biobränsle:	1
Naturgas:	1
Fjärrkyla:	0,4

Beräknat energiprestandavärde	33,1	kWh/m2 Atemp.

Obs detta värde, motsvarande begreppet Byggnadens specifika energianvändning i BBR och ska vara lägre än gällande byggreglers minimikrav. I detta begrep finns inte garagearean medtagen enligt Boverkets definition.

Av detta utgör elenergi	15,3	kWh/m2 Atemp.

Picture 43.

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(som ler och långhalm)

CHALMERS
UNIVERSITY OF TECHNOLOGY

The master's thesis work is the final part of the architectural education, 300 credits, at the Master's Programme Design for Sustainable Development, Chalmers University of Technology. The master's thesis comprises 30 credits, and has been carried out during the spring term of 2015, from January to the end of May.

This master's thesis aims at industrializing straw bale building in Sweden in hopes of making it a conventional and accepted building material, as well as a step towards a more sustainable future.

Sensible straw is a proposal of prefabricated straw wall elements adapted to Swedish conditions. These are also showcased in an architectural proposal for a preschool set in the municipality of Ale in the west of Sweden.