Wood, straw, clay and some rabbit skin…
The evaluation of renewable based low-tech-high-knowledge based housing solutions.

MSc Thesis

György Ängelkott Bocz

LTH, A-program

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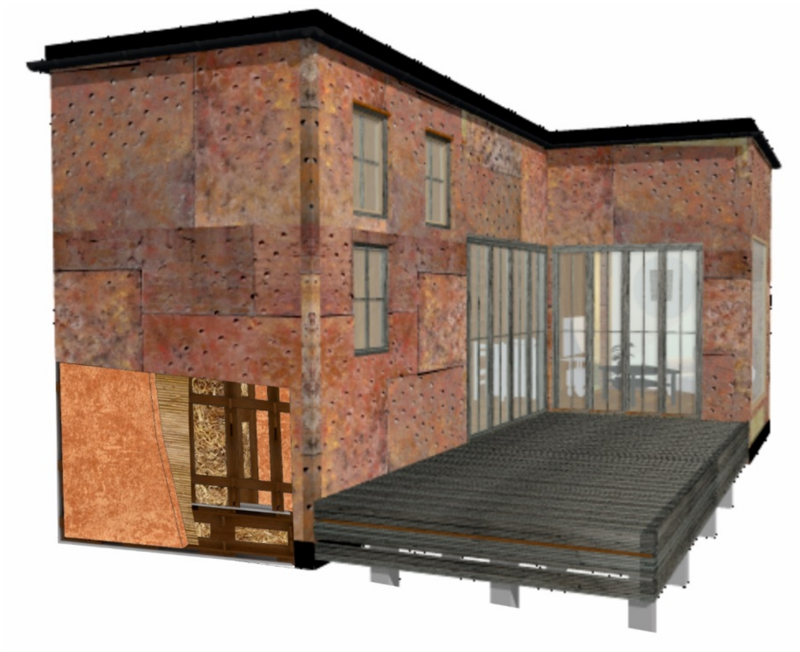
CONTENTS

Vernacular architecture doesn’t go through fashion cycles. It is nearly immutable, indeed, unimprovable, since it serves its purpose to perfection. (Rudofsky, 1987)

Our job as architects is to create small pieces of paradise…. (Joachim Eble-Architektur)

…so when all is lost there is something to start up from [author].

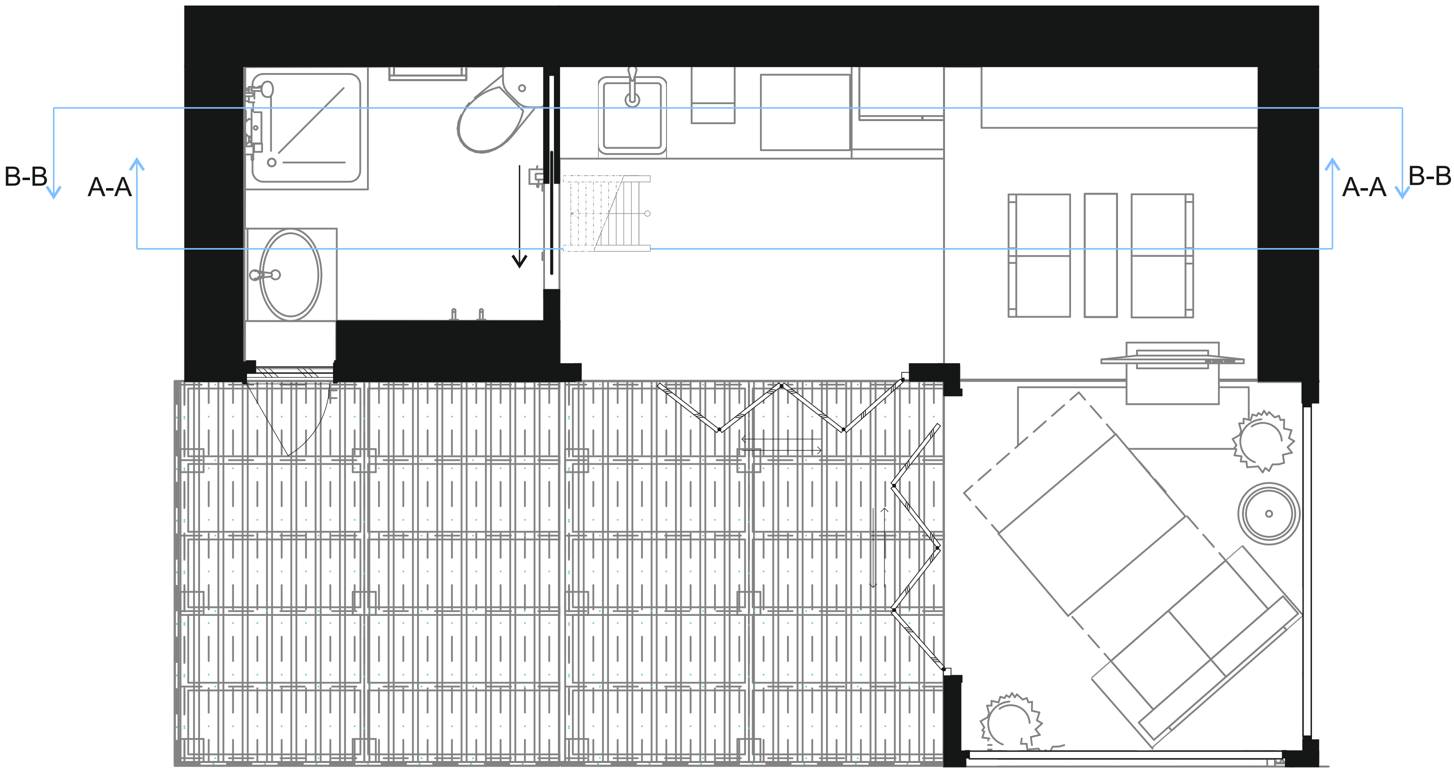
*E*K*O*TTEBO-L



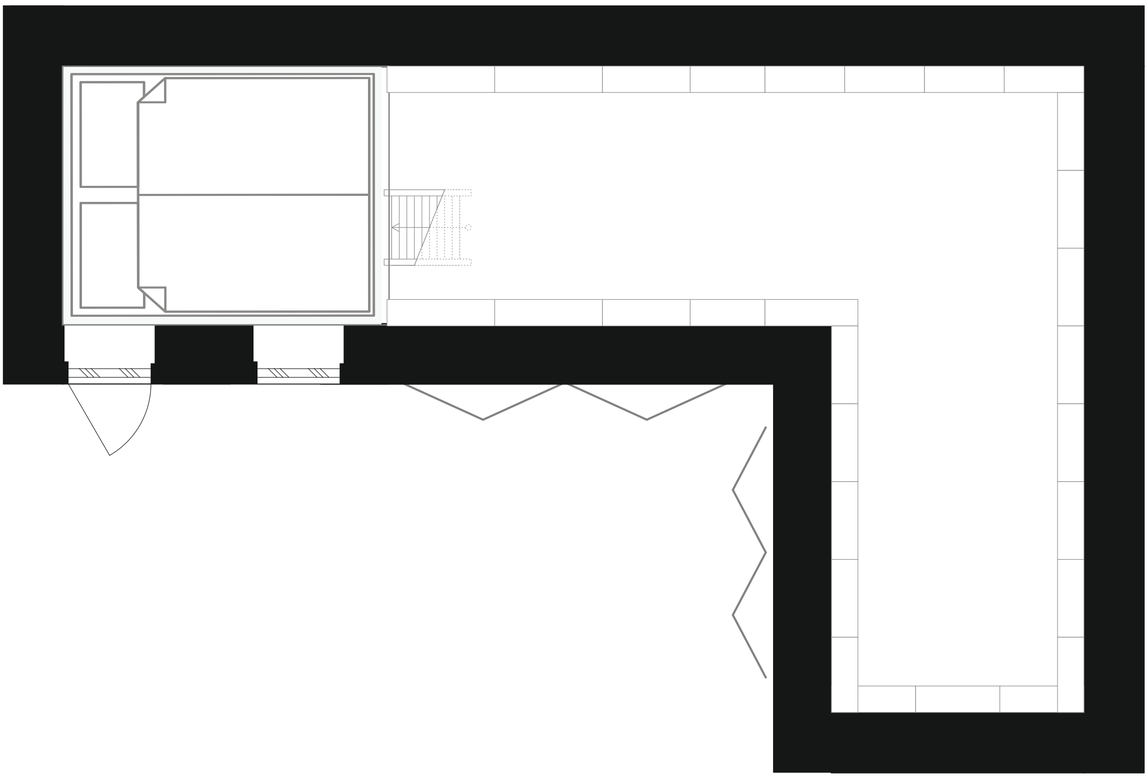
Exploded drawing of the L shaped Attefall construction

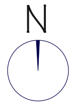
Floor plans
-ground floor-

EkotteBo - L



-1st floor-





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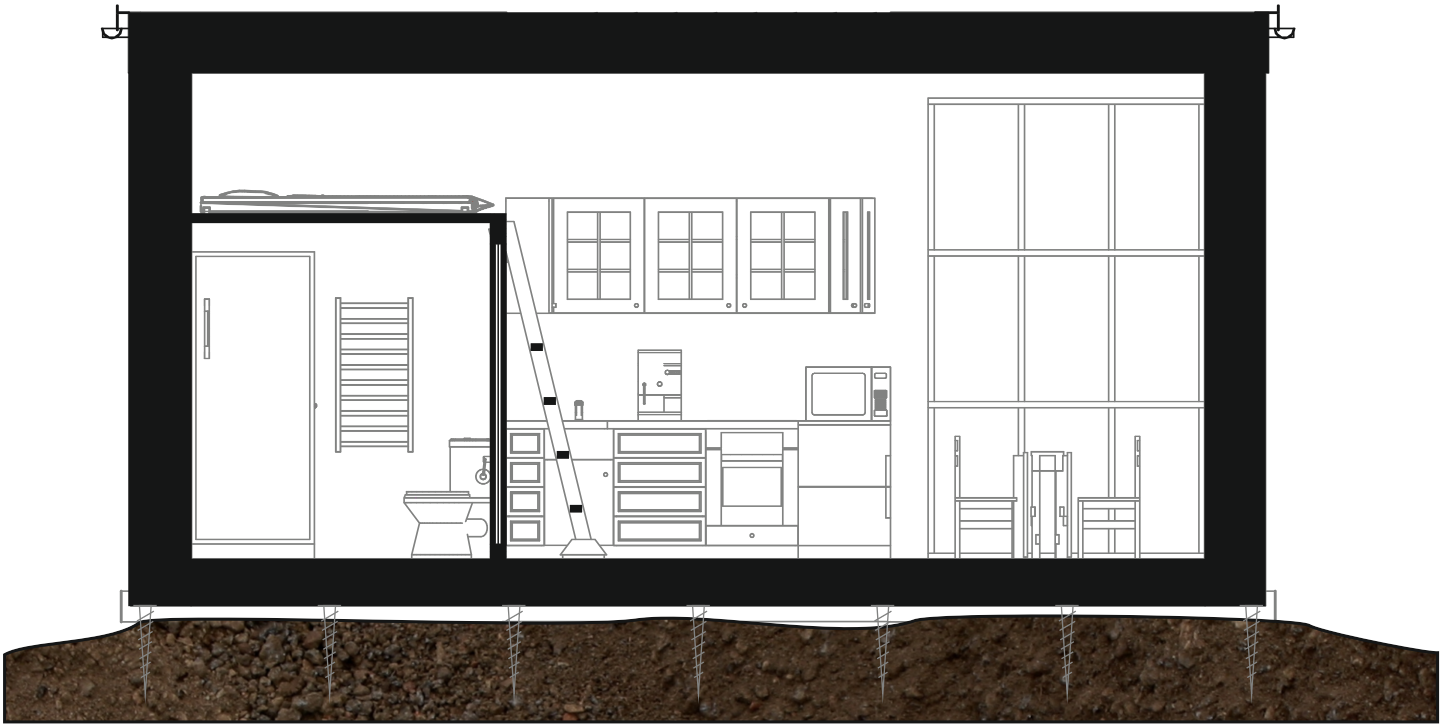
Sections

A-A



B-B

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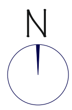
Floor plans - an alternative type interior

EkotteBo - L

-ground floor-

-1st floor-



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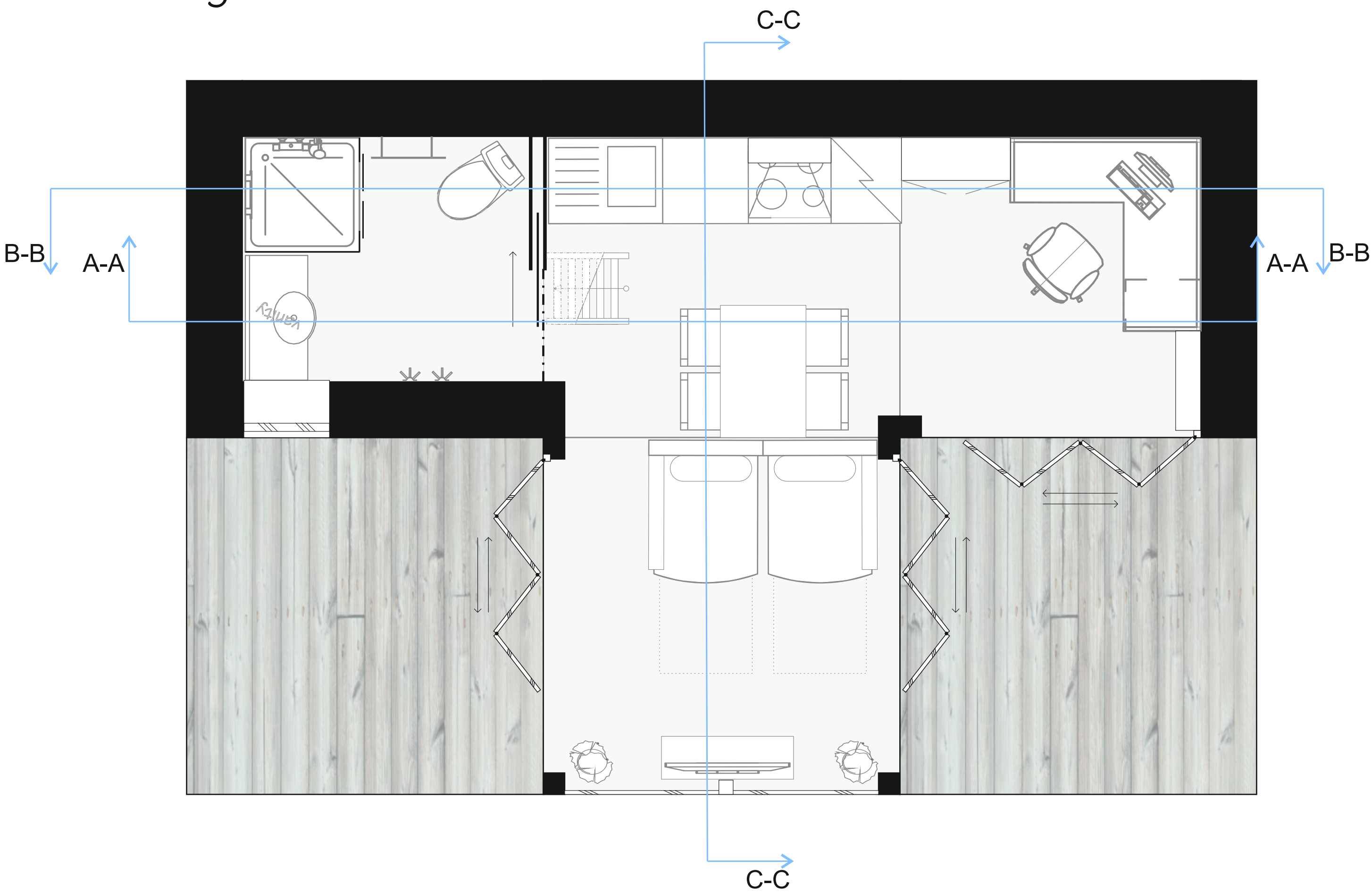
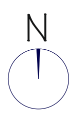
*EKO*TTEBO-T

This building was designed to be a summer house/student housing solution. It provides all amenities necessary for staying for extensive periods of time, including storage and multifunctionality of the spatial set-up and furnishings. The inner and outer spaces are used in a unified manner to create an extended living space for the owners.

Floor plans
-ground floor-

EkotteBo - T





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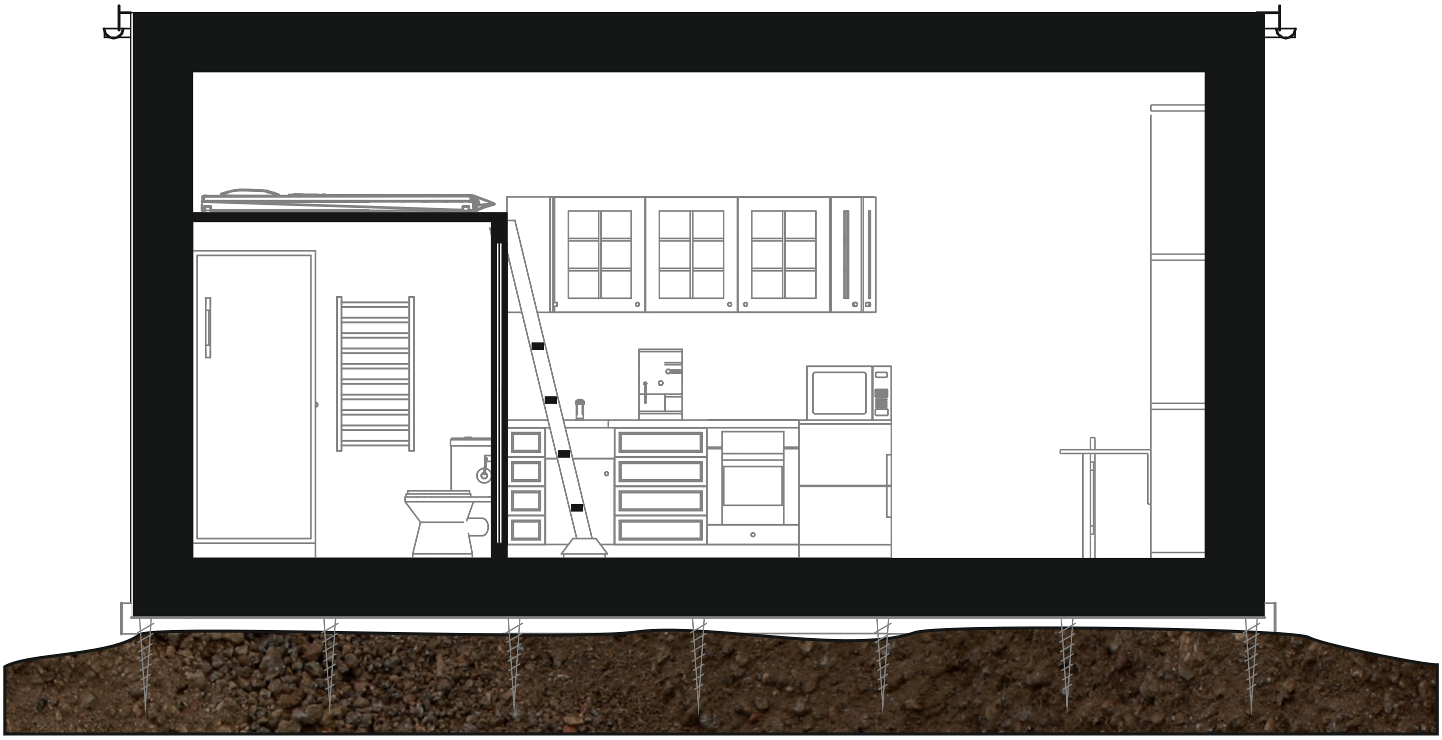
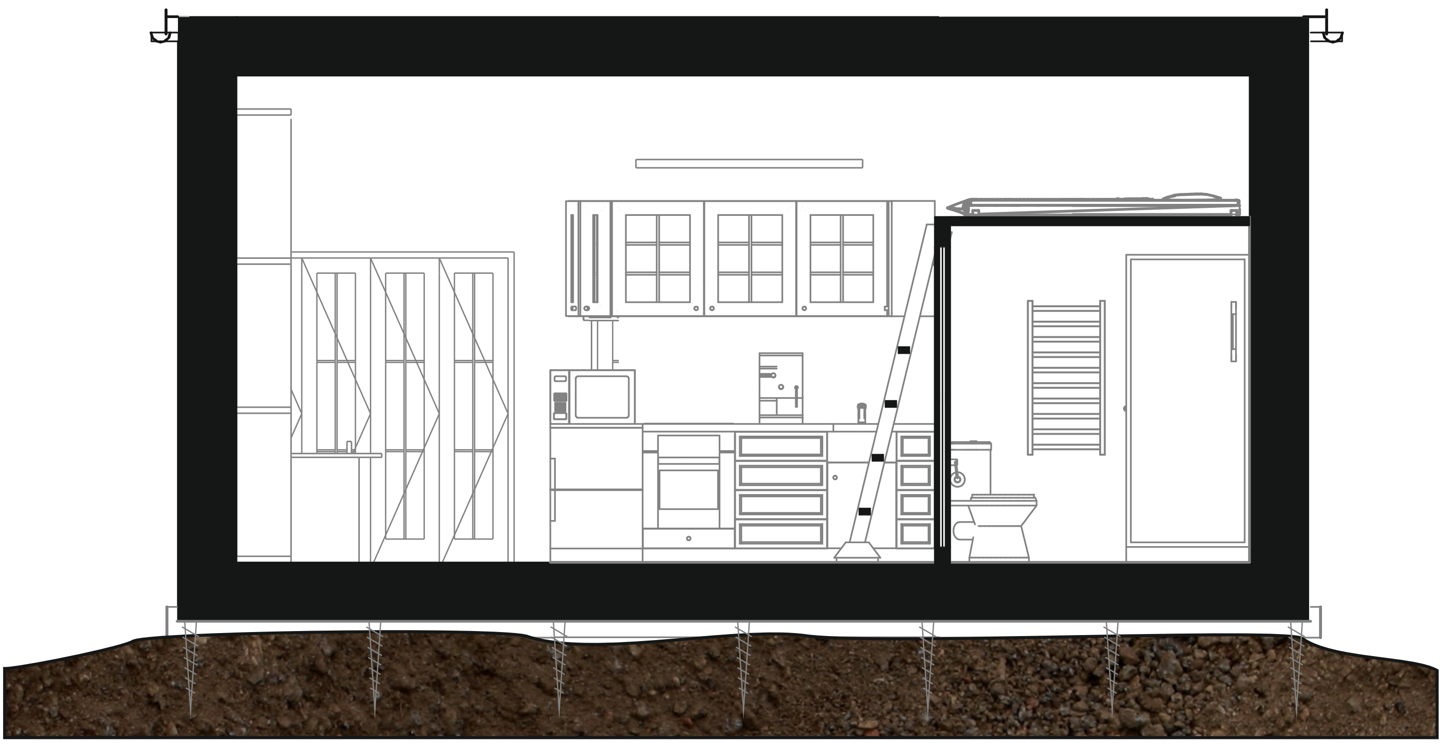
Sections

EkotteBo - T

A-A



B-B



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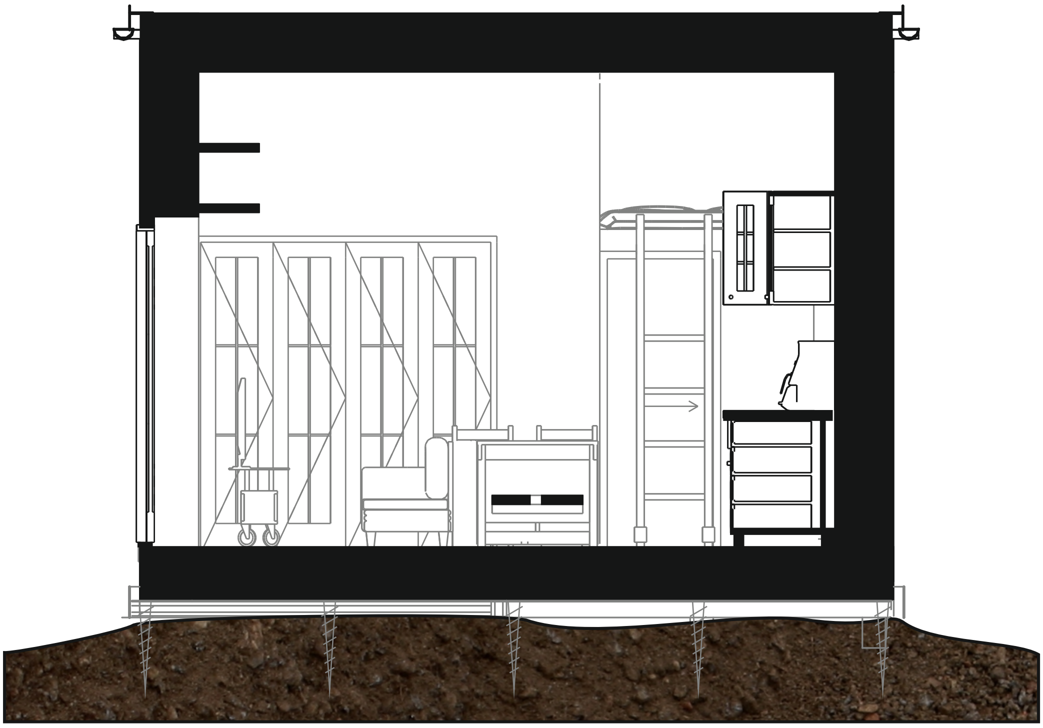
Sections

C-C



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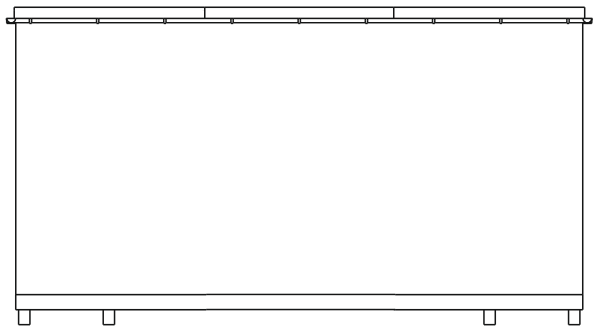
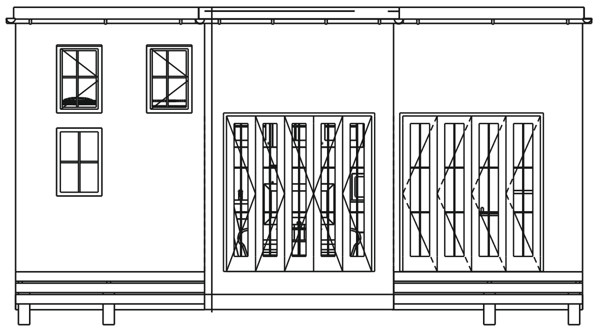
Facades

EkotteBo - T

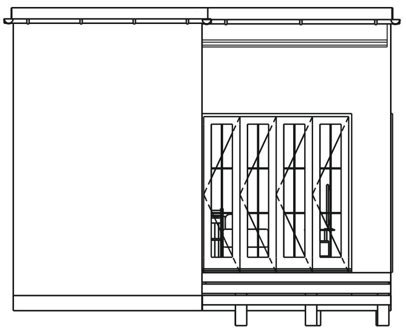
North



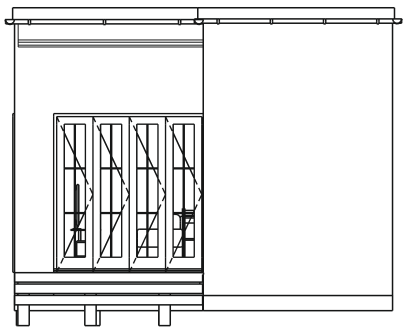
South



West



East



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WHY

NATURAL

BUILDING

?

PREFACE

I have been planning to build a genuinely sustainable construction for longer than I can remember… My main goal has always been to create an aesthetically pleasing and at the same time highly functional building that fulfils all sustainability criteria and even the toughest requirements of natural building. I have come to this conclusion after long consideration of different sustainability approaches and found that the constructions most in the front line of sustainability are the ones built with natural building techniques. It was a long journey, starting from much working experience with conventional building, going through different phases of trial and error using new innovative sustainable materials and, after the last almost five years of- architectural studies parallel with self-studies in alternative building, I have arrived at the present proposal. This project is the culmination of the work, the collected experiences together with research findings. It is intended to spark a creative and constructive debate as a contribution to improving current architectural and building practices and to a long term sustainable world for everyone and everything. However, naturally, no process is ever final.

It is my conviction that it is possible to radically improve the sustainability related performance of buildings. Although current design and building practice openly advocates sustainability there is a lot of room for improvement. The novel approach introduced in this project to reach sustainable building does not necessarily have to cost more (economically), it's more of a change of thinking that I am after, exemplified by the proposed structures of the project. It is notable, that whilst operational energy consumption (insulation standards, lighting, performance of white goods etc.) is regulated by the authorities in Sweden and other countries, there is as yet no straightforward policy or legal framework that enforces building material related energy performance. The environmental performance of building materials was until very recently largely ignored during design, planning and building. The main focus has been on economic and technical performance together with ease of use (ability for mechanization, process simplification and automation, etc.) and availability. To some extent, the environmental impacts of materials are also regulated; a systematic substitutional approach such as enforced by the European Chemicals Agency (ECHA, 2018) concerning the use of chemicals declares that

"Companies are replacing hazardous chemicals with safer chemicals or techniques. This kind of substitution can bring substantial benefits for the company itself, the environment and the health of workers and consumers."

However, as regards embodied energy and climate impacts, there is no such system of policies available and regulatory body existing as of today to enforce choice of building materials for constructional purposes in given contexts. This despite the fact that as shown by much research of the past 10-15 years, the embodied energy of construction may be as much as the total lifetime operational energy demand. It is fully possible in very many cases to replace industrial materials with high embodied energy such as Portland cements, fossil fuel based plastics or sealants and chemicals in various building processes.

The impacts of construction related to greenhouse gases and climate change are well known and are usually expressed in terms of CO_2 or of carbon equivalents. It should be noted here that the impacts related to *carbon* are broadly similar to the *energy* impacts as long as most energy production is from carbon-releasing fossil fuels. In a world where materials are produced from renewable energy sources, the carbon-related impacts would be less, but the questions of embodied *energy* would remain.

I use the term "natural" materials, however this must always be understood as a generalisation. Some natural materials, such as oil or asbestos, are toxic; others are too precious to use in construction, such as threatened species of hardwood timber. Many industrial materials are very beneficial, and if they are very long lasting (as well as recyclable), then it matters little that the *initial* energy to produce them is high. Natural materials such as timber are only acceptable if they are renewable i.e. replanted), whereas other materials and minerals are a finite resource on the planet. In general, however, natural materials require low embodied energy to use in construction, and have few environmental or health impacts.

Most natural, renewable building materials are possible to source locally, they cost only a fraction of their industrially produced counterparts – especially in terms of their embodied energy but also cost - and they may often last longer in constructions than their modern counterparts. So why aren't they used everywhere? Conservatism is one of the reasons; a reluctance to change existing practices. Another is the perception that modern technology is "always" superior to older solutions. This is of course strengthened by trends and advertising encouraging us to use new products. Yet another is that many of these materials when sourced locally do not perform in a standardised and well described-repeatable manner as industrial building materials do, such as required by industrial building companies, financing bodies (state, banking sector) and insurance firms. That there are variations in their consistency, ingredients, fractions, strength and other characteristics is more a rule than an exception. This in turn means that the application of these materials also requires a wider, more practice based knowledge from the designers and the builders throughout the whole building process, and then by the users - from the choice of the actual material to the decision concerning the application and its circumstances.

Recently however, there has been renewed interest in traditional, natural materials: not least for environmental reasons. A wide range of improved or newly developed, renewable materials have been introduced on the building material market which fulfil the previously described requirements from the financial and governing sectors.

All materials have their right places and uses. An open-minded choice from the architect, the project owner or the builder can result in great sustainability related benefits. The construction industry is one of the most conservative of all segments of business. It is highly reluctant to take this step on its own, although this change not only would provide better overall environmental performance but also could significantly reduce costs of production in the long run. I hope the following project illustrates these benefits and helps the change on its way.

How?

INTRODUCTION

1. BACKGROUND

There is a clearly visible dichotomy in sustainability approaches today as shown in figure 1. While there are housing solutions available today that fulfil sustainability criteria, most follow the high-tech industrial approach in doing so, as seen today in mainstream architecture also often called “green architecture” or “sustainable design”. At the other end of the continuum, e.g. in case of low-tech high-knowledge and handcrafted-labour intensive solutions, the architectural and aesthetical qualities are sometimes questionable, at least as far as the mainstream architectural discourse is concerned. Nevertheless, with the growing climate debate and environmental awareness of today the importance of these previously marginal, so-called alternative construction methods - often inspired by vernacular and traditional design and construction methods - is increasing rapidly.

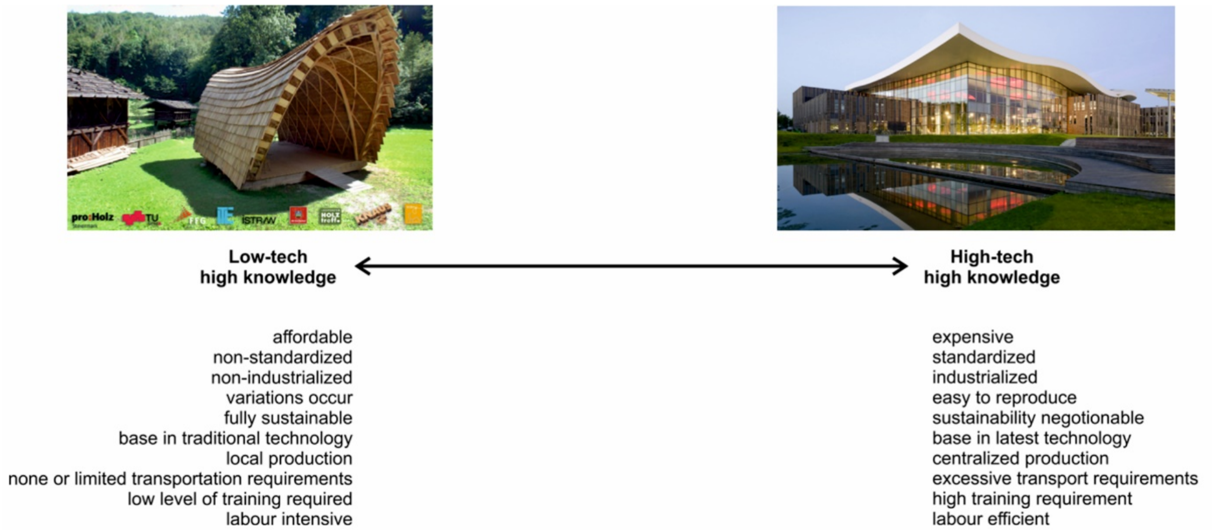


Figure 1. The dichotomy of sustainable design and construction (Picture sources: Baubiologie, RAU)

There is nevertheless a development visible, where even main-stream architecture is catching up with green trends. Figure 2 shows the consecutive steps of this development with the main attributes of each step.

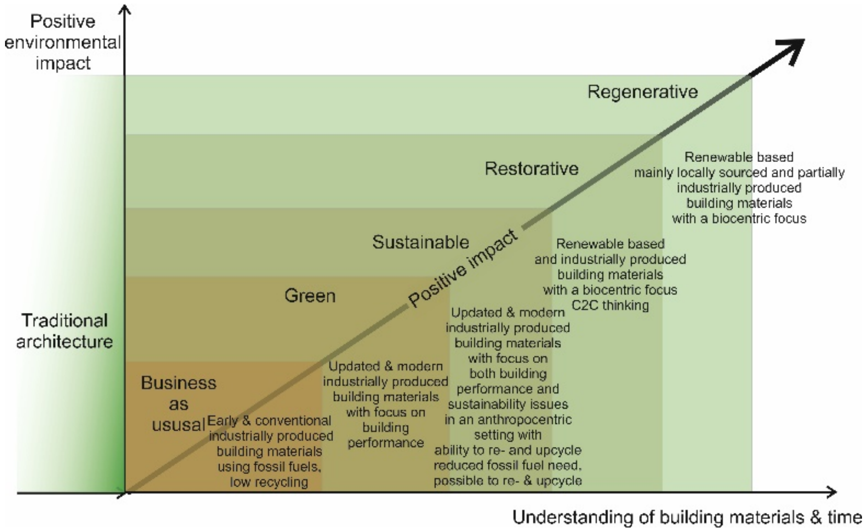


Figure 2. The development of architectural styles and practices in relation to environmental impact (Source: adapted from the material acquired at www.regenerativedesign.org)

1.1. GOALS

The study aims to examine

- whether it is possible (technically, aesthetically and financially) to create fully or nearly fully renewable based, eco-designed, easy-to-assemble, modular and expandable housing solutions that fulfil even the toughest sustainability related and building requirements (functionality, humidity, energy efficiency, indoor comfort and other attributes)
- if there are short-cuts through which short-comings of alternative building techniques (e.g. labour intensiveness, humidity and fire safety issues, etc.) can be overcome

The goal of this project therefore is to demonstrate to designers, architects, engineers, builders and other practitioners and decision-makers of the construction industry that it is possible to radically improve the sustainability related performance of constructions, whilst using almost exclusively renewable materials. It aims to challenge existing understandings of building materials and to be a pilot example for sustainable construction.

1.2. MATERIALS & METHODS

The study is supported by broad experience of current construction, critical observation of existing sustainable housing solutions, traditional building techniques and materials, and recent research and alternative trends. It also relies heavily on written and digital sources and technical-constructional data derived from manufacturers and authorities.

Besides traditional sketching and drawing, vector drawings were created using CorelDraw and AutoCAD. Rhino and its plugins were used for volume modelling, while ArchiCAD was used to create technical drawings and a base for renders. Visualisations were made with the help of Adobe Photoshop and Corel Draw.

Physical models were created in different scales by laser cutting using both soft materials (hard foam board) and plywood. Various manufacturers' products (clay, insulation material, plywood, LVL, etc.) were tested in real life conditions to ensure their applicability in the project.

The final study was created to be a crossover between an architectural-engineering design project, a scientific examination and feasibility study. This approach was chosen as this material is also intended to work as a base material for further product development in scientific publishing and in entrepreneurial activities besides acting as a M.Sc. thesis work.

1.3. PROJECT PROCESS

An inductive approach was used in developing this project. The point of entry in the discourse was in principle three materials and characteristics of modern digital design and production methods. Based on the attributes of wood, clay and straw (together with some similar optional "replacement" materials from the renewable material palette), the work process led to design decisions, which in the end resulted in the described technical element based modular building system.

The materials led to consciously made compromises concerning basic sizes such as wall thickness but also driven the joining strategy and operational attributes such as related to ventilation and heating requirements. The process was started with the collection of a large pool of data on various aspects of the materials, the joining methods, installations, policy related attributes (Swedish planning and building regulations - BBR) and potential functional requirements of the users.

Based on this, in the next stage, the most suitable materials have been chosen to work with together with a building size to experiment on. "Attefall" size was chosen as this is a building permit free construction in Sweden and has multiple utilization areas, suitable for many different groups in society. It was used as guideline rather than a real limitation. The element based modular system was created in such a way as to deliver also even for larger constructions. Concerning the lifestyle of the users I was focusing on young adults and couples together with students, as currently in Sweden there is a serious housing shortage and such an Attefall sized building solution could make a real difference in the housing situation of many.

The technical production method opportunities were examined parallel to choosing materials and starting the drawing and writing process. This latter one was started early with notes and a collection of observations that formed the backbone of the written report later on.

Production methods were both examined using the internet and by contacting companies and talking to professionals in the cutting/milling industry, finding out exact details on accuracy, design issues, cost questions just to mention a few. Two study visits were also made. One was to Hamburg, Germany to Eurolaser, a company producing high quality laser cutting equipment. Here different materials were tested and the suitability of the method was evaluated with professionals from the industry. Another visit was made locally to Vitaby to a small CNC milling workshop, where similar investigations were carried out and the prototyping (phase 2-4) was done.

The initial design and technical sketching was created with pen and paper and included interior room set-up sketches to adjust modular organization to lifestyle related and functional characteristics. Volume modelling was done by Rhino. This part of the process helped to finalize the basic modular set-ups of the project. Detailed drawings were created by ArchiCAD and technical cuts and final presentation materials by Corel Draw and

Adobe. The written report was create using MsWord and some plugins. The oral presentation was made by using MsPowerPoint.

Parallel to the final parts of the writing process two 1:1 models were created which served both as basis for feed-back on the design process, the technical development, test for further materials (renders, etc.) and also as presentation material.

1.4. LIMITATIONS

This study does not include spatial e.g. planning related issues. Although territorial and site zoning circumstances are of major significance in building construction and utilization as they directly influence the performance of the buildings, this study does not include and focus on such issues because of space and time limitations.

The study does not include details of regulatory and other governmental/EU institutional policy related issues although where appropriate e.g. to highlight certain issues some policies and regulations may be mentioned.

Detailed engineering, statics and construction technological issues such as humidity, heat-transfer related considerations, etc. are not forming part of this paper and are only referenced to from other authors just as only mechanical joining methods are described in detail as these are the most relevant to this project.

The primary building use this material is focusing on is private housing although the results can be extrapolated and generalized for other uses, such as public constructions (nursery homes, schools, village halls, official buildings, etc.). It was chosen to study a mini or micro type building solution, since reduced space use is the first rule of reducing our ecological footprint.

From a construction categorisation standpoint, the Swedish “Attefall” house size is taken as a case study size. The basic parameters of this are max. 25m2 gross floor space and 4m height. This was chosen as a standard to build the project on. This unit is interesting as its uses are many faceted including everything from student housing and second homes through offices and event-buildings to cafés, micro-galleries and ateliers.

The main focus of the project is the building envelope. Performance and other characteristics of installations and supplementary fittings such as heating/cooling systems, water and sewage handling, electrics, IT and interior fittings and white goods, etc. are not part of this project and only addressed superficially where appropriate.

Sustainability issues are brought up in this study in relation not only to the construction sector but in a holistic manner, concerning material, construction technique, utilisation, management and several other fields. Although sustainability is a widely discussed subject, understandings on what comprises sustainable construction may differ between researchers or countries. Therefore wherever necessary, the sustainability guidelines or the framework of the analyses are provided.

2. DESIGN PRINCIPLES

2.1. COLOUR, TEXTURE, SHAPE & FORM - AESTHETICS

In this project a largely “form-follows-function” approach was chosen when it comes to aesthetics, as with the Attefall building; the size of space was the limiting factor to adjust to. Although it is fully possible to create curved surfaces using the designed elements in this project, more focus was placed on basic design issues and maximizing inner volume, resulting in a cubically shaped construction. This was coupled with an open structural approach where the border between the indoor and outdoor spaces is blurred intentionally. The indoor volume flows into the outside space with the use of wooden decking that acts as extension of the interior. This, as in many micro-designs, provides extra living space.

When deciding door and window settings, the main decision making factor was also functionality and a wish to create a spacious and open feeling. This was a rather important aspect, especially as the inner volume of the building is so limited as a result of the small gross foot print, limited further by the relatively thick walls. The placement of windows, besides normal static concerns is in principle free for the user/customer to decide over. The windows and the doors can be freely placed between the standing “I” beam shaped studs and fixed to the stabilizer boards of these. During the design phase such solutions were chosen where the most appropriate light, ventilating, access, visibility, etc. conditions could be achieved. This is marked on the floor plans by recommended siting directions according to compass directions and sun movement (northern hemisphere was used). Most of the openings were placed on the southern side to maximize sun penetration. As this may result in problems such as overheating in summer, additional sun protection can be added. Adjustable shading can be easily created with the use of sails, marquise and pergolas. This latter one also adds to the building’s character and provides ecosystem services as plant based shading. It allows natural light to reach the building’s interior but restricts it enough in the sunny summer months to avoid overheating issues.

A mixed approach was used concerning materials. A combination of showing materials as they are (honesty) e.g. in their basic nature, on surfaces, textures and in tactile expression was combined with modernized craftsmanship based detailing. This latter is expressed for example in visible joinery methods (façade, ceilings, walling sheet materials, etc.); in surface treatments with clay; and with the creative reuse of reclaimed materials (interior and façade design). It is nevertheless to be noted that the final decision of each individual unit is intended to be in the hand of the customer and details are also designed to enable adjustment to the specific local environment that the building is to be placed into.

Colours of natural origin are preferred, e.g. earth colours together with natural origin non-toxic paints and painting methods. For wooden surfaces, linseed oil based paints are to be used outdoors and even indoors on e.g. door and window frames, whilst clay based paints are suitable for plastered surfaces indoors or lime based surfaces outdoors. Natural wood treatment methods such as charred wood (Shou sogi ban) or grey wooden surfaces are easy to achieve with choice of the appropriate materials (larch, cedar) even without special treatment (figure 3).

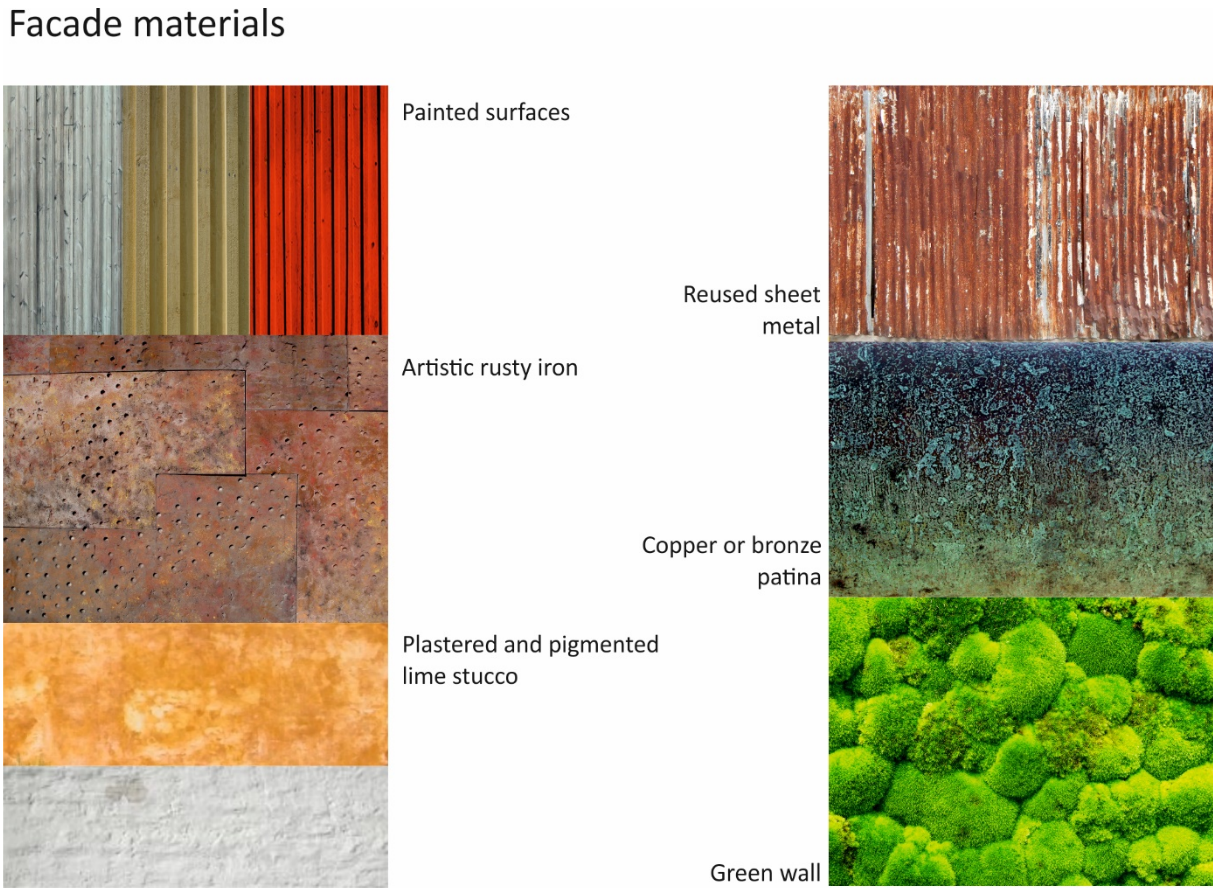


Figure 3. Some surfacing materials.

Many natural elements can also be included in the building's texture, including green roofs and walls, which in turn can also be used as productive units providing vegetables or herbs (naturally to a very limited extent on such small buildings) besides adding ecosystem services such as microclimatic and humidity amelioration for buildings.

2.2. MATERIALITY

The "KISS" (keep it simple, stupid) approach was used to reduce complexity in the construction, as well as in the basic choice of materials. The primary materials used for the envelope were: wood (including plywood), straw and clay/lime plaster.

The main reason for choosing these three is that they all have low environmental impact, as well as natural and/or renewable origin. They are non-toxic and are abundant in most local environments, thereby avoiding long distance transport requirements.

These materials were also chosen for their qualities with the user in mind. All three materials have a positive connotation attached to them in the mind of most people. Their materiality is expressed through several interconnected attributes, some working directly through sensory perception, others acting in the subconscious. Bocz et al. (2011), while researching people's attitudes towards traditional farm buildings used in tourism, including their materiality, listed various characteristics that influence people when visiting such edifices. Tactile, visual and audial attributes work together with for instance scents given off by the building materials or heat emitted from surfaces together with surface characteristics such as evenness and hardness, creating a "complete building experience". The smooth wooden surfaces, the softness or roughness of clay plaster, the warmth of natural clay based earth colour paints, for example, all play a role in the sensory experience. Added to this is the positive awareness of being in a building containing no toxins and dangerous substances, providing superior indoor air and living quality without harm to either others or the environment. This qualitative sensory aspect of architecture is not new. The famous Danish architect, Jørn Utzon described it the following way in 1948 (Andersen, 2018):

"We relate everything around us to ourselves. Our surroundings affect us by their size, light, shadow, color, etc. How we feel depends very much on whether we are in the city or in the country, in big spaces or in small ones."

This is an essential part of architecture. As architects and planners are responsible for our physical surroundings it is not enough to create functional environments, they must also be aesthetically pleasing, provide variety and allow users to make their individual mark. Giving options to users to choose the type of façade materials, interior layouts and other elements in the design allows for an individually tailored variety of expression - and use. As the façade elements on this modular system are of standard size 2,5m x 4m they can be easily replaced with others having the desired colour, texture or material, while the old ones can be dismantled or resold/reapplied in another construction. Surface characteristics can vary greatly, from for example lime-plastered and painted walls to wood panelling, sheet metals or tiles of natural stone, dependent on the customers' wishes and the characteristics of the local environment and site.

2.3. WORKABILITY

Efficient digital design and the laser cutting/CNC milling method enable a production process with almost no waste. The waste created by efficiently designed constructions is much less than in conventional building practices (as mentioned in Chapter 2.4. Element based). It has been estimated that the total material related waste in building construction varies between 4-21% in a conventional building process (Josephson and Saukkoriipi, 2007) as shown on figure 4. The paper furthermore points out that with a calculated overall waste of around 10%, the cost of this can amount to 1-3% of the total project cost.

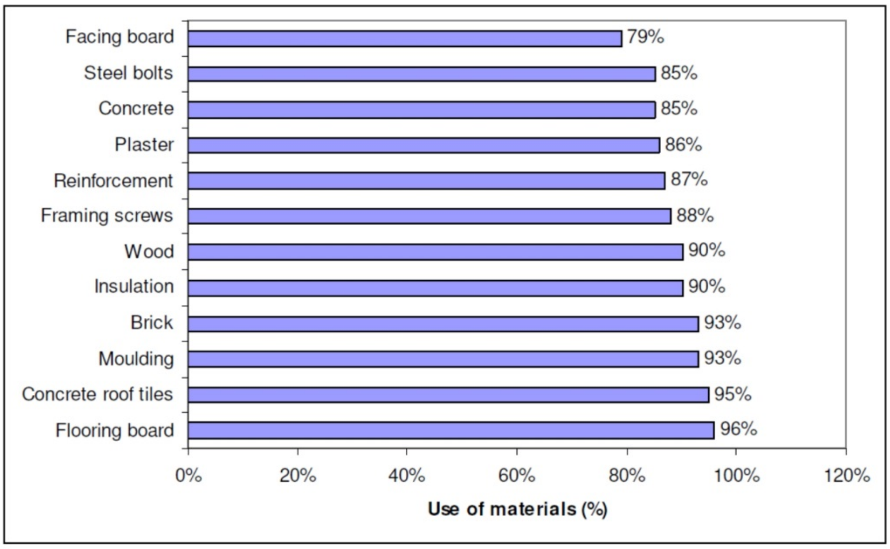


Figure 4. Average amount of building materials, the missing sum is waste. (Source: (Josephson and Saukkoriipi, 2007) p32.)

An illustration of wasteful building practice is shown in a real-life example (figure 5) where it is clearly visible that totally useable large pieces of the otherwise environmentally extremely expensive EPS insulation are simply discarded, together with large pieces of equally usable timber.

Figure 5. Waste at a conventional building site, March 2018, Norra Björstorp, Skåne, Sweden (Photo: Author)

The amount of waste material can be greatly reduced, by proper digital design based planning and by using modern production methods such as additive or subtractive manufacturing. Figure 6 shows the waste after cutting out the elements of a sheet of plywood.

Figure 6. Waste after CNC cutting of the prototype, May 2018, Vitaby, Skåne, Sweden (Photo: Author)

It is important to note that modern constructions require both highly skilled and specialised labour and also a large number of specialised tools and materials that in turn may require additional training and expertise. On top of this, many modern building materials contain poisonous chemicals. During their use, safety measures have to be followed and safety equipment has to be used to ensure the builders themselves don't get sick. Examples are many, including sprays on polyurethane insulation, the use of inorganic fibrous insulating materials such as glass wool or rock wool; even standard gypsum sheets contain carcinogenic VOCs, formaldehyde based synthetic glues, etc. All these factors make construction expensive and the whole process of building alienated from the actual users of the edifice. In line with much recent ecological building as well as industrial design, this project intends to reduce the difficulty level of building processes and the complexity of construction, thereby offering cost savings as well as opportunities for unskilled labour to create buildings.

Concerning ergonomics, it is to be noted that straw bales are relatively light compared to their volume, therefore installing them in the construction is not a problem either for male or female workforce or even children (community building). This is further enhanced by the fact that the construction based on the modular system suggested in this project does not require high levels of constructional knowledge to be put up. The elements are designed ergonomically to fit given purpose without the risk of being for example mixed up or damaged by wrong use. All parts are marked individually and therefore installation is easy and straightforward without the use of complicated building methods and specialised tools.

At last but not least a hands-on approach gives pride to the owners, "I've built my house with my own hands"! By learning about the attributes of materials and how to use them the construction educates and allows users to be able to not only create but later on trouble-shoot and maintain their buildings in the long run. Involvement of users has been shown to result in better maintenance as well as lower energy use. Empowerment of marginalised groups through either community based or private building initiatives have been proven to be a valuable tool in creating long term sustainable results in various communities. This was shown in popular form on the TV programme "Grand Designs" (Season 2. Episode 6.) (McCloud, 2001), where eleven men and women have built their own, and each other's homes although none of them had building skills from the start. A large variety of self-build projects with similar attributes are available on both Youtube and other social media.

2.4. Element based

The whole building system is standardised-element based (figure 7-9). A single, laser cutting or CNC method is used to create all main construction parts. This ensures optimal material use, low production cost both during manufacturing of the elements and under the construction period. It also allows replicability and interchangeability of parts. The speed with which the building can be put up also increases with standardisation, just as the level of skill required to build is reduced. This is especially true for those work phases which traditionally require high levels of expertise and experience, such as carpentry and joinery. It was common in traditional housing to have community based building with the help of only a few actually skilled builders experienced in the trade, most often joiners and masons. These travelled around and carried out building projects with the help of local lesser or otherwise qualified labour.

This project uses the standard straw bale size (see Chapter 6.2 Insulation) in dimensioning the elements. The size of bales therefore determines details such as the wall thickness and door and window settings, as well as functional aspects such as wide window seats or construction of external shutters.

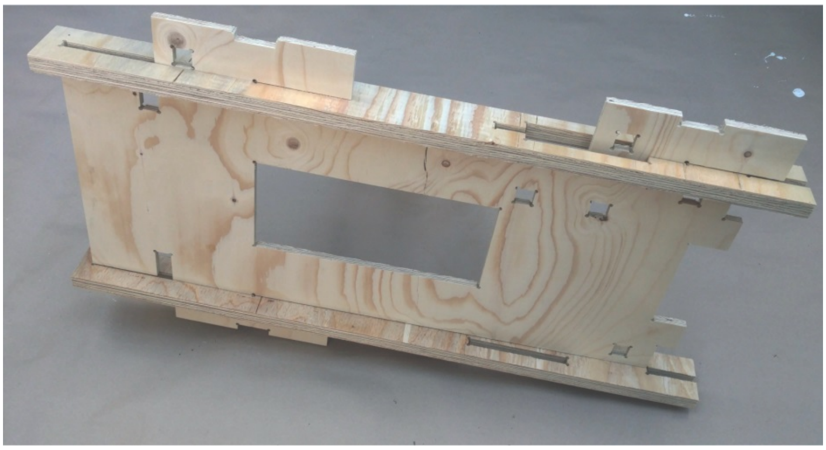


Figure 7. The "I" beam partial prototype in scale 1:1 (Photo: Author)

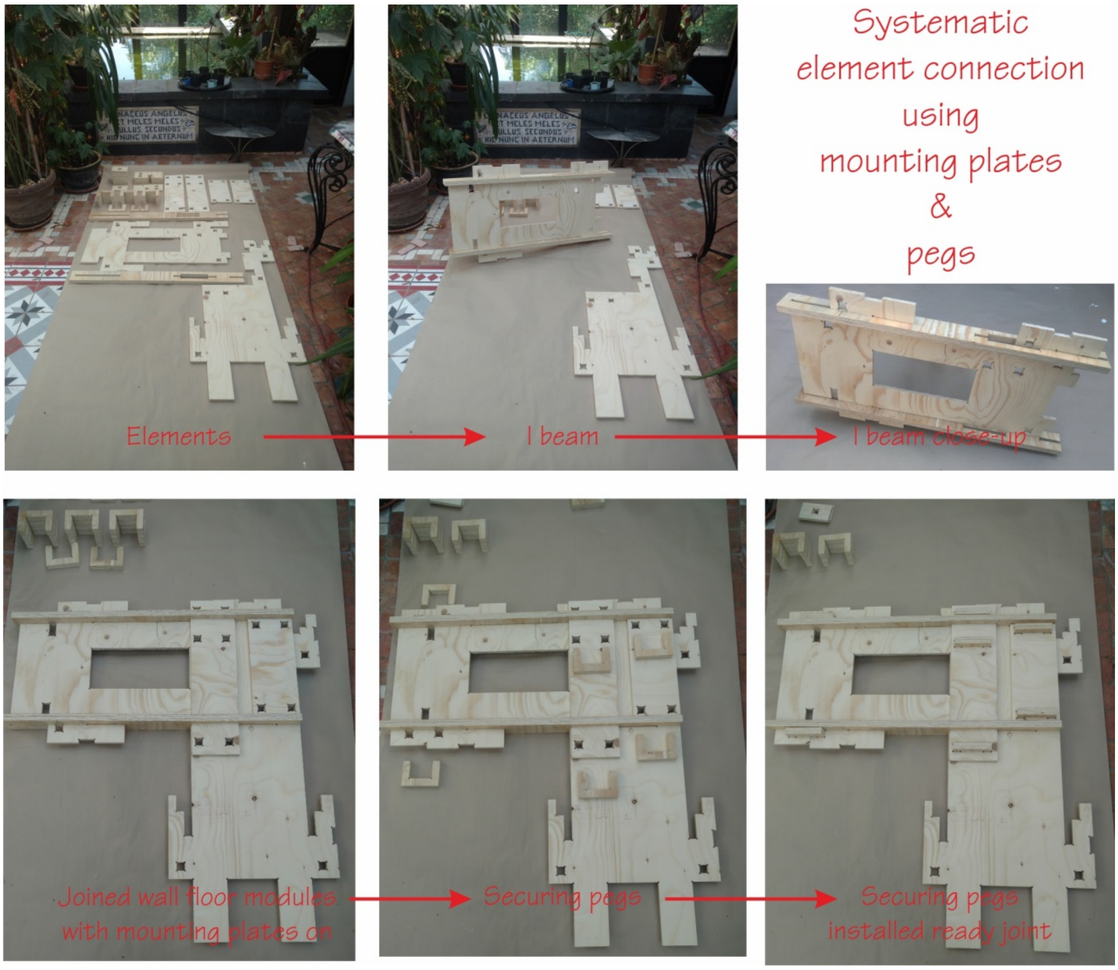


Figure 8. The system of connecting elements (Photo: Author)

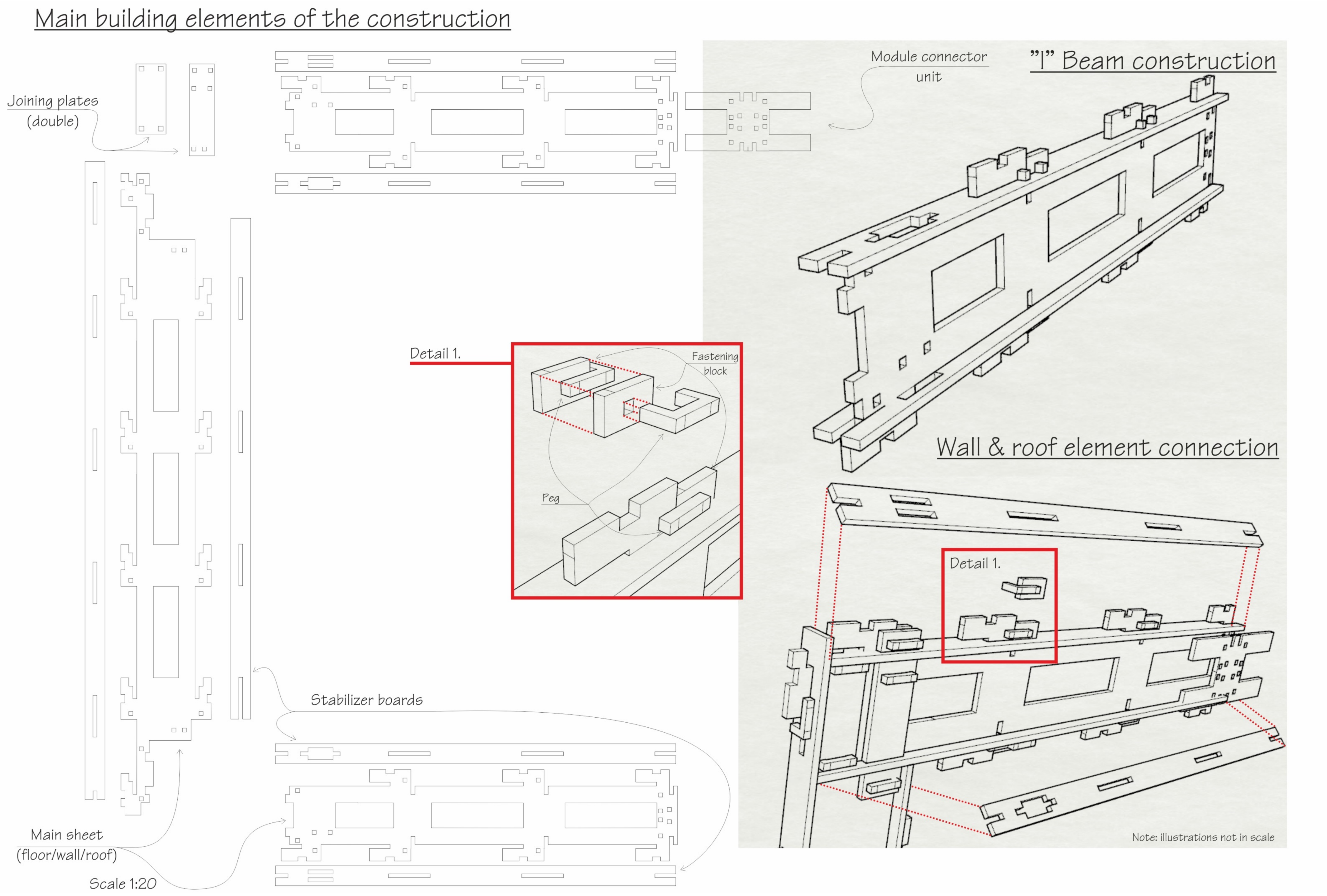


Figure 9. Types of modules and some placement variations

2.5. MODULARITY

Modularity allows not only fast construction but off site pre-constructed elements to be installed into a whole building in a very short time-frame. This minimizes the risk of weather damage caused by rain, snow, humidity, or eventual other damages such as caused by insects, rodents or by simple negligence. Modularity also reduces costs connected to logistics and improves environmental performance simply by requiring fewer deliveries and allowing more effective production in controlled e.g. indoor environment. Table 1 shows the environmental impact of deliveries, where it is clearly visible that coordinated and avoided deliveries can significantly reduce carbon dioxide, sulphurous and nitrous emissions connected to the building process.

Type of transport	*CO_2 (g/ton km)*	*SO_2 (g/ton km)*	*NO_x(g/ton km)*
By air	1650	0.9	7.7
By road			
- Light truck (14 tonnes), diesel	175	0.04	1.8
- Heavy truck (40 tonnes), diesel	50	0.03	0.55
By rail, *diesel*	18	0.005	0.36
By sea			
- Small ship (less than 3000 tonnes), diesel	25	0.4	0.7
- Large ship (larger than 8000 tonnes), diesel	15	0.26	0.43

Table 1. Pollution from transport (Source: Berge, 2009 p.30)

The greatest critique against modular building technique nevertheless is its relative formal and aesthetic rigidity. This results from the fact that the number of elements (in this project’s case 10 in total) e.g. “the variety” building up the whole construction has to be limited to be able to keep costs down and the whole process efficient. Any design that doesn’t follow the strict formal requirements of the elements has to be specially designed and added to the system which in turn increases costs. However this is not strictly true; prefabrication does allow for a broad variety of expression.

This project uses a 2,5m x 2,5m standard gross floor space unit as basis. A module and its constructional characteristics is shown on figure 10. The height of the unit can be easily changed (3,5m-4m) thereby various inner room heights are possible (2m-3m). The modules can also be placed on top of each other forming clusters. The attachment of the modules to each other is carried out by laser cut elements and a wooden peg system, which in turn is removable, therefore the whole module system can be dismantled and moved to another location. Modularity also allows variations of arrangements adjusted to different types of use. Figure 12 shows a few such possible arrangements concerning expandability.

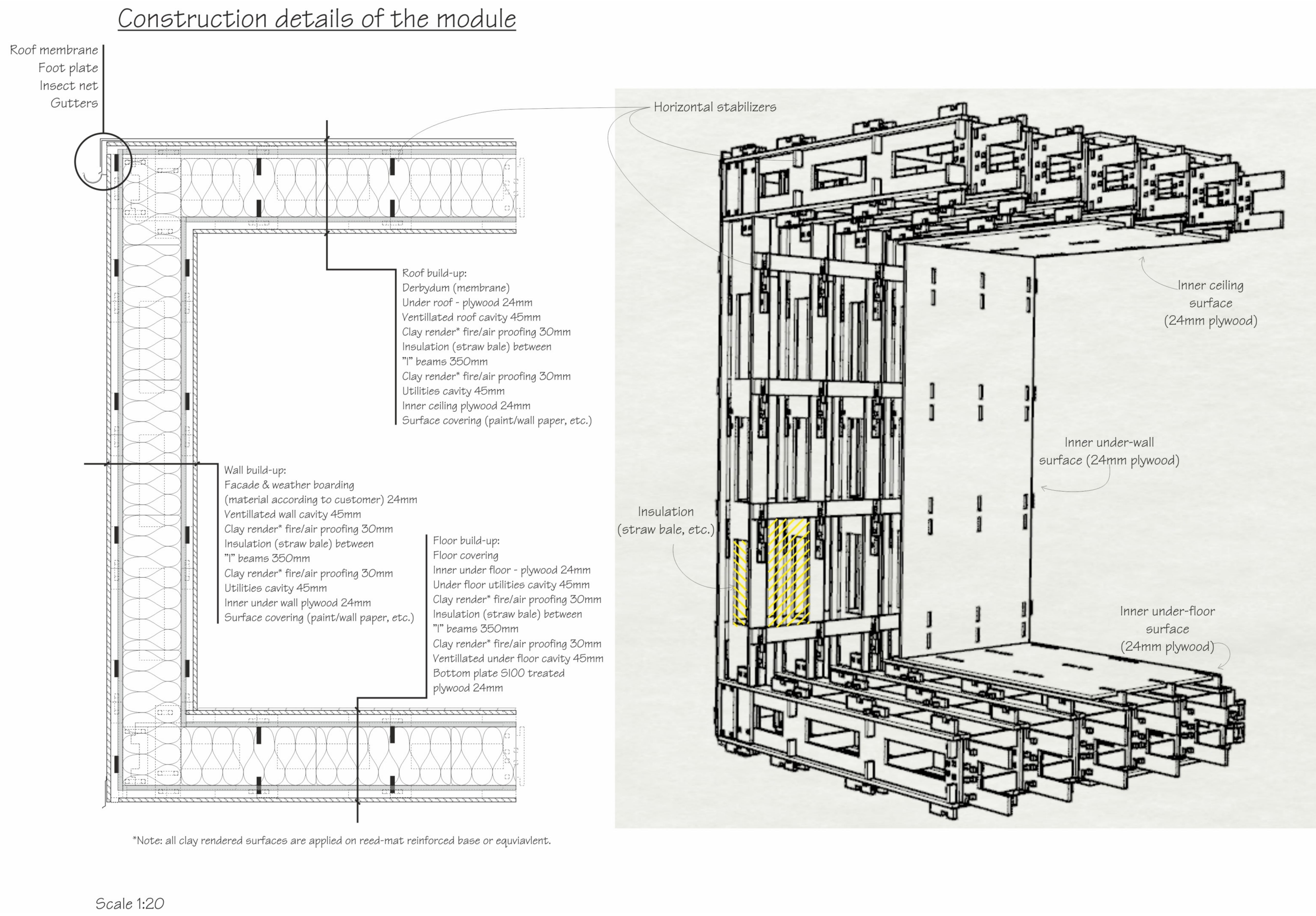


Figure 9. Module details

2.6. MOBILITY

The system is based on modules as was described above. These modules are relatively light and are positioned on a network of ground screw piles acting as a light foundation. This in turn can easily be removed from the ground when for example the building is moved to a new location. The elements that make up the modules can be transported as flat-pack on palettes while ready modules can even be moved on an average car trailer or on a flatbed lorry and lifted into place using small to medium sized mobile cranes. Similar modular transportation and installation techniques already exist on the market and are widely used as shown on figure 11. Even if a number of modules are installed and connected together, as a result of their relatively low weight in comparison to conventional concrete or masonry based constructions, the modules can be easily lifted and moved together as one unit, if so desired. This is more and more important in the world of today, where high mobility is required from people. Mobility of housing together with expandability (see next chapter) allows young people with limited economic means to start up on the housing market at an early age.

Figure 11. Placement of modules by crane in a construction. (Source: https://triumphmodular.com/blog/permanent-modular-construction/)

2.7. EXPANDABILITY

The largest capital asset in the lifetime of the average citizen is his or her fixed assets, especially ownership of house or apartment. Housing should not be therefore cheap per se, the value of the building stock forms a capital that is significant both from a personal but also from a national economic point of view. On a micro economic level it provides many advantages. It creates an economic independence (after mortgages are paid), a significant savings for the elderly years, inheritable large-value asset for the next generations and last but not least can work as collateral against future lending and as a buffer in case of emergencies (e.g. serious illness). Everyone in a modern democratic society has to have access to housing of adequate nature. It is arguable of course which housing is most adequate, where place related characteristics and other factors such as politics, economy etc. play a role in the decision making. The two main housing systems are the urbanized high-density apartment-block systems and individual, semi-detached or similar smaller scale housing solutions. In case of the latter, a system such as proposed in this project offers an easy step-by-step entry into the housing market and can be useful for economically weak groups and young adults in the beginning of their housing career. An example of expansion can be for example based on the organic development of some farm structures as shown on figure 12. Further size and placement variations based on the different element based modules are shown on figure 13.

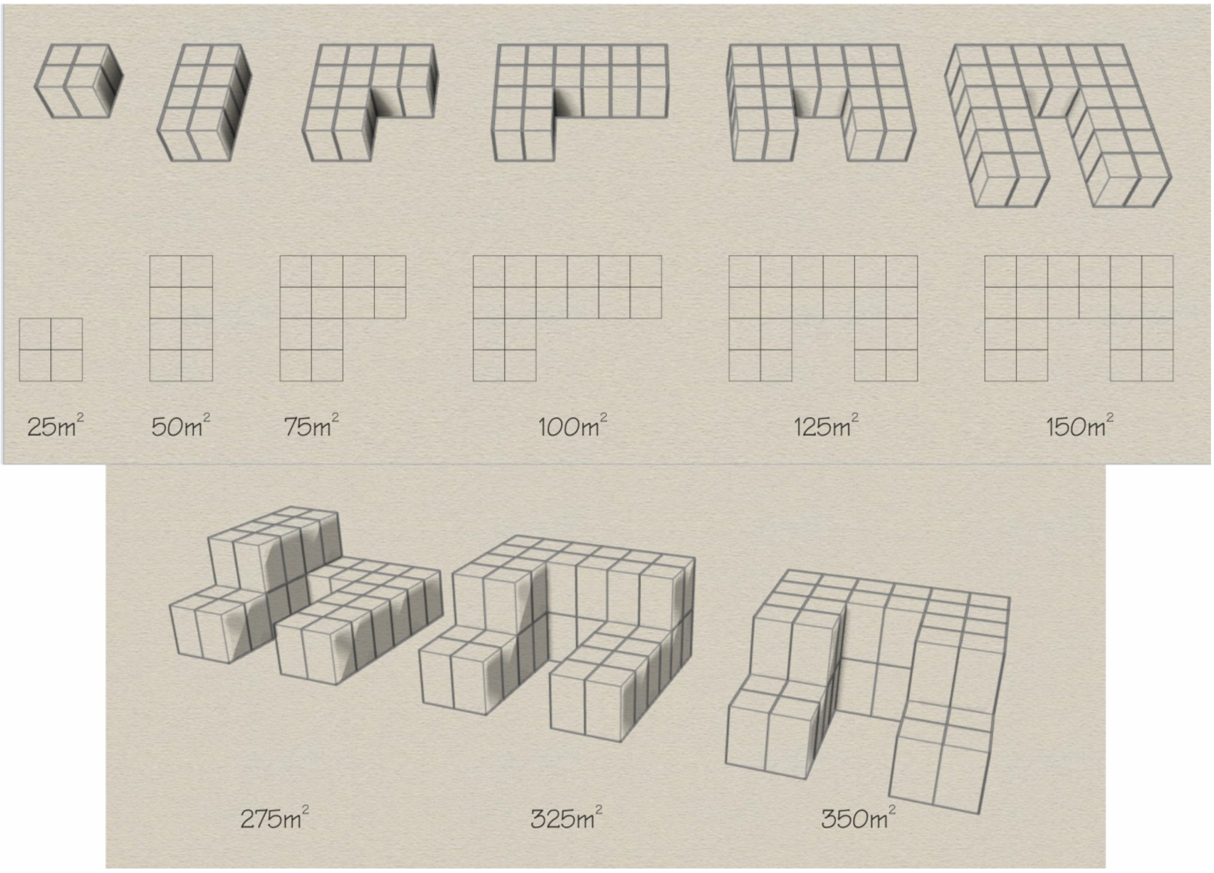


Figure 12. Expansion of a modular housing system – project example partly based on traditional farming structures

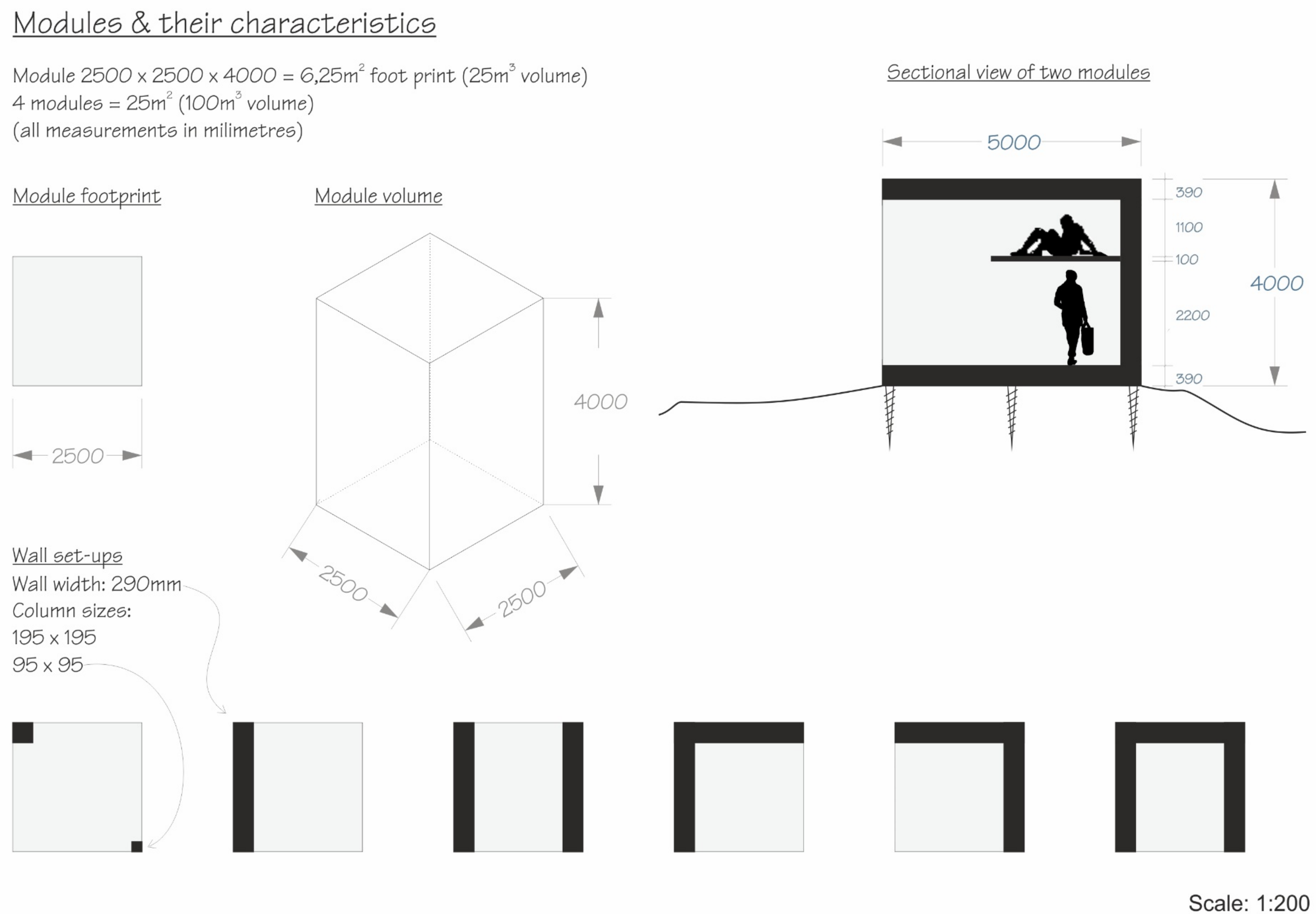


Figure 13. The basis of size and placement variations of the EkotteBo housing system

2.8. INTERCHANGEABILITY

Time is an often neglected consideration in architecture. Both durability and adaptability are important aspects of sustainability. The parts of the individual units, e.g. elements and even whole modules can be exchanged, replaced and upgraded as required. This is stemming from the design solution being based on a few basic formal and material characteristics, which in turn mean that as long as the constraining rules of the basic construction are kept, additional elements can be added. This inter- and exchangeability allows owners and users to update their living environment without major work on site as this usually is very disruptive. Just as in the case of electric goods and other consumer products, trends and fashion have a great influence on buildings and their use. It is rather usual unfortunately that buildings are “modernised” and updated only because of certain fashions. TV programmes such as Äntligen hemma, Sommar med Ernst, Bygglov, etc. encourage home owners to do this although the functional and technical characteristics of the building may still be quite adequate. With this system, parts of the building such as façade/wall sections can be removed and new ones moved in without major work. The removed parts can either be used somewhere else (in another construction) or dismantled, stored, and eventually re- or upcycled. Figure 14 shows the way a façade element can be attached and removed from the module.

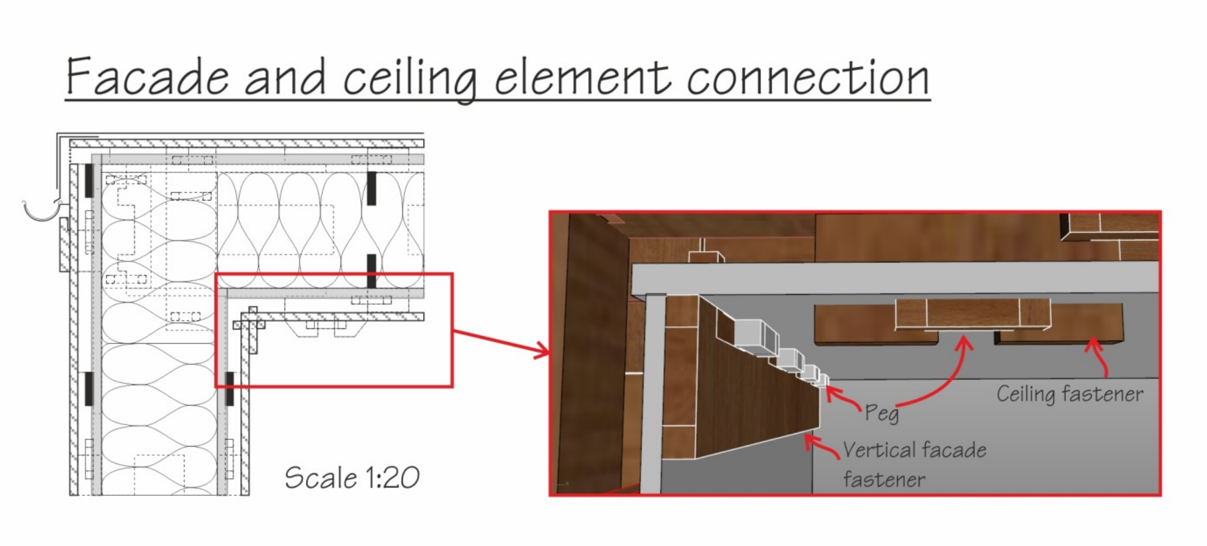


Figure 14. An example of the reversible connection of ceiling and inner façade elements.

2.9. C2C COMPLIANCE

It is the intention of this project to create a housing system that fits and performs well in all the five criteria of Cradle-to-Cradle thinking in sustainable economics and ecodesign. These are as follows:

- Material health
- Material reutilization
- Renewable energy & carbon management
- Water stewardship
- Social fairness

Material choice and use was carefully designed together with technical characteristics to achieve the highest possible C2C certification level (Platinum). In the next phase of the project, after the creation of the prototype a C2C auditing of the construction system is planned using the Danish certification agency Vugge til Vugge ApS.

3. EXISTING BUILDING SYSTEMS

There is a great variety of building systems available on the construction market that deliver element based modular housing systems. These systems deliver quality solutions and fulfil various requirements using different building methods, construction techniques and building materials. Nevertheless as of today, there is no existing housing solution that delivers results fulfilling the highest functional expectations while achieving the toughest sustainability based goals based on the principles of natural building.

3.1. JØRN UTZON'S MODULAR HOUSING SYSTEM

Element based and modular housing systems are nothing new under the sun. Among others Jørn Utzon's building system is created on the basis of element based modularity (figure 15). As Utzon says (Andersen, 2018):

"A consistent utilization of industrially produced building components can only be achieved if these components can be added to the buildings without having to be cut to measure or adapted in any way."

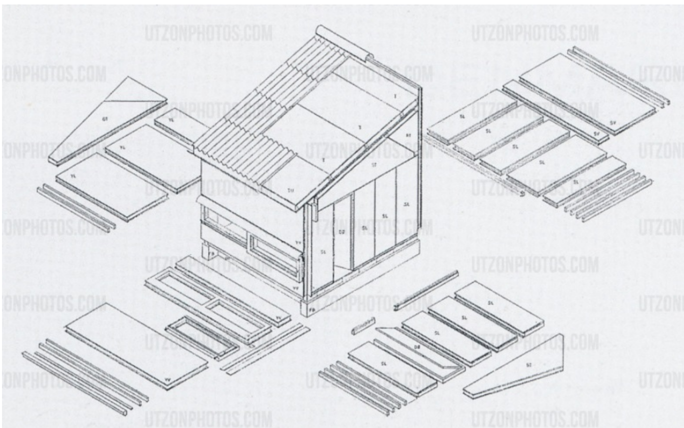


Figure 14. Utzon's additive architectural model (Source: http://www.utzonphotos.com/philosophy/additive-architecture/)

He further describes in his philosophy that *"An intimate knowledge of the materials is needed* [from the architect]*."*, which in turn relates to how we experience our environment and the buildings in it. With Utzon's own words:

"We relate everything around us to ourselves. Our surroundings affect us by their size, light, shadow, color, ect. How we feel depends very much on whether we are in the city or in the country, in big spaces or in small ones."

Utzon also have experimented with additive modularity and worked out several options on how to increase floor space and attach functional units together without jeopardizing functionality or the concept of modularity. This is illustrated on figure 16.

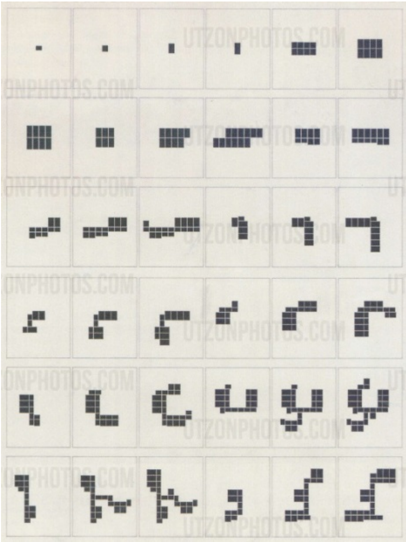


Figure 16. Utzon's sectional housing system (Source: http://www.utzonphotos.com/guide-to-utzon/projects/sectional-housing-system-espansiva/)

It is important to point out that in Utzon's time materials and technology weren't developed enough to fulfil all criteria of element based modular construction in an optimal way. This is probably the reason why his system did not reach general acceptance and spread widely. Nevertheless this system can be considered as one of the first pioneers of its kind.

3.2. KODA

Kodasema (figure 17) is a concrete element based turn-key housing system. The prefabricated elements and modules are craned in on location onto light foundations. The installation is extremely quick and the product is robust and long lasting. The system well represents the high-tech end of the sustainability dichotomy. The company takes pride in low levels of waste materials, the fact that the structural material e.g. concrete is a non-toxic material, the high-tech digital climate and other control systems and the effective VIP (Vacuum Insulation Panel) based insulation. This construction system nevertheless is highly questionable from an environmental point of view as a result of material use. The named materials are representing high embodied energy and high carbon footprint materials which are created using fossil fuel based resources. There system also only allows limited opportunities for reuse and re- or upcycling.

Figure 17. The Kodasema construction (Source: https://inhabitat.com/koda-is-a-tiny-solar-powered-house-that-can-move-with-its-owners/)

3.3. HARCON

The Harcon system (figure 18) is in principle a SIP (Structural Insulated Panel) element block consisting of two layers of sheet materials (reinforced magnesium silicate) glue laminated onto an EPS core. One element fits all, wall, floor and roof systems use the same elements. The structural integrity of the construction is ensured by the reinforced concrete columns and beams poured in the joints between the elements. The system is highly economical and easy to erect. It has very good operational characteristics (insulation, resistance to rot, no cold bridges, etc.) and the production unit of the elements is very simple in construction with very large output capacity (several thousand m^2 per month). The factory can even be a mobile unit therefore it is possible to reduce transport related environmental costs. The elements can be dismantled and reused. The greatest disadvantage of the system is that the EPS used in the system is an environmentally highly questionable material with high embodied energy need and a large carbon foot print.

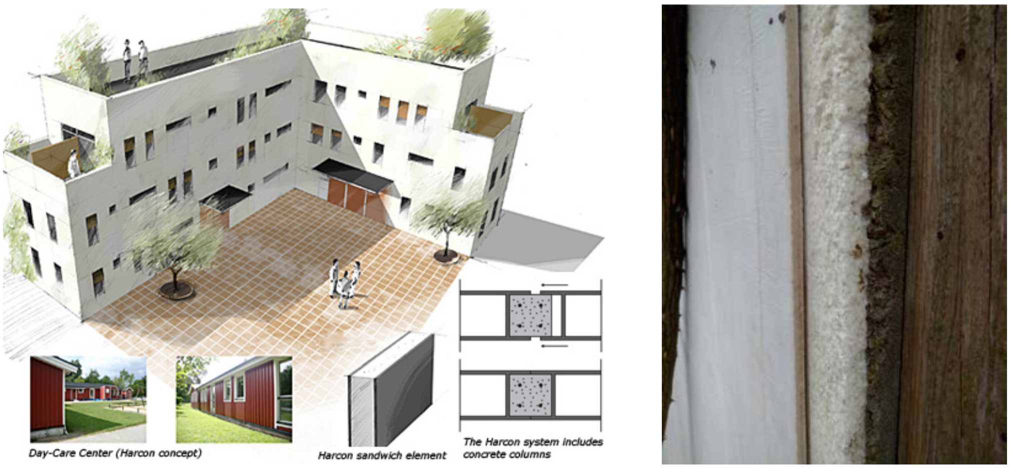


Figure 18. The principles of Harcon construction and the edge of a wall element (Source: http://harcon.se/, author)

3.4. SWIFT

The SWIFT building system (figure 19) is a carbon copy of the Harcon building system with minor changes concerning the materials. This system is using polyurethane insulation as core and wood based sheet material as inner and outer surfacing. The same principles apply to this element based system as to Harcon.

Figure 19. The SIP elements of SWIFT and a construction in progress (Source: http://www.swiftorg.co.uk/design-build/swift-materials/)

3.5. HIVEHAUS

This is basically an insulated sheet material on light framework element based modular building system (figure 20). It is based on the bee's hive octagonal shape. It uses conventional construction methods and materials. No special attention is paid to material choice concerning LCA, carbon foot-print or similar. The project intends to offer a quick to erect, functional, affordable, scalable and modular alternative to small private house design.

Figure 20. The Hivehaus system (Source: http://hivehaus.co.uk/)

3.6. TRÄULLIT HELVÄGG (NIKE ARKITEKTUR)

This is a whole-wall based panel system (figure 21) using cement-bound wood shavings as main material. The elements are prefabricated and connected together on site. The wall thickness is up to 400mm with an U-value of 0,16 W/m² ºK. It is also totally fireproof. The construction is economical to build and has good operational characteristics. A very good product to use, instead of core-insulated (EPS) concrete wall-panel systems (A-betong).

Figure 21. The Träullit Helvägg construction on site (Source: http://www.nikearkitektur.se/nike_arkitektur/Valkommen.html)

3.7. QHAUS

Qhaus (figure 22) is a German element based modular housing system, highly similar to the Hivehaus system in its basic principles. The construction is fast and efficient. It is based on conventional building technology that has been moved indoors, as all production is off site in secure weather proof locations. The ready elements are lifted in and attached on site with often even the final inner wall coverings, fittings, etc. in place. Unfortunately there is no special attention paid to material choice to improve the environmental performance of the construction. Fossil fuel based and high embodied energy materials such as Tyvek (plastic based wind proofing membrane), glass fibre insulation, etc. are used.

Figure 22. The Qhaus system. (Source: https://qhaus.eu/qhaus-timber-products/)

3.8. NUR HOLZ

Nur Holz (figure 23)This is a massive wood panel based building system. It uses cross laminated timber as structural material but the layers of materials are not attached together with glue. The primary raw material is a renewable natural material, timber (spruce) from German woods in the Schwarzwald. The system uses wooden pegs and screws to reach high structural integrity while keeping flexibility inside the panels. The panels are created according to digital design off-site in a factory than moved according to a JIT (Just in Time) system approach for installation on the actual building site. The system is robust although maybe a bit over-engineered, has excellent insulation and good fire resistance therefore it is possible to use even in buildings with several floors.

Figure 23. The Nur Holz building system explained on a study visit in Hamburg and the final product. The passivhouse - “Woodcube”. (Photo: author)

3.9. ECOCOCON

Ecococon (figure 24) is well tried out a wood-straw-clay based structural panel system. It has excellent operational characteristics, is easy and fast build with. The Ecococon constructions have low embodied carbon and energy and provide high environmentally justifiable results. The price of the constructions is comparable to conventional buildings. A disadvantage is the inflexibility of the wall panels to changes that occur after the design process is finished, such as making new openings (insulation material collapse).

Figure 24. The Ecococon system: ready house on Brunnshög in Lund; building under construction on Nesodden in Norway (Photo: author)

3.10. Facit Homes

Facit Homes (figure 25) uses CNC manufacturing based on a CAD digital design process using plywood and light weight beams as primary raw material. The product is tailored to the customers' individual needs, optimized for low operational energy need. It uses ecological insulation such as cellulose, etc. in the CNC milled "boxes" that make up the building. There is a visible commitment to make the construction system sustainable. The system is very quick to erect but after the construction of the envelope the building work (interior decoration, utilities, etc.) is carried out as within any other conventional building.

Figure 25. The principles of Facit Homes construction (Source: https://www.pinterest.se/pin/571042427729740321/?lp=true)

3.11. Wikihouse

This system uses digital design based computerized CNC milling in its production and allows users with limited experience to part take in the building process. The raw materials are partly renewable in origin, OSB or plywood sheets. The system also allows otherwise not in the natural building practice acceptable fossil based materials such as Tyvek membranes etc.. The insulation material can vary between conventional glass/rock wool and renewable origin materials such as cellulose and hemp. The main focus is on the structural system with conventional finishing techniques on the inside. Wikihouse (figure 26) is an open source product and allows anybody to download and utilize the drawings or even add to these thereby further developing the concept. This democratic revolution of the construction intends to help marginalized and economically weak groups to gain a foothold on the market. Although Wikihouse is a good concept, the environmental and economic sides of sustainability are not really thought therefore the product, as of today, can be seen mainly a digital tool development project.

Figure 26. The Wikihouse system. (Source: https://wikihouse.cc)

3.12. COMPARISON OF THE BUILDING SYSTEMS

The various systems mentioned above all have advantages and disadvantages. Dependent on the point of entry into the analysing some systems can be considered well designed while the same constructions may fail to provide adequate results against other types of criteria. This study bases its system of criteria among others on

- natural building related construction techniques allowing wider groups of the population to part-take in the building process (social empowerment)
- economic sustainability and affordable construction
- renewable, low embodied energy and low-carbon footprint based non-toxic materials
- ability to scale-up production
- element based modularity for ease of transport and workability

The following figure (figure 27) illustrates how this project looks at the previously mentioned construction systems in relation to the historic development of construction

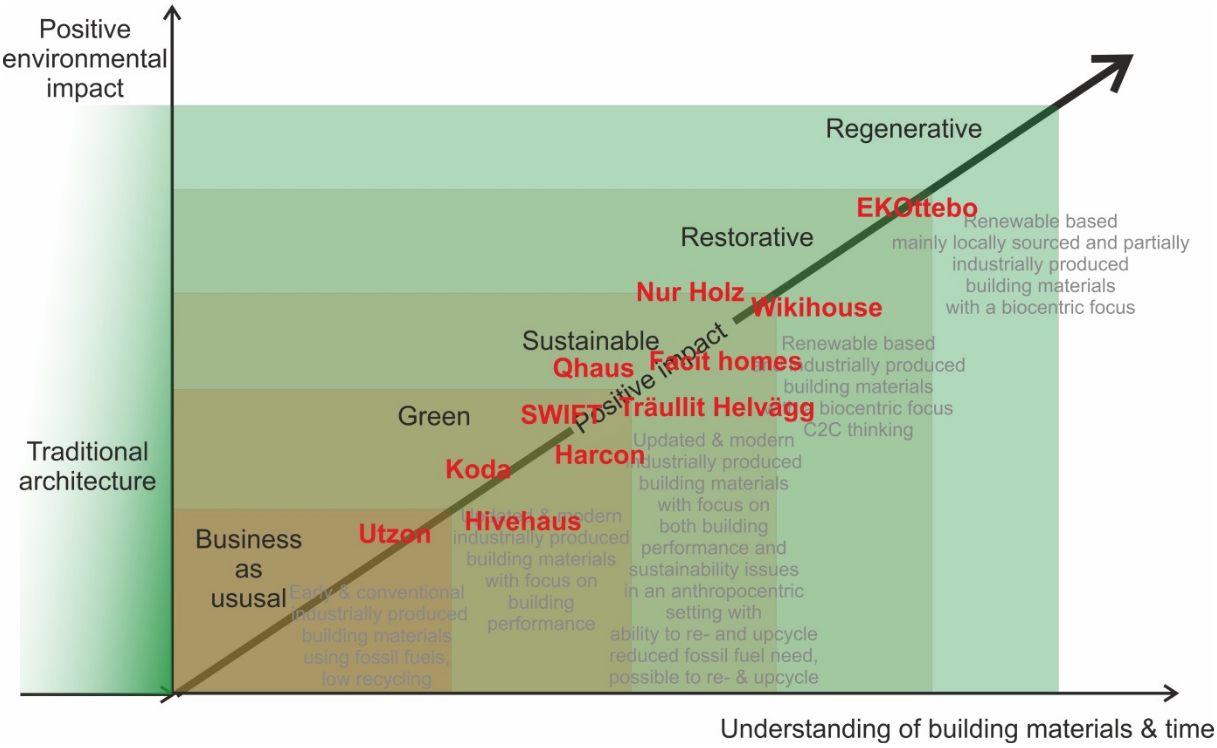


Figure 27. The development of architectural styles and practices in relation to environmental impact (Source: adapted from the material acquired at www.regenerativedesign.org)

4. SUSTAINABILITY

4.1. DEFINING SUSTAINABILITY

Sustainable development was first defined by the United Nations (United Nations, 1987), based on the Brundtland Comission's (Brundtland Commission, 1987) report:

> 'sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.'

Sustainability is a complex phenomenon and certain authors such as Röling and Wagemakers (1998) point out that only a holistic approach can reach truly sustainable systems where all subsystems are themselves are transformed. Fuad-Luke (2008) sees two alternatives to sustainability based on trade-offs: the human focused anthropocentric and the environment centred bio-centric approach. The International Institute of Sustainable Development using the Brundtland Report describes three major aspects of sustainable development (environment, economy and community) and states that sustainable development in short is

> 'Environmental, economic and social well-being for today and tomorrow' (International Institute of Sustainable Development, 2010).

Hedeberg (2018) in turn, as part of the "Natural Step movement" describes the 'Four conditions to achieve a sustainable society' the following way:

The Four System Conditions...	**. . . Reworded as The Four Sustainability Principles**
In a sustainable society, nature is not subject to systematically increasing:	To become a sustainable society we must eliminate our contributions to...
1. concentrations of substances extracted from the earth's crust	1. the *systematic increase* of concentrations of substances extracted from the Earth's crust (for example, heavy metals and fossil fuels)
2. concentrations of substances produced by society	2. the *systematic increase* of concentrations of substances produced by society (for example, plastics, dioxins, PCBs and DDT)
3. degradation by physical means	3. the *systematic* physical degradation of nature and natural processes (for example, over harvesting forests, destroying habitat and overfishing); and...
4. and, in that society, people are not subject to conditions that systemically undermine their capacity to meet their needs	4. conditions that *systematically* undermine people's capacity to meet their basic human needs (for example, unsafe working conditions and not enough pay to live on).

4.2. PRINCIPLES OF SUSTAINABILITY IN A CONSTRUCTION CONTEXT

The actual siting of the building is a major driving force in positioning the different functions within the construction. This makes multifunctional, e.g. a variable set-up of a building in certain utilization areas difficult to design, if not impossible. As an example, a private household has four major functions in a house. Living or common room, bath and kitchen, bedrooms and at last auxiliary spaces such as storage, garage, boiler room, etc.. These spaces have different requirements from the users when it comes to attributes, such as climatic qualities, air-flow and exchange, flooring and light conditions just to name a few. As Olgyay (1963 p.62) pointed out both the shape and the form of the construction just as its orientation is strictly governs its inner functional characteristics. In this project a cubical shape was used as standard, not necessarily for aesthetic reasons but as shown on figure 28 this form is closest to the ideal according to Olgyay's (1963 p.89) research in a climatic context in a cold-wet climatic zone such as Sweden has.

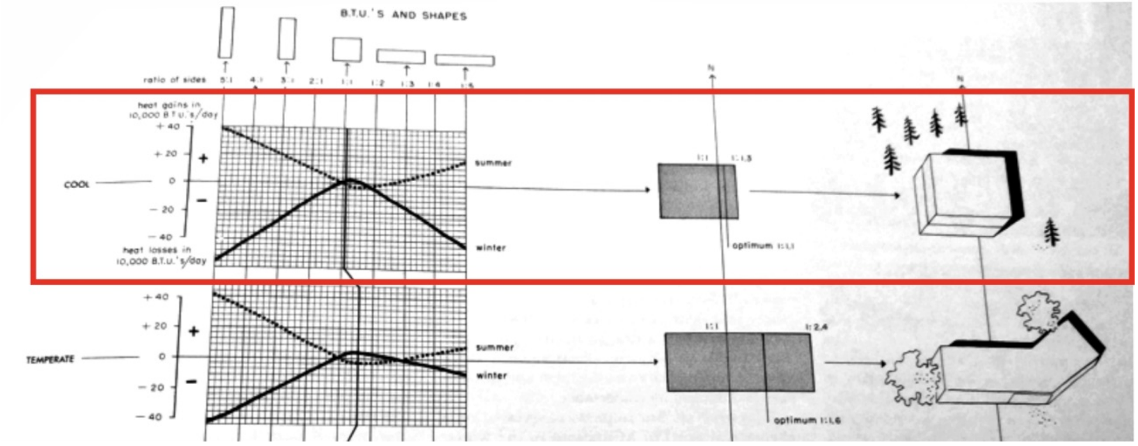


Figure 28. The optimal shape of a construction in relation to its climatic surroundings (Source: Olgyai, 1963 p.89)

The main areas that describe the sustainability characteristics of a construction according to Bokalders and Block (2010) are:

- Planning phase
- Building/construction phase
- Operational phase
    - Energy
    - Interior climate
    - Maintenance
    - Life cycle
- Demolition/reuse/recycle phase

In this project the focus was laid on the first two phases as these are the ones most strongly influencing the sustainability related characteristics of the final construction. Especially important is the design and planning phase as decisions made at this stage can still be adjusted and corrected easily without major economic losses and serious alterations influencing other parts of the project.

Berge (2009 p.35) describes the basic principles of creating climate neutral buildings thereby building sustainably through the whole of the building's life cycle by following the next points:

- Choose low impact materials and constructions
- Reduce all operational energy, in particular that based on fossil fuels
- Maximize storage of carbon

This project aims to use these points as guidelines. Unfortunately as of today there is very little effort made from both the architects' and the builders' side to come to terms with these premises. Only the second, the operational energy has been in the limelight of the building sustainability discourse as of today. The explanation given for this is that it doesn't matter how much a building material "costs" for the environment in material as long as during its life-cycle the construction “earns back” its emissions and negative impacts by low operational energy utilisation. This approach is failing from many angles. The actual life length of current constructions is ca. 50 years when it comes to private housing (Ravetz, 2008) although the planned life-cycle of the built in materials and the construction technology is planned to exceed this many times over. The reason for this is that functional requirements of housing such as size, placement and décor of rooms especially bathrooms and kitchens but especially openness and interconnectedness of spaces, changes with trends and fashion so rapidly compared to previous eras (e.g. before industrialised construction begun) that even otherwise well-functioning constructions are re-built, updated and renovated on a regular basis irrelevant of their actual functionality and condition. This trend is further aggravated by TV programmes such as interior decoration and lifestyle shows such as in Sweden “A summer with Ernst” or “Building permit” (Bygglov), etc.. In these programmes they often do alterations in a manner where they totally disrespect sustainability principles both in design, material use and construction.

Sustainable construction on the other hand does not have to be a complicated theoretical issue. The easier to understand and straightforward it’s explained and put forward the easier it is to transfer this knowledge to designers, planners, builders and decision makers. One such way is through adaptation of the sustainable tourism principles of Leslie (2007) called the 3Rs. This added with two more simple guidelines besides the requirement to procure locally create an easy to understand guideline driven by common sense:

- Rethink
- Reuse
- Refit (upcycle)
- Recycle

5. JOINING METHODS

By definition, joining is connecting two or more pieces of materials (either the same or different origin) in a long-term reliable, secure, effective and verifiable manner, which in turn is the basis of any building and construction. There are three main types of joining (Brandon and Kaplan, 1997):

- chemical (such as gluing)
- mechanical, where friction and residual tensile stresses keep the parts together (joinery, nailing, screws, etc.)
- physical (soldering, welding, etc.).

There may be several acceptable joining methods to carry out the same task although they may differ in their characteristics. Although the principles of joining materials have not changed much during the ages, the actual methods have gone through major development. This development has resulted in stronger connections and resulted in wider range of performance from given joining application, higher efficiency, shortened joining time, etc..

In this project I only intend to focus on mechanical wood-joining methods and only especially those that join two or more elements without the use of other materials (screws, nails, glues etc.) than themselves.

5.1. HISTORIC & TRADITIONAL WOOD CRAFTING METHODS OF JOINERY

Although certain traditional wooden joinery methods provide as strong or even stronger bonds than modern fasteners, they are rarely used in modern constructions. The time needed and the level of knowledge required to create these joints are often much larger than using modern fastening techniques such as nailing, nail-plates and screws. A traditional timber frame joinery construction (figure 29) well illustrates this.

Figure 29. A traditional timber frame joinery construction (Source: http://blackcanyonbuilders.net/2011/12/07/timber-frame-joinery-a-primer-on-the-joints-of-timber-frame-construction/)

Traditional joinery methods were often time consuming in their creation and required long time education and practice to acquire. With modern machinery many parts of the joinery work can be made more efficient nevertheless even in modern constructions the joinery and carpentry work are two of those areas on a building that require most skilled labour to carry out.

An integral part of this joinery method is the creation of interlocking wooden elements with a peg based reversible fastening system (figure 30)

Figure 30. Interlocking wooden elements reversibly attached together by wooden pegs in traditional joinery
(Source: http://www.newenglandbarn.com/glossary)

Modern wood joining methods in construction often rely on nails, gluing or screws. Most of these tools have been widely adapted in construction as these methods save time and require lower level of skill from the labour force. The modern methods are not necessarily better than the old ones though. Many of the old methods of joinery, such as used by both Japanese carpenters and in western areas traditionally (the so called timber frame joinery where barns and house frames were constructed) were found to be more than being able withstand the battering of time's tear and wear. They are especially interesting from a sustainability point of view as these methods provide flexible joining, which results in great strength even in areas where seismic problems occur or where the construction is exposed to high humidity fluctuations, uneven loads from winds, unstable grounds or other forces. These joints age differently than modern ones. They do not corrode like metal fasteners do and don't become brittle with age as plastics (glues) do. Traditional tithe barns, timber framed houses and various roof constructions such as the Glastonbury Abbey barn's nearly 700 years old roof as shown on figure 31 are witnessing the time-proven value of these joining methods.

Figure 31. The original 14th century timber frame roof structure of the Glastonbury Abbey barn. (Photo: author)

5.2. MODERN WOOD CRAFTING METHODS OF JOINERY

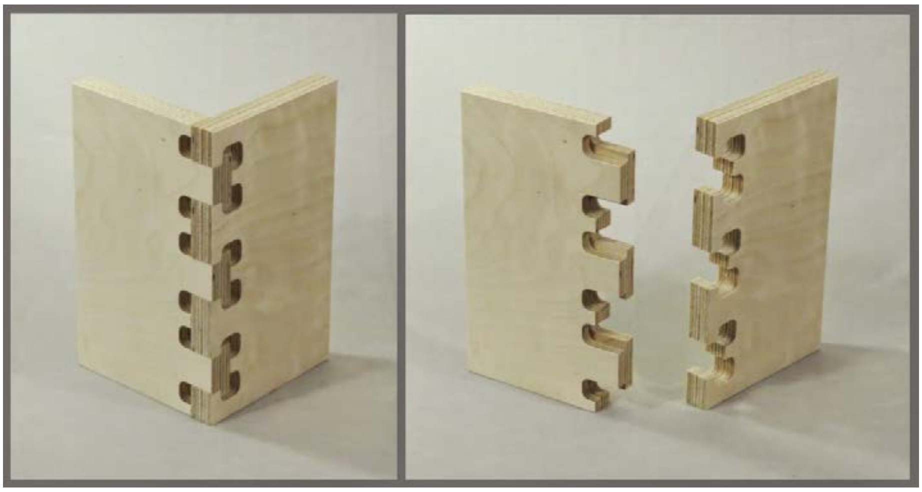
The latest in modern methods of joinery in wood relies on digital processing of the elements. This basically can be done by either of the two digital subtractive methods available today, CNC milling or laser cutting. Figure 32 shows these two machines besides each other. Bothe machines can work with standard size wood based sheet materials such as plywood, chipboards and MDF among others.

While CNC milling machines use a hard-metal drill to cut and mill out various shapes according to the digital design the laser cutting technology uses a gaseous-agent (i.e. CO_2) based laser beam to cut the shapes and forms out of the material. While laser cutters can burn various superficial designs as well by using lower beam strength CNC milling can cut at desired depths within the material thereby creating special joints that laser cutters can't produce. On the other hand laser cutters can cut corners with very little radius (a fraction of a millimetre) while CNC machines have a rounded profile when cutting inner corners which may be inadequate for certain joinery methods. To come around this problem CNC milling uses run-over lines to cut 90° angled elements.

Figure 32. Laser cutting machine from Eurolaser and CNC milling machine (Source: https://www.eurolaser.com/laser-systems/laser-systems-for-wood/l-3200-wood/ and https://www.ebay-kleinanzeigen.de/s-anzeige/cnc-fraesmaschine-2200x2000-fraese-portalfraesmaschine-portalfraese/617045977-249-1151)

These methods offer several advantages compared to traditional joinery, such as:

- the design and planning process can be separated from the actual production,
- as a result of the previous local production is possible which in turn saves on transports
- the raw materials can be utilised to near 100% resulting in a low level of spill (usually >2%)
- the cost of production is low, as a result of low labour requirements
- there is only a few skilled workers needed to operate the machines
- the machines can work around the clock which further increases machine utilization and decreases cost of production
- it is relatively cheap to operate these machines in relation to their output quality and volume
- the accuracy of production is down to a fraction of a millimetre which provides excellent reproducibility
- these machines although requiring significant capital investment are not beyond reach of the average small-middle sized business



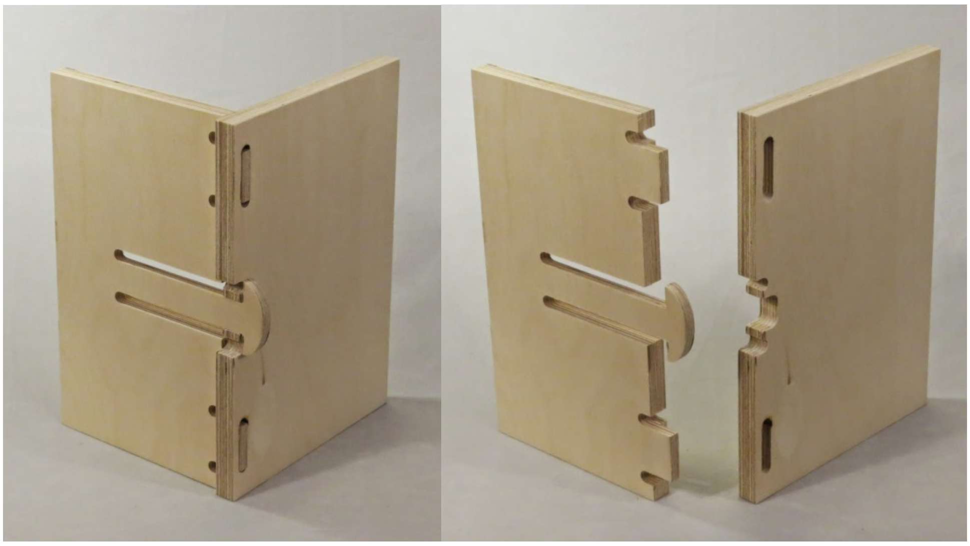


Figure 33. Modern joinery methods – CNC milled attachment examples with and without securing pegs. Note the rounded overruns where as a result of the radius of the cutting tool. (Source: http://mkmra2.blogspot.se/2014/08/cnc-cut-wood-joinery.html)

Figure 34. Modern joinery methods – Laser cut chair as an example. Note the straight lines and 90° angles with hole and in inner corners. Rounded corners and designs are still possible to create but overruns are not necessary as laser beam has under millimetre radius. (Source: https://inhabitat.com/this-flat-pack-laser-cut-furniture-assembles-without-glue-or-bolts/)

Figure 35. below shows the test results of the laser cutting procedure on various materials that are planned to be used in the EkotteBo construction system. LVL and plywood in various thicknesses and Banova were tested on site in the Eurolaser test facility outside Hamburg. It was found that laser cutting is a very useful and economically viable method in creating element based systems such as planned here but the quality of the raw material (glue, evenness, inner cavities, thickness and askewedness, etc.) besides the thickness and hardness of the material has strong influence on the features of the output.

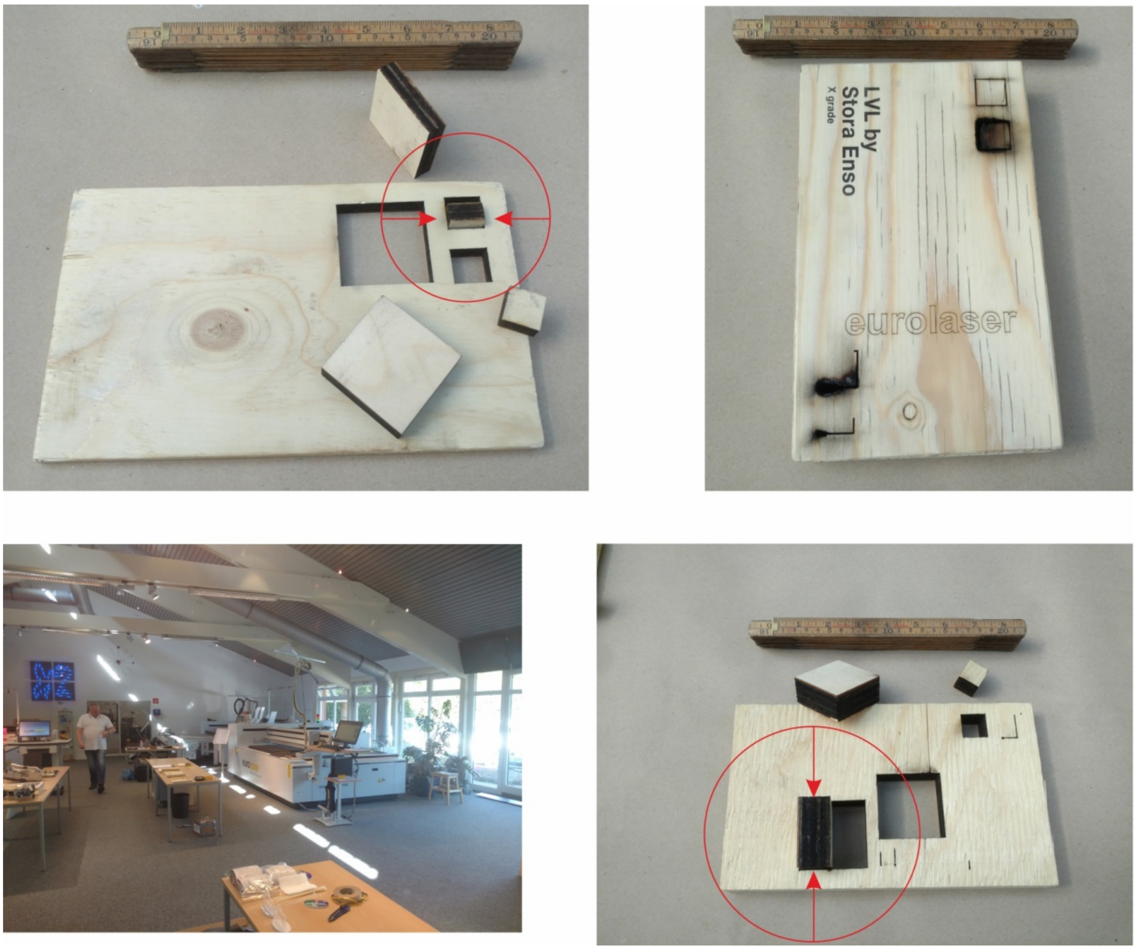


Figure 35. Eurolaser testing facility and some of the test results. Note the burn marks on the material and the excellence concerning cutting accuracy with only ca.0,2-4mm gap between the cut surfaces – marked with red (Photo: Author)

6. MATERIALS

Berge (2009 s.XV) in his work, "The ecology of building materials" describes four different aspects of building materials

- *Work. The methods used to produce each building component. How production takes place and can take place.*
- *Raw materials. Occurrence of material resources, their nature, distribution and potential for recycling.*
- *Energy. The energy consumed when producing and transporting the materials, and their durability.*
- *Pollution. Pollution during production, use and demolition, the chemical footprint of each different material.*

He also points out that there is a large number of building materials on the market that claim to be sustainable without having the right credentials that fulfil all criteria of such materials. He therefore aims to

…contribute towards reducing misleading advertising information. Green products are now much in demand, and many producers are claiming to fit this mould without apparent justification.

This project is focusing on using only three basic materials with minor completion of additional materials that may or may not be renewable in their origin. The basic characteristics of these three materials in relation to steel, which is not used here but otherwise commonly utilized in architecture nowadays are shown in table 2 below:

Material	Density	Embodied energy	Availability	Embodied Carbon
Plywood	500 - 650 kg/m^3	15 MJ/kg	Good	0,221 $kgCO_2eq/kg$
Straw	100kg/m^3	0,24 MJ/kg	Good	0,005-0,0063 $kgCO_2eq/kg$
Clay	ca.1600kg/m^3	0,5 MJ/kg	Good	0,116 $kgCO_2eq/kg$
Steel	ca.7700kg/m^3	24-35 MJ/kg	Good	0,482-0,789 $kgCO_2eq/kg$

Table 2. Characteristics of some of the materials used in the project concerning their environmental impact. It is clearly visible that these materials have very limited negative influence on the environment. (Source: https://www.grisb.org/publications/pub33.htm, http://opus.bath.ac.uk/12382/1/Hammond_%26_Jones_Embodied_energy_%26_carbon_Proc_ICE-Energy_2008_161%282%29_87-98.pdf)

1		2a	2b	2c	3	4	5
Material		Global warming potential GWP			Acidification potential AP	Poisons and ozone depleting substances	Waste category
		Basic impact	Negative modifyers	Positive modifyers		[See Table 2.5]	
		[g CO_2-equ./kg]	[g CO_2 /kg]	[gCO_2/kg]	[g SO_2-equ/kg]		
	Porous boards, wet process	1600	–825	–	9	–	A/D
	Porous boards, dry process	1300	–775	+90	4	54-73-6	B/D
	Porous boards with bitumen	1400	–775	+300	10	12	B/D
	Hard boards	1500	–825	–	5	72-31	A/D
Woodwool cement slabs		1600	–400	–	5	78-30-85	D
Chipboard		700	–775	+200	2.5	72-45	B/D
Plywood		750	–825	+100	0.5	72-45	B/D
Flax fibre	Matting glued with polyolefin/ polyester fibres	1650	–700	+450	11	15-43	B/D
Linoleum		1020	–400	–	1.5	94	B/D
Hemp fibre	Matting glued with polyolefin/polyester	1400	–775	+300	13	43	B/D
Straw bales		5	–800	–		–	A/D
Cellulose	Loose fill 100% recycled	230	–800	–	2.2	45	D
	Matting from fresh fibre, glued with polyolefin/polyester	1600	–775	+300	12	43	B/D
	Building paper, 98% recycled	300	–825	–	0.3	–	A/D
	Building paper with bitumen	320	–750	+600		12	B/D
Cardboard sheeting	Laminated with polyvinyl acetate	400	–775	+100		–	B/D
Wool	Matting glued with polyester	500		+300	5.5	43-15-77	B/D
Recycled textiles	Matting glued with polyester	1320	–325	+300	3	43	B/D

Note: The table is compiled and based on many sources, a.o. Kohler et al., 1994; Weibel et al., 1995; Fossdal, 1995; Gielen, 1997; Mötzl et al., 2000; Krogh et al., 2001; Pommer et al., 2001; Thormark, 2001; Nemry, 2001; Fossdal, 2003; Buschmann, 2003; Jochem et al., 2004; IBO, 2006; Mühlethaler et al., 2006; Hammond et al., 2006; Schmidt, 2006.

The Ecology of Building Materials

Table 3. Comparative table of the environmental impact of some building materials used in construction. Some of the materials used in this project are marked with red. (Source: Berge, 2009 p.46)

6.1. STRUCTURAL MATERIALS

Plywood was chosen as structural construction material. Massive wood and LVL could also be used as it has similar characteristics to plywood but the thickness of the material is a major factor with cutting out the elements therefore massive wood was discarded as option. Vänerply (now part of the Moelven Group) was chosen as supplier, as their product had the best environmental characteristics in comparison to the products price, while allowing ease of production and the use of digital production methods. This plywood (table 4) emits minimal VOCs as described by Vänerply (2011):

Vänerply is exempt from the regulations of Chemical Inspection Board concerning formaldehyde levels as these values are very low and comparable with levels in massive wood [translated from Swedish – author].

FORMAT MM	TJOCKLEK MM	ART.NR	ANTAL ST/BAL	M²/BAL	VIKT KG/M²	ANTAL PLY
2400x1200	9	1090100	80	230,4	4,4	3
2400x1200	12	1120103	60	172,8	5,8	3
2400x1200	12	1120105	60	172,8	5,8	5
2400x1200	15	1150100	50	144,0	7,3	5
2400x1200	18	1180105 1180107	40	115,2	8,7	5 7
2400x1200	21	1210100	35	100,8	10,2	7
2400x1200	24	1240100	30	86,4	11,6	9
2700x1200	12	27001200120105	60	194,4	5,8	5
2700x1200	15	27001200150100	50	162,0	7,3	5
2700x1200	18	27001200180107	40	129,6	8,7	5
3050x1200	12	30501200120105	60	219,6	5,8	5
3050x1200	15	30501200150100	50	183,0	7,3	5
3050x1200	18	30501200180107	40	146,4	8,7	7
VÄGG ERGONOMI						
2440x900	12	24400900120105	50	109,8	5,8	5
2400x610	12*	5120105600	60	87,8	5,8	5

Table 4. Technical varieties of Vänerply. The sizes used in this project are marked with red.

Plywood is a very suitable material for digital production as it has standardised sizes with small tolerances and even quality. It qualifies as a sustainable renewable origin material as it contains only 1-2% of glue which in turn can also be of renewable origin. As Berge (2009 p.340) describes its production:

Plywood consists purely of different veneer layers glued together. The adhesive used nowadays is usually urea or phenol glue in a proportion of about 2% by weight. Animal, casein and soya glue give good results as well.

During discussions with peers (architects, natural-builders and eco-designers) on a study trip to Germany it became clear though that the environmental performance of plywood can vary greatly dependent on the producing company and the actual methods used. Further testing therefore may be required. Another alternative is laminated veneer lumber (LVL) sheets (table 5). Its main characteristics are shown in Table… These also only contain a few percent of glue but has a wider range of thicknesses and can be more appropriate as structural elements than plywood. Two producers with similar products were approached in this project, Stora Enso and Dold. It was decided that for the time being not to use LVL in this project as this material is more expensive than plywood and at a test in Hamburg it was found to be less optimal for laser cutting.

Basic information	Laminated Veneer Lumber (LVL) is an advanced wood product suitable for a wide range of structural applications, from new build to repair. Being one of the strongest wood-based construction materials relative to its weight, LVL provides an ideal solution when strength, dimensional stability and high load-bearing capacity are essential – not forgetting the homogeneous quality and good workability. CE-marked. Produced and monitored according to the harmonised standard EN 14374 in Finland.
Use	Structural applications; studs, post-and-beam frames, wall, ceiling and roof panels
Maximum width	2500 mm
Maximum thickness	75 mm
Maximum length	24 m
Wood species	Spruce (Picea abies)
Adhesives	LVL is consisting of multiple layers of veneers that are bonded together with brown phenolic resin. Top face veneer scarf joints are bonded with clear melamine-formaldehyde resin. LVL meets the formaldehyde emission class E1 according to standard EN 717-1.
Moisture content	8...10% at delivery
Surface quality	Intended for non-visual end usages. Standard LVL is delivered unsanded with a clear glue line on the top face. Calibration and sanding available on request.
Weight	Mean density 510 kg/m³
Thermal conductivity λ	0.13 W/(mK)
Specific heat capacity	c = 1800 J/(kg K)
Usage class	Service classes 1 and 2
Fire class	D-s1, d0 (EN 13501-1)

Table 5. The basic attributes of LVL (Source: LVL by Stora Enso. Technical brochure. www.storaenso.com/woodproducts)

6.2. INSULATION

6.2.1. PRINCIPLES OF STRAW BALE INSULATION

Natural and renewable insulation materials have various advantages in comparison to conventional industrially produced ones, although are also having limitations that have to be calculated with during the construction process. As Sutton et.al. (2011) when describing the multifunctional characteristics of renewable based insulating materials states:

"Natural fibre insulation products can often be used as replacements for mineral- or petrochemical-based insulation. When used appropriately, natural fibre insulation materials can deliver thermal and acoustic insulation comparable to other insulation materials, but with a lower or potentially negative carbon footprint and fewer health issues during installation. They can also assist in regulating relative humidity, and can provide a vapour permeable system. "

Table 6 details the general attributes of such materials.

Advantages	Disadvantages
• High acoustic performance • Low to zero toxins, easy to reuse/dispose of, significant health benefits throughout life cycle • Offers some thermal mass • Protective clothing and masks not needed, more comfortable for installers and others coming into contact with it • Renewable materials store carbon throughout usable lifespan • Robust in handling, transportation and onsite construction • Vapour permeable, works well with other low-impact materials • Often possible to procure or produce locally	• Most products manufactured overseas and imported (Swedish context) • Price currently significantly higher than oil- or mineral based competitors (this may be reduced as demand and supply increase) • Requires thicker walls • Suitability of rendered external finishes limits application • Use limited to above damp-proof course or equivalent level

Table 6. Advantages and disadvantages of natural synthetic insulation materials such as straw. (Source: Sutton et al. 2011)

It is important to point out that as shown in the table above the industrial e.g. synthetic and the natural material based insulating materials have very much the same thermal conductivity and similar types of available formats on the market. Nevertheless, overwhelmingly it is synthetic insulating materials that are today used in the construction sector. One may ask why?

Material	Typical thermal conductivity (W/m/K)	Commonly available formats
Natural materials		
Wood fibre	0.038–0.050	Boards, semi-rigid boards and batts
Paper (cellulose)	0.035–0.040	Loose batts, semi-rigid batts
Hemp	0.038–0.040	Semi-rigid slabs, batts
Wool	0.038–0.040	Semi-rigid boards, rolls
Flax	0.038–0.040	Semi-rigid boards, rolls
Cork	0.038–0.070	Boards, granulated
Synthetic materials		
Mineral fibre	0.032–0.044	Boards, semi-rigid boards, rolls
Glass fibre	0.038–0.041	Boards, semi-rigid boards, rolls
Extruded polystyrene (XPS)	0.033–0.035	Boards
Expanded polystyrene (EPS)	0.037–0.038	Boards
Polyurethane (PUR)/polyisocyanorate (PIR)	0.023–0.026	Boards

Table 7. Comparison of the technical performance of natural and synthetic insulation materials (Source: based on Sutton et.al. 2011; Berge 2009)

As table 7 above shows substitution of glass- and rock-wool insulation with natural, renewable materials don't have to lead to reduced performance. Historically straw has been used as insulation material. The oldest still existing and lived in straw bale house is in Bayard, Nebraska, which was built around 1896 (D'Errico, 2010). Bale-houses exist since the 1800s and several modes of application were developed. Traditionally there are two main types of straw bale construction with several varieties in between.

Figure 36. The oldest European straw bale house in France, built in 1925. (Source: http://lloydkahn-ongoing.blogspot.co.uk/2013/02/oldest-straw-bale-house-in-europe-for.html)

Straw bale as principal insulation material was chosen in this project for the following reasons:

- Straw is a side product of cereal production in agriculture that is produced in very large quantities. Although some of it is used as for example bedding for animals, industrial use, there are large surpluses available for construction related purposes.
- Straw is the stem and in smaller amounts the leaf of cereals such as wheat, corn, rye or oats. Because of its hollow pipe like nature still-standing air is trapped inside the pipe like structures which provide excellent insulating properties.
- It doesn't contain nutritious ingredients such as seeds, only cellulose and lignin e.g. for animals hard to digest parts, therefore rodents and insects (ants, termites, cockroaches, etc.) are not drawn to it.
- Normally bales built in a construction have to have a humidity content less than 14% (Lacinski and Bergeron, 2000 p.78) or according to Summers et al. (2003), less than 20% which hinders fungal growth and microbial activity, therefore the construction is kept sound and the indoor environment healthy. This is easily kept with correct bale handling.
- The size of the bales is standardised, therefore it is possible to easily plan and industrialise production thereby making it also very efficient concerning resource use, labour requirements and technical workability. There are three major size types of the rectangular type bales, which have two of their size parameters (height & width) standardised. Figure 37 shows the standard bale sizes and their weights as used today.
- Straw bale insulation has good sound insulation capacity, especially when combined with lime/clay rendering.

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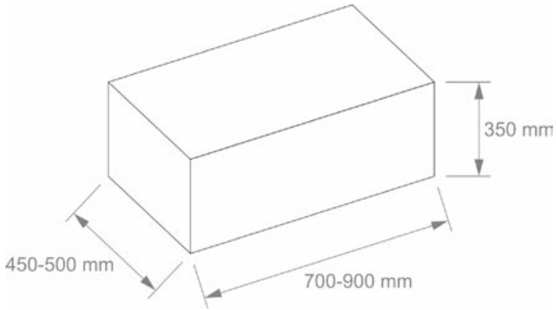


Bale Type	Approx.Weight	Approx.Size (metres)
Hesston	500kg - 550kg each	1.2 x 1.2 x 2.5m
Quadrant	250kg - 350kg each	1.2 x 0.7 x 2.5m
Mini Hesston 4750 or D1010	240kg - 290kg each	0.8 x 0.9 x 2.5m
3/4 Hesston	400kg- 500kg each	1.2 x 0.9 x 2.5m
Conventional Bales	18kg - 20kg each	0.35 x 0.75 x 0.9m

Figure 37. Standard bale sizes and their weight together with the details of the most common building bale, the small bale. (Source: http://www.hay-straw.co.uk/bale-sizes, (Gruber et al., 2008 p.7)

- The density of straw bales is possible to adjust on the baling machine to achieve best isolative performance while still allowing flexibility to adjust the shape and size of the bales even in organically formed constructions (curved, tapered, etc. structures). Most often builders' bales have a density of 100-120kg/m^3 (Gruber et al. 2008).
- Straw bales unlike conventional sheet or roll-based insulation, such as rock- or glass wool, have a structural integrity and stability that is kept for a long time. There is no shrinkage, material collapse, the bales keep their form and size therefore there is no risk for the development of cold bridges. This has been proven by thorough testing as shown on the website of the Austrian Straw Bale Network (Gruber, 2018).
- Straw is a natural material which is harmless both to builders and users of the ready product (house). The only protection used is often a light face mask to reduce dust inhalation, but even this is not really necessary.
- The bales used in most straw bale constructions are light, weighing a maximum of ca.20kg therefore they are easy to handle for builders of all ages and gender.
- As it's a side-product, it is very much affordable. The average small bale costs in Sweden roughly between 6-30 Swedish crowns at the writing of this thesis in 2018, which is about €0,65-3, where the latter figure shows certified "builder's bales".

6.2.2. HUMIDITY RELATED ISSUES IN STRAW BALES

The single greatest issue other than the often misinterpreted fire-hazard concerning straw bale insulation is related to humidity. Humidity, e.g. equilibrium moisture content in normal cases do not exceed 18% and usually expected to be between 13-18%. This figure is not fixed as the material just as many building materials change its humidity content via sorption and absorption dependent on the relative humidity of the surroundings. This is further illustrated by figure 38.

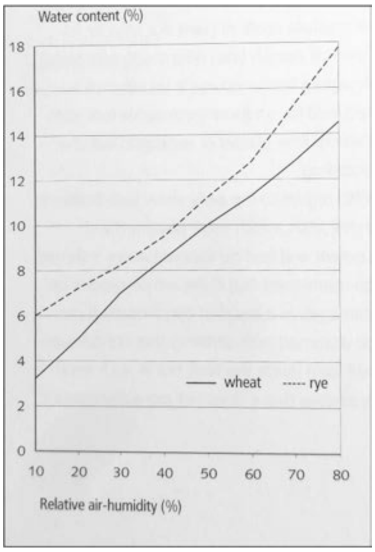


Figure 38. Sorption curves of rye and wheat straw in relation to relative humidity (Minke and Mahlke, 2005 p.32)

Jeppson and Ramberg (2014) in a study examined different types of straw bale constructions from a humidity point of view. They point out that unventilated facades e.g. those that do not include ventilated weather-boarding are not ideal for straw bale constructions, as a risk exists that especially in wet-cold climates indoor to outdoor humidity transfer occur through the construction which may result in mould and fungal problems. Minke et. al (2005 p.31) also carries the same argument and instructs straw bale construction builders to use vapour resistant e.g. barrier effect type surface treatments on the inside of walls to reduce the vapour load on the bales and allow the ventilated façade to carry out more humidity from the wall than what's coming into it though diffusion. This is especially true when the exterior render has higher resistance to vapour diffusion (see figure 39), such as in most cases where lime based plasters are used outside, while clay based on the inside. They also point out that even with an increased clay-plaster thickness on the inside this effect can't be efficiently countered.

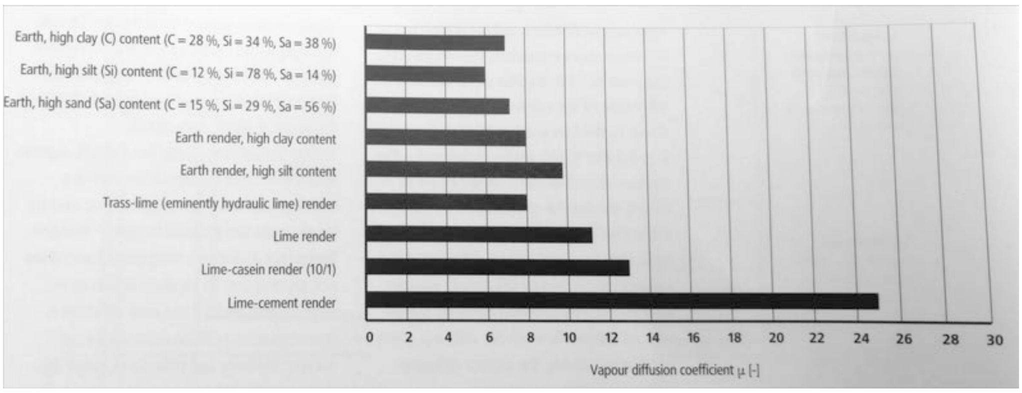


Figure 39. Vapour diffusion of different types of stucco. (Source: Minke and Mahlke, 2005 p.32)

In this project clay and lime/clay based render is used as air flow barrier (instead of a membrane) which still allows vapours to transfer through the material. The same system is planned to be used in wall, floor and ceiling constructions. Clay render on the inside also acts a vapour buffer providing superior indoor climate. The inner rendering of walls, floors and ceilings are also treated with certain agents (lin-seed oil, salts and capillarity hindering agents in the mixture) to achieve a more sluggish vapour diffusion into the construction. Thereafter vapour can be naturally carried out of the construction on the outer side where the chimney effect of the ventilated weatherboarding continuously works on drying out the construction. As long as the drying out is more vigorous than the supply via diffusion from the inside, the bales stay "dry" therefore mould and fungal problems are avoided. To monitor humidity related issues in the construction remote humidity sensors are planned to be built in the construction.

6.2.3. FIRE HAZARD IN STRAW BALE CONSTRUCTIONS

The Austrian Straw Bale Network (Gruber, 2018) on its website gives proof of several independent research institutes organizations including ÖNORM, Technische Universität Wien (shown under here on figure 40), FASBA, Bee Rowan (official fire testing by the standard BSEN 1365-1 1999), etc., which carried out extensive testing of straw bale constructions in relation to fire hazards. Their findings show that dependent on the handling and use of straw bales in the construction the results concerning fire hazard range from "normal" to "highly resistant" to fire. For further information please visit the website at http://baubiologie.at/strohballenbau/strohballenbau/zertifikate-tests/ (in German).

Gruppe Angepaßte Technologie
Technische Universität Wien

Wiedner Hauptstrasse 8-10
1040 Wien

MAGISTRAT DER STADT WIEN
MA 39 – VFA

MA 39 - VFA 2000-0644.04

Wien, 6. Oktober 2000

Prüfbericht

über

das Brandverhalten einer Strohballenwand (mit Innen- und Außenputz)

Antragsteller:	Gruppe Angepaßte Technologie Technische Universität Wien
Antragsdatum:	7. Februar 2000
Prüfgut:	Strohballenwand in einer Holzständerkonstruktion eingebaut, beidseitig verputzt; Gesamtdicke 43 cm
Prüfprogramm:	Prüfung der Strohballenwand als nichttragender, raumbegrenzender Bauteil hinsichtlich der Brandwiderstandsklasse F90 gemäß ÖNORM B 3800-2, Ausgabe 1997.
Kurzbeurteilung:	Auf Grund der Versuchsergebnisse hat die geprüfte Strohballenwand, eingebaut in einer Holzständerkonstruktion, einem Lehm-Innenputz (2 cm), und einem Kalk-Außenputz (2 cm), mit einer Gesamtdicke von 43 cm, die Anforderungen an die Brandwiderstandsklasse F90 (brandbeständig) gemäß ÖNORM B 3800-2, Ausgabe 1997, erfüllt.

neu

Der Bericht umfasst 4 Seiten und 1 Beilage (8 Seiten).

Figure 40. F90 fire test result of a clay rendered straw bale wall with wooden studs. (Source: Gruber, 2018)

6.3. SURFACING & FINISHING MATERIALS

Clay have been chosen as the generally used surfacing material in this project. Clay is a soil material (Berge, 2009 p.120) made up of electrically charged and thereby interconnected particles, which have smaller size than 0,002mm per particle. This fraction is most often mixed with other fractions (silt 0,002-0,06mm, sand 0,06-2mm, gravel 2-64mm) and other organic and non-organic materials. Clay has several advantages in comparison to cement or even lime based rendering products. Berge (2009 p.123-124) lists the following advantages using clay as a building material:

- *it is based on a resource that is abundant in nearly all countries. In many cases the material can be excavated on site.*
- *it requires far less energy than is needed for concrete and fired brick buildings.*
- *if it is carried out correctly, it has a long life expectancy.*
- *it is based on reasonable and simple building methods which make self-help feasible.*
- *it provides good indoor climate due to its temperature and moisture regulating properties.*
- *unfired earth materials can be returned to nature more easily than any other material.*

It is also a recommended rendering and stucco material according to Bokalders and Block (2010 s.77). Sand mixed in surfacing materials is a finite resource although has a low embodied energy (0,5MJ/kg) (Berge, 2009 p.121) but in an unfired clay based utilization is a retrievable material using sedimentation based techniques.

Clay based surfacing materials e.g. render or stucco are mixed up by using clay and sand in a 1:3-4 water based mixture with additional materials such as vegetable fibres, salts, oils, manure/urine and other potential small-amount additives such as animal and vegetable-based glues, dependent on the actual type of use. Recipes vary dependent on local circumstances, climatic and technical factors and traditional methodology. These additives greatly influence the attributes of the final material, such as vapour permeability, shear and compressional strength, water resistance, curing time, etc.. The mixture can also either be mixed in with pigments or different colours of clay can be used to create in its material coloured render mixes. Even quality, well tried out and tested “ready mixes” are available commercially among others from two major German commercial players Conluto and Claytec.

The greatest disadvantage of clay based surfacing materials is sensitivity to frost during construction, shrinkage while curing and sensitivity to dampness even after completion and labour intensiveness in application.

Clay renders have several advantages as well in comparison to conventional renders. As for one there is in principle no waste with application as all waste can be reused even at later dates. The material is not corrosive therefore tools are easily kept clean and unharmed. Clay is also very user friendly concerning labour, there is no need for protective clothing or gloves. The material doesn’t dry or hurt the skin like cement or lime based render does. Tools can be fully cleaned (after some thorough soaking in plain water) easily any time even after extensive use and in case of careless and lazy staff who doesn’t like cleaning after themselves. The tools needed to work with clay as building material are also very simple and are not expensive to acquire. Several of the processes can be mechanised, such as pneumatic spraying, mixing, etc.. A full set of tools is shown on figure 41.

Figure 41. Basic clay working tools. (Photo: author)

It is also important to point out that smaller mechanical damages (scratches, faults, cracks) on the clay rendered surface can easily be repaired by wetting the surface and rearranging the material with adequate tools any time during the products lifecycle. Figure 42 shows clay rendering in progress.

Figure 42. Wall reparation and floor laying using clay. Note the lack of protective clothing. (Photo: Julio Perez)

Table 8 details these attributes in relation to some usually occurring surfacing materials. The table is colour coded for ease of understanding where green signifies the most advantageous while more reddish colour less favourable characteristics.

Material	**Clay**	**Gypsum**	**Lime**	**Cement (Portland)**
Density (kg/m^3)	1650-1700	670	1400	2700-3000
Thermal conductivity (ʎ= W/mK)	0,8-1,3	0,25	0,7	0,3
Thermal capacity (J/kgK)	920-1000	1090	1000	670
Vapour permeability	Very good	Medium-low	Good	Low
Humidity regulating capacity	Very good	Moderate	Moderate	Low
Opportunity to colour	Very good	Very good	Good	Medium
Acoustic properties	Very good	Good	Good/ Very good	Very good
Corrosiveness (PH)	Low (neutral)	Low (mildly alkaline)	High (strongly alkaline)	High (strongly alkaline)
Flexibility (to take up movement of the base material)	Good	Low	Good	Low
Water resistance	Low (can be improved to medium)	Low (can be improved to medium)	Medium-good	Good
Reusability	Very good	Good	Medium	Low
CO_2 footprint (g CO2/kg)	116	243	750 (CO_2 emission largely rebound during setting)	860
Thickness	30-50+mm	3-7mm	5-15mm	3-20mm
Local production & procurement	Possible	Not-possible	Partially possible	Not-possible
Production temperature	-	200°C	900-1000°C	1200-1400°C
Embodied energy (MJ/kg)	0,5	1,2–1,4	4,5–5,0	3,6–4,0
Potentially dangerous additives	Non-typical, other than pigments	Non-typical, other than pigments	Non-typical, other than pigments	Yes e.g. retardants, etc.

Table 8. Some basic physical attributes of different rendering materials. Colour coding of total performance from an environmentally conscious constructional point of view is as follows: Excellent, Good, Medium, Bad. (Sources: (Berge, 2009, Bokalders and Block, 2010) berge p.62, 85, 121, 315-316, Bokalders p.76 http://www.greenspec.co.uk/building-design/thermal-mass/ , https://clay-works.com/product-descriptions/, https://www.scribd.com/document/90936359/Thermal-Conductivity-of-Solids)

6.4. FASTENERS, MEMBRANES AND ADDITIONAL MATERIALS

6.4.1. FASTENERS

One of the main goals of the project was to avoid the use of industrially produced e.g. highly engineered materials and tools. These, here included screws, nails, nailing assembly plates, etc. as these not only increase the cost of the total construction but most often require specialist equipment and thereby connected education, possibly combined with experienced enough staff when using these.

Another aspect behind trying to reduce the use of industrially produced materials was that these materials often have high embodied energy as they are mostly made of metals and materials using fossil fuels during the production process. Reversibility was important when deciding over connecting methods, as C2C principles require possibility to take apart constructions (and reuse them) without damaging the actual elements. Although many of the modern joining methods used in construction are reversible (e.g. use of screws) it is most often not removed when buildings are dismantled, as this process is rather labour intensive. This results in discarding of the materials which in turn reduce their environmental performance. Glues were also considered as a viable alternative for adjoining elements, but the lack of scientifically supported information and their relative sensitivity to humidity made it impossible to rely on traditional glues (bone/skin) glues.

The aggregated result of the previously mentioned factors was that in most cases, the construction relies on traditional joinery methods in connecting pieces of the construction. These come in various forms and shapes and are fully possible to dismantle, furthermore can use the same material and production methods as the rest of the construction elements. Some of the fasteners used in this project are shown on figure 43.

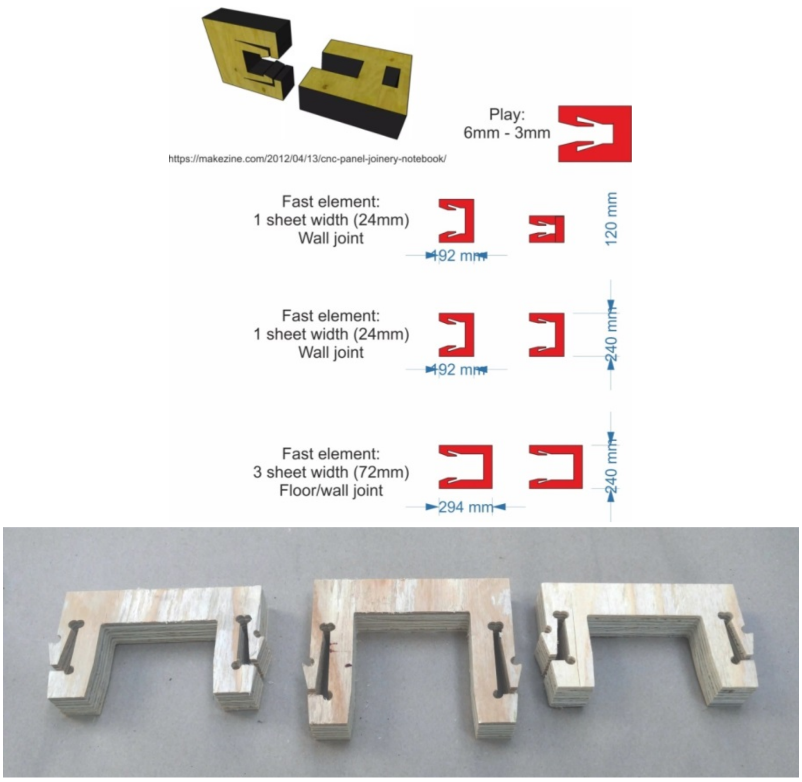


Figure 43. Some fasteners in the drawing and in the prototype (CNC) phase. Note that these are reversible joining pegs although a securing mechanism (flexible notches) is part of the design. These pegs both in shape and function are closely related to and originated from traditional joinery based fastening methods.

6.4.2. SEALANTS, TIGHTENERS AND PUTTIES

Unfortunately it was very difficult to find acceptable materials to fulfil modern requirements for these purposes. Around windows and doors traditional hemp, cellulose or flax strips are planned to be used. As sealant linseed oil based putties are viable alternatives to modern materials which often contain VOCs such as isocyanates. Otherwise as Bokalders and Block (2010 p.95) points out that in certain areas it is acceptable to use acrylate-based putties and silicone sealants (e.g. bathrooms and wet-rooms).

6.4.3. ADDITIVES

The insulation of the modules is planned mainly to use straw bales, in case of thinner wall structures hemp or cellulose insulation. Straw bales can be sprayed with additives such as boric acid to reduce the risk of fungal development. As Berge (2009 p.91) describes:

Borax and boric acid may be mixed in organic insulation materials, such as cellulose fibre and straw, in small amounts (1-5%) to reduce fungal activity and as fire retardants. The substance is moderately poisonous, in larger quantities can negatively influence freshwater fish and plant life.

It is also possible to use a powdered lime additive, so called “technical” lime ($Ca(OH)_2$). In small-amounts (1-3%) this increases the PH, e.g. this is a highly alkaline additive. The purpose of adding this is that in organic insulation materials, such as straw bale insulation, it hinders eventual rodents and ants to destroy the material and it also works as an anti-fungal and anti-bacterial agent.

6.4.4. MEMBRANES

There is a need to include membranes in modern constructions. A comparison of various approaches to reach “membrane effect” e.g. to handle airflow, humidity and gaseous transfer is illustrated by figure 44.

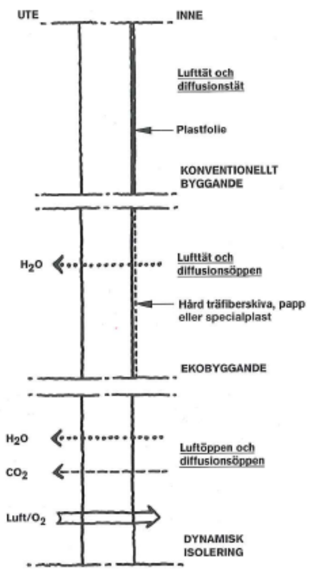


Figure 44. Different approaches to airflow, vapour and gaseous transfer. (Source: Bokalders and Block, 2010)

The membranes used in the project are as follows:

- One that works both as vapour and air flow barrier such as on the roofs and in wet-rooms. On the roof a natural vegetable-oil and harts based C2C certified membrane is planned to be used from Derbigum, called DerbiPure (figure 45). The wet rooms planned to have polyester, polyethen (PE), polyolefin or polypropen (PP) based water tight membranes.

- One that works both as air flow barrier but allows vapours to transfer through the material such as the case in wall, floor and ceiling constructions. Here clay and lime based stuccos and rendering materials are planned to be used as these provide air tightness but allow vapour diffusion to a certain degree, while also acting, especially in the case of clay based render, as a vapour buffer (as described in chapter 6.2. Insulation).
- Another type of membrane otherwise commonly used in modern conventional building constructions such as passive house building today e.g. ageing resistant plastic foil is not used in this project. In this case the membrane hinders the transmission of both vapour, air flow and the movement of all sorts of gaseous materials ($CO^2/0^2$, poisonous agents such as VOCs, etc.) which accumulate in the building and have to be removed with ventilation. The usual fossil fuel based wind proofing e.g. brand - Tyvek, etc. is not used either.

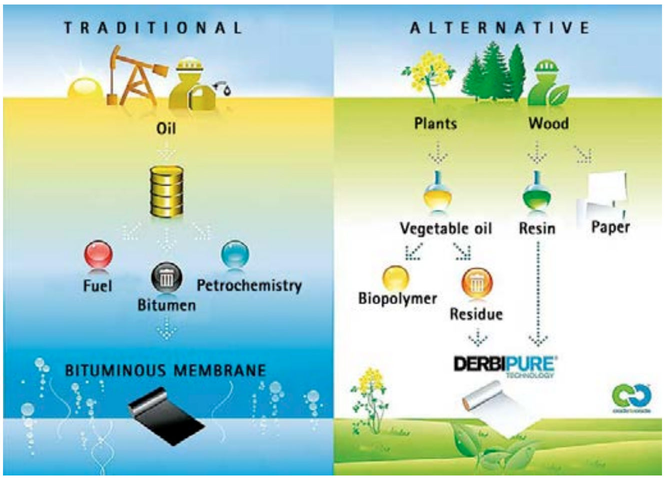


Figure 45. The difference between conventional fossil based and Derbipure membrane. Note the C2C logo under the Derbipure product. (Source: http://www.tectonica-online.com/products/2256/waterproofing_vegetal_reflective_derbipure/)

7. CONSTRUCTION DETAILS

The main types of straw bale construction methods are described below with the use of diagrams. The two main types are the supported stud-frame bale insulated, so called fill-in system and the self-load-bearing, so called Nebraska style straw bale construction method. Several sub-varieties exist between these two, just as straw bales can also be used as additional insulation on existing constructions. The newest addition to the straw bale based construction methods is the modular element based construction method (such as Ecococon).

The following figures show the principal differences in between different types of straw bale constructions.

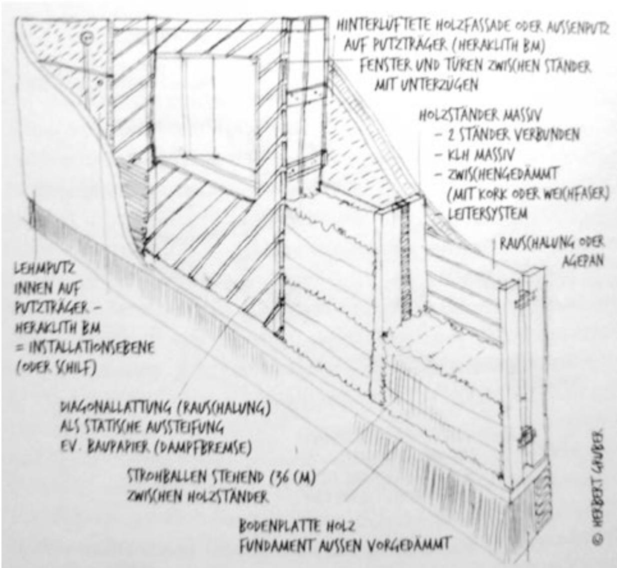


Figure 46. The fill in straw bale construction method. Here the bales have no support function other than carrying their own weight. (Source: Gruber et al., 2008 p.72)

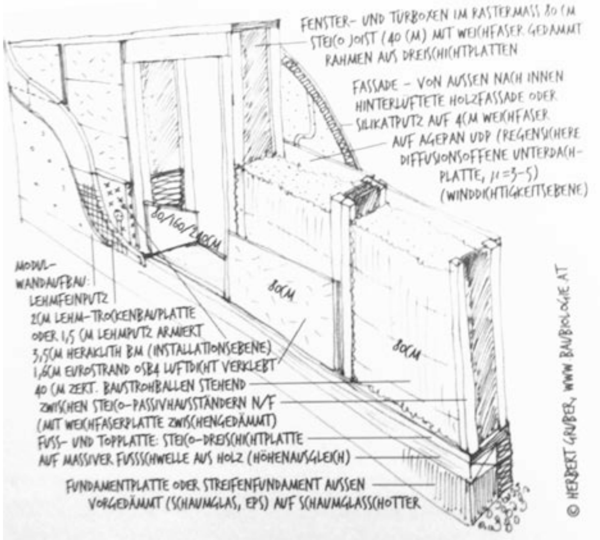


Figure 47. The modular type straw bale construction method. Here the bales have no support function other than carrying their own weight. A similar type is used by the company Ecococon from Lithuania (Source: Gruber et al., 2008 p.76, www.ecococon.eu)

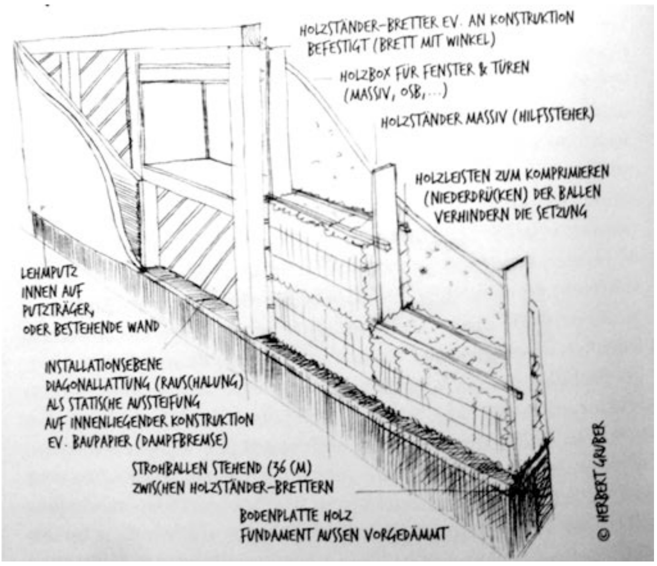


Figure 48. The hybrid type straw bale construction method. Here the bales have some support function but the construction is still carrying most of its own weight. (Source: Gruber et al., 2008 p.64)

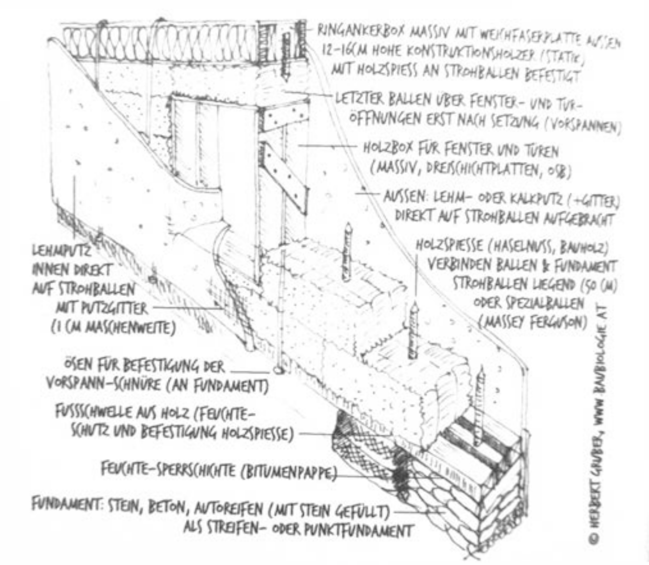


Figure 49. The principals of load-bearing “Nebraska style” method. Here the bales are compressed by the weight of the construction and other loads and are carrying all the weights occurring. This method was developed on the Great Plains (USA) as a direct result of lacking timber and/or stone resources. (Source: Gruber et al., 2008 p.56)

This project intends to follow a fill in type construction method using modern manufacturing methods to reach optimal results in creating the constructional framework into which the insulation material is placed into. This is done in order to simplify the building process, to make it cheaper and faster and to improve insulation properties.

7.1. Foundation

One of the most damaging parts of a construction, both concerning the site and regarding energy use, is the creation of the foundations for an edifice. Although foundation works (dependent on ground condition of course such as subsoil etc.) only consists of a minor part (ca.10-15%) of the total construction costs, the making of a foundation most often is an energy intensive, disruptive and invasive process leaving lasting marks on the surroundings. By using ground screws this can be avoided and in case the building is to be (re)moved from the site the screws can easily be removed leaving very little trace of the fact that a building was placed there. Figure 50. shows a selection of Krinner ground screws that can be installed in various ground types and to fit different load requirements.

Figure 50. Krinner ground screws (Source: http://www.krinner.com/)

The ground screws can be installed either by machine or manually (in case of smaller ones). Their advantages are manifold:

- short assembly times
- lower cost than using slab based foundations
- non-exposure to radon related problematics
- long life-span
- suitable for all ground types
- instantly loadable, no lag time in the building process
- extremely stable
- reversible
- ~100% recyclable

The screws have various top attachment surfaces offering both horizontal and vertical adjustability and high precision fine-tuning opportunities.

A very important aspect of keeping the building off the ground is the hard to detect radon, a poisonous, colourless and odourless gas that is carcinogenic. By keeping the construction off the ground and allowing free ventilation under the floor the radon problem is eliminated.

7.2. WALLS

7.2.1. OUTER WALLS

The outer walls are constructed as ventilated wall structures with weatherboarding cavities (ca.45mm) in between the insulating bales and the outer and inner wall surfaces. Both the outer façade and some types of the inner walls planned to be interchangeable in the modules. This can be achieved by a peg system that holds the wall panels in place in the construction attaching it firmly to the wall and the ceiling. By simply removing the pegs, the wall surfaces can be lifted off and new surfaces can be set in their place. The base, fire proofing render is ca.25-30mm thick both on the inside and the outside.

Another inner surface option is only clay render without the use of sheet material. Cabling (electricity, piping, etc.) can either be placed in the cavity behind the sheet material on the inside or enclosed in the clay render. This is applied directly onto the bales and is up to three layer, e.g. between 30-70mm thick. The mixture consists of clay, chopped straw, sand and natural building method based additives (salts, oils etc.). This mixture of rendered and on the inside fine plastered, surface both provides fire proofing and on the inside gives the decorational surfaces. This render/plaster surface also functions as air flow barrier, vapour buffer (with higher resistance on the inside than on the outside as described in Chapter 6.2.2) and adds a heat-battery on the inside of the construction allowing evening out temperature and humidity levels.

This project proposes the use of straw bales which in turn offer good insulating characteristics but as the bales are wide (350mm onside or 450-550mm on flat side) they require substantial space. This in turn reduces the utilizable floor space of the construction. Table 9 shows the wall thicknesses in relation to insulation thickness and floor space. Another option is to use alternative renewable insulating materials such as hemp or sheep's wool. These insulation materials, although more expensive than straw, come as sheets or rolls in various thicknesses (50-100-150mm) and are easily adjustable to the requirements of the construction.

Insulation thickness (mm)	Net	Ca. net/gross area ratio per 25m^2 Attefall house	Total wall thickness (mm)		Material	Appropriate use
			Both walls of sheet material	Inner wall clay render (70mm)		
50mm	20,42	0,82	240	238	Sheep's wool/hemp	Storage/garage
100mm	19,54	0,78	290	288	Sheep's wool/hemp	Storage/garage
150mm	18,66	0,75	340	338	Sheep's wool/hemp	Summer house (SBFP)
200mm	17,8	0,72	390	388	Sheep's wool/hemp	Holiday home/student housing (SBFP)
250mm	16,97	0,68	440	438	Sheep's wool/hemp	Housing/public (SBFP – MBFP)
300mm	16,16	0,65	490	488	Sheep's wool/hemp	Housing/public (MBFP – LBFP)
350mm	15,37	0,62	540	520	Straw bale (on side)	Housing/public (LBFP)
500mm	13,1	0,52	690	670	Straw bale (flat)	Housing/public (LBFP)

Table 9. Wall thicknesses in relation to insulation thickness and floor space with most appropriate area of use. Straw-bale based constructions (bale on edge) are marked with red. Note: SBFP - Small Building Footprint, MBFP – Medium Building Footprint, LBFP – Large Building Footprint

7.2.2. INNER SEPARATION WALLS

The inner separating walls planned to be up to 100mm thick and can be made either from wooden sheet material or using plastered clay based sheet materials on wooden stick frame appropriately plastered with in-its-material-coloured clay as the customer requires it. Figure 51 illustrates some traditional clay walling techniques.

Figure 51. Clay walling techniques. The Clay Library at Gaia Architects, Nesodden, Norway. (Photo: author)

7.3. FLOORS, ROOFS AND CEILINGS

The floors and the roofs (and the ceilings thereby) in principle are built up just like the walls. The inner wall cavity alternatively the clay render allows the drawing of cables and carrying out installations (electricity, piping, heating, IT, etc.). The same construction system is used in all three parts utilizing the same basic elements as well. This reduced number of elements reduces costs and allows people with relatively low knowledge of the building trade to construct their own houses.

7.3.1. FLOORS

The floor coverings are individually tailored according to the customers' wishes. Either a solid clay-based floor, stone floors (both these placed on reinforced flooring-type gypsum sheets) or "floating" wooden floorboards/parquet can be laid as finishing surface on the plywood sheet based underfloor.

7.3.2. ROOFS, INNER FLOORS

The roof is designed using a special ecological membrane that was developed by Derbigum (as described in the membrane section). Their Derbipure membrane is created using only natural, renewable raw materials and is water and vapour tight. Alternatively the company also has a green roof membrane also with very good environmental characteristics. It is fully possible to create slanted roofs with any degree of inclination. The only element that needs to be adjusted to achieve this is the attachment boards on the ridge of the roof and at the wall-roof connection. As this project was focusing on creating maximum space utilization in an Attefall-size-constrained context no details of this or intermediary system of joints (inner floors) are discussed. This latter also uses a peg-secured standardised attachment plates to connect inner floors to the walls. Multiple-floor systems are therefore possible to build with this building system, although structural and statical calculations have to precede the construction process.

7.3.3. CEILINGS

Ceilings are created in a similar fashion to floor and wall surfaces. The only difference in case wooden sheet material is chosen as finishing option is that the pegs holding up the roofing sheets are kept visible (figure 52).

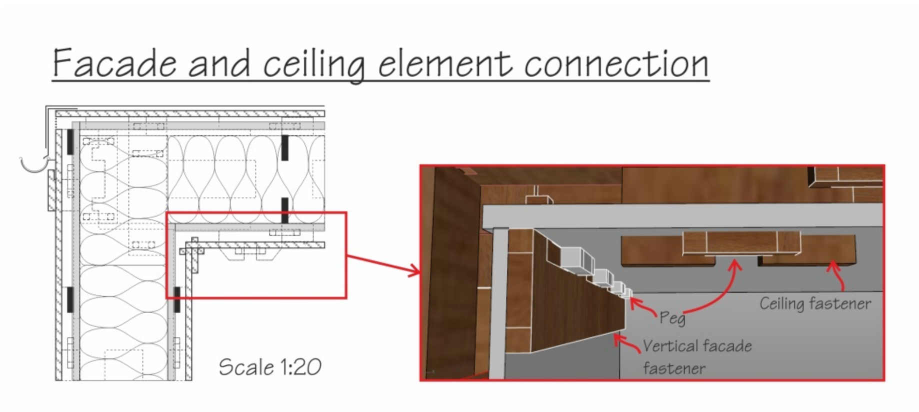


Figure 52. Ceiling attachment method. Note that the visible ceiling upholding element can be decorated according to the customers' wishes (various shapes, colours, finishes, etc.).

7.4. DOORS AND WINDOWS

The Hungarian architect, Imre Makovecz in his philosophy on organic architecture, compared buildings to living creatures where windows were the eyes of the living being while doors its mouth. These openings not only allow flow but also light and heat transfer and have profound effect on the flow and the aesthetics of the building.

Daylight and light in general creates both general comfort, good working environment (e.g. kitchen, study), helps safety but also allows us to appreciate shapes, textures, colours. Daylight and lighting conditions are an important part of creating a well working building solution. In Sweden “BBR 6:3 Light” building-regulations-policy-set covers this area. It is preferred to use daylighting (through windows and doors) to artificial lighting as it requires no energy, has a superior light quality compared to most artificial lighting and also has additional positive effects (for instance UV kills bacteria, provides vitamin D, passive heating, etc.). Nevertheless overheating, blinding, strong reflections and high saturation is to be avoided.

When designing the system the intention was to create flexible window and door setting opportunities, thereby allowing the owner to decide (with the help of architect, lighting designer) on where and how much light intake the building shall have. Another intention was to connect the outer surroundings and inner volume, using decks to enlarge the seasonally usable space thereby increasing the otherwise limited inner volume. This flow can also further signalled by the laying of floors connecting to the decks outside matching both in colour and the relating materiality. Structurally, windows and doors can be easily set between the “I” shaped element-based frames. Attachment of these windows and doors is also to the flange of these “I” frames. The overhead structural weight carrying line is possible to build with also digitally designed and machine cut easy to assemble insulated box beams notched into the weight carrying wall or post (plywood made insulated box construction) type structure. Under and overlaying plywood boards (also created in a similar manner as detailed above) notched into the frames can work as window/door-setting assembly parts. Spacing is decided by c/c distance, in case of straw bales this is 450mm, so any window size fitting a multiplication of this figure will fit snugly in the construction. In case of conventionally produced natural insulation materials such as hemp sheets c/c 550mm is to be used.

After having browsed through the Swedish manufacturers and haven’t found any good enough window/door solutions German manufacturers were found who can provide high quality solutions with good environmental characteristics. An example of this is shown on figure 53.

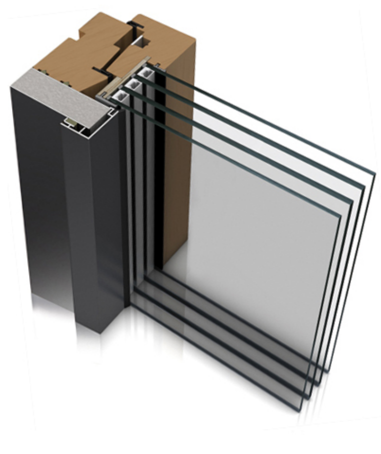


Figure 53. Passive house standard window solution. ENERsign®arctis* with an overall U-value of 0,45 W/m2K. Note the multiple profiling of the connecting surfaces. (Source: http://www.enersign.com/passivhausfenster/enersign-arctis/holz-alu-passivhausfenster-system.html)

It is important to point out that windows and doors are the most costly part of the envelope other than the roof. To overcome this problem it is recommended to use fixed-pane glazing in most places with thin-layer removable insulation for the colder seasons. Cheaper doors also can be chosen with lower insulating values in case additional insulated shuttering is included, which is more cost effective in the long run than installing highly expensive low U-value doors and windows. These insulation panels can be either permanent-installed and hinged to open and close when needed (e.g. shutter system) or removable and stored separately when they are not in use. Several varieties exist as was shown in "Movable Insulation" (figure 54).

Figure 54. Movable insulation handbook by Langdon (1986)

7.5. INSTALLATIONS

The installations are not strictly forming part of this project as described in the 1.4. Limitations section but as many of these are requiring special often not entirely environmentally friendly materials in their construction and strongly influencing the sustainability profile of the building a short description is hereby provided.

7.5.1. ELECTRICITY

A dual electric system is planned to be installed in the building, including a 220V AC (mains connected) and a low-voltage system. The 220V system is covering the main functions connected to heating and household electricity other than lighting. This is run by the 12V DC low-voltage system. The system can be made off grid with standard PV and storage units (batteries).

7.5.2. HEATING, WARM WATER, SHADING

As the total volume of the Attefall buildings is only ca.100m3 the heating in a well-insulated building context is a lesser issue than cooling, especially concerning siting in a Nordic climate (south facing). The user's own heat can provide the basic energy (ca.100-120W/person) together with waste heat from household appliances (water heater, cooker, fridge). There are two options to the heating problematics. In temporarily lived in constructions e.g. weekend houses, together with the use of wooden sheet based walling (e.g. low heat storage capacity) an air-to-air heat pump based heating system or a direct-electrical heating unit is recommended with A+++ characteristics. It is of extreme importance to ensure the filters of the heating system are cleaned. In larger buildings a ground or air to water heat-pump working against a water based battery and floor/wall heating system is recommended as in a larger construction there would be more space allowing for a boiler/utility room. In permanently lived in buildings, thick clay plastering allows good thermal storage evening out temperature peaks, therefore water based wall heating is recommended as described above.

Shading structures are to be installed in front of the large window/folding door surfaces facing south. These can take several form. The easiest and most economical is to use pergolas and trellises over the decking attached to the construction and have seasonal climbers do the job. Such plant species are wines of different kind (Vitis vinifera ss.), clematis (Clematis vitalba, etc.), climbing roses or even berry producing semi-climbers such as mini-kiwi (Actinidia argute) or bramble (Rubus fruticosus) to mention a few (figure 55).

Figure 55. Trellis based shading method. Note that while in summer when the heating effect of the sun is highest the canopy of the plants protect the interior from overheating while in winter when leaves have fallen sun can freely penetrate through glazed surfaces and warm up the interior heat batteries (floor/wall surfaces). (Source: http://williamhefner.com)

Another option is marquises or the use of removable/adjustable shutters as was shown before. These can be either insulated or non-insulated ones, on the major glazed surfaces that partially or totally cover the glazed surfaces both resulting in energy savings and avoidance of overheating problems. As shading as an issue is complex in nature and is connected to user preferences and siting related issues, etc. it is not covered in this study.

7.5.3. WATER AND SEWAGE

The building can be connected to the fresh water mains via a HPE pipe connection. The inner piping is planned to be done with PE (crosslinked polyethylene) piping such as the PEX system.

Sewage connection is through a 110mm metal pipe such as produced by Gustavsberg. This material does not contain dangerous chemicals like plastic, has a longer life-length than PVC piping and is in principle 100% recyclable. Sewage treatment is suggested to be done in a decentralised manner, locally, using an ecological waste water treatment system such as offered by ACT (Alnarp Cleanwater Technology). Alternatively composting toilet can be installed.

7.5.4. VENTILATION

Natural ventilation is suggested to be the primary source of ventilation. As described by Miller (2017) inadequate ventilation is one of the major causes of unhealthy buildings, bad indoor air quality and generally a poor living environment. This being especially true in modern high-tech passive house constructions where the interior is hermetically e.g. “air-tight” sealed off from the outdoors. In cases like this the various poisonous agents (VOCs, flame retardants, carcinogenic preservation agents such as formaldehyde, etc.) seeping out from among others building materials, hard and soft furnishings, electronic gadgets, etc. together with dust and micro particles from plastics, etc. can accumulate in the indoor air. This emission in turn has negative influence (tiredness, illnesses, cancer, etc.) on the inhabitants.

The ventilation is planned to be based on self-regulating ventilation solutions built in the windows together with manual ventilating dons placed at adequate heights to increase flow even in case of relatively low temperature imbalance between in- and outdoors (summer). The placement of openable windows at high positions, such as in the sleep loft, together with large folding doors allows the effective cross ventilation of the building even in high summer, which reduces the risk of heat overload. This ventilation solution together with the gaseous vapour buffering and temperature equalizing capacity of the thick clay based plastering ensures an even indoor humidity level, low levels of dangerous agents in the air and even rooms temperatures without draft.

Alternatively, Trombe walls with escape vents can be installed in the construction simply using the “I” frames of the construction elements, creating easy to install efficient built-in type ventilation and natural heating/cooling systems (figure 56).

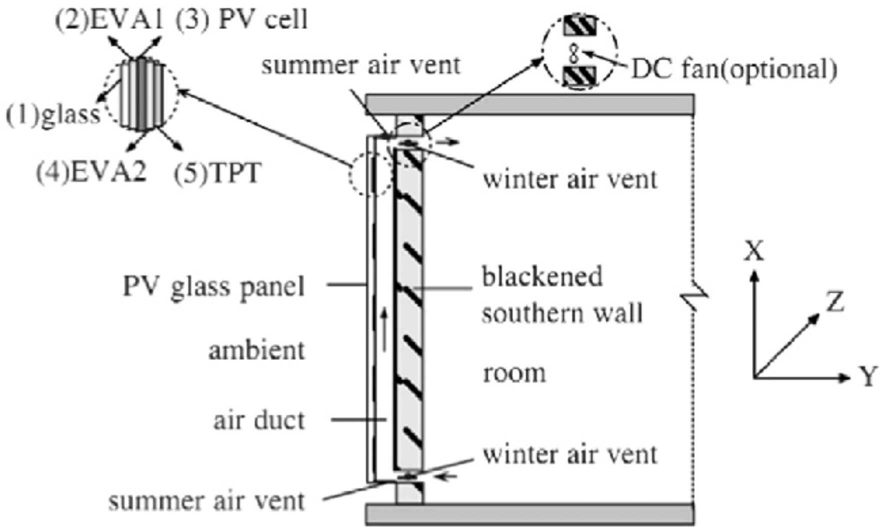


Figure 56. Trombe wall. (Source: https://www.researchgate.net/figure/PV-Trombe-wall-with-DC-fan-for-winter-heating-25_fig10_311619642)

7.5.5. Wet-rooms (bathroom/toilet)

The most sustainable adequate solution to create a wet room membrane is to use polyethen, polyester (PE) or polypropen (PP) based products (Bokalders and Block, 2010) while also keeping to the highest building standards. The chosen wet-room membrane of Upofloor made with a material combination of Enomer is sold under the name LifeLine. This enomer mat consists of 80 % $CaCO_3$ and 20% thermoplastic polymers (Bülow, 2013). The interior of the bathroom is either wood panelled or thick clay-plastered as it ensures the best humidity buffering and takes away the need for the use of mechanical out-ventilation of vapours caused by the water use (shower, cooking, etc.). Additional treatment in splash-on areas is carried out, as the customer requires it either with the use of tiling, via tadelakt treatment or similar clay surface treatment method such as using linseed oil based painting. All wet room taps are to be chromium free made either from copper or stainless steel.

8. Evaluation

8.1. Findings & Discussion

- On design & materials

This project was focusing on the technical design of an element based modular construction system and only secondarily the architectural, functional and aesthetical attributes of such buildings. It may be considered a weakness of the project that no detailed functional lifestyle-connected design is presented, on the other hand it was a conscious choice as the matter at hand to examine was related more to the technical fields. Nevertheless from an architectural point of view it is clear that the project has proven, it is possible to create renewable material based element-built modular housing solutions. It was also proven that modern technology can create short-cuts in reducing labour intensiveness, cost efficiency and waste reduction. However, when looking at the system in this project from a functional-design point of view, it is striking, just how little certain aspects of the construction deliver when it comes to an optimal result, concerning the aimed-at Attefall type construction. If reverse engineered, one could see several points that could easily be enhanced and improved on by using other materials or choice of construction methods. Most probably, if one started from "the other end", e.g. trying to design an Attefall construction first and fitting into this "constrain" the materials and technical design that may be applicable, a very different result would have been reached. In this latter case some renewable materials such as straw bales would have been discarded, while others such as wood would have been kept, although maybe in other forms. Here function and design would have dictated material choice/construction method and not the other way around. One may say therefore that this design is inadequate for the Attefall size as other systems would have delivered a better solution. Massive wood technologies are such methods. It is therefore an important learning outcome of this project that renewable materials just as modern technical materials have their adequate places and there is no one quick fit to all problems, however attractive these may look at first sight… Design and technical strategy should not follow a single preferred material choice but rather chose material with the right attributes from a pool of acceptable (here renewable origin) materials.

A good example of this dilemma is insulation. As described in 7.2.1. Outer Walls chapter the insulation thickness will have a profound influence on both the operational characteristics of the building but also on the available net floor-space in the construction. As straw bales are of standardised sizes (see table 37. in Chapter 6.2.1.) other elements of the construction have to be adjusted to this. At the end of the day this therefore may not deliver optimum results in case of for example a holiday house solution, which is only used in the warm seasons (spring/summer/autumn) or in case of auxiliary constructions where insulation is of lesser importance (ateliers, seasonal café, small workshop, etc.). As the bales provide excellent insulation and their minimum thickness is ca.350mm the U value on the total construction will be as low as 0,12W/m^{2}K (Minke and Mahlke, 2005 p.29). This super-insulated construction coupled with large south facing fixed pane windows, glazed folding door surfaces and a relatively small inner volume (total building volume is 100m3) can easily cause overheating problems even in the winter months (if the building is used in such times). Several shading and ventilation strategies were outlined in the previous chapters, nevertheless many of these can be avoided by adequate functional adaptation. So, the lesson learned is to adjust insulation, light intake and orientation to functional needs of the building and the lifestyle of its residents.

- On composition related to shape, aesthetics, historical and architectural traditions

Following the acceptance of the size and other Attefall constraints such as maximum height, a conscious decision was made to focus on the cubic shape (Chapter 4.2.) to maximize the inner volume and make the construction more suitable for Nordic climate. This in a way was driving the aesthetics of the project as well at this stage. This formal limitation may be one of the main weaknesses of the current presented designs, as most constructions today are cubical -one way or another- and this design doesn't introduce change to that trend. Otherwise in the Swedish building historical context cubic constructions are not new, since the early 20th century "funkis" and later on modernist housing have been using this shape frequently. When deciding over facades, colours, surfacing materials and other attributes of external cladding a freedom of choice were intentionally kept to be able to blend the constructions in any given environment from countryside to urban milieus. Although it should be natural for humans as part of the animal kingdom to feel at home in and among natural materials, this is not necessarily true in our ultra-modern extreme urbanized society where the average westerner has very limited understanding of nature, where food comes from or how wildlife and nature actually works. Some people never leave or have been outside a city… It is therefore difficult to convey feelings related to natural building materials or aesthetical considerations related to natural forms and processes to that part of society which thinks asphalt, concrete and high-risers are the norm. The designed buildings are solid and represent metaphorical expressions of the "my-home-is-my-castle" attitude. Or rather "my home is my den" as the used natural materials will create rather a natural hideaway type structure. One doesn't have to be a biophil to appreciate the buildings created by this project. The indoor qualities summarized by an intense sensory experience (see chapter 2.2. Materiality) together with the background consciousness of healthy materials in the building fabric and the use of sustainable construction methods shall put the visitor or inhabitant of this building at ease.

- On lifestyle, function and character including greening, urban agriculture, ecosystem services

The lifestyle of the inhabitants will decide over design factors as outlined above, but certain building related factors are following trends. Greening of the material choice and inclusion of new, alternative urban lifestyle strategies are becoming more commonplace and accepted day-by-day. It is important to point out therefore that the construction with its flat roof allows the use of a green roof and parallel to that green wall systems that can be included in supporting for example urban food production (urban agriculture). The green roof and wall systems also may allow the creation of new habitats specially for insects and smaller cold and warm blooded animals thereby providing ecosystem services. As the materials are of natural origin in the construction it should fit snugly in natural milieus. Wildlife and even most humans wouldn't find these alien or repulsive, unlike to many modern artificial materials. The character of these natural materials, their texture, colour, the surface attributes together with their scent and audial characteristics fit well in with nature, therefore no animals or humans shall feel these constructions being uninviting or unattractive.

- On resilience and sustainability concerning technical installations

The previously mentioned urban agricultural opportunities together with rainwater harvesting and water recirculation (e.g. shower affluent to toilet flushing water or irrigation for green roof/wall) can reduce urban vulnerability and improve urban resilience. As Attefall is of small size and a well-insulated construction's energy need is limited, additional improvements can be achieved by installing off-grid stand-alone solutions, such as PV and battery based dual electric system (24V/220V) as described in Chapter 7.5.1. Electricity or using water-mantled cooking stove such as Wamsler (http://en.wamsler.hu/), which can both provide heating, cooking and warm water. The relatively high inner ceiling height (over 3m) allows temperature layers to develop therefore ventilation is easy to solve based on natural "heat stack" attributes. This type of ventilation works even when the main electric grid is down, thereby providing further resilience in exposed emergency situations.

- On multifunctionality and multi-layer set-up in relation to function

Placement and size of different functions can be a design issue in Attefall sized constructions. As these often will be used as seasonal habitations or student housing with lesser requirements concerning comfort, such as the expensive-to-build bathroom/wet-room/kitchen function may be considered of lesser importance, thereby can take lesser space of the inner volume. It is arguable whether it is worth doing or not. It is possible to reduce the size of this unit, compress and multi-functionalise it, e.g. the use of taps and sinks where one such thing would serve both the bathroom and the kitchen thereby reducing installation cost and space requirements. Nevertheless, when carrying out the "Mini-Maxi" project in year 2 of the architect program at LTH, where minimal floor space student housing solutions were developed, it became clear after a questionnaire based examination of student's needs and preferences that most people find bathroom/kitchen water sharing units unhygienic and a well-functioning kitchen and own bathroom were cornerstones of feeling at home and at ease. In this project these areas were bundled together to reduce piping and installation requirements and opportunities exist to take away for example parts of the bathroom allowing storage or other new functions to be included in the design.

The functionality of the created spaces was also a subject of discussion on several forums before this project was started up. As a result of this, a conscious choice was made to abandon multifunctional interiors per se, other than standard off-the-shelf multifunctional furnishings such as found at IKEA (bed-sofa with storage, foldable tables and study corners built into shelving, etc.). The nowadays very popular multi-layered living and individually designed tailor-made multifunctional furnishings -especially favoured by Tiny-house advocates- were only partially utilized (see sleep-loft) as many of these features although adding functions to the building also create a camper-van feeling and a cramped and ephemeral atmosphere in the living space. This, as far as the author of this project is concerned, based on having lived outside Oslo for half a year in a camper as an architect trainee, is not optimal in the long run. Most people would accept this for shorter periods of time but will not settle with these cumbersome features in the long run and find them "worky" after a while…

- On performance in relation to similar other projects and products

When comparing the outcome of this project to existing structures and modular systems -as introduced in chapter 3- it is obvious that the system in this project has several advantages concerning environmental performance. This may not be true to other areas. These include small things such as availability of raw materials as certain insulating materials may be non-conventionally available on the market, structural disadvantages such as thicker walls, lower prestige and status related to certain materials such as in case of clay and simply not being taken seriously just because of being outside mainstream practices. This latter may hit back concerning financing, insurances and in similar areas. From an architectural point of view it is difficult to justify the creation of conventional looking buildings when using renewable based natural materials, as to many, these materials are closely connected to another, often lesser appreciated niche architecture: hobbit houses, community-built projects created on a shoestring and "harsh-green" oriented self-built housing in general. Some of these materials used in this project are also difficult to harmonize with modern urban environments as they do not follow the aesthetics of the fast changing urban trends and are made with different aims in mind than to be self-cleaning, graffiti-resistant or fire and sabotage/damage-proof.

- On the overall process

It was found, that creating a renewable based system is difficult but not impossible, this having been gradually becoming clearer during the course of the project. The originally staked-out structure of the project as described in Chapter 1.3. Project Process was followed through and seems to have worked adequately. An important learning and conclusion though is that in an architectural design context it is probably better to use a form and material follows function, size and other limitation type approach than working with a standard set of materials as a starting point. More on this further down here.

Another outcome of the project is that it is not to be underestimated just how differently people look at the same materials. Lifestyle, background, education and other factors strongly influence this and it is not to be taken for granted to have general acceptance -especially not within the industry- just because of choosing healthy, good quality and adequately used materials. Another piece of learning is that construction method and technology is uninteresting to many, even sometimes within the professional circles. Large parts of the population has no or very limited interest in trying to understand construction methods and technology and they take the word of the architect and the designer at face value not being able to evaluate the actual value of the product's ingredients.

To come from an idea to the actual prototype is long and expensive process. This project was based on many years of concept development and it was therefore surprising and very educative to learn that the practical creation of drawings, models and the testing of these in real life production and user environments can add so much to the process itself. In future similar projects these phases will have to start at an earlier stage.

8.2. SUSTAINABILITY ANALYSES

8.2.1. ECOLOGICAL

As a result of the material choice, e.g. solely relying on verified naturally sourced renewable raw materials and materials with industrial origin -which have low negative environmental impact- this project can be considered a benchmark in low embodied energy and low carbon footprint based construction. Figure 57 shows below the carbon footprint of a modern passive house construction in Sweden. It is easily visible that the lowest dark blue 50% of the pie-chart is concrete and reinforcement related part of emissions. That is exactly half of the total. So what would happen if we could reduce this?

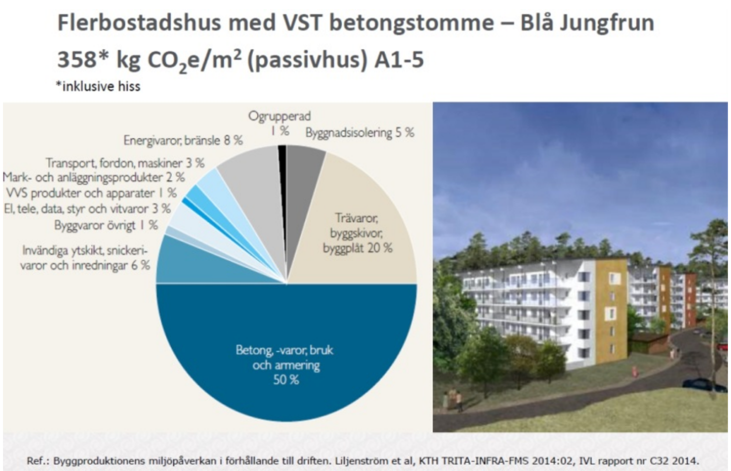


Figure 57. CO_2 emission of apartment blocks with concrete framework – the example of the passive house "Blå jungfrun" from Sweden. (Source: Conference material from Träbyggnadsseminariet "Lär dig bygga flerbostadshus i trä", Martin Erlandsson, IVL. Organised by Hållbart Byggande Syd Förening. 07.03.2018. Malmö, Sweden)

This shocking proportion of carbon footprint related emissions related to concrete is also shown by Alcorn and Donn (2010) who have investigated different materials environmental impact on a carbon emission basis. It was also found that concrete is the single largest source of carbon footprint related building material in constructions and that timber based strategies and straw bale insulation may improve carbon footprint related environmental performance of constructions very efficiently (Table 10)

	CO_2-e reduction (kg)	CO_2-e reduction (%)
Wind generator	1,031	47
Aggregate of timber strategies	*739*	*34*
Strawbale insulation	491	29
Solar hot water heater	472	22
PV panels	435	20
Lightweight timber wall v concrete masonry	350	16
Efficient refrigeration	170	7. 8
Timber window frames	139	6.3
Efficient lighting	110	5.0
Roof shingles	110	5.0
Efficient appliances	90	4.1
Timber linings	77	3.5
Unpainted materials v painted	69	3.1
Timber suspended floor v concrete slab	54	2.5
Wider eaves and verges (1 m)	9	0.4

Table 10. Total annual CO_2 reduction - a comparison of all strategies. Note: relevant data marked with red
(Source: Alcorn and Donn, 2010 p.9)

Based on the above found data it is clear that natural building has significant advantages. Designers, architects, planners, decision makers and the construction industry have to wake up and change tack.

8.2.2. SOCIAL

Digital technologies, both on the design and production side erase workplaces, without a doubt. Nevertheless, as this project allows less privileged groups to come onto the housing market, learn a trade and make them feel that they have achieved something creates a long lasting empowerment and positive socio-economic development. A professional well trained carpenter, just like other trades is almost also a must to make sure the "build" goes well, so at the end of the day one could say that this new technology, although taking workplaces also strengthens the social and professional standing of others. When a carpenter not only nails a frame together but helps and educates people, a new world is born.

8.2.3. ECONOMIC

In alternative construction the common understanding is that the three-way relationship of quality, cost and speed (figure 58) is a bond that is nearly impossible to satisfy on all three levels.

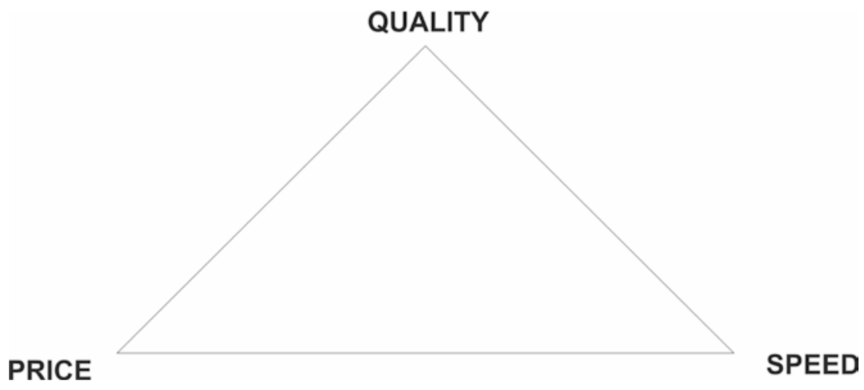
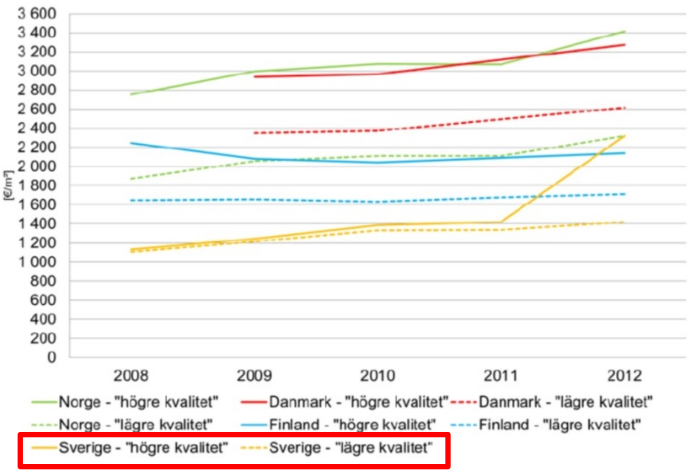


Figure 58. The triad of construction.

Two of the triad's parts may be true but this pushes the third always into an inferior position thereby reducing performance. As an example, using reclaimed and refitted materials will reduce price but may decrease quality and as extra labour input may be required to prepare the material it can also decrease the speed of the construction. Similarly in case lots of capital is available it is easy to build with high quality and in a speedy manner but the price will be high…

So how to overcome this problem? The economic analyses of the Swedish Housing Board (Boverket, 2014) describes the development in the cost of housing. Prices range between €1200-2200 (e.g. ca.12.000-22.000SEK) per m^2 (figure 59). It is also important to note how the cost difference has exploded between the low and high cost segment around 2011.

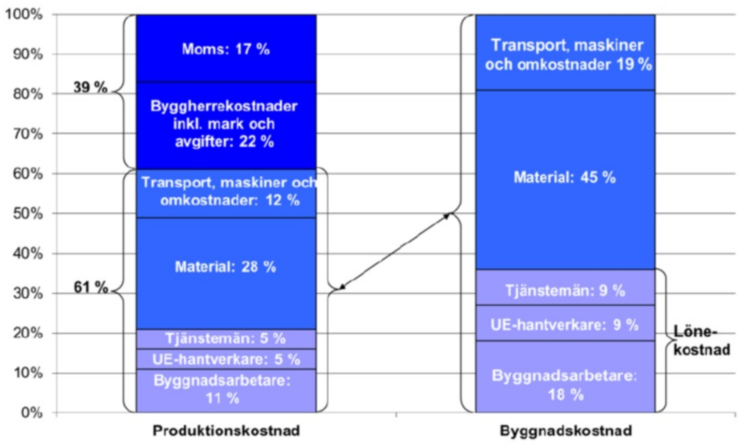


Källa: Gardiner och Theobald (2008–2012)

Figure 59. Construction costs in an international comparison. Note: Sweden marked with red. "högre kvalitet" – higher quality; "lägre kvalitet"- lower quality (Source: Boverket, 2014 p.30)

It is not clear why this is happening as far as the report is concerned but certain factors such as digitalization of newly built homes (e.g. internet of things and appliances) together with high-tech based sustainability solutions (materials, construction technology) can work as pointers…

It is also interesting to see how the costs of a construction are built up. Figure 60 shows just this.



Källa: Sveriges Byggindustrier (2013)

Figure 60. Division of costs in construction (Sweden). (Source: Boverket, 2014 p.17)

It is clear that materials (45%) and construction/installation related labour (27%) are major parts of this cake. According to generally accepted “rough” figures in construction, up to 12-15% of the total building cost can be related to foundations and ca.30-40% to the envelope. The remaining part is divided up between planning/ design and additional costs (administration, management, bank costs, etc.) 8-15% and installations which may form up to nearly 50% of the total budget. This segment is increasing the most in current constructional practices as a result of the previously mentioned processes. So where are the opportunities to reduce costs and make building homes cheaper?

The “envelope” and the foundations are areas one could focus on from a the construction sectors’ point of view as these are necessary and unlike the installation part (bathrooms, kitchens, white goods and appliances), where the customers may have special requirements, these areas are in the hand of the designers and builders as long as the basic law and policy based premises are kept. Any saving here (a rough estimate is 10-20 even up to 30% on the total production cost) as a result of cheaper raw materials, more effective construction technology, efficient use of resources together with savings on the waste material side may form comparative advantage against the corporate based construction industry. It is worth noting that in Sweden there is an oligopoly as far as the business economics based definition is concerned. Three companies Skanska, Peab and NCC own ca.60% of the total turnover of the building market when it comes to the production of the 50 largest companies in construction (Lundgren, 2016). It is therefore not surprising that housing prices are high and several less advantageous groups in society are outside the reach of the housing market. The mentioned savings therefore may be used to create more affordable constructions. These savings may also allow the creation of new financing methods based on sustainable cooperative lending practices such as proposed by the Swedish JAK bank and explored by Prof. Dr. Margret Kennedy (2012) a revolutionary economic researcher from Germany.

Based on these above premises, this is where alternative, modernized natural building techniques can show cutting edge advantages and allow sustainable economic models to develop.

9. Conclusions

This project set out to analyse whether it was possible (technically, aesthetically and financially) to create fully renewable based, eco-designed, easy-to-assemble, modular and expandable housing solutions that fulfil even the toughest sustainability related and building requirements (functionality, humidity, energy efficiency, indoor comfort and other attributes). It also intended to develop short cuts to overcome hinders usual in alternative building techniques such as labour intensiveness, humidity and fire safety issues, etc..

The research shown in this material together with the real-world example prototype shows that renewable based, eco-designed, easy-to-assemble, modular and expandable housing solutions are possible to create without major difficulties. The sustainability related issues and building requirements (functionality, humidity, energy efficiency, indoor comfort and other attributes) are not jeopardised just by a natural building approach, as long as the premises of a sound to-material-tailored construction methodology is kept. It is also obvious that the usual critique against natural building, e.g. that it is labour intensive, backward and construction-technique and quality wise insecure is not valid. Modern semi-industrialised materials based on traditional renewable sourced raw-materials are easy to tailor to industrial building processes such as CNC milling or laser cutting therefore standardised and replicable performance can be achieved. Labour costs can be reduced by using modern digital technology based production while still keeping a high social sustainability related performance as this method also allows simplification of the building process which in turn result in easy access to self-building for exposed groups in society. It was proved that hinders usual in alternative building techniques, such humidity and fire safety issues, etc. are not a problem with modern building physics based approach in choice of material and construction technology.

There are some shortcomings originating from using natural building techniques though, which have to be counted with. These include reduced space utilisation performance in case of smaller footprint buildings, as natural insulation materials may require thicker walls. Straw bale based building techniques especially are less suitable in this context for example when it comes to creating Attefall size buildings. It was also a difficulty to find adequate entrepreneurs who have the right knowledge to work with these unconventional materials. Insurance companies banks and local building authorities may place hinders in the way of these projects as a result of ignorance or lack of knowledge. Nevertheless, the larger number of such alternative natural-built constructions exist, the easier it will be for newcomers to join in building such healthy, user friendly, economical and environmentally well performing buildings. Another conclusion is that the project, although have delivered adequate results on many levels, also has failed when it comes to the most effective and optimal way to run an architectural design process. It is better to start the design process from functional and technical requirements and thereafter choose materials to be used than the other way around, as it was done in this project.

The newly developed, digitally designed and laser cut element based construction method has shown that it is possible to solve several of the shortcomings of natural building techniques. These constructions can be more competitive on the market, while also allowing economically disadvantaged groups to take their first step onto the housing market at the same time can educate and work as a social empowerment tool. Hopefully seeing the prototype and its performance, together with this study, will challenge existing understandings of building materials and can work as a pilot and a benchmark in sustainable construction. This way not only convincing hard line green thinkers but also designers, architects, engineers, builders and other practitioners and decision-makers in the construction industry.

As far as the future of the project is concerned, it is planned to be continued with further testing and development of the building system. Simplification of the elements' design is in the pipeline together with application of various other insulating materials (hemp, sheep's wool) and certain ecologically acceptable sheet materials (such as clay) is planned to be further investigated.

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WEBSITES & RESOURCES

Properties and suppliers of clay products:

http://www.greenspec.co.uk/building-design/thermal-mass/

https://clay-works.com/product-descriptions/

Conluto http://www.conluto.de/

Claytec http://www.claytec.de

Properties of straw bales:

https://www.grisb.org/publications/pub33.htm

https://www.greenbuildermedia.com/buildingscience/carbon-smart-straw-bale-structural-insulated-panels

Baubiologie – Austrian Straw Bale Network http://baubiologie.at/strohballenbau/strohballenbau/zertifikate-tests/

Certification

Vugge til Vugge ApS https://vuggetilvugge.dk/

Building systems:

Hive house method - http://hivehaus.co.uk/

Facit Homes http://facit-homes.com/the-facit-home

Harcon building element http://harcon.se/

Swift Building SIP - http://www.swiftorg.co.uk

Träullit house, nike arkitekter http://www.nikearkitektur.se

Ecococoon - http://www.ecococon.lt/english/

Qhouse - https://qhaus.eu/

Koda - http://www.kodasema.com/

Nur Holz http://www.nur-holz.com

Other related technologies

Siio http://sioox.se

Organo Wood http://organowood.com/en/

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This project is credited to and was powered by Badger. You make the world go around.

APPENDIX 1. DEFINITIONS

Traditional buildings: buildings erected in style-typical manner of an area using traditional, locally available traditional building materials and locally adapted construction technology and available knowledge base, usually in a communal-building process. Design follows material and place based limitations. These buildings formed the bulk of housing related constructions before the arrival of late industrialism, e.g. the late 19th century.

Conventional buildings: buildings erected according to the style-typical manner of the nation and current trends of the relative near-international environment using both industrially produced and locally available traditional building materials and locally adapted construction technology and an updated formalised knowledge base. Design follows material (limitations) but starts to break away from place based limitations. These buildings arrived with the late industrialism, e.g. from the late 19th century to the middle of the 20th century.

Modern buildings: The large majority of these buildings have no local connection, they are international in their construction, aesthetics and materiality and in style they most often belong to one or other sub-era of the modernism. These buildings were built during the second half of the 20th century, using thorough understanding of heat, humidity and other building physics related issues, when advanced building materials and industrialised building methods formed the basis of everyday construction.

Natural building: a building methodology where construction technology relies on "updated" traditional building methods and where naturally occurring, renewable and non-fossil fuel based building materials are used, which in turn are often produced locally or regionally in a non-industrialised manner. The building process is often small scale, labour intensive and community based.

Post-industrial construction: the buildings created by methods of the post-industrial era using highly advanced often modular or element based methods and efficient high-tech materials (such as nano-materials, plastics and special polymers, etc.) and digital design techniques. These are created using vertically integrated construction-production systems where the whole building process is digitally controlled, often by either one user or a user group. Tasks may include software based design and planning (including testing and modelling by Rhino/Grasshopper, Revit, Cad), often automated even AI based production (3D printing, CNC milling), coordination and harmonization of building parts and systems including inventory management (BIM), logistics, economic and administrative functions, etc.. These systems can only be operated by highly qualified professionals. They have only a fraction of labour requirement compared to construction systems of previous eras. Players on this market are usually large companies or very large international corporations with wide range of interests both in the construction industry and building material production sector (e.g. Skanska).

Stucco/render/plaster: outer or inner wall facing and surfacing material. The term is used as interchangeable in this project although in the exact nomenclature there are certain differences. Render is the innermost "rough" surface onto which a thinner stucco layer is applied. An alternative word for this thin outer layer is plaster. Both these, e.g. the outermost layer is often gypsum based in modern constructions while traditionally it could both been of gypsum or clay origin.

High-tech building materials: an industrialised approach to building materials. These complex materials are produced by modern technological production methods in an industrialised setting, using many, standardised, often already in-themselves processed industrial raw materials as ingredients. These materials are unsynchronised with the characteristics of the local environment and allow users to create constructions that doesn't take the human scale into consideration and utilize places where otherwise construction would not be possible or would result on non-optimal results. Design dictates material. Their use is clearly defined and often very specific for the given task in the building process and the area in the construction with detailed instructions on use and installation and auxiliary performative requirements. High level of knowledge (including long-term education) supplemented by special courses, organized most often by the producing company, are necessary to correctly install these materials in the building construction. Industrial produced highly specialized tools may be needed for correct application. These materials' characteristics, behaviour and ready-built e.g. delivered results are tested, standardised in nature and guaranteed in case of prescribed utilization. They often have high-embodied energy and are often either based on fossil fuel-related resources or use large energy and other material inputs in their creation. They are not possible to dismantle without damage therefore are non-reusable in multiple-utilization circles, their recycling mean their destruction, upcycling is difficult. Production is often dangerous for the environment and has otherwise unusable and dangerous side products. The producers of these materials are often large sometimes multinational companies with centralised production and are often themselves part of international corporates with no or limited local-roots. Long transport routes with several intermediate-storage are in use.

Tools of the modern builder, pouring concrete (Source: http://www.jbsa.mil/News/News/Article/462329/concrete-pour-underway-for-parking-garage/)

Low-tech (high-knowledge) building materials: the antonym of high-tech building materials. These are either the same or updated versions of building materials originally used in traditional constructions. They are simple in nature, complexity in ingredients is limited. They are highly synchronised with the local environment and follow local climatic, geological, geographic etc. recurrence patterns. Their production in turn is highly local -or at most regional- with short transport routes. With these materials material dictates and limits the design. The characteristics of these materials are most often not tested and standardised and their attributes may change from place to place. The knowledge needed to use these materials correctly in a constructional context is based on experience rather than only on formal education. Although this knowledge is crucial for an adequate result, it is possible to transfer this knowledge to users, in a rather short time-frame, in comparison to high-tech materials. The tools required to build with these materials are often unspecialised, few in number, simple, even home-made in construction, thereby cheap and easy to acquire. An example of this is shown on the figure below concerning straw bale working tools. As their procurement is local, these materials mainly benefit the local community. They have low-embodied energy and are often based on renewable resources or and other local material inputs in their creation. They are either possible to dismantle and re-erect without damage therefore are reusable in multiple-utilization circles or can be reused in other natural cycles where they form an integral part of the local systems without their actual destruction.

Straw bale working tools (Source: http://www.abc.net.au/news/2014-09-09/tools-of-the-trade--hay-mallet-spike-and-strapping.jpg/5727564)

LVL: Laminated Veneer Lumber. A glue-laminated sheet material made of strips of wood. For further details see for example Stora Enso.

Green-building (new production): a Swedish building certification system that ensures that a local building has a documented less than 25% of the energy use of a normal building as described by the Swedish Building Regulations (BBR), its indoor climate and ventilation is according to existing regulations and its producer/owner fulfil certain administrative criteria (reporting, energy-calculations, etc.).