Documentation of the Limnologen Project

Overview and Summaries of Sub Projects Results
Preface

This report is the result of a truly joint effort. The aim has been to give an up to date insight to all the R&D projects concerning Limnologen in Växjö, Sweden that have been and still are running. These projects have been possible to run thanks to the engagement shown by the town of Växjö, Växjö University and SP Trätek, making it possible for researchers from three universities and one research institute to follow this unique building project.

This version is a translation from the Swedish final report. In addition, the separate sub-projects will be reported by the respective sub-project leaders in more detail in separate reports, scientific papers and conference proceedings. A list of publications related to the Limnologen project – more or less accurate at the time of finishing this report – is given in Part 1.

Thus, the current report has been the work of a large number of authors, whose names are given in each of the summaries presented in part 2 of this report. My own effort has been to reformat the various texts into a common format.

The research presented here would not have been possible without the financial support received from CBBT – Centre for Building and Living with Wood, Växjö University, The South Swedish Foundation for Forest and Wood research (Stiftelsen Skog- och Träforskning i södra Sverige), The Educational Programme of the National Timber Construction Strategy (Nationella träbyggnadsstrategins utbildningsprogram) and Midroc Property Development AB. This support is greatly acknowledged!

Special thanks also to Mr. Kjell Johansson, LBE arkitekter, and Mr. Hans Andrén, Vällbroar, who have met the challenge of co-ordinating the projects. Thanks also to Prof. Carl-Johan Johansson, who wrote the first draft for the research programme, to Mr. Anders Persson, Midroc Property Development AB and Mr. Gregor Lindgren, Martinsons Byggsystem AB, who also have been involved in the project steering committee.

Last, but by no means least, I would like to express my gratitude to the management and the staff at the building site, all showing an incredible amount of patience when we have been disturbing you in your everyday work.

Växjö, June 2009

Erik Serrano
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Part 1
Background and overview
Background and Introduction

Välle broar – Limnologen – Modern timber construction

The area between the two lakes “Trummen” and “Växjösjön” is called Välle Broar. This area has for a long time been somewhat overseen in planning, due to its location between the Town Centre and the Teleborg area. About 2002 this changed when the municipality of Växjö, in order to develop a town planning strategy, announced an architect competition for the area.

Figure 1. View of southern part of Växjö, the Välle Broar area is marked with in red
(www.vallebroar.se)

Already at a very early stage, when the architects’ contributions were received, the parties involved felt that the area should be used for projects using timber construction. The great interest in wood and timber available in the region, led to the municipality starting to work with a local timber construction promotion strategy. This strategic work drew the attention of the Swedish parliament, leading to a similar strategic work being initiated – and eventually finalised – on a national scale. The aim with the national timber construction promotion strategy was to increase the R&D efforts within the field and to increase the amount of timber and wood based products used in construction. After a 120-year period of prohibition there was a need for giving timber a chance to compete with other building materials (concrete and steel). Such efforts could, if successful, also lead to increased profits for the wood-based industry by increasing their market shares in Sweden, but also abroad.

In Växjö, the work with the local strategy continued and resulted finally in 2005 in a programme called “More wood in construction” (“Mer trä I byggandet”). The local strategy is closely connected to the Välle Broar area, and it states that in all construction, wood should be considered as one alternative. Within Välle Broar, all construction realised must be based on the use of timber or wood based products. This was motivated by the following facts:

- Växjö is situated in a region dominated by large forest areas and by companies within the wood-working sector. A large number of smaller towns within the region and the rural areas are dependent of this industry. If Växjö can contribute to the development of this industry both the community and the industry would benefit.

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1 The text is based on [3], [4], [6], [11].
Part 1. Background and overview

- Promoting the use of timber in construction is in line with the environmental policies set by the municipality of Växjö.
- Realising projects based on modern, industrialised timber construction, would draw the attention to Växjö, giving the town a clear profile.
- Wood-related research is one of the focus areas at Växjö University. Thus, the municipality of Växjö and the university can support each other.
- The municipality of Växjö is a large property developer and building owner, and thus has a clear interest in reducing building costs.

The Välle Broar project started in autumn 2006, and is planned to run for at least ten years, finalising one or two building projects every year. Välle Broar is a good example of what the academy, the municipality and industry can realise in a joint effort. The Välle Broar programme has drawn a considerable amount of attention from all around Sweden, but also from abroad.

The first building project being realised within Välle Broar is the construction of the tallest timber building ever built in Sweden in modern times – Limnologen. Limnologen consists of four eight-storey houses, seven timber storeys on a concrete foundation and concrete first floor. The company Midroc Property Development owns the project, which apart from the 134 apartments also consists of a parking deck and community facilities.

The Välle Broar programme is open for those who are interested in developing timber construction. Every building project being realised will be open for R&D activities, making it possible for universities and research institutes to perform research during a long time. In addition, the research can include all parts of the building process from town planning to real estate management.

The documentation and evaluation project

This report reports on the different research and information activities that have been performed at Limnologen. The Limnologen project gives an important - and unique – opportunity for full-scale development of timber construction. Especially thanks to the engagement from the municipality of Växjö, the regional industry through CBBT – Centre for Building and Living with Wood, but also thanks to the fact that every takes place close to the university and close to SP Trätek. The Limnologen project has also been followed by The Educational Programme of the National Timber Construction Strategy (Nationella träbyggnadsstrategins fortbildningsprogram). By being eble to offer such full-scale R&D, evaluation and documentation, Växjö plays an important role in Sweden – and Europe – for the development of modern multi-storey timber construction.

Similar R&D efforts are foreseen for the upcoming building projects at Välle Broar.

Limnologen – Short facts

Structure

The load bearing structure consists of CLT elements (Cross Laminated Timber), delivered by the company Martinsons Byggsystem. The CLT is used in both walls and floors. In addition, traditional timber framed walls are used in some walls (those separating apartments) The bottom floor is made of concrete, mainly due to the increased self-weight thus facilitates the anchoring of the above storeys.

The relatively complex geometry of the Limnologen complex, means that it is far from optimal for the building system used.
Since also inner walls are used for stabilisation, but at the same time an open floor plan is desired – it is of utmost importance that the dialogue between the architect and the structural engineers works well. All exterior walls are parts of the load bearing system. Some of the vertical loads are also taken by interior walls. The stabilising system consists of, the exterior walls, the floors, and the apartment-separating walls. The horizontal loads are transferred by the floors - acting as stiff plates – to the top of the walls. In some parts of the buildings, glulam columns and beams have supplemented the load bearing system in order to reduce the deformations.

**Stabilisation**

In order to handle the lift-up as a result of wind loading, 48 tension rods have been mounted in every building. These tension rods are anchored in the concrete of the first floor, and extend all the way up to the top floor – inside interior walls. In this way the force is transferred between the storeys and down to the foundation. This design means that load-transferring connectors between the wall elements are not needed. The tension rods must be re-tightened after some time due to relaxation in the steel, creep deformations in the wood and due to possible drying of the wood.

**Fire**

The Limnologen complex is equipped with residential sprinklers. This is not needed according to the Swedish legislation, but it has made it possible to use designs that would otherwise not been possible. As examples, the south façade is made of wood, the vertical distance between the windows on the north-west façade has been minimised and the wooden surface of the CLT-slabs of the balconies are visible from below. These re-designs are possible since it can be shown that the total fire safety of the building sufficient.

The requirements of the legislation on fire safety are independent of the material used in the load bearing structure. Since the buildings are of more than three storeys they are classified in class BR1, a class having the highest requirements. The apartments are separate fire cells, and are according to the Swedish building code designed in class EI60, the only exception being a pram storage room on the first floor which is classified as EI30.

**Acoustics**

Acoustics in large building with timber based floor systems could be a problem. Examples of this includes the risk of flanking transmission and impact sound transmission.

Already at the very early stages did the property developer put forward the demand that at least sound insulation class B should be achieved. The larger apartments (i.e. those having more than two rooms+kitchen) have one room that is especially sound insulated, the master bedroom. The bathrooms are also especially sound insulated.

Martinsons has some experience with the current building system from a previous project in Sundsvall (“Inre Hamnen”). In that project it has been shown that the acoustic requirements are well fulfilled. The walls are not continuous across storeys, in order to reduce the flanking transmission. Also the floor slabs are discontinuous. A polyurethane sealant, Sylomer® och Sylodyn®, is used between the walls and the flange of the floor elements. The screws and washers used to connect the floor and wall elements are also fitted with Sylomer® to reduce the sound transmission.
Part 1. Background and overview

Figure 2. Connection between interior wall and floor (Martinsons)

The above figure shows an example of a connection used in Limnologen. Note that both the wall and the floor elements are discontinuous through the joint area.

Moisture and weather protection

It is of utmost importance that the complete building process is moisture proof, including all events from manufacturing at the production plant, transportation to the erection and finalisation on site. The wall and floor elements are manufactured indoors, and are stored before being transported to Växjö. The wall elements are wrapped in plastic film, covered by a tarpaulin for transportation and transported in vertical position with open trucks. The floor elements are covered by tarpaulins, stacked one on another and are transported with covered trucks.

Unloading on the site is done using a forklift, and the elements are put on the ground without any additional covering until being moved to the lifting zone for assembly. The weather protection system being used involves a large tent with an integrated overhead crane, a system that has been a prerequisite in the project. The crane has a maximum capacity of 3.3 tonnes (the maximum weight of an element is 2 tonnes).

Figure 3. Packaging and transport of wall and floor elements.
Part 1. Background and overview

Installations
Most of the installations running in the lengthwise direction of the floor elements are installed already at the production plant. Installations running across the element’s are mounted on sites. The installations are for ventilations, water, electricity and sprinklers.

Walls
Three main wall types are used in Limnologen for the load bearing structure. These are (a) exterior walls of 3-layer CLT, (b) apartment separating timber framed walls and (c) 3-layer CLT interior walls, see Figure 5. The façades are either plastered or covered by wood panels. All walls are finished on site by being covered with gypsum boards.

Figure 4. The weather protection system with integrated overhead crane.
Floor structure
Every floor consists of a total of 30 floor elements. All storeys are equal in plan, except for the top storey. The 30 elements per storey are all different, however. The load bearing part of the floor element consists of a 3-layer CLT slab strengthened by T-shaped glulam beams, which are fully interacting with the top slab. The glulam beams are placed with a distance of 600 mm, see Figure 6. At delivery to the site the floor element includes parts of the installations, see description above, and parts of the insulations and the self supporting ceiling.
At Limnologen a floor heating system is used (water based). The floor has pre-cut grooves in the lengthwise direction of the floor elements for the heating tubes. These grooves are finished with additional cuts made at the site to make it possible to fit in the tubes. In each apartment the central is placed in a small wardrobe-like room, Figure 7.

**Finishing and management**

The first two buildings at Limnologen were finally finished during spring and early summer 2008. The second stage, containing the last two buildings will be finished during late spring 2009. The buildings are owned by the tenants, who form a tenant-ownership community.

The heat and water consumption is being measured individually in each apartment. Each apartment owner has access to a private web-page for the monitoring of the consumption. It is expected that the energy consumption will be less than 90 kWh/m² (per year) and that the individual monitoring will result in up to 30% reduction in energy consumption.
## Facts and figures

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
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<tbody>
<tr>
<td>Number of buildings</td>
<td>4 8-storey buildings</td>
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<tr>
<td>Number of apartments</td>
<td>134 apartments</td>
</tr>
<tr>
<td></td>
<td>6 1 room+kitchen, 40 2 rooms+kitchen, 44 3 rooms+kitchen, 28 4 rooms+kitchen and 16 two-storey apartments with 3 – 5 rooms+kitchen.</td>
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<tr>
<td>Apartment sizes</td>
<td>37 – 114 m$^2$</td>
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<td>Includes parking deck (timber) for 140 vehicles, community buildings and storage facilities.</td>
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<td>Cash investment (for tenants)</td>
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<td>Annual fee (rent)</td>
<td>640 – 740 SEK/m2 and year depending on apartment</td>
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<td>Builder</td>
<td>Midroc Property Development with Midroc Projects AB as main contractor Project manager: Anders Persson, Midroc Projects AB</td>
</tr>
<tr>
<td>Architects</td>
<td>Arkitektbolaget Kronoberg Architect Ola Malm</td>
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<td>Part 1. Background and overview</td>
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<td><strong>- Subcontractor timber frame</strong></td>
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<td><strong>Entreprenadgolv i Växjö</strong></td>
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<td><strong>Roofing</strong></td>
<td><strong>Tak Rekond</strong></td>
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<td><strong>Lifts</strong></td>
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<td><strong>Automation</strong></td>
<td><strong>ByggnadsAutomation</strong></td>
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<td><strong>Total building time</strong></td>
<td><strong>Approx 17 months per stage</strong></td>
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<tr>
<td><strong>One storey erection time</strong></td>
<td><strong>10 days</strong></td>
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Project aims – overview

Aim
The primary specific aims of the project have been to:

- to follow and document the building project by taking pictures, doing time studies etc, with respect to environmental aspects, moisture protection, deformations, acoustics, stabilisation, transportation and logistics etc.,
- contribute to the quality assurance of the Välle Broar related projects, by documentation of errors done and problems encountered,
- contribute to the development of modern timber construction including the building process,
- study the economic effects of choosing timber in construction, and,
- organise for the information activities needed in connection with the many technical visits to Välle Broar being realised.

In general terms, the aims are to:

- continuously deliver knowledge to the organisations involved in construction at Välle Broar, and to other national or international organisations that show an interest.
- create a dialogue and fruitful climate in the exchange of ideas and results between the researchers and the builders at Välle Broar, and also for other building projects in Sweden and in the Nordic countries.

Contents – Background and overview
The decision to realise the current R&D project was in part due to inspiration from a previously conducted R&D programme in Sundsall (Inre Hamnen). In that project, five 6-storey buildings were erected, and in connection to the building project a R&D and information project was performed, which was very successful in several respects.

The idea of performing the current project was put forward on the 6th of October 2006, when the formal start at the building site of the Limnologen project took place. Representatives from the Välle Broar project, Midroc Property development AB, “Träbyggnadskansliet”, The municipality of Växjö, VKAB, Martinsons Byggsystem AB, Växjö university and SP Trätek met, and there was a consensus of performing some kind of R&D and informational activities. Midroc also declared that they would be prepared to financially support some of these activities.

The general idea has been that by following and documenting the building project, which must be said to be unique although timber construction has developed considerably lately, the parties involved in the building project will gain knowledge. Knowledge about construction in general, and about multi-storey timber construction in particular. The following questions were identified as being of special interest:

- What can be improved in the building process and in technical solutions?
- How does the currently used building system compete economically with other previously used building systems (timber based and others)?
- What are the attitudes towards timber construction among the end-users?
- What are the environmental impacts of choosing timber and does the choice of timber contribute to the creation of a sustainable society?
- What are the main concerns in terms of managing a multi-storey timber building?
Taking into account the limited financial and human resources available, and taking into consideration that the project has been performed in parallel with the building project itself, it has not been possible to address all the above questions. Thus, the following areas have been considered in the present R&D project:

- **Planning**: Documentation of suggestions put forward and decisions taken during the early stages of the planning and building process.
- **Quality**: Documentation of errors committed and problems encountered.
- **Technology, energy and environmental aspects**: Inventories of the technical and environmental performance of the different solutions chosen. This includes e.g. mounting different measurement devices to monitor performance during service life.
- **Economy and market aspects**: Customer perceptions of timber construction.
- **The building process**: Time studies, logistics etc.
- **Information**: Supplying information to visitors.

Part 2 of this report contains the reports in summary of sub-projects, as presented by the researchers.
Bibliography


Part 2
Sub-project reports
Planning and Project Work for Timber
Erland Ullstad, Välle broar and Olof Thedin, Arkitektbolaget

Summary
Almost all high-rise buildings in Sweden are built with a load bearing framework of concrete and steel. The aim of this report is to describe the process of a practical case, that led to a different result, as a guide and inspiration to those municipalities, commissioners of such projects, project personnel and building companies who wish to build in timber.

The report is based on interviews with key people during the ongoing process, as well as plans, documents and drawings from the process.

Strategies
With more than a 100 year ban (1874-1995) on using timber for load bearing frameworks for buildings higher than two storeys, timber became marginalised throughout the whole broad spectrum of building construction. Experience, education and training, practice, organisation, norms, the market, etc., were all adapted for concrete and steel construction. When the norms were changed in 1995, from a ban on timber to a requirement that timber frameworks should be able to withstand fire for a certain period of time, a certain number of pilot projects of high-rise timber buildings were carried out to demonstrate that it was possible and with the hope that such construction would also be cheaper.

Södra Skogsägarna took the initiative to Valludden in Växjö, with 2, 4 and 5 storey buildings. The municipality was strongly committed to the project by means of site-exchange, town planning and in the jury for the architectural competition that was announced.

Despite all the attention the pilot project received, timber construction for high-rise buildings did not really take off to any greater degree. In 2004 the basis for a national strategy for "More timber in building construction" was produced. This was an important new starting point. On the national level, the strategy principally relates to information, good examples, education and training and research.

The Municipality of Växjö asked itself the question: What can a municipality do to develop timber construction?

A municipal strategy was formulated and passed by the council 2005-02-17, § 25 (See www.vallebroar.se)

The municipality’s strategy: More timber in building construction.
In the strategy document from 2005-02-17 the emphasis lies on clarifying the motives that exist for municipal commitment in the issue. The following aspects were highlighted:

1. The development of the region’s forest-based industries to thereby strengthen economy and employment
2. The environment
3. The strengthening of Växjö’s profile as a timber building town
4. He support Växjö University’s efforts in research surrounding timber and wood in general
5. The reduction of building costs
6. Co-operation with the government’s initiative
With a clearly and strongly motivated starting point, the strategy poses the question as to what instruments the municipality has at its disposal. In principle, they are three:

1. Planning and development operations. The municipality has the planning monopoly and major holdings of land. Even for the development of private land, the municipality has a major influence through town planning and the possibility of development agreements.

2. Their own building. The municipality is a major commissioner of buildings for homes, municipal services and installations.

3. The municipality’s role as a major and trustworthy party in society can be used to advantage within collaborative projects, opinion making and the building of networks.

The next link in the strategy is to point out how these tools should be used in order to achieve the goal of "more timber in building construction". The municipal council’s directive is brief. On one page two different lines are developed:

On the one hand that the municipality’s boards/committees and holding companies shall take into account the stated motives and always test the possibility of using timber. The city council’s strategy was consciously cautious and not imperative in the first line of action - "to always test the possibility of using timber". This was based on an understanding that in many cases timber was not chosen, because the question of timber never arose. A well established practice is conservative and much discussion is required to break such a practice or trend.

On the other hand, in the Välle Broar area, "The modern wooden town", shall, to as great a degree as the municipality can influence it, all building shall contribute to the development of timber building construction. This means that the municipality, as land owner or commissioner of buildings, orders a timber construction and only invite those parties that are willing and able to develop modern timber building construction.

In its complete form, the city council’s directive was formulated as follows:

The municipality’s goal is an increased use of timber in higher (high-rise) buildings. During the coming 10 year period, Välle Broar shall develop into a modern wooden town. The municipality’s boards/committees and administration/companies shall, in the course of their operations take into account the motives stated above. This particularly applies:

- In the physical planning at the inception of a project, timber construction shall be tested. In the detailed town planning the planning description shall, where relevant, clearly show how the issue has been dealt with and the description of its execution shall show how such ambitions have been realised.

- There shall be plan preparedness for smaller projects where sufficient space is given to entrepreneurs engaged in developing timber construction.

- All buildings within the Välla Broar area, that is to say, the land between Vallviksvägen/G Veijdes väg and the Växjö Lake/Lake Trummen, as far as the municipality is able to influence the matter, shall contribute to “the modern wooden town”. This may be a question of techniques used, production or architecture. It may be a question of timber in the framework, wooden façade cladding, wood used in the carpentry and fittings. It can be a question of pure timber/wood solutions but also the developments of the possibilities of timber/wood in conjunction with other materials.

- All projects within Välle Broar shall be open and accessible for research and evaluation.
• In the plans for Välle Broar the general aspect of the town as a “wooden town” need to be regulated in town planning decisions made.

• Plans, land directions and development agreements shall be taken advantage of to establish collaboration with the commissioners of buildings and entrepreneurs who wish to develop timber building construction.

• The Engineering Board shall, for construction in public environments, test the possibilities of timber.

• The municipality’s own companies shall, in every building project, test the possibilities of timber. The companies shall develop their competence and skills in timber building construction. Completed timber building projects shall be evaluated technically and from an administrative perspective. A knowledge base shall be established and spread.

• Affected administrations and companies shall, taking resources and benefits into account, take part in research projects, networks and the spreading of knowledge.

In the other line of action, “in the Välle Broar area…” there was a reservation “to as great a degree as the municipality can influence it…” The municipality’s ability to control is limited, particularly if the land is not municipally owned. "Shall" means that those projects that for technical, economic or other reasons are unable to deal with developing timber construction shall not be built. An acute conflict arose surrounding the Pålaträdan area, which is a part of Välle Broar.

The timber strategy was, as it was formulated in 2004, somewhat unclear in terms of what was meant by timber construction. It wasn’t until a later stage that it was clear that in the first instance this related to timber in the load bearing framework.

Välle Broar included two projects the Pålaträdan and Limnologen areas, that were started long before the timber strategy from 2004 and which therefore, at least in part, followed different rules.

Figure 1. Illustration plan for Välle Broar
Residential blocks in the Pålaträdan area

In the Pålaträdan area there was one major private property owner, Fermera AB. This was established long before the municipality’s commitment to timber construction had been formulated and had developed into an adopted strategy. Fermera AB had been promised an alteration in the town planning and to be able to acquire municipally owned land south of their property in order to build rental properties and approximately 4,000 square metres of commercial space. The alteration to the town planning took longer than anticipated due to major traffic issues and during the on-going work, the municipality’s timber strategy came into the picture.

Fermera AB were positively disposed to build with timber and paid for an architectural competition to develop the buildings and to find the right firm of architects for the assignment. ArkitektBolaget in Växjö won the competition. The detailed plan stated that the objective of the plan was to build with timber and the municipality’s land in the area was sold to Fermera AB.

In the autumn of 2006, Fermera applied for building permission for 72 apartments in 4 storey tower blocks. The building was planned to be built in timber and constructed by Skanska who helped Fermera AB to develop the project. Instead, Skanska wanted to construct the buildings with concrete frameworks. Fermera AB claimed that load-bearing timber frameworks would be too expensive and that on the current market of the time, it was difficult to find suppliers of timber frames. The local building committee rejected the application with reference to the requirement for timber in the detail plan. Fermera AB appealed against the decision to the county administrative board that judged that the local building committee did not have just cause for their rejection of the application; the detail plan may not demand that the load bearing framework shall be constituted of timber.

The project was now seriously pressed for time as worsened loan conditions would negatively affect the economy if the building was not started before then end of 2006. If the local building committee had appealed, the project, regardless of the outcome of the appeal, would have been dead and buried. The local building committee therefore abstained from appealing against the county administrative board’s decision.

The municipality’s conclusion was that possession of the land is the best steering instrument and therefore decided that in future, no land sales within Välle Broar shall be finalised before building permission has been obtained.

The Limnologen area, from 4 storey concrete to 8 storey timber buildings

The idea to build homes by the shores of Lake Trummen had already been hatched in 1997. It was seen as an opportunity to unite south and central Växjö here. In the section of land between the Växjö lake and Lake Trummen there was a deal of undeveloped “impediment” land. A preliminary sketch with three storey student accommodation, Sjöbägen, was produced.

A detail plan was accepted and a pair of different projects were sketched out, without ever being implemented. All projects from 1997 to 2005 were conventional residential buildings with load bearing concrete frames.

In August 2005 Midroc purchased the property and entered into discussions with the municipality of Växjö relating to common guidelines for continued work. The demand from the municipality of Växjö to enable Midroc to purchase and build in the Limnologen area was “elements of timber”.

From the beginning, Midroc had not thought about taking this to its fullest extent. The decision to choose only timber grew from the discussions.

At that time, the municipality had its prepared strategy, but only small possibilities to compel the building of a structure in timber against the will of the commissioner of the building.

The municipality and Midroc began to discuss the forms of continued collaboration surrounding the development of the area, and to produce common guidelines for this continued work.

Midroc was willing to organise an architectural competition to develop a timber construction concept. Two firms of architects with good experience of timber construction were invited to compete. The winner of the competition was the Växjö-based company ArkitektBolaget (www.arkitektbolaget.se) that has a great deal of experience of timber from previous projects.

This was the start of close collaboration between Midroc and the municipality.

The buildings grew in height and Midroc applied for an alteration to the plans in February 2006. 31/2 months later, the local building committee approved the new plan.

In the Limnologen area the municipality did not have the ownership of the land as a steering instrument. Instead, it was the parties common desire to achieve a good building and a collaboration based on confidence in each other that became the method.

Midroc gained a lot of time, increased the development possibilities and received a huge amount of attention in their efforts. The municipality’s efforts in Välle Broar, the modern wooden town, got off to a flying start thanks to Midroc’s and Martinsson’s great competence and skill and willingness to accept the challenge to build Sweden’s tallest, modern timber building.

Figure 2. Location plan, Limnologen
The decision to build exclusively in timber

In November 2005, a timber/wood seminar was held at the University of Växjö. Martinsons recounted their experiences in building high-rise timber buildings and informed the seminar that they had now mastered the problems of fire and sound dampening. It was now possible to satisfy sound class B, (that is to say, better than the stipulated sound class C).

Magnus Skiöld and Anders Persson from Midroc were amongst the listeners and were convinced that there was now so much experience in high-rise timber construction that Limnologen could be built exclusively of timber. Limnologen, as a timber project, started, mentally, at this seminar. Midroc’s commitment owed a great deal to the fact that they had a visionary and fearless Managing Director. This was a determining factor for the project to be able to start.

Planning

As stated above, Midroc took the responsibility to engage two firms of architects and a designer with the objective of developing a timber construction concept with the starting points that applied for Välle Broar and the national timber construction programme.

In October 2005 the invited architect firms presented their proposals. In November, the winning proposal was announced.

At the beginning of 2006 a first thorough investigation of available suppliers of timber frames was carried out. Martinssons were deemed the most interested and at the same time, the most interesting.

Midroc saw themselves as beginners building high-rise in timber. Internally it was determined that Midroc must find a supplier of timber frames who had built high-rise building before. The management were particularly worried about sound and fire.

Initial investigations pointed towards having to use a concrete framework and that the building was too tall to build solely in timber. Tyréns prescribed a hybrid construction: steel frame, timber beams and curtain walls. Midroc did not want this solution as they had experienced problems with such a construction previously.

It was decided to compare the costs for timber with the costs of a traditional construction. Tyréns produced a proposal with concrete framework plus curtain walls as well as with timber framework and a lift shaft of concrete.

The rough calculation showed 3-4% higher costs for the timber alternative.

How the peripheral costs were affected had to be weighed up in these prices: Limnologen has a small area to build on and is a very big project. What does the site look like?

You can build quicker in timber. How are the final costs affected by this? After the preliminary economic study and against the background of the above reasoning, it was decided to go ahead with the timber alternative and with Martinsons.

When Martinsons came into the picture the static problems were solved.

Midroc’s experiences from Lagerhuset in Eslöv (a grain warehouse from 1918 that was converted into apartments, (www.lagerhuset.nu) meant that they knew how to solve the fire problem in the cheapest way, namely with the help of sprinklers and technical exchanges.

Martinsons had a complete solution. They would not merely take the responsibility for the project work for the buildings (“A” project activities were carried out by ArkitektBolaget) but also for the installations and complementing of beams.
Midroc travelled up to Sundsvall and carried out full scale sound tests, to satisfy themselves that the sound problems had been solved.

Martinsons produced the drawings and calculated a price. The basic idea was accepted, as was the price. No negotiations were necessary.

Martinsons went into the project with the aim of having better control of the complete process, in order to be able to control the costs and quality.

**Project work**

During the period between December 2005 and February 2006 the architectural documents were processed. In June 2006 the project received building permission and during the period from June to October, the architect’s project operations took place.

From the beginning, the idea was to construct the buildings with a concrete raft on the ground and timber framework. Martinsons suggested instead that the whole of the lowest floor be constructed of concrete – for the sake of stability.

Martinsons drew up the design/construction drawings for the Limnologen area themselves.

Martinsons’ project operations were comprehensive and consumed a great deal of time, due to the fact that at the same time, a completely new concept was being developed.

In Limnologen they have developed the design so that sound, fire, dimensioned loads, vibrations, etc., have now been mastered.

![Figure 3. The façades, Limnologen](image)

**Procurement**

Midroc received a first quotation from Martinssons in February 2006. Midroc drew up a list outlining the borders of responsibility that was sent to Martinsons so that they could
determine what they wanted included to achieve the best productivity possible on the building site.

The sub-contractors that Midroc had thought to use in the project did not have the time. The building construction market was over-heated at the time. It was decided that Martinssons should also have the sprinkler systems, ventilation and plumbing included in their sub-contract.

Midroc produced lists outlining the borders of responsibility for project operations, framework, delivery and installation.

The installations were to be carried out at the factory, up to the determined shaft.

Midroc and Martinson shook hands and formed a joint project of Limnologen in September 2006.

The question that arose was what the installation sub-contracting would entail? A functional description for plumbing, ventilation, electricity, sprinkler systems and lifts was needed. Bygfast produced the frameworks for how the installations should be. The most important document was again the list drawing up the borders of responsibilities. In October 2006 the final revisions were made. Without all this, there would have been complete chaos.

![Figur 4. Third storey, house C, Limnologen](image)

**Implementation**

The first saw-cut for the project was made on the 4th October 2006.

Surprisingly little had been forgotten or not thought of, according to Midroc and Martinsons felt that it had been a very positive experience working with Midroc.

For the timber building project in Sundsvall Martinsons did everything in the factory, apart from the electrical installation and the sprinkler systems. In Växjö they have done everything apart from the electrical installation.

During the on-going construction they have continually followed up determining issues vital to the final result. When the first building had reached four floors, for example, a fire meeting
was called with 8 experts in the field. At this meeting they went through all fire seals in the joist system, the shaft, etc. This showed that the beam complementing people hadn’t thought things out completely. The through-wall sections didn’t work using traditional solutions. No other project has included so many controls, checks and taking of samples. Faults have been discovered at an early stage.

Another example is the problem of dampness. During the construction period there was a great deal of discussion in Sweden about the problem of mildew on the most exposed façades of a building. Midroc immediately called everyone to a dampness – rendering meeting, where the method being used for the buildings was closely scrutinised and approved.

The first building was ready for occupation at the end of February 2008.

Experiences

Due to the fact that the beams used for Limnologen were of a more slender dimension than those used in Lagerhuset (see above) it was not possible to make as many technical exchanges. The result of this was that more plasterboard was used in Växjö. It has been shown that there are different interpretations in different towns as to the technical exchanges that can be made.

The weather protective tent meant that the concrete of the lowest floor was already completely set and dried out when construction had reached the third floor. This drying out occurred on its own. The tent is thus important even for a conventional concrete construction. With this building system there is no alternative to the tent. The building work must be carried out in the dry. The building is going to exist for a hundred years and it must satisfy quality demands.

Under-floor heating has caused problems. The sawdust from the milling of the tracks for the heating pipes have been difficult to dispose of. Under-floor heating has also been a problem in terms of borders of responsibility. One thing that has been learned is that under-floor heating should not be employed in future projects. It entails too much work.

The borders of responsibility for the ceilings has not been successful – or perhaps the actual product was not ready.

The requirements for the weather protection tent have become more stringent in order to be able to more rapidly lift floor by floor and to be able to work on the façades. Martinsons have started manufacturing their own weather protection. (First installation week 5, 2008.) Collaboration has also begun with Lindbäcks bygg for completed, ready to install wc/bathrooms.

Martinsons believe that a pre-condition to making such a project profitable is that you build and install the walls yourself. You can then have full control of all costs.

Martinsons have also determined that, to make it attractive to take part in a residential project, then the project must be for 10 identical floor plans, in order to make the project profitable. Better instruments for project work are also required.

The (technical) installation in buildings is the toughest area to develop. They are included in existing systems and structures.

Without a visionary Managing Director at Midroc this timber project would not have even got off the ground at all. Without a committed and skilled project manager it would not have been possible to run this project from Midroc’s side.

Without Martinsons’ commitment and enthusiasm all the technical innovations that have been developed for this project would never have seen the light of day.
Part 2. Sub-project reports

**Limnologen Växjö – Lifecycle primary energy use and carbon analysis of an eight-storey building**

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Ecotechnology, Mid Sweden University, Östersund

**Summary**
In this study we analyze the primary energy use and carbon dioxide (CO$_2$) emission over the lifecycle of the Limnologen building, an eight-storey apartment building in Växjö, Sweden made with a wood structural frame. The analysis covers all the life cycle phases of the building, including the acquisition of raw materials, the processing of raw materials into building materials, the assembly of materials into a ready building, the occupation or use of the building, the demolition of the building and the disposal of the demolition material. We determine primary energy use by including the entire energy system chains from the extraction of fuels to the delivered end-use energy. We track fossil carbon flows including their conversion, transport, and emission to the atmosphere, and we track biological carbon flows from their uptake in the forest through the entire wood product chain to their eventual release back to the atmosphere.

We find that the operation of the building uses the largest share of lifecycle energy use, becoming increasingly dominant at the life span of the building increases. The type of heating system plays a major role for primary energy use and CO$_2$ emission, since it affects what type of energy supply chains are used. A biomass-based district heating systems achieves low primary energy use and very low CO$_2$ emissions. During the construction phase of the building, more bioenergy can be obtained from residues from the wood products chain (forest residues, wood processing residues, and construction site residues) than is used to produce the building. Additional bioenergy can be obtained at the end of the building life cycle if wood-based demolition residues are recovered and used as biofuel. The use of recovered biofuels to substitute for fossil fuels significantly reduces the net emission of CO$_2$. Considering only the construction-specific lifecycle inputs (excluding household hot water and electricity), a negative lifecycle emission of CO$_2$ can be achieved with a biomass-based energy supply system including district heating with cogeneration of heat and electricity. The results of this study show that it is important to adopt a life cycle perspective involving both construction and energy supply when evaluating the primary energy and climatic impacts of buildings.

**Introduction**
The scientific community points out that the emission of carbon dioxide (CO$_2$) from human activities affects the global climate system. Sweden and many other countries have set long-term goals for CO$_2$ emission reduction to mitigate climate change. The building sector accounts for a large part of the total energy use, and has great potential for reducing primary energy use and CO$_2$ emission by reduced heating demands, increased efficiency in energy supply chains, increased use of renewable energy, and substituting wood materials in place of concrete, steel, and other materials.

The aim of this study is to determine the primary energy use and CO$_2$ emission over the lifecycle of the Limnologen building in Växjö, an eight-storey apartment building made with a wood structural frame. The building has 3374 m$^2$ of floor area, and 33 apartments. All the life cycle phases of the building, including the production of materials, construction, operation, disassembly and waste management are considered in this study. We account for the full flows of energy and materials from natural resources to useful services. We determine
primary energy use by including the entire energy system chains from the extraction of fuels to the delivered end-use energy. We track fossil carbon flows including their conversion, transport, and emission to the atmosphere, and we track biological carbon flows from their uptake in the forest through the entire wood product chain to their eventual release back to the atmosphere.

Methods

We estimate the total quantities of materials in the building, broken down by type of material and building component (foundations/ground floor; outer walls; inner walls; floor structure; roof; windows; balconies; and interior fixtures) based on analysis of construction drawings and personal communication with staff of the construction industries involved in the Limnologen project. We account for waste material generated during construction by increasing the material quantities by a specific percentage, depending on the material type (Björklund and Tillman 1997).

Calculation of energy and carbon balances of the materials followed the methodology developed by Gustavsson et al. (2006), Gustavsson and Sathre (2006) and Sathre (2007). We use data on specific energy use for extraction, processing and transport of materials from Fossdal (1995) from Norway, and Björklund and Tillman (1997) from Sweden. Data on forest production energy (seed production, nursery operations, site preparations, and pre-commercial thinning) are based on Berg and Lindholm (2005). Based on total material mass inputs for the buildings (including construction waste), and specific energy demand data for the manufacture and transportation of each material, we calculate the total final-use energy needed to provide the building materials. We then calculate total primary energy use for the building materials by taking into account efficiencies of fuel cycle, conversion and distribution systems.

We assume that 100% of biomass residues from wood processing, construction, and demolition are recovered for use as biofuel. Of harvest residues, we assume the recovery of 75% of branches and 25% of needles. We assume appropriate moisture content and heat values of the various types of biofuels. Energy inputs for the recovery and transport of biomass fuels, which we assume is diesel fuel, is quantified as 5% of the heat energy content of the recovered harvest residues, and 1% of other residues. Biofuel is assumed to replace fossil fuel that otherwise would have been used, resulting in avoided fossil emissions. The two reference fossil fuels we consider for replacement by recovered biofuels are coal and fossil gas. Appropriate combustion efficiency conversion factors are used to relate the heat value of the biofuel to the avoided fossil emission.

Specific full-fuel-cycle CO$_2$ emission from fossil fuel use is taken to be 0.24, 0.29 and 0.40 kg CO$_2$/kWh end-use energy, for natural gas, oil and coal, respectively (Gustavsson et al. 1995). We include calcination emissions from the manufacture of cement, and assume a gradual carbonation uptake of 8% of the initial calcination release over a 100-year span. We assume that on-site construction activities for the Limnologen building use 80 kWh/m$^2$, and assume that half of the construction energy use is electricity and half is diesel fuel.

Calculation of the primary energy use and CO$_2$ emissions of the building operation followed the methods described by Gustavsson and Joelsson (2007) and Joelsson and Gustavsson (2009). The operation phase includes energy for space heating (energy for heating system and electricity for operating the ventilation system), domestic hot water, and electricity for household use and facility management purposes. Energy use for maintenance during the building life was not included. We consider 2 different life spans: 50 years and 100 years.
The energy use for space heating and ventilation during the operation phase of the building was estimated by computer modelling using ENORM software (EQUA 2001). ENORM computes the energy and average power demand over a twelve-month period based on outdoor temperature and average solar radiation on a 24-hour basis. The program accounts for factors including the thermal transmittances and the areas of the building envelope. The indoor air temperature is assumed to be 22° C inside the apartments and 18° C in other parts of the building.

The primary energy used for operation was calculated by using the computer software ENSYST (Karlsson 2003). It estimates the fuel input at each stage in the energy system chains, and take into account the energy efficiency for each process. The operation phase was also compared with respect to net CO\textsubscript{2} emission, which was calculated in the same way by ENSYST. The assumptions used in ENSYST regarding the production and transportation of fuels for electricity and heat were the same as those made by Gustavsson and Karlsson (2002, 2003). We evaluate the operation phase of the building for several types of energy supply systems. The heating systems compared were electric resistance heating (RH), bedrock heat pump (HP) and district heating (DH). For the bedrock heat pump we assumed a heat factor of 3, and an effect of 35 kW which covered 98% of the heat demand. Electric heaters integrated with the heat pump system covered the remaining demand.

All of the heating systems require some electricity to run and the base-load electricity was supplied from power plants with different fuel and technology: coal-based steam-turbine (CST), biomass-based steam turbine technology (BST) and biomass-based integrated gasification combined-cycle systems (BIG/CC). These systems were assumed to cover 95% of the heat demand in the electrical heating systems, while peak production with light-oil-fired gas turbines covered the remaining 5%. For the district heating systems analysed here cogeneration plants covered the base-load heat demand, while light-oil-fired boilers covered the peak demand. We assumed that the electricity cogenerated in the district heating system replaced electricity that would otherwise have to be produced elsewhere, using condensing power plants based on similar technology and with the same kind of fuel as the corresponding cogeneration plant (Gustavsson and Karlsson, 2006). This cogenerated electricity was hence subtracted from the cogeneration system to give heat as the output function of the system. The domestic hot water and household electricity was generated with technology and fuel corresponding to the heating system (Gustavsson and Karlsson, 2006).

We assume that demolition of the Limnologen building will require 10 kWh/m\textsuperscript{2}. We calculate demolition-related carbon emissions based on the assumption that the demolition energy is from diesel fuel. We assume that 90% of the wood-based demolition materials are recovered and used as biofuel.

**Results**

The primary energy use and net carbon emissions resulting from the production of materials and the construction of the Limnologen building are shown in Table 1. The biggest share of energy and emissions are due to end-use fossil fuels and electricity for material production. Cement process reactions and on-site construction have relatively minor contributions. The temporary storage of carbon in wood building materials offsets much of the fossil emissions from material production.
Table 1. Primary energy use (kWh/m²) and carbon emissions (kg CO₂/m²) from material production and construction of the Limnologen building, with reference fossil fuel of either coal or natural gas.

<table>
<thead>
<tr>
<th></th>
<th>Primary energy (kWh/m²)</th>
<th>CO₂ emission (kg CO₂/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coal Ref</td>
<td>NG ref</td>
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<tr>
<td>Material production (fossil fuel end-use)</td>
<td>445</td>
<td>445</td>
</tr>
<tr>
<td>Material production (electric end-use)</td>
<td>294</td>
<td>235</td>
</tr>
<tr>
<td>Material production (biofuel end-use)</td>
<td>154</td>
<td>154</td>
</tr>
<tr>
<td>Cement reactions a</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Carbon stock in wood building materials b</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>On site construction</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Total</td>
<td>973</td>
<td>914</td>
</tr>
</tbody>
</table>

a Net cement reactions are shown, including calcination emission during manufacture and carbonation uptake during a 100-year lifespan.

b The carbon stock in building materials is a temporary storage that will be released at the end of the building’s life cycle.

The primary energy use for operation of the building is listed in Table 2, using different energy supply systems. The actual heating system in the Limnologen building most closely corresponds to biomass-based steam-turbine district heating (DH BST). The choice of heating system for space heating and tap water has a great influence on the primary energy use. For coal-based systems, district heating results in 70% less primary energy use for space heating than if using resistance heaters, and 35% less for the total operation. The choice of electricity supply system also makes a difference, and using BIG/CC instead of BST reduces the primary energy use for the operation by around 15%.

Table 3 shows the CO₂ emission from building operation, which depends heavily on the carbon content of the fuel used in the energy supply systems. The natural gas-based systems have lower emission than the coal-based systems, and the biomass-based systems are the lowest.
Table 2. Primary energy use (kWh/m\(^2\)) for a 50 year operation phase of Limnologen building, using different energy supply systems. For a 100 year life span of the building, all values are doubled.

<table>
<thead>
<tr>
<th></th>
<th>Space heating</th>
<th>Ventilation</th>
<th>Tap water</th>
<th>Electricity for household use and facility management</th>
<th>Total operation</th>
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</thead>
<tbody>
<tr>
<td><strong>Coal-based steam turbine (CST)</strong></td>
<td></td>
<td></td>
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<tr>
<td>Resistance heaters</td>
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<tr>
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<td>District heating</td>
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<td>799</td>
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<td>1069</td>
<td>596</td>
<td>5405</td>
<td>7317</td>
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</tbody>
</table>

Table 3. \(\text{CO}_2\) emission (kg \(\text{CO}_2/m^2\)) for a 50 year operation phase of Limnologen building, using different energy supply systems. For a 100 year life span of the building, all values are doubled.

<table>
<thead>
<tr>
<th></th>
<th>Space heating</th>
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<tr>
<td>Resistance heaters</td>
<td>596</td>
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<td><strong>Natural gas-based combined cycle (NGCC)</strong></td>
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<tr>
<td><strong>Biomass-based steam turbine (BST)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance heaters</td>
<td>61</td>
<td>40</td>
<td>168</td>
<td>204</td>
<td>473</td>
</tr>
<tr>
<td>Bedrock heat pump</td>
<td>37</td>
<td>40</td>
<td>91</td>
<td>204</td>
<td>373</td>
</tr>
<tr>
<td>District heating</td>
<td>20</td>
<td>40</td>
<td>49</td>
<td>204</td>
<td>314</td>
</tr>
<tr>
<td><strong>Biomass-based integrated gasification combined cycle (BIG/CC)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance heaters</td>
<td>57</td>
<td>38</td>
<td>158</td>
<td>193</td>
<td>446</td>
</tr>
<tr>
<td>Bedrock heat pump</td>
<td>10</td>
<td>38</td>
<td>24</td>
<td>193</td>
<td>264</td>
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<tr>
<td>District heating</td>
<td>8</td>
<td>38</td>
<td>18</td>
<td>193</td>
<td>257</td>
</tr>
</tbody>
</table>
Table 4 shows an overview of the primary energy use and CO\textsubscript{2} emissions for the different life cycle phases: production, construction, fossil fuel replaced by biomass residues, operation with DH BST, and demolition. The biomass recovery from production and construction phases and the recovery of demolition wood show negative primary energy use, since they result in usable energy. The biofuel recovered from production and construction processes corresponds to more primary energy than is used in those processes. Household electricity is by far the largest single user of primary energy.

Table 4. Primary energy balance (kWh/m\textsuperscript{2}) and carbon balance (kg CO\textsubscript{2}/m\textsuperscript{2}) of the life cycle of the Limnologen building, for a 50 and 100 year life span. The heating system is biomass-based district heating (DH BST). Positive numbers indicate energy used and CO\textsubscript{2} emitted, and negative numbers indicate energy that is available and CO\textsubscript{2} emissions avoided.

<table>
<thead>
<tr>
<th></th>
<th>50 years (kWh/m\textsuperscript{2})</th>
<th>100 years (kWh/m\textsuperscript{2})</th>
<th>50 years (kg CO\textsubscript{2}/m\textsuperscript{2})</th>
<th>100 years (kg CO\textsubscript{2}/m\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material production</td>
<td>894</td>
<td>894</td>
<td>287</td>
<td>287</td>
</tr>
<tr>
<td>Construction</td>
<td>80</td>
<td>80</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Biomass recovery from production</td>
<td>-1182</td>
<td>-1182</td>
<td>-468</td>
<td>-468</td>
</tr>
<tr>
<td>Operation</td>
<td>8843</td>
<td>17687</td>
<td>314</td>
<td>627</td>
</tr>
<tr>
<td>-Space heating</td>
<td>391</td>
<td>781</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>-Ventilation</td>
<td>1240</td>
<td>2480</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>-Tap water</td>
<td>942</td>
<td>1883</td>
<td>49</td>
<td>97</td>
</tr>
<tr>
<td>-Electricity (household and facility)</td>
<td>6271</td>
<td>12542</td>
<td>204</td>
<td>409</td>
</tr>
<tr>
<td>Demolition</td>
<td>10</td>
<td>10</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Biomass recovery from demolition</td>
<td>-571</td>
<td>-571</td>
<td>-225</td>
<td>-225</td>
</tr>
<tr>
<td>Total</td>
<td>8074</td>
<td>16918</td>
<td>-62</td>
<td>251</td>
</tr>
</tbody>
</table>

The primary energy use for hot water and for household and facility electricity constitutes a significant part of the energy in the operational phase, but these demands depend to a large extent on the users. Figure 1 shows the primary energy use for Limnologen during 50 years, excluding hot water and household and facility electricity, for five different energy supply systems. The primary energy use is divided in six parts. The space heating constitutes the largest single part, while the primary energy use for on-site construction and demolition together constituted 3% of the primary energy used. The amount of fossil fuels replaced by recovered biomass was the same independent of energy supply system, while the primary energy use for operation varied.
Figure 1. Primary energy use for a 50 year life cycle of the Limnologen building using five alternative energy supply systems for space heating: resistance heaters (RH), heat pump (HP) and district heating (DH), combined with coal-based steam turbines (CST), and DH combined with biomass-based steam turbines (BST) or biomass-based integrated gasification combined-cycle systems (BIG/CC).

Figure 2 shows CO₂ emissions of a 50 year life span of the Limnologen building, using different energy supply systems. With biomass-based district heat, the CO₂ emission from space heating is small. If the building used resistance heating with fossil electricity, the CO₂ emission from space heating would dominate over the CO₂ emission from the other life cycle phases. The Limnologen building shows negative emission in the production and construction phase due to the replacement of fossil fuel with biomass by-products from the production and construction. A biomass-based energy supply system, including cogeneration of district heat and electricity, gives negative total life-cycle CO₂ emission.

Figure 2. CO₂ emission for a 50 year life cycle of the Limnologen building using five alternative energy supply systems for space heating. For supply system abbreviations, see Figure 1.
Discussion and Conclusions

The results of this study show that it is important to adopt a life cycle perspective involving both construction and energy supply when evaluating the primary energy and climatic impacts of buildings. During the construction phase of the Limnologen building, because of its wood frame, more bioenergy can be obtained from residues from the wood products chain (forest residues, wood processing residues, and construction site residues) than is used to produce the building. Additional bioenergy can be obtained at the end of the building life cycle if wood-based demolition residues are recovered and used as biofuel. The use of recovered biofuels to substitute for fossil fuels can significantly reduce the net emission of CO$_2$.

The choice of heating systems plays a major role for primary energy use and CO$_2$ emission. District heating and bedrock heat pump are heating systems where a low primary energy use can be achieved. Biomass-fired supply systems based on combined heat and power plants provide service with very low net CO$_2$ emission. Considering only the construction-specific lifecycle inputs, excluding hot water and electricity for household use and facility management, a negative lifecycle emission of CO$_2$ can be achieved due to the wood-based construction materials and a biomass-based energy supply system.

Quantities of materials in the building were estimated based on construction drawings and information provided by the staff of the construction industries, however there remains some uncertainty regarding material quantities. Some types of materials which exist in small quantities in the building were aggregated to simplify the production energy calculations. Production energy data are not available for all materials, so in these cases we use data for similar materials. Data on material production energy are from studies about ten years old. It is expected that industrial efficiency improvements have been made since then, thus it is likely that energy use for material production has been slightly overestimated in this analysis.

We have assumed the use of sustainably managed forests, and the effect of forest management on carbon stocks in forest ecosystems is not considered in this study. The analysis of the energy supply chains is based on detailed assumptions of many different processes and technologies that are representative of Swedish conditions. No alternative exactly matches the conditions in Växjö, although the Limnologen building is heated with district heating based on biomass-based steam turbines (DH-BST).

Acknowledgements

We gratefully acknowledge the assistance of NCC, Midroc, and Martinsons. Bengt Abelsson of Martinsons has been particularly helpful.

References


Deformation measurements
Bertil Enquist, Erik Serrano and Johan Vessby, Växjö University

Summary
Deformation measurement equipment was permanently mounted (fixed to the solid wood panel) along a line in the outer wall. This equipment measures the vertical relative displacement storey by storey. The relative humidity (RH) and the temperature are both measured at two points along the same line. The results obtained are in line with the expected creep (long-term) deformation. After one year, the rate of deformation diminished considerably. The measurements will, however, continue for at least another 12 months.

Background
The load-bearing structure of a timber building tends to settle with time, more or less depending on the design, the load level and the climate. In general one can expect this deformation to take place mainly during the first year after erection. In low-rise buildings, the deformation is generally small, even negligible, but in multi-story buildings, the total deformation could be rather large. For the case when the façade is sensitive to deformation (e.g. cement-based materials) it is of great importance to consider the deformations. In extreme cases, when the deformations are large, the load distribution could be affected.

For timber based structures, it is of utmost importance to consider the large difference in loading parallel and perpendicular to the grain. The moisture content (MC) of the wood must also be considered, since the MC highly influences the wood stiffness. In conventional timber frame systems studs loaded parallel to the grain are supported by sills loaded perpendicular to the grain. Such designs will, generally speaking give rise to larger vertical deformation in the wall than structures based on cross-laminated timber (CLT) panels. For either case, however, it is of utmost importance that connections and floor supports are designed carefully, by making use of stiff connectors, minimising the amount of wood loaded perpendicular to the grain. These requirements could sometimes be contradictory to the requirements set by the demand of good acoustical performance (minimising the risk for flanking transmission).

Only a few previous study of full-scale, in-situ, measurements have been performed. In the five storey timber-frame buildings of Wälludden in Växjö, erected in the 1990s, such measurements were performed. The vertical deformation of the building with time was measured using a tape measure. During the first year after erection of the buildings, the deformation increased to approximately 20 mm. After this, the deformation has more or less stopped.

Present investigation
Measurements, materials and methods
The measurements are being performed at Limnologen building B (the first building erected). The measuring equipment was mounted along a vertical line on the outside of the CLT panel of the north-west façade, cf. Figure 1. All equipment, except for a data logger, was mounted inside a plastic cover, cf. Figures 2 and 3. The relative deformation between two points is measured storey by storey in the six timber storeys. For the first timber storey, the deformation is measured from the concrete floor to the upper edge of the CLT panel. Thus the deformation registered for this storey, does not include any deformation taking place in the floor-to-wall junction. For the measurement in the subsequent storeys, the measuring devices are for practical reasons slightly shifted in the horizontal direction although the measurement is made relative a point at the same vertical level, cf. Figure 3b. The measurement devices are
mounted in the same manner up to the sixth timber storey, cf. Figure 3c. The set-up used makes it possible to register the storey-wise deformation, including for each storey (except the first) the deformation taking place in the floor-to-wall junction. By summing the deformations, the total vertical displacement (settlement) of the timber structure can be obtained. In addition to measuring the deformation, the relative humidity (RH) and the temperature is measured, each of these at the first floor and the top floor respectively (Figure 3a and c).

**Figure 1.** Left: Placement of the measurement equipment. Right: Detail from wall-to-floor junction.

The equipment for measuring the deformation, consists of steel bars, 20 mm in diameter and with rounded ends, cantilevers for supporting the bars and concentric bearings supplying lateral support for the bars. The cantilevers and the lateral supports are screwed to the CLT panels. At one end of the bar a deformation measurement potentiometer (Regal – WPL 50EFZ) is mounted. The steel bar is supported at its lower end by the cantilever, and is only supported in the horizontal directions by the aligning devices. Each of the potentiometers is separately connected to a data acquisition device – the logger (Datataker DT85). The temperature and RH (capacitive) is measured with a device of brand Vaisala model HMP50.

The data logger contains a built-in battery which supplies back-up power for retaining already acquired data. In case of power failure, additional data acquisition is, however, not possible since the measurement equipment operates with external low voltage power supply.

The accuracy of the deformation measurements is estimated to be approximately +/-0.12 mm. Of these 0.12 mm +/-0.05 mm relate to the accuracy of the potentiometer itself. The remaining uncertainty relates to the thermal expansion of the bars at a temperature change of 10 °C. The bars are made of a special alloy with a low coefficient of expansion, \( \alpha = 1.5 \times 10^{-6} \text{/K} \). The corresponding value for ordinary steel alloys is \( \alpha = 12 \times 10^{-6} \text{/K} \).

The accuracy of the RH measurements is estimated to be +/-3 %, and the accuracy of the temperature measurements is estimated at +/-0.6 °C.

The equipment is contained in a plastic channel, 60 mm deep and 100 mm wide, cf. Figure 2. Thus the insulation thickness is diminished from 180 to 120 mm along the line of
measurement. However, since this only affects a small width, and since the channel is filled with insulation before closing the channel with its plastic cover, no major influence on the local temperature and moisture distribution is expected at the level were the measurements take place (outer face of the CLT).

The equipment was mounted in late July 2007, since at this time it was possible to make use of the scaffolding raised for work with the insulation and the cladding of the façade. Obviously it would have been of great interest if the equipment could have been mounted during the erection of the building, making it possible to record the early settlement of the lower floors. However, for practical reasons this approach was abandoned at a very early stage of planning of the project. In retrospective, a slightly different measurement set-up could also have been of interest, i.e. measuring the deformation across each wall-to-floor junction separately. This would, however, have been at the expense of mounting four additional steel bars and deformation gauges.

Figure 2 Details of the set-up used. Left: Vertical section of the outer wall with measuring lengths indicated. Right: Cross-section of the channel containing the equipment.
Figure 3  a) The lower support of the measurement bar and one temperature and RH gauge. b) Horizontal shift of the line of measurement at the wall-to-floor junction c) Upper end of the line of measurement, 6th storey, and temperature and RH gauges. d) The channel was filled with insulation and closed with a plastic cover.
Results, discussion and conclusions

The data acquisition started September 9 2007, and has been ongoing since and at varying sampling frequencies. Initially, data were acquired every ten minutes, and at present data are acquired once every hour. It is estimated that the measurements will continue for at least two years in total, thus ending September 2009. During November and December 2007, a loss of power resulted in no data being acquired during approximately four weeks. Note that the measurements started after all self weight including gypsum boards, installations etc were in place.

Figures 4 and 5 present the measured deformations and the climate recorded in the plastic channel, respectively. The total deformation is within the range expected, in total about 18 mm. It seems that the rate of deformation has diminished. In a diploma work, [16], additional details about the deformations can be found. One major result reported in that work is that the initial deformation is mainly due to drying of the CLT and that the subsequent moisture variations give rise to small variations of the deformation.

As is obvious from Figure 4, the deformation values obtained for the first storey are not the largest ones obtained, in spite of the fact that this storey is exposed to the highest load level. This can be explained by the fact that the deformation measured for this storey does not include the deformation across the floor structure of the same storey (which is a concrete slab), cf. Figures 2 and 3a. In addition, since the measurements started at the same instant in time for all storeys, the values obtained from the lower storeys to a lesser extent include “long term deformation”. Finally, it should be noted that rubbery seals are used in the junctions between floors in order to minimise the spread of noise and vibrations. These seals (Sylomer) are of different stiffness in different parts of the building (e.g. for different storeys).
Figure 4. Deformations.

Figure 5. Temperature and relative humidity.
Testing of wooden floors in laboratory versus in situ – an investigation on changes in vibration properties

Kirsi Jarnerö1,2  Anders Olsson2  Bo Källsner1,2

Summary
In order to investigate how the vibration properties of a floor system is changed as it is set up on the supporting walls and is integrated with the structure, a single floor element and complete floors have been tested. The influence of floor geometry and a flexible support has also been investigated by in situ testing. The change in damping properties has been studied by means of testing a single floor element first in laboratory and then in situ at different stages of erection. The influence of a flexible support has been studied in a room with an intermediate support consisting of a glulam beam. The influence of room geometry has been studied in a room where the width to length ratio of the room is larger than 1:2. The applicability of the point load criterion is investigated by comparing calculations and results from in situ testing. The influence of the parquet flooring on measurements has been checked. The damping in this type of structural system is high compared with what is recommended to be used in design calculations. The point load criterion is not always reliable to use for this kind of floor structures. The calculation of natural frequencies is highly dependent on support conditions and the geometry of the floor in relation to the stiffness properties in the longitudinal and transverse directions of the floor system.

Background
Increased use of long span floors in connection with wood based building systems will increase the risk of annoying vibrations induced by human loading. The current design criterion in the Swedish design code is based on the velocity response of the structure caused by an impulse force, the first natural frequency and the damping of the structure. The damping values have to be more diversified and more knowledge of the damping of wooden floors is needed. The influence of floor geometry and support conditions also needs to be clarified.

The prefabricated floor elements in the Limnologen project are generally 2400 mm wide and consist of a three-layer cross-laminated timber board and glulam beams in the load carrying part of the floor. The cross-laminated timber board at the top of the elements is 73 mm thick and the beams underneath consist of glulam (class L40) webs and flanges, with dimensions 42×220 mm2 and 56×180 mm2 respectively, see figure 1 (a). The space between the beams is filled with mineral wool. The ceiling is separated from the load carrying part and is self-supporting on the walls in the underlying room. Half of the secondary spaced boarding in the

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ceiling is pre-assembled at the factory and the rest is nailed up in situ. Water and sewage installations are placed in the top load carrying part of the floor. Ventilation, sprinklers and electricity are placed in the lower part, in the ceiling. All horizontal installations except the electrical ones are mounted at the factory. The connections of conduits between elements, the vertical shafts and the connections between them are made at the building site. The ends of the floor elements are placed on the walls or beams below resting only on the cross-laminated timber board. If there is an intermediate support the flanges are placed on it.

![Figure 1](image)

**Figure 1** (a) Basic layout sketch of floor element. (b) End of floor element. On top of the wall a Sylodyn® batten is seen. (c) An end of a floor element that will be laid up on a beam. Attached to the bottom side of the cross laminated timber board is a Sylomer® batten. Sylodyn® and Sylomer® battens are mounted to prevent flanking transmission.

**Testing**

To investigate how the vibration properties of a floor element changes as it is integrated in the structure a single floor element with well defined support conditions was tested in laboratory and in situ at different stages in the construction process. Tests to investigate how the vibration properties are influenced by an intermediate flexible support and tests on the floor with largest span and consequently the greatest risk of annoying vibrations were also performed.

The floors were excited with an electromagnetic shaker, LDS V406-PA500, which was suspended with elastic cords from a tripod standing on the floor. The force was registered with a force transducer, Kistler 9301B, mounted to the cross laminated board with a wood screw. The vertical vibrations were measured with 14 accelerometers, Kistler 8772A, with sensitivity 1000 mV/g and a reference accelerometer, placed at the excitation point, with sensitivity 100 mV/g. The accelerometers were mounted on the floor with mounting clips and hot melt adhesive. To excite both the first and second vibration modes two different placements of the shaker, both a symmetric and asymmetrical placement, were used. The collection of measurement data was performed in a series of excitations and the accelerometers were moved to new measurement points before each new excitation.

To examine the influence of parquet flooring on measurements results and vibration properties two measurements with impulse hammer were performed on a floor. The first measurement was performed before the parquet flooring and underfloor heating were installed and before the supplementary grooves for the heating were milled. The second measurement was performed when the flooring was completed. The excitation was made with an impulse hammer, PCB 086D20, as attachment of the shaker in the flooring was not allowed.
Laboratory testing
To investigate the vibration properties with as little influence as possible from surrounding structural parts laboratory tests with well defined support conditions were performed. A single floor element, 1.5 m wide and 5.4 m long, which is a duplicate of a floor element in a bedroom floor on the third floor in one of the houses in Limnologen, was tested. As the ceiling is self-supporting and not in contact with the load carrying part of the floor the element was tested without the ceiling. The floor element was tested with free-free support conditions on sprung mattresses and simply supported on rigid supports of steel beams on the ground underpinned with mortar, as shown in figure 2.

![Testing arrangement in laboratory.](image1)
![Floor element with free-free support conditions.](image2)
![On rigid supports simply supported floor element.](image3)

Figure 2 (a) Testing arrangement in laboratory. (b) Floor element with free-free support conditions. (c) On rigid supports simply supported floor element.

In situ testing
To investigate how the damping in a floor changes as it is integrated in the building a simply supported floor in a 3.1 m wide and 5.2 m long bedroom, see figure 3, was studied at different stages of building construction.

![Plan drawing of floor layout.](image4)

Figure 3 Plan drawing of floor layout. The surfaces where vibration tests were performed are marked blue.
To get comparable results with the simply supported floor in the laboratory test the first series of measurement was made after the floor had been laid up on the supporting walls and still not had been coupled to the adjacent floor elements, but with the ceiling lowered to its right level in the room below. The second series of measurements was made after the floor elements had been coupled to each other. The next two series of measurements were made after the walls of the current storey had been raised and after the floor elements of the next storey had been mounted. The subsequent measurements were made after mounting of each storey including wall and floor elements. The last series of measurements was carried out after the top storey had been erected, the partitions in the measurement room was built and gypsum board had been mounted on walls and ceiling, and the stabilizing tie-rods had been pre-tensioned, but before the roof had been erected.

To investigate the influence of a flexible support on the vibration properties of the floors tests were performed in an apartment where the kitchen and living room are placed next to each other and throughout the width of the building, see figure 3. The floor is at its ends supported on the cross-laminated timber board in the external walls and has as an intermediate support a glulam beam with dimensions 215×270 mm$^2$. The total length of the floor is 11.7 m, with the beam placed 6.3 m respectively 5.4 m from the ends. The width of the room is 3.8 m.

The room with largest risk of annoying vibrations is a living room with the length 7.9 m and the width 3.7 m, see figure 3. In a short part of the width the span reaches 9.7 m. The floor element is here reinforced by means of beams 45 mm higher than in the regular floor elements. In the same room tests were made to investigate the influence of parquet flooring on measurement results.

In the design guidelines from the National Board of Housing (BKR, 2003) it is stated, concerning springiness in wooden floors, that “For wooden floors the risk of annoying vibrations has to be taken into consideration”. For residential floors with solid wooden joists in the load carrying direction the point load criterion may be used. The criterion states that the deflection caused by a 1 kN point load at the middle of the span may not exceed 1.5 mm. In the rooms where vibration tests were performed also the deflection caused by a point load in the middle of the floor span was measured. The measurements were made before the underfloor heating and parquet flooring were installed. First the vertical position of the floor, in the unloaded state, was determined. Then the floor was loaded by a person placing oneself at the loading point and making a new reading of the vertical floor position. The measured deflection was later adjusted to correspond to a deflection due to a 1 kN point load.

### Calculations and results

The results from the in situ testing presented here should be regarded as preliminary ones since a complete modal analysis of data has not been carried out yet. This means that the first natural frequency might after a complete analysis prove to be something else than the first bending mode of the floor. The results from the laboratory tests, presented in table 1, are, however, more confident since the interpretation of these data is more unambiguous.

<table>
<thead>
<tr>
<th></th>
<th>Free-free</th>
<th>Simply supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>8.8</td>
<td>20.5</td>
</tr>
<tr>
<td>Damping (%)</td>
<td>3.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>

*Table 1. First Natural frequency and damping of a single floor element tested in laboratory.*
In table 2 the first natural frequency and damping of a floor element are presented, as the floor is gradually integrated in the structure at different phases of construction.

Table 2. First Natural frequency and damping of bedroom floor.

<table>
<thead>
<tr>
<th></th>
<th>Free floor element</th>
<th>Coupled floor elements</th>
<th>Walls storey 3</th>
<th>Walls/floor storey 3</th>
<th>Walls/floor storey 3,4</th>
<th>Walls/floor storey 3,4,5,6</th>
<th>Walls / floor storey 3,4,5,6,7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>19.1</td>
<td>21.8</td>
<td>25.9</td>
<td>25.7</td>
<td>26.6</td>
<td>26.8</td>
<td>29.0</td>
</tr>
<tr>
<td>Damping (%)</td>
<td>6.2</td>
<td>6.3</td>
<td>4.5</td>
<td>4.5</td>
<td>5.3</td>
<td>5.5</td>
<td>9.1</td>
</tr>
</tbody>
</table>

The deflection and the first natural frequency of a simply supported, one metre wide, floor strip loaded with a 1 kN point load have been calculated for the floors in the three different rooms. In the calculations it has been taken into account that the three layers in the cross-laminated timber board have different directions and consequently different stiffness values. For the same reason different stiffness values have been used for the webs and flanges of the glulam beams. The stiffness in transverse direction of the floor has not been considered in the calculations. Since the floors were tested without flooring parquet it was assumed that the mass of the floor is composed of the mass of wooden parts in the top load carrying part of the floor and the insulation between the beams, with a small addition of mass from installations. The calculation results are presented in table 3 together with corresponding results from the in situ testing.

Table 3. Calculated and measured deflection values due to a 1 kN point load in the middle of the span and first natural frequency of the different floors.

<table>
<thead>
<tr>
<th>Room</th>
<th>Length of span (m)</th>
<th>Deflection (mm)</th>
<th>First natural frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated</td>
<td>Measured</td>
<td>Calculated</td>
</tr>
<tr>
<td>Bedroom</td>
<td>5.1</td>
<td>0.20</td>
<td>0.27</td>
</tr>
<tr>
<td>Kitchen / living room</td>
<td>5.4</td>
<td>0.16</td>
<td>0.38</td>
</tr>
<tr>
<td>Living room</td>
<td>6.3</td>
<td>0.24</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Excitation of the floor with or without parquet flooring with impulse hammer showed only small differences in the first natural frequencies. The most obvious difference seems to be, without any closer analysis, that the third natural frequency has moved downwards when compared with excitation with shaker.

Discussion and conclusions

As no complete analysis of the test results has been performed it is only possible to give some preliminary conclusions:

- From the laboratory tests of a single floor element and in situ testing of a floor in the bedroom it can be seen that the damping is high compared with the general value of 1% that is recommended for design of wooden floors with respect to annoying vibrations. It is also seen that the damping to a large extent is affected by the degree of integration of the floor to the surrounding structural parts, especially by the addition of partitions. In design calculation it might be possible to take this into account in cases where the partitions are permanent.
The results from the in situ measurements in the bedroom indicate that calculation of the first natural frequency of a one metre wide floor strip seems to be accurate considering a floor with support conditions corresponding to a simply supported beam on rigid supports. For floors with flexible supports, as in the kitchen – living room case, or floors where the length-to-width ratio is special, as in the living room where the load carrying direction is perpendicular to the regular case, the calculation results are misleading as the structural system is more complex than a simply supported beam. Both the flexibility of the supports and the transverse stiffness of the floor should be taken into account.

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Measurement of vibration distribution
Åsa Bolmsvik, Torbjörn Ekevid and Anders Olsson Växjö University

Conclusion
Flanking transmission is the main source of complaints from inhabitants in wood framed houses, if their living environment due to sound is studied. Within a PhD project within Växjö University (Bolmsvik 2008) a study of vibration distribution has been performed at Limnologen during the autumn 2007. A well defined source has been used to investigate how the vibrations are distributed to the walls and the roof surfaces in the room below. At the same time as the vibrations of the surfaces were registered the sound pressure in the room was measured. The measurements have shown that this measuring technique gives information about which surfaces contribute to the sound pressure for different frequencies and at what frequencies the frame is most sensitive. The measurements have shown that by using this technique it is possible to identify the surfaces that mostly contribute to the sound pressure for different frequencies. The energy distribution between the flanking surfaces in the room due to vibration distribution has been studied, showing that the roof in the examined room is the surface that distributes most of the added energy. Thereby this surface is the one that primarily should be addressed if any design alterations are being considered.

Background
Traditionally and according to standards the impact sound (sound that is generated due to hits towards surfaces) is measured with a tapping machine and several microphone measurements in a room below. The microphone measurements are weighted together resulting in the room being classified as belonging to a certain class. In measurements reported herein a source that creates impact sound at known frequencies has been used. An earlier investigation by Bolmsvik (2006) has showed that this is desirable. Sound pressure is registered in the recipient room at the same time as vibrations in the frame are registered at several frequencies. The aim has been to see if there is a coupling between the vibrations in the walls and the roof and the sound pressure in the room. Furthermore the goal has been to identify the surface vibrations having the strongest influence on the sound pressure. The main advantage of measuring flanking transmission directly on the surfaces is that the building does not need to be completed. The surfaces, except the one studied, do not need to be covered to see what surface that causes the main energy distribution.

Project description
Measuring disposition
The measurements were performed in the south part of house 2 between floor 6 and 5, see Figure 1.

Figure 1. Section of the house where the measurements were performed.
The shaker that was used as the source in the measurements was placed in room C6, see Figure 2a. The shaker creates sinusoidal signals at a predetermined frequency. In this experiment the force was swept from 0 to 500 Hz, which creates a constant load within this frequency range. The shaker was placed in the centre of the room, see Figure 2b. Close to the shaker a, reference accelerometer was mounted.

![Figure 2a: Shaker position in Room C6](image)

**Figure 2. The measuring disposition: a) the shaker used as source and b) the shakers position in the room.**

On all walls and in the roof in room C5 the acceleration response was measured with help of 12 accelerometers. These were placed in a square pattern with 0.5 to 2 metres distance. The accelerometers were moved to new positions 15 times and by that 181 points positions could be registered, see Figure 3a. A microphone was used to register the sound pressure in the room at the same time and for all frequencies. The microphone was held at 15 different positions, all at a level corresponding to half of the room’s height, see Figure 3b. The signal processing has been performed with the software SignalCalc (2002).

![Figure 3a: Pattern of accelerometer placements and microphone placements](image)

**Figure 3. The figure shows the pattern for a) the accelerometer placements and b) the microphone placements (at half of the room’s height).**

When the measurements were performed all walls in the recipient room had a raw gypsum board surface, thus without any finishing. The floor had no covering material and the floor heating had not been placed in position. However, work with boring for the floor heating had started. The walls in the measuring rooms have been named according to Figure 4.

![Figure 4: Definition of the surfaces in Room C5](image)

**Figure 4. Definition of the surfaces in Room C5.**
Results, discussion and conclusion

Sound pressure in the room

The sound pressure measured in the room is not possible to compare with traditional measurements, since a different source has been used. Furthermore, the measurements do not give any information to establish a sound class. However, the relative pressure levels at different frequencies are interesting as a high sound pressure level at any frequency is believed to be the result of vibrations in a part of the structure at the same frequency. The result from the 15 microphones that has been used is showed as sound pressure in Figure 5.

![Figure 5. Sound pressure in dB re 20e-5 Pa for the 15 microphones.](image)

The relation between sound pressure and FRF for different surfaces

The frequency response function, FRF, between added load and acceleration for a certain accelerometer is calculated. This is done by dividing each accelerometer reading with the added load over the whole frequency span. A single FRF mean value has been calculated for a single surface by summing over all FRFs over that surface. In a similar way the mean value of the sound pressure in the room has been calculated. When all FRF mean values versus frequency are studied in the same plot, Figure 6, the correlation between sound pressure and vibration in the structure can be seen.

![Figure 6. The surfaces mean FRF and the mean sound pressure /1000 in the room.](image)
Energy distribution between flanking surfaces

The vibrations in the five examined surfaces are assumed to be the only source of sound pressure in the room. This means that the kinetic energy in the surfaces is converted to sound pressure in the air in the room. If the kinetic energy is low, also the sound pressure will be lower. Thereby to be able to reduce the sound pressure at different frequencies it is interesting to see what surface has the highest kinetic energy at the corresponding frequencies. During the measurements the accelerometers have been positioned in a square pattern, therefore each accelerometer can be supposed to represent the surrounding surface area (windows etc have been excluded). The acceleration-FRF is transformed to velocity-FRF and the kinetic energy can then be calculated. This is multiplied with its corresponding surface area and the area-weighted percentage of the kinetic energy distribution, over the whole frequency area, can be calculated, see Figure 7.

Figure 7. The energy distribution between the different flanking surfaces.

Discussion and conclusion

The described way of measuring is not so common. Often the standard measurements, with a tapping machine as source are used and sometimes these are refined to various degrees. In research, the above described way of measuring gives valuable information. It increases the knowledge about how the energy is distributed and how the different frame parts interact. By using a shaker, where the loads’ frequency contents can be controlled is good, the load amplitude within the complete frequency span used can thereby be decided. As early as 1982 Craik (Craik 1982) concluded that using impulse loads is to prefer when structure bourne sound is studied.

The measurements have showed that the roof is the surface that within the studied frequency range has the largest movements. If the roof would be re-designed for improved low frequency behaviour, probably also the sound environment could be improved considerably.

References


Acoustics and Vibrations Measurements at Limnologen
Delphine Bard, Lund University and Lars-Göran Sjökvist, SP Trätek

Introduction
For high-rise wooden buildings the largest acoustical challenge is to determine and reduce sound transmission, especially flanking transmission.

In this study the impact sound level and sound reduction index were measured between apartments in the vertical direction at Limnologen. The measurements were made at different heights in order to see if any systematic differences exist.

To minimise the flanking transmission in the building, elastomer seals at the floor element supports are used. The flanking path will thereby be less announced. In the lower parts of a high building the load on the elastomer is higher and therefore a stiffer elastomer is used there than higher up in the building. It is thought that these different elastomers will make the vertical sound transmission to differ. An investigation of the transmission path through a cross junction has been done in order to have a better understanding of the structure borne sound propagation in this type of constructions.

This study includes also an examination of the vibration pattern of the floor structure.

Measurements
Several measurements were made in order to evaluate the acoustical behaviour of the building:

- The sound reduction and impact noise were measured between several stories to obtain the influence of the different elastomers used to combine vibration damping with correct static load bearing,

- The vibration pattern of the floor structure was measured for one of the larger floor structures,

- Flanking transmission through a cross junction.

Sound reduction and impact noise
The sound reduction and impact noise were measured between several stories to obtain the influence of the different elastomers used to combine vibration damping with correct static load bearing. The vibration pattern of the floor structure was measured for one of the larger floor structures.

Table 1. The placement of elastomers in the building.

<table>
<thead>
<tr>
<th>Floor</th>
<th>Wall 1</th>
<th>Wall 2</th>
<th>Wall 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Sylodyn NF</td>
<td>Sylomer  T</td>
<td>CB 14-R</td>
</tr>
<tr>
<td>3</td>
<td>Sylodyn NF</td>
<td>Sylomer  T</td>
<td>CB 14-R</td>
</tr>
<tr>
<td>4</td>
<td>Sylodyn NF</td>
<td>Sylomer  V</td>
<td>Sylodyn NF</td>
</tr>
<tr>
<td>5</td>
<td>Sylodyn NF</td>
<td>Sylomer  V</td>
<td>Sylodyn NF</td>
</tr>
<tr>
<td>6</td>
<td>Sylomer  T</td>
<td>Sylomer  V</td>
<td>Sylodyn NF</td>
</tr>
</tbody>
</table>
Vibration pattern set-up
The vibration pattern of a floor structure was measured at random points in an area measuring 4×4 m². The random placement was used since such a placement makes the conclusions from the study being valid for the entire measurement area. The randomization was performed to get 96 measurement points within the measurement area. One point of excitation was also chosen at point (2,0.8), which is near the middle of a bay and in the middle of the measured area. The x axis is along the beams.

The tapping machine was used for excitation. However, only one hammer was used in order to minimize the spatial spread of the excitation. A picture of the setup is shown in figure 1.

Figure 1. (a) One hammer was used in order to minimize the spatial spread of the excitation. (b) Accelerometers were fixed to the floor at the random measurement points with two screws.

Figure 1 also shows that the floor structure has grooves on the top surface, thus the surface of the top plate was not flat. Accelerometers as shown in figure 2 were screwed to the floor at the random measurement points with two screws.

Flanking transmission set up
In order to measure sound propagation, direct (1) and flanking transmission (2), through a wood cross junction (see Fig.3 (a)); two types of instruments are needed: A tapping machine and accelerometers, Fig 3 (b).

The test structure was excited by a tapping machine, delivering reproducible impacts. One hammer was used. An array of 16 accelerometers registered the response. The accelerometers were re-located to determine the vibration pattern, at 4 different positions on the floor/wall/ceiling in each room.

Figure 2. Flanking transmission set up.
Results

Sound reduction and impact noise

Figure 4 shows the difference of the impact level (per floor) in the eight-storey building.

![Figure 4](image)

_Figure 4. The difference of impact sound insulation between the floors, mean values (circle) and its 95% confidence limits, for each 1/3 octave band. Positive values means higher impact sound level at higher floor._

The measurements were performed with the floors one to five as receiving rooms. The difference is shown as decibel per floor. Between 250 and 500 Hz the mean difference is between 1 and 2 dB. One can therefore expect an impact sound level difference between the ground floor and the top floor of more than 10 dB in this frequency range, considering that it is an eight-storey house.

Vibration Pattern

The vibration pattern was measured for one floor structure area that that measured 4×4 m². The attenuation was calculated with its 95% confidence interval. The calculations was made for directions along the beams and orthogonal to the beams. The resulting attenuation can be seen in figures 5 (a) and (b). The attenuation is very weak for the present floor structure. Mostly, the attenuation was well below 0.5 dB per meter.
Figure 5. (a) The mean attenuation in the direction along the beams (circle) together with its 95% confidence interval. (b) The mean attenuation in the direction across the beams (circle) together with its 95% confidence interval.

Figure 6 shows the average damping from divergence.

Figure 6. The mean wave divergence away from the exitation and the corresponding 95% confidence interval.

Flanking transmission – The excitation room
The configuration of the room in which the tapping machine is placed is an important criterion to be taken into account for the understanding of the measurements results. The actual setup for the floor measurements is illustrated in Figure 7, with the wall junction under study at the top, and the position of the underlying T-beams indicated as vertical lines in the picture. The coordinates along the $x$-axis are indicated at the bottom, in meters. The tapping machine is situated roughly in the middle of the room, represented by a red sign. The path of the vibration wave, from the source to the wall is illustrated by straight lines putting in evidence what the measured data correspond to. As the sound waves propagate into the floor, through the junction and into the walls, they will cross internal beams, which will affect them. Also, the finite dimensions of the room had to be taken into account. The levels measured along the wall under study were affected by reflections along the remaining walls of the room. One reflection against the wall (affecting sensor number 13 in that case) is illustrated to the left, with a dashed line. The accelerometers were disposed in such a way as to measure on each side of each beam and in-between almost every pair of successive beams. The 16 accelerometers were fixed on the floor at distances of 5 cm and 50 cm from the wall respectively. Then, they were fixed against the wall, first at a distance of 10 cm, then 1 m from the floor.

The accelerometer placement was reproduced identically in the adjacent room. This means that each accelerometer had its counterpart placed symmetrically on the other side of the wall. Finally, the device placement of both rooms was mirrored in two rooms one floor underneath, however with accelerometers attached to the ceiling instead of the floor, and at 10 cm and 1 m
under the ceiling for the wall measurements. Thereby, a total of 16 measurements sets were collected, each of them consisting of 16 accelerometer channels of data over a period of 10 seconds. The acquisition system samples the data at a frequency of 9500 Hz.

![Figure 7. Placement of both lines of accelerometers in the room](image)

**Measurements in the excitation room**

The measurement data obtained in the room where the tapping machine was placed provides crucial information about the nature of the impact wave that propagates through the structure. Several parameters influence the result obtained.

- The distance to the source: the impact magnitude is expected to show an exponential decay over the distance. This assumption will be verified and taken into account.

- The angle of incidence: since the floor is constituted of several superimposed layers of timber and crossing each other at right angles, one would expect the propagation characteristics to be angle-dependent.

- The reflections on walls: the measurement delivered by an accelerometer placed close to a side wall will be altered due to vibration waves being reflected on the wall nearby, and superimposed to the incident wave. The closer the wall, the shorter the delay between the direct and the indirect waves, and the smaller its attenuation.

The maximum magnitude of the acceleration is plotted as a function of the distance to the impact source (Figure 8 (a)). The distances range from about 30 cm for the accelerometer at the middle of the first row to about 2.63 m at the extremities of the second row. The curve is traced using a semi-log scale. As expected, the measured points align along a straight line. However, only half of the points, corresponding to the accelerometers in the middle of the room, obey to this trend. For the remaining points, the opposite trend can be observed, namely the magnitude getting larger as the distance to the source increases. The reason is that the reflections from the wall increase in importance as the distance to the wall decreases. The indirect impact wave is superimposed to the direct wave and their magnitudes either sum up if they are in phase, or subtract if they are out of phase. Eventually, when the distance gets even larger, the delay between the peaks would be such that they no longer merge into one bigger peak. Calculations will show later in this section whether this hypothetical case is likely to happen.

Since the exponential decay rate of the acceleration peak magnitude is known over the distance, we can determine from the measurements what would be the peak magnitude at a distance of 1 m. We plot this normalized acceleration magnitude as a function of the incidence angle $\theta$ between the propagation direction and the wall. The result is represented in Figure 8 (a). A similar approach can be used to determine the speed at which the impact
acceleration wave propagates. Since the accelerations resulting from the 16 sensors were recorded simultaneously, one can determine the time at which the peak of the acceleration wave reaches each accelerometer. By plotting the time delay as a function of the distance to the source, we obtain a straight line, as seen in Figure 8 (b). The slope of this line gives us the speed of propagation of the impact wave in the floor, which is found to be equal to 674 m/s.

The experimental data shows that the average length of an impact peak is about 40 ms when considering only the direct wave path, i.e. for a sensor that is not located close to walls. We can consider as a rule of thumb that peak superimposition can be clearly detected when the time delay between the direct impact wave and the first indirect wave is at least half the peak length, which is 20 ms. According to the propagation speed that we have calculated, this would mean a wave path length difference of around 13 m. Therefore, a condition for clearly separating superimposed peaks would be to consider only sensors placed at a minimum distance of 6.5 m from any wall (the wave has to travel twice the distance when it bounces on a wall and returns to the origin point), which is not an option in our configuration. As a consequence, using a large number of sensors and analyzing statistically the data they deliver is probably the safest way to extract relevant information.

**Transmission ratio of the junction**

The propagation characteristics of the junction are considered for all different wave paths: from the wall of the excitation room to the wall in the same room, and to the walls and floors or ceiling in the 3 adjacent rooms. Since the acceleration is recorded at a position that does not lie exactly along the wall, the value actually measured has also been extrapolated to fit the value that it should have along the wall.

The results are plotted in Figure 9 for the measurements done on the walls. The coefficient plotted represents the ratio of acceleration magnitudes in the considered room over the magnitude recorded on the floor of the excitation room.

It can be observed that the impact wave is transmitted from the floor to the wall in a significant way only in the excitation room. In that particular room, the magnitude recorded is four times higher than in the adjacent room, or in the rooms underneath. Also, it must be noticed that the transmission ratio is slightly larger on the left side of the room. This can make sense when we consider that the wall on the left side of the wall is a stronger and thicker external wall, thus probably reflecting a high part of the vibrations.

![Figure 8. (a) Normalized impact acceleration magnitude as a function of the incidence angle. (b) Time delay of the impact acceleration as a function of the distance to the source.](image-url)
The results for the measurements made on the floor of room 1 and at the ceiling of rooms 1 and 2 are presented in Figure 10. In contrary to the wall vibration measurements, we can distinguish here a rather high transmission ratio from the excitation room to the room 1. In addition, both left and right extremities show much higher values, which can be explained by the presence of the walls. Also, the transmission from the excitation room to the room 3, underneath it, is rather high. However, this can not be attributed exclusively to the junction beam, but rather to the direct transmission through the floor itself.

Figure 9. Transmission coefficient of the junction for a impact wave path propagating from the floor in the excitation room to the wall in excitation room (upper left), in room 1 (upper right), in room 2 (lower right) and in room 3 (lower left). The coefficient is defined here as the ratio of the acceleration before and after the junction, and is plotted as a function of the X-coordinates along the junction.
Figure 10. Transmission coefficient of the junction for a impact wave path propagating from the floor in the excitation room to the floor in room 1 (upper right corner) and to the ceiling, in room 2 (lower right) and in room 3 (lower left). The coefficient is defined here as the ratio of the acceleration before and after the junction, and is plotted as a function of the X-coordinates along the junction.

Conclusions

The attenuation for the floor structure was low compared with common joist-beam structures. The attenuation was also approximately the same in both the main directions. The average damping from divergence seems to be strong compared with the attenuation in the main direction. It is therefore likely that the upper plate mainly governed the vibration pattern and that the beams did not have much influence of the vibration pattern for this floor structure. The upper plate of the floor structure was probably too thick for the beams to make any major impact for the vibration pattern.

The sound insulation between floors was measured with both airborne noise and impact noise. The results in figure 4 shows that the impact sound might differ more than 10 dB depending on at which floor level that is measured. Since the construction was made with softer elastomer between the upper floors and harder elastomer between the lower floors one can expect to see a difference. The measurements here could not confirm any regular differences within the 95% confidence interval, although there are large differences between apartments that are nominally equal except for the elastomers. Variations from the construction and measurement technique were too large to prove any major regular differences caused by the different types of elastomers.

For the first time to our knowledge, extensive measurements of vibration propagation characteristics of a junction beam have been performed in a modern wood building. There is almost no vibration reduction (3dB) in the horizontal direction through the junction beam, as the acceleration magnitudes measured on the floor of the adjacent room reaches almost 50% of the magnitude before the junction. Other measurements on lightweight structures have shown a junction reduction of 25dB. Though, the junction reduction doesn’t tell about the final sound isolation. In contrary, the levels measured against the walls in all rooms (except the excitation room) are quite low.
Desired and Perceived Customer Value – are the Limnologen end-users satisfied?

Tobias Schauerte, Växjö University

Summary
This study shows that end-users, who bought an apartment in the Limnologen houses A and B, perceive wood as a structural frame material in a very positive way, much better than their expectations were before.

The end-users overall satisfaction is positive. Determinant factors for this satisfaction are “promotional material”, “optional choices”, “accurate exposition of all steps in the selling process”, “view/scenery”, “size of apartment” and “kind of construction material in structure frame”.

Activities connected with the product itself, like ”information about moving”, “co-operation between foreman and craftsman”, “apartment being ready to move into”, and “selling process”, have to be improved since they show the highest discrepancy between Desired and Perceived Customer Value.

Background
During the last years, the market share of wooden multifamily houses has risen on the Swedish construction market. Globally, Swedish construction companies are at the forefront of construction development in this area (Näringsdepartementet, 2004). The national strategy for building with wood strives to improve the position of wooden multifamily houses by, e.g., further developing industrialised production processes. This, to utilise the advantages of wood as construction material in order to improve the quality of the final product.

Yet, working with positioning of a product entails far more than developing production processes or improving technical characteristics. Positioning is how customers’ minds are affected. A product’s position is the place in the mind of the customer (Ries and Trout, 1981), i.e., how the target group perceives and experiences the product in question. A positive perception leads to positive Customer Value and Satisfaction (Woodruff, 1997), which in turn can be regarded as one of today’s largest competitive advantages (Cengiz and Kirkbir, 2007). Consequently, end-users, in this context those who bought an apartment in the Limnologen houses A and B, and their satisfaction, are crucial in positioning wooden multifamily houses.

Studying Perceived Customer Value only could nevertheless lead to wrong conclusions. If the Perceived Customer Value is high, yet, customers’ expectations even higher, wrong conclusions would be drawn. Therefore, Perceived Customer Value has to be regarded relative to Desired Customer Value. Together, these two factors mirror Customer Satisfaction.

Project realisation
Subject of this investigation were the Limnologen houses in Växjö; four eight-story houses, A – D, with wood as structural frame material. At the time, only houses A and B were inhabited, while houses C and D still were under construction. Thus, only residents of house A and B are included in this study. The product is each apartment respectively in combination with the complementary rooms and spaces each inhabitant uses like, e.g., laundry room, store rooms or parking areas.

Above named keywords “Desired Customer Value”, “Perceived Customer Value” and “Customer Satisfaction” were investigated. While “Desired Customer Value” was measured before the end-users moved into their apartments but had accomplished the buying process,
“Perceived Customer Value” was measured some weeks after they had moved in. Data was collected by means of two questionnaires, prepared in cooperation with the building proprietor and adjusted for scientific purposes to allow statistical analysis. Both open-ended and closed questions were posed. For the closed questions, a 10-point Likert-scale was used.

The first questionnaire was sent to 65 persons, of whom 31 persons had bought an apartment in house A and 34 in house B. Of these 65, 30 responded (14 house A, 16 house B), resulting in a response rate of 46%. All 30 respondents received the second questionnaire as well. For methodological reasons answers in the second questionnaire, from persons who did not respond to the first one, would not be usable since these would influence the validity of this study negatively. On the second questionnaire, 22 responded (12 house A, 10 house B), a response rate of 73%.

Regression and correlation analyses were performed with the statistical software SPSS, version 16.

Result, discussion and conclusions

The presented material was selected by the author and is supposed to represent a general and holistic view of the inquiry. For a more comprehensive account, the reader is referred to later publications as well as building proprietor Midroc Property Developments’ project manager and information officer.

Desired Customer Value

The Desired Customer Value, i.e., the expectations of the end-users, was very high for most of the questions. Many questions had accumulated answers with median values between 9 and 10 out of 10. The highest score belonged to the question concerning the “final result”, i.e., the finished apartment, where all respondents marked the highest possible value, 10. This seems quite natural, since expectations and desires are used to be high when it comes to important investments like apartments. Other questions with high median values comprise factors like “competent sales person”, “clear information material before contract agreement” or “relation between investment and monthly payment”, “standard of the apartment”, “cleaned apartment when moving in”, and others. Table 1 shows one question as an example:

Table 1. Distribution of answers on the question: "How important do you value a positive approach by the sales person?"

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>1 (not important)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very important)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>2</td>
<td>23</td>
<td>30</td>
</tr>
<tr>
<td>Distribution in %</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>7</td>
<td>76</td>
<td>100</td>
</tr>
</tbody>
</table>

Yet, certain answers did not result in values being as high as those described above, i.e., end-users expectations were lower. Among these are “jointly owned facilities”, “playground”, “garden” and “pram storage”. Reflecting on end-users probably subjective attitude toward each of these factors, it seems quite understandable that the answers did not score very high.

The same reasoning might be applicable for the factor ”structural frame material”. The answers to this question were not unambiguous but rather more evenly distributed, as Table 2 indicates. The median value reaches 6.93, which could either imply that the kind of construction material was unimportant, or that the end-users do not really know what to expect and thus answered in a more measured manner.
Table 2. Distribution of answers to the question: "The structural frame material is very important to me."

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>1 (do not agree at all)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (totally agree)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>3</td>
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<td>Distribution in %</td>
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<td>3</td>
<td>10</td>
<td>13</td>
<td>20</td>
<td>10</td>
<td>20</td>
<td>7</td>
<td>17</td>
<td>100</td>
</tr>
</tbody>
</table>

Perceived Customer Value

The Perceived Customer Value, i.e. how the end-users perceive their apartments, is generally quite positive and most answers reach a median value between 6 and 8. The factors that scored highest were “view/scenery”, “ceiling height”, “room layout” and, as Table 3 shows, “structural frame material”.

Table 3. Distribution of answers to the question: "I am satisfied with the structural frame material in this building."

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>1 (do not agree at all)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (totally agree)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
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<tr>
<td>Distribution in %</td>
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<td>5</td>
<td>14</td>
<td>19</td>
<td>57</td>
<td>100</td>
</tr>
</tbody>
</table>

The perception of wood as structure frame material in the Limnologen houses is thus positive, and implies that there is an acceptance for wooden multifamily houses on the market. So, even if the kind of construction material was not of importance, compare table 3, end-users are quite satisfied with the material wood in the structure frame.

Factors that did not meet with the same acceptance, and consequently have lower median values, are, e.g., “co-operation between foreman and craftsman”, “apartment being ready to move into”, “parking place”, “bike storage” and even “final result”, as indicated by Table 4.

Table 4. Distribution of answers to the question: "How is the final result?"

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>1 (very bad)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very good)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>171</td>
</tr>
<tr>
<td>Distribution in %</td>
<td>6</td>
<td>6</td>
<td>12</td>
<td>6</td>
<td>23</td>
<td>6</td>
<td>0</td>
<td>35</td>
<td>0</td>
<td>6</td>
<td>100</td>
</tr>
</tbody>
</table>

Some of the above named results can possibly be explained by the fact that at the time of the study, parts of the jointly owned facilities were not yet finished. Furthermore, it has to be concluded that problems occurred with supplementary works after control inspection, which are not finalised yet, but nevertheless affect end-user opinions negatively.

Relation between Desired and Perceived Customer Value

Regarding all investigated factors shows that end-users expectations were higher than their perceived experiences in 70 % of all cases. Some of the factors where the negative difference between Desired and Perceived Customer Value is at its highest are, e.g., “final result”, “co-operation between foreman and craftsman”, “apartment being ready to move into”, “parking place” and even “information about moving”. Categorising factors shows that the negative

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1 Five out of 22 did not answer this question but chose to comment like e.g.: It is not finalised yet!
relation is particularly marked when it comes to buying process (10 out of 10 factors), jointly owned facilities (3 out of 4), moving in (4 out of 5), and some details about the apartment itself (10 out of 19).

Yet, in certain cases, Perceived Customer Value scored higher than Desired Customer Value. Some of these factors are “pram storage”, “ceiling height”, “room size” and even “structure frame material”. The latter factor has a Perceived Customer Value median value 2.17 higher than the Desired Customer Value one, which is noticeable.

Comparing the two concepts of Customer Values shows that wrong conclusions would have resulted, had only Perceived Customer Value been investigated. This since most of the Perceived Customer Values turned out to mirror positive experiences. Since end-users expectations were high on many factors to begin with, these factors have to be regarded more critically since the product could not live up to these expectations.

**Customer Satisfaction and significant factors**

Measuring Customer Satisfaction the first time resulted in a median value of 8.97, as Table 5 shows. This was after the end-users had bought their apartments.

*Table 5. Distribution of answers to the question: "How satisfied have you been since buying your apartment?"

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>1 (not satisfied at all)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very satisfied)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>Distribution</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>23</td>
<td>17</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

The majority of the respondents were really satisfied at that point in time, 50 % were very satisfied. By means of regression and correlation analysis, factors determinant for Customer Satisfaction could be identified. These are: “selling material”; “optional choices”; “accurate exposition of all steps in the selling process”.

The second time Customer Satisfaction was measured was some weeks after the end-users had moved into their apartments. At that time, the median value was 7.73, and the distribution of answers according to Table 6.

*Table 6. Distribution of answers to the question: "How satisfied are you overall, after you have been living in your apartment for a while?"

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>1 (not satisfied at all)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very satisfied)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>2</td>
<td>3</td>
<td>22</td>
</tr>
<tr>
<td>Distribution</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>14</td>
<td>23</td>
<td>36</td>
<td>9</td>
<td>14</td>
<td>100</td>
</tr>
</tbody>
</table>

Even if the end-users still are satisfied, the value for the median value decreased with 1.24, compared to the first measure. Furthermore, the number of respondents being very satisfied decreased from 50 % to 14 %, a significant drop.

Here, regression and correlation analysis indicate that “view/scenery”, “size of apartment” and “structural frame material” are most important for Customer Satisfaction.
Completing results
In addition to the results above, end-users are of the opinion that:

"I bought 'the ideal apartment'.” (Median 8.23)
"My apartment is worth the money.” (Median 8.29)
"I feel safe in my apartment.” (Median 9.5)
"I feel comfortable in my apartment.” (Median 9.24)

Moreover, the majority of respondents answered that they could not “…buy a better apartment for the same price than they just bought.”

Discussion and conclusions
A number of wooden multifamily houses now exist in Sweden, e.g., “Wälludden” in Växjö with five storeys, and “Inre hamnen” in Sundsvall with six storeys. Yet, since Limnologen is the first stage within the “Välle broar” project\(^1\), these four eight-storey houses can be seen as references for modern construction with wood. This is true even in an international context; many guests from abroad have shown their interest and visited the construction site. Hence, positioning activities for wooden multifamily houses are already in progress. As stated above, end-users have a central role in this positioning process, and the following conclusions can affect the position of wooden multifamily houses both positively and negatively:

- End-users perception of wood as structural frame material in multifamily houses is very positive, much more positive than their expectations.

- Customer Satisfaction was positive both after the buying decision and after having lived in the apartment for a while.

- The most important factors for Customer Satisfaction after the buying decision are “selling material”, “optional choices” and “accurate exposition of all steps in the selling process”.

- The most significant factors for Customer Satisfaction after moving in are “view/scenery”, “size of apartment” and “structural frame material”.

- Most end-users think that they bought the 'ideal apartment’, which is 'worth the money’, and that they could not have bought a better apartment for the same price.

- End-users expected “selling process”, “moving in”, “jointly owned facilities”, and certain details when it comes to the apartment to be better than they turned out to be.

It can be concluded that those factors, which end-users have a negative opinion about, do not directly belong to the core product itself but are included in the service or work connected with it. “Selling material”, ”information about moving”, “co-operation between foreman and craftsman”, “apartment being ready to move into”, etc., all somehow belong to planning or other management areas. Yet, these can not be neglected, and improvements have to be done.

Positioning wooden multifamily houses is a dynamic process, affected by all parties involved. End-users perceive wood very positively and are very satisfied with their apartments. If the activities around the core product itself should improve, the strategy for ’more wood in construction’ and the positioning of wooden multifamily houses will be even more successful.

\(^1\) Read more about the Välle broar project in the beginning of this compendium.
References


Time study of the installation of load-bearing structures in the Limnologen block

Johan Vessby, Växjö University

Abstract
A virtual BIM (Building Information Model) was created for analyzing the times required for installing prefabricated planar building elements in constructing the load-bearing structures of two of the four multi-family houses located in the Limnologen block as it is called. Two major conclusions that could be drawn were that the average time required for installing prefabricated building elements was less in house 3 than in house 1, and that the average installation times tended to be shorter on floors higher up in the respective houses. This was seen to indicate possibilities for future reductions in the installation times required for constructing buildings of this type.

Background
During the period of 1968 to 1998 the production costs for multi-family houses in Sweden doubled, whereas those for single-family houses increased by only about 70% (Lutz and Gabrielsson, 2002). This suggests that small, one-family houses are produced in a more efficient way than large, multi-family houses are. These two segments of the construction industry are difficult to compare, however, due to the preconditions varying considerably from case to case (Ekholm, Jönsson and Molnár, 2008). Nevertheless, there are good reasons to believe that a decided increase in the efficiency of producing multi-family houses can be achieved.

One possibility in constructing both private homes and multi-family residential housing is to utilize wood for load-bearing purposes. Whereas the use of wooden frames for such purposes is completely dominant in the construction of private homes (Ministry of Industry, 2004), in the multi-family residential housing sector the situation is quite different. Although the proportion of wooden houses constructed in that sector is increasing, on a national basis there are still few timber-based houses more than five floors in height.

<table>
<thead>
<tr>
<th>2D- cad</th>
<th>3D- cad</th>
<th>vrml- file</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="2D-cad" /></td>
<td><img src="image2.png" alt="3D-cad" /></td>
<td><img src="image3.png" alt="vrml-file" /></td>
</tr>
</tbody>
</table>

Figure 1. A 2-dimensional drawing (left), converted first to a 3-dimensional model (middle), this being converted finally to a vrml format (right) so as to create a model readily employed in a variety of applications.
Because of the lesser efficiency builders appear to have shown in constructing multi-family buildings, and the no more than short-term experience most of them have had in constructing wooden buildings of this type, it appears reasonable to believe that a considerable increase in the efficiency of producing wooden multi-family buildings can be achieved. In the present study, concerned with the construction of such buildings, the times needed for installing prefabricated planar elements that have been delivered to the assembly site are analyzed. The aim is to identify different parts of the assembly process and evaluate the time-efficiency shown in carrying out these tasks, a virtual BIM being used for visualization purposes.

**Project implementation**

**Development of a geometrical model**

The software AutoCAD was used to produce 2-dimensional drawings of multi-family houses that were to be constructed in the Limnologen block. These drawings constituted the basis for 3-dimensional models that were created in AutoCAD Architecture (formerly termed Autodesk Architectural Desktop, ADT). The resulting models were converted then to vrml format. This simplified visualization of the houses and prepared for connections being made between the geometry of the structures and the times recorded for installing the prefabricated elements. Having the models in vrml format allows them to be published in readily understandable form on the web (Vessby 2008a). Figure 1 is a schematic presentation of the three stages that development of the geometry underwent in going from 2-D cad, to 3-D cad, to vrml-format.

**Data collection concerning time intervals**

The times needed for installing the prefabricated elements were recorded. House 1 and house 3 differed in the methods used for collecting this data. In house 1, the time needed for installing each of the wall and floor elements was clocked from when installation began, or the moment when the element was hooked to the gantry crane, on to the point in time when installation of the element was completed and it was unhooked from the crane. Altogether, the installation of approximately 500 elements was clocked in this way, since 27 floor elements and 60 wall elements were installed on each of the six stories. In house 3, in contrast, measurements were made, for days on which construction was in progress and the installation of building elements took place, of the time that elapsed between when the first installation of a building element began and when the last installation of a building element was finished. The number of elements installed during that time was also noted. For both houses, the data gathered was evaluated in both Excel and Ceco Visual, see Table 1.

**Visualization of the time data and creation of a geometric model**

The model created can be termed a building-information model, or BIM (Kiviniemi et al. 2008, Chung Ling 2008). The present model differs from a conventional BIM, however, in that information linked with the model is used for evaluating the construction process rather than as a virtual tool prior to construction taking place. Connections between the geometric model and the times taken for installation of the separate building elements were assessed by use of the software Ceco Visual. This program, which makes use of the vrml file that was created, shows how the building was constructed element by element in the order of installation of the different elements. In the visualization stage the fourth dimension is that of time. This enables installation to be studied in a virtual sense, element by element, before, during and after completion of the construction process. Figure 2 shows how the collection of the geometric data and the time data takes place and how the two are coupled finally and visualized. The data can also be used separately in any given phases if called for.
Table 1. Raw data on times taken for installing prefabricated building elements, collected in the one case (House 1) for each of the elements installed, and in the other case (House 3) for separate working days (in that case through the time elapsed from the start of the first installation to the close of the last installation being measured each day). The data was evaluated by Excel and Visual Ceco.

<table>
<thead>
<tr>
<th>Examples of raw data from the site</th>
<th>Analysis of times contained in the spreadsheets.</th>
<th>Evaluation by the software Ceko Visual.</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Raw data image" /></td>
<td>Evaluation in which the installation each element can be studied separately.</td>
<td>Analysis in 4D, each of the elements being represented separately.</td>
</tr>
<tr>
<td><img src="image2.png" alt="Raw data image" /></td>
<td>Evaluation in which each day on which installation occurs can be studied separately.</td>
<td>Analysis in 4D, each day installation occurs being represented separately.</td>
</tr>
</tbody>
</table>

General comments on the load-bearing structures

The elements that are installed can be divided up into four separate categories: walls (the outer and the inner walls, as well as beams and columns), floors, access balconies and walls of the elevator shafts. The general practice has been to install the outer and inner walls, as well as the beams and columns during one week, and the floors, the access balconies and the walls of the elevator shafts during the week thereafter. On the weekend following that, preparations are made for another two weeks of installation and the weather protection measures needed are taken. Figure 3 shows a photograph of each of the four stages of installation. A video presenting still images of the installation process is available on the web (Vessby 200b).

Figure 2 Two separate processes, those of development of the geometric model and collection of the time data, are linked by means of 4-dimensional visualization of the installation process.
Results, discussion and conclusions

Results

The installations considered here involve, in each of the two houses, 27 flooring elements for five full-size floors and 60 wall elements for six full-size floors. Thus, there is a total of 135 flooring elements and 360 wall elements that were installed in each house. Additional building elements were installed in the half-size eighth floor and in the roof structure. The present report concerns the wooden flooring of the first five stories and the wooden walls of the first six stories. Figure 4 shows the numbers of elements installed in house 1 on each of the separate working days, together with the dates involved. To enable a comparison to be made with results for house 3, those results are also added to the chart, the dates being adjusted so that installations are designated as having started the same week as for house 1.

<table>
<thead>
<tr>
<th>Installation of wall elements</th>
<th>Installation of floor elements, access balconies and elevator shafts</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Wall installation" /></td>
<td><img src="image2" alt="Floor installation" /></td>
</tr>
<tr>
<td><img src="image3" alt="Access balconies" /></td>
<td><img src="image4" alt="Elevator shafts" /></td>
</tr>
</tbody>
</table>

(a) (b) (c) (d)

Figure 3. The weight-bearing structures that were installed can be divided up into four separate categories: (a) walls, (b) floors, (c) access balconies and (d) walls of the elevator shafts.

Figure 4 shows that the schedule of having walls installed one week and flooring the next appears to have worked out well in both houses. Installing the walls took about 2.5 working days per storey whereas installing the floors took approximately 1.5 working days per storey. In terms of a 40-hour working week, installation of the walls took approximately 55% of the working time (in each of the two houses). The corresponding results for the flooring were that installation of it took about 33% of the working time in house 1 and about 26% of the working time in house 3. The 7 percentage-unit reduction in installation time for the flooring in house 3 indicates the floor-installation procedures in that house to have been more effective.

Figure 4. The numbers of wall and floor elements installed in house 1 on the dates shown. The corresponding results for house 3 are superimposed on these results

For the wall elements as a whole, the average installation time per wall element was found to be approximately 22 minutes. The corresponding figure for installation of the floors elements
was found to be about 26 minutes. This suggests that under normal circumstances the floors elements are slightly more time-consuming to install than the wall elements are. This may partly be due to difficulties in fitting the flooring elements to each other. A more detailed analysis of the average installation times is presented in Figure 5, the average times there being shown as a function of which floor was involved. It was found that the highest and the lowest average time per storey for installing a wall element, both of these being for house 1, were approximately 29 minutes and 18 minutes, respectively. The corresponding figures for the flooring elements were 30 and 17 minutes, respectively, the first of these being for each of the two houses and the latter for house 3. Such differences suggests that the installation process is very sensitive to disturbances and that it is possible to shorten the installation times for both flooring elements and wall elements appreciably. A linear regression analysis utilizing the least square method showed that for installation of the wall elements there was a tendency in both houses for installation to take a shorten time higher up in the building, despite the fact that the time required for transportation of each element from the ground level to the storey on which it was to be installed obviously increased with height above the ground. Two explanations of the time required being lower at higher levels above the ground could be that more and more adjustments were made to improve the fit of the separate elements as the site of the work moved upwards in the building, and that workers became trained increasingly in use of the system and in the recurring operations to be carried out. For the flooring elements in house 3 there was likewise a decrease in installation time at higher levels in the building.

Figure 5. Average installation times in houses 1 and 3, respectively, for (a) wall elements, and (b) floors element. The figure indicates that, with the exception of the floors in house 1, shorter times were required for installations that were carried out higher up in the houses.
Part 2. Sub-project reports

For the flooring elements in house 1, however, the situation differed, the linear regression results there indicating a marginal increase in the time required for installation of the flooring higher up in the house. This result can be seen as reflecting the difficulties associated generally with the installation of flooring.

Figure 6 shows the average installation time per working day. Two observations can be made, each concerning a marked deviation from the assumption one might otherwise make that the time required for installing a particular element is independent of the day on which installation occurs. The one observation is that in house 1 the average time needed for installing wall elements was considerably higher the first day than the other two days. An analysis of how this average came about shows that the high average value was largely a function of the time taken for installation of wall elements on storey 2 on that particular day. The other observation is that on the second day the average time needed for installing flooring elements was 9 minutes higher in house 1 than in house 2. This difference is not due to the results for any particular storey or the like, but appears rather to be an indication both of the installation of flooring being considerably more effective in house 3 and of the fitting together of the floor elements there being better.

Discussion and conclusions

The results presented are based on the times that the installation of flooring elements and wall elements in houses 1 and 3 in the Limnologen block were found to take. Overall, installation of the 60 wall elements took about 55% of a working week and installation of the 27 flooring elements about 30% of a different working week. The remainder of the time in both weeks was taken up by the installation of beams and column and of access balconies, by complementary work around stairs and elevators, by safety work, which itself can be rather time-consuming, and by the job of installing rails on the flooring for the walls that were to later be installed.

The average installation time for an element of a given type was found to generally be lower higher up in the building. This can be seen as being due to increasing routine on the part of the workers, who learn to carry out their tasks in an increasingly effective way. It also indicates there to be considerable potential for further increase in the speed of installation through workers who possess routine from experience with similar construction tasks earlier being engaged.

The total time required for installing a load-bearing structure is influenced by a variety of factors. Deadlocks in the installation process due to supply misses or to using building
components displaying a large number of defects readily results in an increase in building time. Delivery of the correct elements to the proper place at the right time is essential. Use of a control system based on RFID (Radio Frequency Identification) could be of considerable help in avoiding delivery misses if adequately adapted to this purpose. A number of different projects aimed at exploring the possibilities that this technology provides are in progress (Erabuild 2006). The results could clearly be of interest to construction of the type that Limnologen represents.

References


Experiences from supply logistics and assembly

Abstract
This project aims at collecting and structuring problems and potentials for improvements regarding supply logistics and assembly of the first house built at Limnologen. The project is based on daily reports from the workers on site, workshops and meetings discussing experiences. Problems and potentials for improvements have been structured in a mindmap, see figure 1. The project concludes that a number of factors have affected the speed of the assembly amongst others weather protection and its elevation (working in cycles of two weeks) and the quality of production of building elements.

Realization of the project
This project has been carried out in two steps; step 1 regards the data collection whereas step 2 focuses on structuring and analyzing the collected material. Data has been gathered by daily reports from the workers on site, workshops with the different teams of workers, and a meeting where NCC and Martinsons discussed experiences from the building process. Further, Limnologen has been visited 2-4 times a week by at least one of the authors and photos documenting the process have been taken and organized.

A mindmap has been used in order to structure identified problems and their sources see figure 1. The identified problems have been assigned to one of the seven systems; flooring, walls, balconies, elevator and stairs, weather protection, safety issues, and logistics (most of them being physical prefabricated components). Some of the systems (flooring, walls, and logistics) have been further divided into main causes, which indicate the origin of the problem.

![Mindmap of problems and efficiency losses](image)

Figure 1. Overview of problems and efficiency losses divided into seven different systems and their respective main cause.
Results, Discussions and Conclusion

In the beginning of the assembly, workers from Martinsons were involved in order to facilitate, but also to contribute with their knowledge regarding assembling from previous projects. Around 10 workmen, including management and crane operator, conducted the assembly at Limnologen. The relative small number of workmen indicates that smaller companies, closely connected to the manufacturer, might have a possibility to establish and manage the whole assembly process. Such a company might possess considerable knowledge from similar tasks and the time for the assembly might be reduced.

There have been a number of factors determining the speed of the assembly. Two of these are the weather protection including its elevation and the production of building elements. One level is assembled in ten working days and the weather protection has been raised every second week. The rising of the weather protection is time consuming and it has therefore taken place over weekends in order not to disrupt the assembly. The elevation of the weather protection is time consuming due to the fact that is secured for wind stabilization against the building. Another self stabilizing weather protection would have been preferable.\(^1\)

Working under weather protection is perceived positively by the workers. The type of weather protection used at Limnologen implies specific requirements on the rest of the building under construction. The current design of the tent demands a separate fork lift truck to reload the trucks, whereas another type of design of the weather protection and the overhead crane would have made it possible to lift complete racks from the trucks. However one problem connected to such a solution is the capacity of the overhead crane; in order to do such a lift a capacity of at least 10 tonnes would be necessary and the present capacity is 3.2 tonnes. With a more powerful overhead crane the racks would be lifted to the current assembly floor and the elements lifted from there to the mounting place instead of from the ground to the mounting place. This could possibly be time saving.

There have also been some deviations from the orders in deliveries, particularly regarding missing material. This has caused some disturbances in the assembly process. As these types of deviations affect the assembly speed negatively, effort needs to be put in minimizing them. One method that lately has grown popular is tagging by Radio Frequency Identification Devices (RFID). Assume that all elements were marked at the manufacturing; deliveries could be notified at each node of the distribution channel. It would also be possible to track a missing element as well as to utilize automatic supervision.

\(^1\) This problem has been noticed by Martinsons Byggsystem AB and a new weather protection has been developed.
Manufacturing of floor components and walls about 1200 kilometers away from the building site causes high costs for transport which should be included to the ordinary costs (such as inventory carrying costs and inventory costs) at each step in the distribution channel. The total cost for this set up, regarding economies of scale through centralized production and large batch sizes, should be comparable with local manufacturing as well as with just-in-time-production.

The floor components and walls are kept in stock at the manufacturing sites (i.e. Bygdsiljum and Umeå) and there might be a number of reasons for this. One reason being that the production pace is faster than the pace of assembly, another reason being that deliveries take place only with full trucks. In order to reduce the amount of tied up capital, there might be possibilities to rearrange the manufacturing closer to Limnologen. However, in this scenario the amount of tied up capital in the distribution channel will be reduced but the benefit from economies of scale in production would also be reduced. Reduction of the transport volume and increase of the frequency of deliveries is dependent on transport agreements.

References

Information and Marketing Project

Hans Andrén, Välle Broar

Background and events leading to today’s situation

Following the Swedish governmental commission “More Wood in Construction” Ds 2004:1, Växjö municipality delegates took their own decision to put “More Wood in Construction” in motion 2005-02-17. A plan was made to build a number of wooden buildings on a site yet to be determined. This resulted in the Välle Broar project - a construction site in Växjö, located between the city centre and the university campus. When completed, the project would cover an area of 25 ha, and would consist of 1200 apartments, in addition to commercial premises.

The Välle Broar project name will become well-known in Växjö as other buildings are constructed around the town under the name.

The first project within Välle Broar is Limnologen which consists of 134 self-owned apartments, with Midroc Property Development as the building proprietor. The project features four eight storey apartment blocks, an annex, a community house and a two storey car park. All the buildings in the project have wooden frames. The project should be completed by summer 2009 and is currently Europe’s tallest modern wooden house project.

A number of things have resulted from the Välle Broar project. The University’s investment in education involving wood related materials is growing and local industries, the university and Växjö municipality have founded the “Centre for Building and Living with Wood” (CBBT), which is a research and development organisation, also the main funding body for the research projects reported herein. The organisation consists of Södra, Växjö University, Rörvik Timber, Trivselhus, Setra Group, Derome, SP Trätek, Välle Broar/Växjö municipality, Vida Timber, JGA and Möckelns sågverk.

Furthermore Välle Bröar has generated interest both in Sweden and abroad. Over the last 24 months, 230 groups have visited the project (approximately 2800 people in total), including 40 groups from abroad and about 30 from other municipalities and government work groups.

In the summer of 2005, Södra commissioned an architectural competition to design a small, mobile information centre, to cater for the inevitable influx of visitors. The competition was aimed at younger architects and received 106 entrants from all over the world. The winner was Gustaf Wennerberg, a Swedish 2nd year graduate at Oslo architecture school. He was awarded the winning prize at Södra’s Annual General Meeting in November 2006. The information centre is designed by Tyréns, in Växjö.
The Information Centre – The Wooden Cube

The information centre was financed by CBBT. The finished centre, known as “The Wooden Cube” stands on municipal land near Limnologen.

A management organisation is under development to run and maintain the centre and visitor interest is increasing week by week. Costs are split between the main parties of CBBT. Visits are organised by Hans Andrén, Välle Broar, Växjö municipal planning office and the Technical Visits department. (hans.andren@vkabvaxjo.se)

The centre contains information on all the wooden house projects in the region carried out during the years (Välludden, Kvarngården och Tävelsås) and imminent projects: Portvakten (64 apartments in energy saving houses, 2 eight storey buildings). Naturally, information on wooden house projects in Sweden and on Scandinavian wooden cities is available to visitors. In addition, the information centre will also be used for seminars and exhibitions, holding up to 40 people.
Monitoring of temperature and relative humidity
Erik Serrano and Bertil Enquist, Växjö University

Abstract
This project aims at monitoring the temperature and the relative humidity (RH) in the load bearing structure. Using in total 96 channels, data is sampled from six different locations in the building. At every location a total of eight temperature and RH-gauges have been mounted at different positions through the outer wall (including gauges for in- and outdoor climates).

Realization of the project
In building number 3 six different locations were chosen for monitoring the temperature and the RH through the outer walls. Three locations are situated on the second floor (concrete) and three in on the 7th floor (timber floor structure). For each floor, the three locations are at a bedroom wall (plastered), at a bathroom wall (wooden facade) and at a second bedroom wall (wooden facade). The below schematic shows how the gauges were mounted (showing the case of a plastered facade).

Figure 1. Placement of gauges through the outer walls.
Results, Discussions and Conclusion

This project will continue for at least one year after all gauges have been mounted, i.e. until summer 2010. Final results and the conclusions drawn will then be thoroughly reported. However, below some early results from one measurement location is shown for the period June 2008 – February 2009. The results are depicted as temperature and RH-profiles through the outer wall. Profiles are shown for several dates with 20 days interval.

![Figure 2. Preliminary results showing the temperature and RH profiles.](image-url)