Efficient Production of High-Rise Buildings
Efficient Production of High-Rise Buildings

Hanif Hoseini

KTH Architecture and the Built Environment

Licentiate Thesis
KTH – Stockholm, Sweden
Feb 2007
Preface

This Licentiate thesis is the result of my work at the Division of Building Technology at the Royal institute of Technology (KTH) in Stockholm. The work was financed by Hesselmans Foundation and the Swedish Research Council for Environmental, Agricultural and Spatial Planning (FORMAS). The construction of the Research tower was possible thanks to a long list of corporate sponsors who contributed with both materials and know-how.

I would like to thank my supervisor Prof. Gudni Jóhannesson at KTH, my secondary adviser and close colleague Dr. Kjartan Gudmundsson and Docent Folke Björk for their continues guidance during the entire course of this work. I am very grateful to Mr. Arne Hellström at Strängbetong AB, Mr. Håkan Larsson at Lindab and Mr. Rolf Öhman at Gyproc AB for their engagement in the project. Dr. Tim Weber and Prof. Torsten Höglund at KTH are kindly acknowledged for their fruitful discussions and comments.

The following companies have been involved in the realisation of the Research Tower

- Strängbetong
- Lindab
- Hilti
- Gyproc
- Dorocell
- Sto
- Paroc
- FBS
- Ensto
- Velfac
- IV Produkt
- RLI Byggdata
- Intab
- Thermisol
- Per Sommerhein
- WBM
- Scandos

Hanif Hoseini

Stockholm, Februari 2007
Abstract

Production of one family houses has over time developed successfully in Sweden and producers have managed to reduce the production costs and industrialize the production process. The development has however not been that successful when it comes to high-rise buildings. There are many attempts made, but no one has really managed to create a product that can persuade the market. The systems used are not flexible and cannot cope very well with variations in the design. The aim of this work has been to develop and evaluate the idea of prefabricated high-rise buildings within the outlines of a scientific research. By understanding the problems that the building sector experiences today it will be possible to identify the solutions that are needed tomorrow. The main objective has been to develop new technologies and system concepts for buildings. Concepts that are highly flexible and respect the ambitions of the architect and technologies that will facilitate a more effective building process and address relevant key issues in building physics and building construction for cost reduction and a sustainable performance. Aside from the actual production cost it is also important to consider the lifecycle cost of the building. The production cost represents only a fraction of the total lifecycle cost of a building.

A background research has been made to understand the building process and its problems, this information served for the formulation of a building concept. The work has been interdisciplinary and has not been limited to only one single point of view. Because of the nature of the method the work has resulted in new construction techniques. The initial idea of the prefabricated high-rise building has during the course of this work developed to a complete building concept. The Symphony Concept as it is called is about industrial prefabricated buildings that are assembled on site and is based on the idea of large and flat building elements with a very high degree of prefabrication. To evaluate the concept technology detailed researches have been made in different fields. The detailed researches made in this thesis regards the strength of sheet metal studs embedded in stiff insulation blocks, hazards connected with plastering on light weight constructions and fire protection of light weight constructions. The experiences from these researches are then applied in the building concept. Theory was put to practice with the construction of an experimental building called the Research Tower. The purpose of this pilot-project was primary to evaluate the construction technology and secondary to evaluate the properties of the building concept.

To be able to find methods for production of sustainable, cost-effective and attractive high-rise buildings it is necessary to have a holistic view. A holistic concept that takes into consideration the whole building process will yield time- and cost-efficient production while it will also make it possible to achieve better quality. The detail researches shows that embedding of the sheet metal profiles in the rigid insulation blocks will increase the buckling load of the stud and that the thickness of the plastering layer and the material properties of its substrate will affect the strains in the plastering layer and the moisture stored in it. Regarding the fire protection it could be stated that the Symphony outer wall construction protected with a double layer of gypsum board can maintain segregation of the fire up to 60 min as long as the gypsum boards do not crumble. In the production of the pilot projected it could be stated that the fact that the whole building was designed by one homogenous team with information about all details, made it possible to foresee many problems. The production of elements even in the temporary experimental production facility proved to be fast and economic, even with untrained labour force and the elements could be prefabricated to a very high level with facades that are plastered before assembly.
List of Publications

This Licentiate thesis consists of a comprehensive summary based on the following research and conference articles.


1 INTRODUCTION

1.1 Background

1.2 Objective

2 THE SWEDISH CONSTRUCTION SECTOR

2.1 The million unit programme

2.2 The building sector

2.3 Building materials and contractors

2.4 Problems

3 INDUSTRIAL CONSTRUCTION

3.1 Tolerances

4 THE SYMPHONY CONCEPT

4.1 Conceptual idea

4.2 Foundation

4.3 Primary Structure

4.4 Outer walls

4.4.1 The CasaBona System

4.4.2 Structural design of the CasaBona building elements

4.4.3 The Symphony outer-wall elements

4.5 Roofing

4.5.1 Roof construction

4.5.2 Roof water drainage

4.6 Installations

4.6.1 Vertical connection

4.6.2 Horizontal connection

4.7 Exterior finishing

4.7.1 Flashing work

4.7.2 Joints

4.7.3 Plastering

4.7.4 Moisture modelling in the plastering

4.8 Interior finishing

4.9 Fire safety

4.9.1 Regulations

4.9.2 Spread of fire between different fire cells

4.9.3 Fire modelling of the outer walls
1 INTRODUCTION

This thesis is the result of a project within the field of Building Technology. The main objective is to develop new technologies and system concepts for buildings, technologies that at the same time will facilitate a more effective building process and address relevant key issues in building physics and building construction for a sustainable performance and reduced costs. The thesis can be divided in three parts (see figure 1). The parts are presented in the following order but the limits between the different parts are not clear-cut. As described in figure 1 the work on each part is continues, they start in the below described order but continue parallel.

- Background research
  The purpose of the background research has been to understand the building process and its problems. Focus has not been put into the learning of how “things are done”. The idea has been to tackle the problem without being locked in “old habits”. The understanding process has been a combination of literature review and information gathered from discussions with people in different positions and from different fields of the building sector.

- Concept formulation
  The concept formulation is a continues process which extends beyond the outlines of this theses. The purpose in this case is not to find an absolute solution which answers all the questions but to study possible alternative approaches. The work has been interdisciplinary and was not limited to only one point of view. Because of the nature of the method the work has resulted in new construction methods. To evaluate these new methods detailed researches has been made in different fields. The purpose of these researches has been to understand the problems that could be connected with the different details. The detailed researches made in this thesis regard the strength of sheet metal studs embedded in stiff insulation blocks, hazards connected with plastering on light weight constructions and fire protection of light weight constructions. These detailed researches have later resulted in scientific papers. The experiences from these researches are then applied in the experimental building project.

- Experimental building
  An experimental building was erected where the theory was put to practice. The slender proportions of the building and the purpose of its erection motivated its name, the Research Tower. The purpose of this project was primary to evaluate the construction technology and assembly techniques of the elements and secondary to evaluate the properties of the building concept. Climatic and acoustic measurements are being performed in the building whereas the goal is to even perform a full-scale fire test eventually.
1.1 Background

Production of one family houses has over time developed successfully in Sweden and producers have managed to reduce the production costs and industrialize the production process. One-family houses are delivered in flat packages or as volume elements with totally finished interior and very little left of the exterior work. The development has not been that successful when it comes to high-rise buildings. There are many attempts made, some more successful than others but no one has really managed to create a product that can persuade the market. One reason can be the bad reputation of the prefabricated high-rise buildings from the million unit programme of the sixties, others can be the fact that production and economic efficiency often take precedence of the architectural design. Prefabricated high-rise buildings are often regarded as low-cost/quality buildings this is not correct but still valid in the public eye. The often poor aesthetics of these buildings does very little to overcome the accusations. Moreover it can be mentioned that the prefabricated high-rise buildings are not very flexible. They can be more considered as some kind of type-houses that are reproduced with the same design. Too much significance is often given to reproduction in the field of industrial construction. The systems used are not flexible and cannot cope very well with variations in the design. Furthermore the production costs in general are increasing and are relatively high. This has started a quest for lower production costs. While some companies focus at optimizing the management and the buying of materials many more are moving towards more industrialized production methods. The general idea seems to be that it is possible to reduce the production cost by reducing the working hours and increasing the reproduction factor. Is this correct, and if so what qualities need to be sacrificed?

1.2 Objective

The aim of this work has been to develop and evaluate the idea of prefabricated high-rise buildings within the outlines of a scientific research. The definition of high-rise buildings in the frame of this thesis is buildings being 3 stories and higher – excluding skyscrapers and buildings higher than 20 stories – intended for dwellings or offices. By understanding the problems that the building sector experiences today it will be possible to identify the solutions that are needed tomorrow. One of the main objectives has been to develop a concept for production of high-rise buildings that is highly flexible and respects the ambitions of the architect. Note that the aim is not to develop beautiful buildings but to create a system which will allow a high level of flexibility regarding the architectural design. Whether or not the building will have aesthetic values will depend on the architect involved in each project. The idea is to have building components that can be built together
in individual manner to create unique buildings similar to that of LEGO-blocks. A holistic
approach is made and focus is put on the whole building process, not only on some specific
details.

Aside from the actual production cost it is also important to consider the lifecycle cost of
the building. The production cost represents only a fraction of the total lifecycle cost of a
building. The production cost is important for the developer and thus relevant for the
decision of ever building the building. The life cycle cost on the other hand is important for
the operation of the building and will have an impact on the society as a whole. The major
part of the lifecycle cost of a building is related to energy consumption, low energy
consumption will also have a positive impact on the environment. In the rush for effective
production methods it is thus important not to forget the key term sustainability.
2 THE SWEDISH CONSTRUCTION SECTOR

This chapter aims to describe the Swedish construction sector with its experiences and particularities. This will also help the reader to understand more about the environment in which this work was initiated.

2.1 The million unit programme

One of the greatest achievements of the Swedish construction industry which is also the most discussed one is “miljonprogrammet” or “the Million Unit Programme” translated in English. During the sixties Sweden suffered from low supply on housing and the existing stock was of poor quality and very old. 1964 the Swedish parliament decided that one million apartments should be produced during the years 1965 – 1975. This was an effort to renew the stock as much as increasing it. One Million units were produced but many old buildings were also demolished and in the end the net increase of units was only 650 000 [Wikipedia]. Today the buildings from “the Million Unit Programme” represent 25% of the existing housing stock in Sweden.

To be able to build so many units in such a short time in a small country like Sweden required radical means. It was important to reduce the time, effort and cost of the construction.

Characteristic for the buildings of “the Million Unit Programme” are the prefabricated high-rise buildings built with prefabricated concrete elements. Large temporary infrastructures were established at the site with railroads for the cranes and provisional “facilities” that produced the concrete elements. The large size of the projects motivated the cost of this infrastructure. Landscaping with trees and green areas were made after the projects were finished [Wikipedia]. The buildings were functional but very little attention was given to their aesthetics and with time they have also shown many signs of constructional defects. This is easy to understand when put in relation to the shortage of time and other facts but the public opinion knows no mercy. These buildings are not very popular among the inhabitants and have given a negative tone to the word prefabricated.

Although these buildings represent only 25% of all the buildings produced during this time they are the ones most noticed and have come to form the mental picture of this political programme. The same production methods were used later in East Germany with similar results. Buildings associated with less attractive townscapes that are not popular. Even though “the Million Unit Programme” left the negative association to the word prefabricated it has also benefited it and left behind valuable experience about prefabrication and industrialized construction [Vidén, 1992].

2.2 The building sector

It is worth mentioning that according to the Swedish law the responsibility is on the client to make sure that the building is built in the correct way and according to norms and regulations [PBL, 1987]. The definition of the client is necessary in this context. The client is here defined as “anybody that builds for him self or let somebody else build on his account” which in other words means an ordinary developer or a private customer to a building company. Since the client often is not competent in the construction field he will try to compensate for this by putting the responsibility on to the contractor. The contractor on the other hand uses often many subcontractors and outsourcers different fields. The responsibility is at the same time partly delegated to the subcontractor. The consequence is
that the responsibility is like a hot potato that everybody tries to pass on and keep away from. As a result, disputes take place when mistakes are made and everybody blames each other. This is also natural since the limits between the different contracts are not always clear-cut. The contractor does not have to answer to the law if he makes any constructional mistakes; he only needs to answer to the customer. His responsibilities towards the client are hence not legal but contractual. The problem is that the client more often has limited insight in the field of construction and the legal contract terms connected to it. It is a pure battle of the strongest, the big building companies win this battle against weak clients while small building companies lose it. Neither from the client’s point of view are there any benefits with this legislation. If the contractor does not build correctly and according to the regulations, the client cannot complain to the law, instead he has to answer to the law. The floating line of subcontractors and the lack of responsibility have created a non healthy atmosphere in the sector with reduced quality and many mistakes.

Today there are a few big companies that possess the great majority of the Swedish building market and there exists oligopolic features in the sector as Ann-Christine Nyqvist, the general director of the Swedish competition authority describes it in the report “Bostadsbrist – Javisst” [Oskarsson, 2002]. With a market share of this size they have large influence on the price of materials and the general cost of production.

2.3 Building materials and contractors

The market of building materials is not transparent and the prices are not official. The detailers have a so called list price that is official but this price is in general very high and very seldom applied. Instead when they sell their products they apply “rabatt” or discount. This discount is dependent on each buyer and is more or less individual. This system with the lack of visible prices impedes the possibility of comparing prices and choosing what material to buy from which detailer [SOU 2000:44]. It is impossible to negotiate with all detailers for one product thus you will keep your collaboration with the detailer you have and try to get better discounts. The result is that the buyer stays loyal to the detailer to get better prices. The negative aspect is that the system does not put enough pressure on the detailers to compete on the basis of price. This could be contributing to the fact that prices on building materials have increased faster than both PPI (production price Index) and FPI (Factor price index) during the recent years [Jagrén, 2003].

It is clear that in such a system small companies disappear when it comes to buying for reasonable prices. The lack of competition is not healthy for any business in the long run and the same goes for the building sector.

The price of the building materials will also affect the price of the contract. Often when a contractor is hired he will offer a price for both materials and working ours. Some contractors do not even take the job if they cannot deliver the materials. This is especially valid for the contracts regarding the electricity and HVAC systems [Oskarsson, 2002; SOU 2000:44]. In these cases the detailers do not sell the products to any other companies than the ones who are specialized in these fields. The price for the materials that the electrician for example will get from the detailer will not be visible in the offer that he gives to the client. The contractor will furthermore provide the client with the technical solution of the contract. It is clear that the designed solution will not be the most cost effective one since the same company that prescribes the materials is also selling them to the client.

Alf Göransson, the former Vice President of the second largest building company in Sweden says in an interview regarding foreign contractors: “In some subcontracts we want to buy materials and working hours separately, this is a way of pushing down the prices.
Some of our traditional Swedish contractors refuse however to deliver only the working hours. Foreign subcontractors can be the solution for us in these cases” (Byggindustrin, 2004).

2.4 Problems

Of special interest are moisture related damages in the Swedish building sector. Certain problem areas have been frequent over the last years.

- Insufficient drying out of concrete before adding polymeric glues and floor materials. This has in severe cases lead to emissions giving rise to sick building syndromes.

- The most common technology for multifamily housing has been adding one story high wooden frame curtain wall elements in a concrete structure. As this normally is done from the bottom and up this technology has proved especially vulnerable for periods of driving rain during the erection process.

- A relatively new problem in Sweden is that especially plastered but also painted exterior surfaces of buildings are attacked by the growth of mould of algae. This has clearly a relation to increasing insulation but new material combinations and the more environmentally feasible paints have also been mentioned as possible causes.

- Water and moisture damages in bathrooms also cause high sums in insurance claims each year. This has often more complex causes but an insufficient sealing of floors and walls is often a part of the picture.

It is interesting to note that most of these problems have a strong relation to the building process. A common understanding is that a remedy for this would be to slow down the building process to allow for drying out of materials and give time for an effective multilayer sealing of bathroom floors etc. The hypothesis in this thesis is however that prolonging the building problems also creates risks and that the economic realities in the building sector do not allow for costly delays with increasing capital cost as a result. The solution has to be to reconsider the process and the technologies in order to reduce the risks at the same time that the speed is increased.
3 INDUSTRIAL CONSTRUCTION

The term industrial construction is being used more often in the past years and has in a way become a goal that especially larger building companies attempt to achieve. There is a tendency of connecting industrial production with automated machines as a substitute for workers which is incorrect. According to the author the keyword is in fact optimization. Automation is only a result of production optimization. The task is thus to optimize the construction of a building. Here it is important to clarify the definition of the word optimization in the way that it is used in this thesis. Optimization in its mathematical sense means to find the absolute best solution, i.e. minimum or maximum for a given parameter. It is not possible to find the absolute best way of constructing since there exists too many variables. This can thus not be set as the final goal for this work but more as a compass direction. By optimization is meant taking significant steps to approve efficiency of the building process (Management, technologies, structures and material efficiency, labour cost, financial cost etc). The optimization of the construction has been going on during a long period; items like the nail-punch and ready to install windows are examples of important steps in that direction. Today the sector is in a type of paradigm shift that is moving towards a radical change in the way we construct our general type of buildings by means of more industrialized construction methods. The key words for success in industrial construction are (according to the author) optimization, control and precision.

Manual labour costs are rising and contribute to the high construction costs. Apart from the cost the construction time at site and the waste needs to be reduced. In the report “waste in construction projects” [Josephson & Saukkoriipi, 2005], the authors analyse the waste in construction projects from a so called “lean production” point of view [Womack & Jones, 1996]. When observing the construction workers at site it could be stated that the direct value adding work was 17.5% of the total working time. 45.4 % of the time was spent on necessary preparations which include handling of equipment and materials on site and temporary works including safety preparations. 14% of this 45.4% was spent on transportation of materials to the working spot. Walking around consumes too much energy that does not produce and also increases the chance of unexpected scenarios such as accidents. The analysis of the waste is continued to the efficiency of engineers and architects, efficiency of the management, pure waste of materials, unused equipment at the building site and much more. In an enclosed space the work area is more controlled both in terms of climatic changes and access to equipment. When the item being produced is in movement while the production equipment is unmoving it is possible to use larger and more powerful equipment. Controlling this movement is the reason for the success of the manufacturing industry, not the mass production as we often incorrectly believe. The mass production is only a result of the optimization of the use of this equipment. It requires an ergonomic study of the human body together with a psychological analysis of the workers mind to find the optimized conditions for production. A great part of those conditions are found in a controlled environment such as a factory. Furthermore the tasks of each worker need to be optimized. Take for example a simple thing as measuring. Measuring is a very time-consuming task that has serious effect on the product. Optimizing this task will save a great deal of time while it at the same time will increase the precision. With a more detailed design it is possible to receive building components that are pre-cut and thus will not require the same amount of measuring. When Volvo is producing cars you don’t see people running around with rulers?

In a controlled space you don’t have any climatic changes, no snow blizzards or hot summer days that can affect workers, equipment or structures. It gives an overall more
regular working speed which results in a more precise calculation of the required working
time and thus the cost. The product will most certainly be produced in the exact same
amount of time every time it is produced.

Of course it is not possible to produce an entire multi-storey building inside a factory and
deliver it to the site, at least not yet but the goal is to finish as many building elements as
possible in advance. The fewer the elements to be mounted together at site the faster will
the mounting proceed, this gives that the prefabricated elements need to be large. The
larger the elements are the fewer elements are required. This needs of course to be
balanced against the cost and possibilities of transportation and effective logistics, crane
capacity and such.

3.1 Tolerances

A general obstacle for the use of prefabricated building elements is the fitting on site.
Prefabricated elements are often delivered by different contractors with limited adaptation
to the actual building being built. This is a classic example of local optimization; one
component is optimized without taking into consideration the rest of the building. There is
often no guarantee that the prefabricated component will fit as it was intended to.

Furthermore it should be pointed out that the standard tolerances used today in
construction need to be prescribed in a different way. The components and materials with
the largest tolerances are often the ones that are used earliest during the production of the
building such as the concrete foundation and the steel structure [Holm et al, 1987]. The
earlier a component is built the more forthcoming components it will affect. Large
tolerances in the early phase of the construction will thus grow even larger towards the
completion of the building. The earlier a component is built the more important is the
precision. This will help keeping the total tolerances at a low level and assembly of the
prefabricated elements successful.
4 THE SYMPHONY CONCEPT

The initial idea of the prefabricated high-rise building has during the course of this work developed into a complete building concept. The purpose of this concept is to optimize the construction of high-rise buildings regarding the energy consumption, flexibility, production time and total economy. A holistic approach have been made by considering the entire building process, from architecture, structural engineering, fire and environmental design to production, transport and logistics at the same time. Symphony is about industrial prefabricated buildings that are assembled on site and includes a range of technical solutions. The main innovations in the concept are the symphony elements:

- The full height vertical outer wall elements.
- The prefabricated installation elements with all the vertical installations integrated.
- The full height vertical joint elements.
- The light weight prefabricated roof elements.

The outer-wall elements are light weight prefabricated outer-wall elements produced with a width of 3-4 m and a height corresponding to 3, 4 or 5 storeys. These elements are prefabricated in factory with all the windows and doors integrated. The elements are also plastered and painted at the factory resulting in a totally finished exterior façade. They are mounted from the outside with a crane and fastened from the inside at each floor level.

The installation element is an outer-wall element were all the vertical ducts, piping and cabling needed for the vertical connection of installations are integrated. Horizontal junctions are prepared at each floor level to facilitate the connection of the installations at each floor to the installation element.

The joint elements are elements with a width corresponding to the width of the joint between two outer-wall elements and with the same height as the outer-wall elements. These elements contain the pipes for the roof drainage system. They are mounted from the outside with a crane and fastened from the inside at each floor level. The joint elements have integrated sealing stripes and do not need to be sealed after assembly.

The roof elements consist also of prefabricated light weight constructions. The roof is delivered to the building site with insulation and roof covering. Even the roof drains are mounted at delivery and need only to be connected to the drainage system.

The production of the building can be divided into 4 parts:
- Casting of the foundation
- Assembly of the load carrying Steel frame and Hollow core concrete floor slabs
- Assembly of the Prefabricated Symphony roof and outer-wall elements
- Erection of partition walls and final finishing of the internal spaces

The design of the foundation will be dependent on the current soil conditions. Once the foundation is ready the steel frame components and the hollow core concrete slabs will be assembled to form the load carrying structure. In this phase the staircase and elevator shafts and the stabilizing elements such as shear walls and crossings will also be assembled. When the structure is ready the mounting of the Symphony elements will begin starting with the roof. The roof elements will be assembled before the outer-walls to protect the structure from precipitation. When all the roof elements are mounted the joints
between these elements need to be sealed. With the roof finished, work will start on the assembly of the outer-wall elements and the joint elements. The outer-wall elements will be mounted one by one running around the whole building. The joint elements are simultaneously mounted covering the joint between two outer-wall elements.

When the roof elements, the outer-wall elements and the joint elements are assembled, the work will continue with the sealing of the joints between the roof elements and the outer-wall elements. After this stage the building has a totally finished exterior surface including a finished roof with a full working roof drainage system.

At the same time that this work has been going on the erection of the partition walls have already started inside the building. The efforts needed to finish the building’s installations are substantially reduced thanks to the Installation elements. These Symphony elements contain all the vertical installation pipes needed for the vertical connection of the installations between different floors. It only remains to connect the installations of each apartment to the Installation element. Finally the ultimate finishing of the internal spaces is completed according to the architect’s prescriptions and the building is ready for use.

4.1 Conceptual idea

Symphony is a building concept which implies a different way of viewing the construction of buildings. It involves a holistic view of the whole production of the building and includes everything from design to construction and installations and extents to the long time performance of the building in operation. The building in full is seen as one product with everything that is included in it. It is not a structure filled with installations and finished with surface materials. Everything can be integrated and all the included components must be regarded and planned for during the design phase. To achieve this, a more detailed and competent design process is needed. The design team includes representatives from all the different contracting fields. The members need to work more intimate and share all the information in real time with the rest of the team.

"Creating a symphony requires an entire orchestra with numerous instruments of different characters. Every musician has to know exactly which piece to play, when to play it and for how long. To their help the musicians have carefully elaborated notes and an experienced conductor. One instrument by it self might not sound spectacular but with proper organization and close collaboration they can achieve perfection." (Hoseini, 2004)

This concept is based on the same foundations: Organization, collaboration, accuracy and quality. A so called “Whole Building Design” Approach is applied [wbdg]. Normally different parts of the building are planned separately; there are architects, construction engineers, ventilation engineers, logistic planners and so forth. These parts are basically planned separately but built simultaneously at the construction site. The symphony concept prescribes the opposite, namely to design the building together and build it separately in sequences. A design team is formed including all needed consultants. This team works together in close collaboration. In this way they are all aware of how single details affect the rest of the building, they are able to prevent unnecessary problems and can find common, cost-effective solutions that will solve several problems at the same time. In the same way focus is put on separating the production of these parts at the construction site to reduce the number of different contractors working at the same time. This will create clear responsibility limits for the different contractors. Creating distinct limits between the contracts does not only reduce physical clash between the activities but it will also facilitate the tracing of mistakes. As a result increased pressure is put on the contractors to improve the quality control and reduce mistakes. Working with the whole Building Design
model will also facilitate the possibility of buying only the working hours when hiring a contractor. This is because all the technical solutions exist and the material can be specified.

It is important to remember that the architectural design is integrated with the rest of the design since the function of any object influences its design. The relationship between function, cost and design is very intimate. The physical shape arrives from the different technical details and their limitations. Having considered this in an early stage of the design it will lead to more efficient solutions and faster production which automatically yield economic savings.

4.2 Foundation

The foundation of a Symphony building is performed in the same way as for any other structure and is made in situ. As always, the exact design of the foundation is dependent on the soil and terrain conditions.

4.3 Primary Structure

Basically the structure of the Symphony concept is based on hollow core concrete floor slabs that carry the vertical loads and distribute them to vertical columns in the façade (see figure 2). This is a building system that has been used for a long time by Swedish producers of prefabricated concrete elements and the structural properties and performance of such structures are well established.

![Figure 2: Concrete floors or decks rest on horizontal steel beams that in turn are supported by the steel columns in the façade.](Strängbetong, website)

The steel frame work is built up with hot rolled steel columns and beams. The type and dimension of columns used depends on the building geometry and the current loads. The columns are situated in the façade and are built in to the outer walls so that they are not visible. The concrete slabs are then mounted to form the floor. The thickness of the slabs is also dependent on the geometry and current loads. The floor slabs are mounted on each floor leaving the last floor of the frame work empty for assembly of the light weight roof elements. Both the frame work and the floor slabs are thus prefabricated and assembled in situ. This will yield a very short production time for the Primary structure.

Components such as lift- and the stairway-shaft are produced at the same time as the structure and contribute to the stabilization of the building. Once the structure is assembled further stabilizing elements will be added, the solutions used here are as always dependent on the geometry and the current loads.
It is important to mention that flexibility is a key parameter in the formulation of the concept. The concept is not locked to one specific solution. Regarding the Primary structure it is favourable if the above mentioned solution is applied. If necessary, it is however also possible to use other type of structures such as column and deck structure with in situ casted concrete or suchlike. The important thing is that the mounting of all the elements is considered and planned for and that there are no load-bearing walls in the façade because then there would be no reason using the prefabricated outer-wall elements.

4.4 Outer walls

The prefabricated buildings from “the Million Unit Programme” are not associated with contemporary state of the art architecture. This have made that people automatically associate prefabricated buildings with poor architecture and reproduced houses. One of the main details that characterize these buildings is the visible joints that divide the façade into a grid which yells out “low-cost building”. This bad reputation will be one of the greatest challenges to overcome for the new era of industrialized constructions. The same goes for the Symphony concept. The full-height vertical outer-wall elements will eliminate the horizontal joints and break the grid and leave only vertical joints. It is of great importance to integrate these joints and make them a part of the façade design. Integration is another keyword in the concept, integration in the sense of functions. Integrating several functions into one element will give a much better utilisation of resources and thus a more sustainable solution.

The outer-walls are not load-bearing but work more as a climatic shell which transfer the wind loads to the primary construction. They are therefore not accounted for as primary construction elements. The fundamental idea is to reduce the production time and efforts on site. The outer-wall consists normally of several layers which are usually produced in different stages of the building process by different contractors such as carpenters, painters, plasterers and suchlike. It is also a building element that is associated with many risks as it is situated at the edge of the building and involves working in dangerous conditions at high altitudes. The production of outer-walls is in need of many temporary constructions for safety and production reasons. Scaffoldings can be mentioned as one of these temporary constructions. The scaffoldings are built all around the building façade and cost a lot of money. Still they are not totally safe to work on. The prefabricated outer-wall elements with finished facades eliminate the need for scaffoldings and save both money and work related injuries.

Large building elements do not only reduce the production time but give also an easier quality control. The quality control at site is reduced to inspection of the correct mounting of the elements. The quality control on site is always more difficult than at a factory.

Both outer-wall and roof elements are so called Symphony elements. The outer wall-elements are produced in factory were all the doors and windows are built in and the installations are integrated. The elements are also plastered and painted at the factory before they are transported to the building site. The exact dimension of both the roof element and the outer-wall elements are dependent on both the geometry of the building and the current transportation possibilities. The Symphony elements are built up with a core construction of sheet metal profiles integrated with stiff insulation blocks according to the CasaBona system.
4.4.1 The CasaBona System

During the recent years there has been a great deal of research and experimental projects at the Division of Building Technology at KTH with the aim of developing efficient building systems, [Jóhannesson et al. 1995]. This work has among other things resulted in a patented building system called the CasaBona system. CasaBona is a light weight integrated construction consisting of light gauge sheet metal Z-profiles integrated with pre-cut stiff insulation blocks. The CBZ-profile (CasaBona Z-profile) has a slotted web to reduce heat conductivity through the stud which gives the construction a coefficient of thermal transmittance comparable to a wooden stud [Nieminen et al 1995; Jóhannesson 1999]. The shape of the Z-profile together with the pre-cut stiff insulation blocks offers a very fast build-up of the construction (see figures 3 & 4). The stiff insulation supports the profile and strengthens it against local buckling. Through the use of water-resistant materials such as expanded polystyrene or rigid mineral wool, a moisture resistant construction is obtained. The system is highly flexible and allows different material combinations. The polystyrene can easily be exchanged for high-density mineral wool to meet specifications on fire safety and acoustics. Experimental houses have also been built with Adobe materials as insulation. The CasaBona profile can be produced in heights of 100/150/200 mm and the thickness varies between 1.0 and 1.5mm. The intention today is to take the development of this technology further in the direction of high-rise buildings.

Figure 3. Incisions in the Insulation blocks made with high precision yield perfect fit.

Figure 4. The pre-cut system offers a very fast build-up of the wall construction (4 man-min./m²).

Photo credit: Gudni Jóhannesson
4.4.2 Structural design of the CasaBona building elements

Accurate calculation models are required for the CasaBona System. Calculation of the profile strength has so far been performed using standard elementary methods such as the ones prescribed in Eurocode or the Swedish norms. The contribution of the rigid insulation blocks to the buckling stress has been investigated to see if it can increase the critical buckling load of the CBZ-profile. Both the CBZ-profiles and the insulation blocks are pre-cut with very high precision resulting in a perfect fit. Thanks to the perfect fit of the components, the sheet metal is supported by the EPS. This tight support should strengthen the profile against local buckling.

4.4.2.1 Method

Neither the Eurocode nor Softwares using final strip analysis are able to consider the affect of the EPS embedding on the local buckling strength of the profile. To find answers it is important to go back to the fundamental theory and the governing equations of buckling and elastic theory. The general equation for bending of plates is

\[ \frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{q}{D} \]  

[Timoshenko, 1959]  

(1)

Where \( w \) is the deflection of the plate and \( D \) is the flexural rigidity of the plate. Equation 1 can be solved in various modes for different load applications and boundary conditions. This equation is the basis for most of the elementary methodology where it is solved with one specific elementary boundary condition, namely that the plate is able to buckle freely without any lateral support. This is the main reason why the CasaBona profiles cannot be evaluated with elementary methods because they are embedded in Polystyrene and thus have lateral support.

Figure 5. Rectangular plate uniformly compressed in one direction with an evenly distributed force per length \( N_x \)

Timoshenko introduces a method for buckling of a bar in elastic medium using the energy method [Timoshenko, 1936]. In this case the EPS can be regarded as the elastic medium. Equation 1 is solved with the energy method where the work done by the compressive force is compared to the strain energy needed for the deformation of the bar plus the energy required for deformation of the Elastic medium. Timoshenko solves this problem for buckling of a bar in 2 dimensions. Here the same method is used in three dimensions to solve equation 1. The deflection of the plate \( w \) is represented in the form of a trigonometric series.

\[ w = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} a_{mn} \sin \frac{m \pi x}{a} \sin \frac{n \pi y}{b} \]  

(2)

Where \( a \) and \( b \) are the sides of the plate and \( m \) and \( n \) are the number of half wave lengths in which the plate buckles in the direction of \( a \) and \( b \) respectively. This equation satisfies the given boundary conditions for simply supported edges along all sides.
Consequently the strain energy for bending of the plate is:

\[ \Delta V_1 = \frac{\pi^4 ab}{8} D \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} a_{mn}^2 \left( \frac{m^2}{a^2} + \frac{n^2}{b^2} \right) \]

The work done by the compressive forces during buckling of the plate is:

\[ \Delta T = \frac{1}{2} \int_{0}^{a} \int_{0}^{b} \left( \frac{\partial w}{\partial x} \right)^2 dx dy = \frac{\pi^2 b}{8a} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} m^2 a_{mn}^2 \]

And the energy required for deformation of the elastic medium can be described as follows:

\[ \Delta V_2 = \frac{\beta}{2} \int_{0}^{a} \int_{0}^{b} w^2 dx dy = \frac{\beta ab}{8} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} a_{mn}^2 \]

where \( \beta \) is the modulus of foundation of the elastic medium. The critical value of the load at which the straight form of equilibrium changes to unstable is determined from the equation:

\[ \Delta T = \Delta V_1 + \Delta V_2 \]

Substituting equations 3, 4 and 5 into equation 6 and solving for \( N_s \) gives

\[ N_s = \frac{\pi^2 D}{b^2} \left( \frac{mb}{a} + \frac{n^2 a}{mb} \right)^2 \]

It can be seen that the smallest value of equation 7 is obtained when taking \( n \) equal to 1 which means that the plate can buckle in several half-waves in the direction of the compressive force but only in one half-wave in the perpendicular direction. Comparing this equation with the equation of buckling of a thin plate without elastic medium

\[ N_{s,\text{void}} = \frac{\pi^2 D}{b^2} \left( \frac{mb}{a} + \frac{n^2 a}{mb} \right)^2 \]

[Timoshenko, 1936] (8)

it’s easy to identify the contribution from the elastic medium to the compressive force. The magnitude of \( N_s \) is not only dependent on the proportions of the plate \( a \) and \( b \) and the modulus of foundation \( \beta \) but also on the value of \( m \) and \( n \). It is commonly known that local buckling in plates occur in a rectangular shape. This can be seen by examining equation 8. The lowest value for \( N_{s,\text{void}} \) is achieved when \( a = b \). The critical value of \( N \) is the lowest value that is required to buckle the plate. The value of \( m \) and \( n \) will have a great impact on the critical value of the compressive force. The next step is to examine how the plate will buckle and evaluate the values of \( m \) and \( n \). If \( \beta \) is set to zero then both \( m \) and \( n \) will be equal to 1. When \( \beta \) is very small \( m \) will again have to be set to 1. Thus for a very flexible elastic medium the plate will buckle without inflection points. By gradually increasing the value of \( \beta \) the system will arrive at a certain point were the value of equation 7 is smaller for \( m=2 \) than \( m=1 \). The limiting value of the modulus \( \beta \) at which the transition from \( m=1 \) to \( m=2 \) occurs is found from the condition that at this point the value of equation 7 is the same independently of whether \( m \) is equal to one or two. This condition together with the earlier condition of \( a=b \) gives
\[
\left( \frac{m}{a} + \frac{a}{mb} \right)^2 + \frac{\beta a^2 b^2}{m^2 \pi^4 D} = \left( \frac{m+1}{a} + \frac{a}{(m+1)b} \right)^2 + \frac{\beta a^2 b^2}{(m+1)^2 \pi^4 D}
\]

from which

\[
\beta_{cr} = \frac{\pi^4 D}{a^2 b^2} \left( \frac{m^2 (m+1)^2 + 1}{2m+1} \right)
\]

Equation 9 gives the value of \( \beta \) required for the system to jump to the next buckling mode. It can be seen that the required value for \( \beta \) increases rapidly for higher modes of buckling. It can also be seen that the value of \( \beta \) is also dependent on the size of the plate. Large plates require a lower value for the modulus of foundation to reach the transition point than smaller plates.

The value of the modulus of foundation for the material used is checked towards the value for \( \beta_{cr} \) calculated with different values for \( m \) and \( n \). If \( \beta > \beta_{cr} \) buckling will occur in higher modes. The obtained values of \( m \) and \( n \) are submitted into equation 7 and the critical compression load for a certain plate can be calculated.

4.4.2.2 Results

Equation 9 is used to calculate the value of \( \beta_{cr} \) required for skipping the first mode of buckling and get to the second mode were the plate buckles in more than one half wavelength. Table 1 gives the values of \( \beta \) together with the parameters used. It can be seen that the value of \( \beta_{cr} \) increases with decreased size of the plate. Furthermore it can be seen that it declines with reduced thickness of the plate. Examining equation 9 it can be seen that \( \beta_{cr} \) is directly proportional to the value of \( D \). The flexural rigidity of the plate \( D \) is \( E h^3 / 12(1 - v^2) \). This value is strongly dependent on the thickness of the plate \( h \).

<table>
<thead>
<tr>
<th>( \beta_{cr} ) (MPa/m)</th>
<th>Thickness of the plate (mm)</th>
<th>m/n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>300</td>
<td>2,342</td>
<td>1,199</td>
</tr>
<tr>
<td></td>
<td>12,488</td>
<td>6,394</td>
</tr>
<tr>
<td>200</td>
<td>11,854</td>
<td>6,069</td>
</tr>
<tr>
<td></td>
<td>63,222</td>
<td>32,37</td>
</tr>
<tr>
<td>100</td>
<td>189,667</td>
<td>97,109</td>
</tr>
<tr>
<td></td>
<td>1012</td>
<td>517,917</td>
</tr>
<tr>
<td>60</td>
<td>1463</td>
<td>749,301</td>
</tr>
<tr>
<td></td>
<td>7805</td>
<td>3996</td>
</tr>
</tbody>
</table>

Table 1. The value of \( \beta_{cr} \) required for different values of \( m \) and \( n \). The first value in the cell is that when \( m \) is chosen as 2 and \( n \) as 1 while the second value is calculated with \( m \) and \( n \) chosen equal to 2.
4.4.2.3 Modulus of Foundation

Duškov gives a formula for the relation between the modulus of Elasticity and density for expanded polystyrene [Duškov, 1997].

\[ E = A \rho_{\text{EPS}}^B \]  

(10)

Where \( A \) and \( B \) are empirically derived constants with the values 0.1284 and 1,368 respectively.

Table 2. The modulus of Elasticity of EPS for different densities

<table>
<thead>
<tr>
<th>Density of EPS (kg/m³)</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (MPa)</td>
<td>5.21</td>
<td>7.73</td>
<td>13.47</td>
<td>19.96</td>
</tr>
</tbody>
</table>

Table 2 gives the values of modulus of elasticity for EPS for different densities calculated according to equation 10. The Modulus of Elasticity has the unit (N/m²) while the modulus of foundation \( \beta \) requires the unit (N/m²/m).

How to obtain the value of modulus of foundation for the EPS? There is no easy answer to that question. The modulus of foundation is used very often in the field of soil mechanics and there are various theories for how to calculate it. The values used are mostly empirical methods based on measurements. In this paper a method prescribed by the Swedish Road Administration is used where the following equation describes the relation between Young’s Modulus and the modulus of foundation \( \beta = 2E/l \). In this equation \( l \) is the length of the plate corresponding to the side of the plate \( a \) in figure 5. Table 3 gives the values for the modulus of foundation for the EPS calculated according to the equation stated above. It needs to be mentioned that these values serve only as estimations. Laboratory experiments are required to achieve more accurate values.

Table 3. The value of the modulus of foundation calculated for EPS with different densities and for plates of various sizes.

<table>
<thead>
<tr>
<th>( \beta ) (MPa/m)</th>
<th>Density of EPS (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>34,734</td>
</tr>
<tr>
<td>20</td>
<td>51,53</td>
</tr>
<tr>
<td>30</td>
<td>89.80</td>
</tr>
<tr>
<td>40</td>
<td>133.1</td>
</tr>
<tr>
<td>300</td>
<td>104.2</td>
</tr>
<tr>
<td>200</td>
<td>154.6</td>
</tr>
<tr>
<td>100</td>
<td>269.4</td>
</tr>
<tr>
<td>60</td>
<td>399.2</td>
</tr>
<tr>
<td>Side of the plate ( a=b ) (mm)</td>
<td>Density of EPS (kg/m³)</td>
</tr>
<tr>
<td>15</td>
<td>34,734</td>
</tr>
<tr>
<td>20</td>
<td>51,53</td>
</tr>
<tr>
<td>30</td>
<td>89.80</td>
</tr>
<tr>
<td>40</td>
<td>133.1</td>
</tr>
</tbody>
</table>

Comparing the values of \( \beta \) in table 1 with the modulus of foundation for EPS from table 3 it can be seen that for the case discussed in this paper the value of the modulus of foundation for the EPS depending on the geometry of the plate is enough to arrive to the transition point of the next mode. As the plate size decreases the value of \( \beta \) increases rapidly.

4.4.2.4 Critical value of the compressive force

The values found in the previous paragraphs are submitted into equation 7 to calculate the value of the critical compressive load \( N_{\text{cr}} \). Table 4 presents the different values of the
critical load depending on the parameters used. The first value represents the general situation where \( \beta \) is equal to zero. The second value is calculated with the value of \( \beta \) taken from table 3 and the number of half wave-lengths that it results in. When the value of \( \beta > \beta_c \), the plate will buckle in more than one half wave-length. The number of half waves-lengths in which the plate will buckle is presented in the parenthesis in table 4. It is seen that the contribution of the elastic medium to the critical load is increased with increased size of the plate and decreased thickness. This is easy to understand since a large plate which is thin requires very small loads to buckle. In these cases even smaller lateral supports will make a great difference.

Table 4. The value of \( N_{cr} \) calculated for different geometries and half waves. The upper value represents the general value when \( \beta \) is set to zero. The value in the middle is the calculated value when the contribution of the EPS is considered and the lower value is the ratio between these two.

<table>
<thead>
<tr>
<th>( N_{cr} ) (kN/m)</th>
<th>Thickness of the plate (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side of the plate ( a=b ) (mm)</td>
<td>1,5</td>
</tr>
<tr>
<td>200</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>302,7 (3)</td>
</tr>
<tr>
<td></td>
<td>473%</td>
</tr>
<tr>
<td>100</td>
<td>256,2</td>
</tr>
<tr>
<td></td>
<td>501,5 (2)</td>
</tr>
<tr>
<td></td>
<td>196%</td>
</tr>
<tr>
<td>60</td>
<td>711,8</td>
</tr>
<tr>
<td></td>
<td>954,4 (1)</td>
</tr>
<tr>
<td></td>
<td>134%</td>
</tr>
</tbody>
</table>

4.4.2.5 Conclusions

It’s clear that the existence of an elastic medium does have an impact on the critical load for buckling of a profile. This impact will depend on the dimensions of the plate and the value of the modulus of foundation for the elastic medium. By examining equations 7, 8 and 9 it appear that the real impact of the elastic medium to the critical buckling load is proportional to the ratio between \( \frac{D_{mb}^2}{\pi^2 \sigma^4} \) and the integer 4. Furthermore the calculations has shown that for the studied case the modulus of foundation for EPS is large enough to make the plate buckle in higher modes depending on the geometry of the plate. For a plate with a width of 60 mm which is the case for the CBZ-profile the critical value for local buckling is increased between 134 and 195 percentages depending on the thickness. The calculations also show that the impact of the elastic medium increases with increased size of the plate and decreased thickness of the plate.

These calculations have been performed on the basis of specific boundary conditions. Namely a thin plate simply supported along all edges and uniformly compressed in one coplanar direction with an evenly distributed force. By examining the CBZ-profile more closely it can be argued that this situation is not the weakest situation for this profile. The lips of the profile have a rather long length and they are free on one side. This detail has most certainly a lower value for the critical buckling load than the detail studied. The boundary conditions in this case will be a rectangular plate, simply supported along 3
edges and a free edge parallel to the direction of the uniformly compressive force. These boundary conditions will most certainly give lower strain energy for bending of the plate and thus the relation between this energy and the energy required for deformation of the elastic medium will be more significant. This will give that the elastic medium will have a larger impact on the critical buckling load of the profile.

4.4.3 The Symphony outer-wall elements
The core of the Symphony outer-walls is based on the so called CasaBona system as mentioned earlier. Both the sheet metal and the stiff insulation are delivered to the factory pre-cut with high precision. The insulation blocks have incisions for the flange of the Z-profile with which they will be built together, see figure 3. The width of the blocks gives automatically the distance between the studs and no measuring is required. The Expanded Polystyrene blocks are exchanged to blocks of stiff mineral wool alongside the connection to the intermediate floor slabs for fire security and acoustic reasons. Notice that the elements are produced in horizontal position beginning with the inside. After finishing the inner layers of gypsum boards, horizontal studs and additional insulation, the element is turned over to finish the outside layers (see figure 6). Before the turn over it is possible to integrate electrical wiring behind the outermost gypsum layer. On the outside the element is covered with another layer of 50mm stiff mineral wool before it is plastered. The elements are also plastered and painted at the factory before they are transported to the building site. Notice that the walls are plastered in horizontal position which facilitates the procedure and lowers the amount of working hours.

The outer wall elements are 3.6 m to 4.1 m wide and up to 15 m high, each one can thus pass by up to 5 floors. All the doors and windows are built in and the installations integrated at the factory. The outer-wall elements will be finished to 90% when delivered to the building site. Some of the wall-elements will also be containing the vertical HVAC and electrical installations needed for the building.

The outer-wall elements will be mounted after the roof. In this way an early weather protection of the building is achieved. As soon as the outer-walls are mounted a closed shell is created. The wall-elements will arrive at the building site on trucks, loaded horizontally. At the building site they will be lifted to vertical position by mobile cranes. Special lifting devices for the crane will be used to lift the wall elements. Once in vertical position they will be transported and hung up on the floor structure where they will be fixed from the inside on each floor. Since the outer-wall elements contain windows and doors they have to be mounted in exact vertical position from the start. Adjusting possibilities for the outer-wall elements are therefore of great importance. Even small angle deviations will cause inclining windows which will be difficult to adjust afterwards.
Figure 6. The elements are produced in horizontal position beginning with the inside. They are then turned over to finish the exterior façade.
4.5 Roofing

The roof is another part of the building which is associated with very bad working conditions. Besides the life threatening risk of falling down from the roof, the worker is directly exposed to precipitation and wind. These conditions slow down the production time and require extra temporary safety constructions that have to be removed once the work is finished. This is a severe waste of resources and will yield efficiency if eliminated. In the framework of the Symphony concept the roof elements are finished at the factory with roof-covering and roof dwells mounted. The element has a finished roof drainage construction which is ready to be connected to the building’s roof-water drainage system.

4.5.1 Roof construction

It is not economical to design light weight low slope roof elements that span over the whole building between two outer-walls without load-bearing partition walls [Lundgren, 2005]. The large span can lead to complex and expensive solutions when excessive deflection of the roof is to be avoided. It is therefore important to have total control of the roof deflection and design of the internal partition walls with respect to these movements. With the Scandinavian snow loads the CBZ-profiles will be able to span a maximum of approximately 5 m depending on the design. Hence the Symphony roof elements are once again used as secondary construction elements which will transfer the loads to the primary construction. The design of the primary construction of the roof is dependent of the geometry and climatic conditions of the building in question. With the primary structure in place the roof elements will be mounted easily with cranes which significantly reduce the need for workers on the roof. The roof will not be completely finished when mounted but the working hours on the roof are substantially reduced. The building of the roof construction and its different layers is limited to the fastening of the roof elements while the finishing of the roof covering is limited to the covering of the joints between the elements. It is seen clearly that bigger elements will yield reduction of the on-site working hours.

4.5.2 Roof water drainage

The roof elements will be delivered with required inclination and the roof covering finished at the factory. Even the roof drains will be mounted on each roof element together with the piping needed to connect to the roof water drainage system. Each roof element that leaves the factory is thus a water tight unit with a functioning drainage system. The drainage system is designed to be easily connected to the finished drainage system but also to function during the construction time. The surface material of the roof covering is dependent on the roof inclination and thus also of the architecture of the building. High inclination with protruding eaves will require different materials than low inclination roofs with vertical roof edgings as part of the outer-walls.

4.6 Installations

The costs of the installations mount to approximately 20% of the total production cost in the case of dwellings [Malmström, 2001]. A reduction in this field will yield a large impact on the total cost of the building. The installations include all the piping for water and sewage, ducts for ventilation and the electrical cabling. The Swedish building codes require mechanical ventilation for all apartments [BBR, 1993]. This leads to a great deal of ventilation ducts and equipment that needs to go through the whole building. These equipments often require their own constructions for hanging and fastening and so on. The
installations are often outsourced to several subcontractors, usually one for the electricity and one for the HVAC systems. The prices offered by the subcontractors are difficult to evaluate and include both material and working hours. The mutual agreements and discounts between the subcontractor and the detailer are all affecting the price. The prices of each post in the offer are not transparent. This absence of transparency makes it difficult for the client to evaluate the price in relation to the value, quality and efficiency of the contract [SOU 2000:44]. Separating materials and working hours could yield large savings for the client. These savings would in turn have a strong impact on the total production cost. It needs also to be mentioned that the cost per hour of the installation workers on site are higher than assemblers at a factory [SCB]. Integrating parts of the installations into the prefabricated elements will not only save time but it will also mean that factory assemblers are doing the same job for a lower cost. Moreover it will open the possibility to buy the materials directly from the detailer and in that way benefit from the discounts.

The symphony concept integrates part of the installations into the prefabricated elements. In this way the double work of inserting the installations into a finished building afterwards is reduced. This is not to be underestimated since this type of work very often include opening of wholes in constructions such as load carrying walls or floor slabs which is very costly. In reality every whole taken in a building is a waste of recourses since effort has been made to create the solid material and more effort is needed to remove the same material in less favourable circumstances. The installations can be divided into vertical and horizontal installations.

4.6.1 Vertical connection

The vertical connection of ventilation ducts, piping of the water and sewage and the main cabling for the electricity is integrated into the outer-wall elements. The vertical ducts and piping have junctions at each floor level to allow for the horizontal connection of the installations from the apartments. This is made in the factory and does not require any double work for inserting them afterwards. As a result the building will not need any internal vertical shafts which occupy expensive living area. The production cost of a building and the profit made from it are both accounted for per square meter and every square meter not sold is an expense. Integrating the installations long before the building is finished requires a high degree of planning and a detailed design of the whole building. Here the benefits of the whole building design procedure are obvious and competitive. Furthermore it is important to bear in mind and plan for the risks of integrated installations in the outer-walls. The placing and fastening of the ventilation ducts and piping in the outer-wall require elaborated design. Bad insulation of the pipes towards the exterior may lead to large energy losses from the heated air and water as well as condensation in the ventilation ducts while incorrect fastening and insulation towards the inside of the building can lead to acoustic problems between the apartments.

4.6.2 Horizontal connection

The horizontal connections of the installations are reduced since the distance between the actual device in each apartment and the junction to the vertical ducts are substantially reduced. The installations of each apartment are connected to a connection point somewhere in the outer-walls of the same apartment. This will not only facilitate the actual connection work but will also require less internal space inside the building reserved for the ducts and pipes. The building has a raised floor structure which will be presented in detail in the coming chapters. This raised floor creates an empty void of up to 230 mm between the concrete slabs and the floor which can be used for placing of the horizontal

22
installations. This facilitates especially the electrical cabling. The cables are able to run to the connection points the bird way and do not need to follow the internal walls. This will not only reduce the amount of meters cable needed and facilitate the work but will also give a more flexible building. Renovation of an apartment will be much easier when non bearing walls with no hidden cables inside are to be moved. The same discussion is valid for the water- and sewage-pipes. Sewage pipes that are not cast in to the concrete slab create totally different possibilities when it comes to changing the place of a floor drain.

4.7 Exterior finishing

The purpose of the symphony concept is to reduce the working hours needed at the building site by producing prefabricated elements with a high degree of prefabrication. The outer-wall elements are therefore delivered with finished exterior surfaces. Also the arising joints between the elements need to be covered in a time efficient way. Other details needed on the exterior of the building are the downpipes for the water drainage system. The work needed for the finishing of the exterior façade when the building is mounted require operating on high altitudes which takes more time and involve special equipment and temporary constructions. Reduction of this type of work will thus lead to larger savings than the actual reduced working hours. Even the joints are consequently designed as prefabricated elements to be mounted on site. The piping for the water drainage system is integrated into the joint elements which results in hidden downpipes and an undisturbed façade while the assembly time for the downpipes is almost eliminated.

4.7.1 Flashing work

The detailed flashing work needed around the windows and other openings in the façade are not to be underestimated. Fastening and adjusting these details at the factory while the wall is in horizontal position is favourable since it is possible to walk between the windows instead of climbing between them. But this obviously necessitates a greater responsibility in the design phase and the previous production phases. It is vital that all the windows are mounted in exact right position and angle before the window edge flashing is fastened. The windows need to be mounted in the correct position in correlation with each other and the outer limits of the element since the whole outer-wall element can be adjusted but one specific window cannot. An incorrectly mounted window that needs to be adjusted after that all the details around it are finished will require much more time than in the normal case. This argument is valid for the whole prefabrication philosophy. Quality control in prefabrication is extremely important. The efforts needed to exchange a component in a prefabricated element are much more costly.

4.7.2 Joints

The joints are covered with the specially designed joint elements. The goal is to cover the whole height of the joint at once. The joint element is therefore a full length element with the same height as the outer-walls. This element is to be lifted with the crane and mounted on the façade covering the whole height of the joint. To make this possible it is required that the joint element is a rigid construction.

The building has a low slope roof where the water is prevented from pouring down the roof edge by the outer-walls. These conditions favour the use of siphonic roof drainage systems [Arthur & Swaffield, 2001] where the gravity acting on the water gauge in the vertical pipes will suck down the accumulated water from the roof. One benefit with the siphonic full-flow systems is that smaller diameters can be prescribed for the pipes. This goes well
with the design of the joint elements and the pipes can easily be integrated into the joint elements.

Aesthetically the joints can be treated in different ways. Depending on the architectural design they can be either exposed and enhanced or totally hidden to create an even façade. When chosen to be exposed the exterior surface material of the joints is simply applied to it before assembly. The joint element will in this execution have bands of expanding polyurethane attached to it before assembly. The bands will expand and no post sealing is required. These elements will be mounted by the crane and fastened from the inside at each floor level and give a finished façade instantly. The same types of joint elements are used when the joints are chosen to be hidden. The only difference is that these joints need to be treated after the assembly.

4.7.3 Plastering

Plastering or rendering the outer walls at the factory in horizontal position is faster and more comfortable than in vertical position at the building site. Except for the fact that it is possible to walk across the façade instead of climbing, it should also be noticed that moving around of equipment is much easier. Pre-plastering of the elements at the factory requires precautions in the design. When the elements are to be lifted to vertical position at the building site they will be exposed to bending. This will yield compressive and tension forces in the element. The elements are thus lifted with the plastered side up because the material is stronger in compression than tension. The bending can still lead to tension forces at the inner layer of the plastering depending on the bending radius and the thickness of the plastering layer. The radius of curvature on the other hand will depend on the rigidity of the element and the way it is lifted. Further more will the thickness of the rendering layer affect the acoustic resistance of the outer-wall towards traffic sound, the thicker the layer the more mass it will have and thus it will absorb more of the low frequency sound waves produced by the traffic sound. It is seen that it is not easy to just choose any kind of plastering and apply it on the outer-wall element.

4.7.4 Moisture modelling in the plastering

Plaster on substrates such as EPS with a low thermal conductivity, low thermal inertia and relatively low moisture permeability undergo relatively larger variations in temperature and humidity during a diurnal cycle than plaster on high density construction materials. Large temperature variations will also give rise to large moisture variations. This combination will create strain on the plaster which will expand and shrink in response to the variations. Expansion and shrinkage of the plaster will increase the risk for cracks. Higher moisture levels will also increase the risk for mould and algae.

The drying out of a plastered light weight outer wall construction during extreme climatic conditions is studied in order to grasp the problem. For this purpose, a calculation model has been created in which the drying out of the construction can be studied. It is also of great importance to have a general model in which the different parameters can be easily exchanged to facilitate the study of different cases. This model is based on the following general assumptions and simplifications.

- Non steady state calculations are performed in one dimension.
- Moisture transport is assumed to occur only by diffusion and capillary transport. Moisture transport by convection is not considered.
Capillary transport is assumed to occur only in the plastering layer. The material behind the plastering has coarser pores and will thus prevent capillary transport away from the plastering. The capillary transport of condensed moisture in the other materials is not considered.

Moisture balance in the materials is assumed to occur instantaneously.

Materials are assumed to be homogenous with uniform material properties throughout the whole volume.

The sorption curves used are not temperature dependent.

The case studied is a post rain situation where the plastering is assumed to be moisture saturated. The drying out of the construction is then followed during 5 days.

The studied wall is a light weight construction (see figure 7) with materials according to table 5. The height of the wall section is 3 m and the calculations are performed at a section between the sheet metal profiles.

Table 5. Construction of the wall section studied.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 x Gypsum board</td>
<td>26</td>
</tr>
<tr>
<td>mineral wool between horizontal sheet metal profiles c/c 450 mm</td>
<td>50</td>
</tr>
<tr>
<td>polystyrene between sheet metal CBZ profiles c/c 900 mm</td>
<td>200</td>
</tr>
<tr>
<td>polystyrene</td>
<td>50</td>
</tr>
<tr>
<td>calcium cement plastering</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 7. The wall section is divided into ten elements with the element numbering beginning on the interior side.

4.7.4.1 Method

The temperature and moisture distributions in the construction are obtained through numerical solution of the governing equations for heat and mass transfer during transient
conditions. The heat transfer equation in one dimension with no internal generated heat gives the temperature difference \(dT\) as follows:

\[
\frac{dT}{dt} = \frac{\lambda}{\rho c} \cdot \frac{d^2T}{dx^2}
\]

(11)

\[\rho = \text{density} \ [\text{kg/m}^3]\]
\[C = \text{heat capacity of the material} \ [\text{J/K}]\]
\[t = \text{time} \ [\text{s}]\]

The water vapour rate is.

\[
g = -\delta \cdot \frac{dv}{dx} \ [\text{kg/m}^3] \quad (12)
\]

\[\delta = \text{the vapour conductivity of the material} \ [\text{m}^2/\text{s}]\]

When the moisture content of a material reaches the critical moisture content \(w_{cw}\), the water content in the material is sufficiently high to connect the pores and allow capillary transport of moisture in liquid form. A common convention is to express the moisture transfer in a material as a sum of two processes [Jóhannesson, 2002]:

\[
g = -\delta \cdot \frac{dv}{dx} - k_u \cdot \frac{dv}{dx} \quad (13)
\]

\[k_u = \text{liquid moisture transport coefficient}\]

where the first term describes the amount of moisture transferred via diffusion and the second term describes the liquid transport through capillary forces. The liquid transport can also be described using the suction \(s\) as the potential [TC 89]. The lack of adequate data does however obstruct the use of this method.

The moisture capacity of the materials is dependent on the relative humidity \(\varphi\) and is decided by the sorption curve [Nevander & Elmarsson, 1994] which gives the value of the moisture content \(w\) in the material as a function of the relative humidity \(\varphi\) \(w(\varphi)\) [kg/m³]. The sorption curve has to be translated into some kind of mathematical function which can describe it with passable precision. This can be done in various ways; in this model a linear interpretation has been used. The sorption curve is divided into several straight lines that follow the curve with adequate precision. In this way the sorption curve can be described by means of the equation of the straight line between the placed points.

4.7.4.2 Calculations

The calculations are one dimensional non steady state, performed using a forward step finite difference approach. The construction is divided into 10 elements and has 12 nodes one additional node for the indoor and one for the outdoor (see figure 7). The nodes are placed in the middle of each element except for node 10 which is placed on the outer surface of the plastering. Radiation heat is considered on the outside and ignored on the inside since the temperature differences are relatively low.

The temperatures in each node at each time step is first calculated using equation 11. The calculated temperatures are then used to calculate the humidity of air at saturation and the moisture content.
The change in moisture content during each time step is derived from the net moisture flux into the node, and the amount of moisture stored which is depending on the relative humidity in the element $w(r)$. When the moisture content $w$ is known the vapour content $v$ can be calculated. An initial value for the moisture content is found with a steady state calculation. The vapour content is then used to calculate the moisture content in the next time step and so on. In node 9 and 10 (in the plastering layer) capillary transport will contribute to the moisture transport. Moisture transport in these elements is formulated as seen in equation 13. As long as the moisture content is below the critical moisture content, the transport of moisture will take place only by diffusion. When the moisture content of the element reaches the critical moisture content the pores contain enough water to allow capillary transport. Moisture transport by capillary forces is much larger than the one by diffusion.

4.7.4.3 Transport coefficients

The amount of moisture transported by capillary forces is much higher than that transported by diffusion. The type of transport used is defined by the transport coefficient. For moisture transported via diffusion the vapour conductivity $\delta$ is used and for capillarity the capillary transport coefficient $k_c$. The problem occurs when it has to be specified weather the moisture is transported via diffusion or capillary forces. The nodes are situated in the middle of the elements, this means that the transport between two nodes is defined as the moisture transported from the middle of element one to the middle of element two. The law of the conservation of mass is valid which means that the conserved mass inside each element is the sum of the mass transported in to the element and the mass transported away from the element. It is also said that if the moisture level in the element in question is higher than $w_{cr}$, the transport is performed by both diffusion and capillary forces and if it is below $w_{cr}$ it is only performed by diffusion. Now, how can the transport be decided if the element in question has a moisture level above $w_{cr}$ while the adjacent element has a moisture level below $w_{cr}$? For the element in question the transport coefficient is obviously chosen to allow capillary transport while the adjacent element will only allow transport by diffusion. The amount of moisture transported away from the element in question is consequently much higher than the amount of moisture which is transported into the adjacent element. The condition is therefore set to use the mean value of the moisture content of two adjacent nodes instead of the moisture content of only the node in question. The calculation method is still not totally correct since the mean value of the moisture content in two nodes can be higher than $w_{cr}$ while it is lower in one of the nodes.

4.7.4.4 Results

It can be seen in the results that moisture content varies fiercely in the surface element (see figure 8) while it declines more harmonic in the element behind. The strong temperature variations at the surface are due to the added radiant heat flow to and away from it. During the day solar radiation will raise the temperature at the surface significantly while it is decreased below the outside temperature during the night because of radiation to the sky which has a lower temperature than the outside air when the sun is not present, this will have a direct effect on the relative humidity in the materials. Further it can be seen that moisture stored in element 9 can be transported to element 10 through capillary forces while it can only be transported by diffusion to element 8. This is due to the fact that the plastering has finer pores than the expanded polystyrene. A great part of the moisture
transported to the deeper plastering element is thus conserved there until the surface element has dried out to a fair level and it can be seen how the surface element virtually pumps out the moisture from node 9 during its daily cycle (see figure 8).

It can also be noticed how the moisture content in element 9 decreases strongly during the day when the surface element dries out while the decrease is slowed down during the night. During the night relative humidity increase due to lowered temperature (see figure 9), the moisture content in the surface element increases because of condensation from the air outside and moisture transported into the element from element 9.

*Figure 8. Moisture content w in the nodes during 5 days (7200 min), the calculation starts at midnight.*
Figure 9. Relative humidity $\varphi$ in some of the nodes including the exterior air.

Figure 10. Temperature distribution in the nodes during 5 days (7200 min). Node number 9 & 10 in the plastering layer has almost the same temperature.
4.7.4.5 Conclusions

It can be seen clearly that the temperature distribution of an outer wall is strongly dependent of the radiant heat transfer at the surface. The frequency of the temperature variation in the construction is strongly dependent on the thermal inertia of the construction. This is why a light weight construction is subjected to stronger temperature variations during the day. It is seen that added thermal inertia in the construction is healthy for the plastering and that some moisture buffering behind the plastering layer can be necessary. The high amount of moisture that is stored in the interface of the EPS and the plastering can lead to cracking if a sudden temperature fall occurs. Furthermore it can be stated that plastering materials used on light weight constructions should be less sensitive to temperature variations in ways of expanding and shrinkage.

As a result the EPS behind the plastering can be exchanged to high density mineral wool which has a higher thermal inertia and can give more inward diffusion during the drying out process. Regarding the plastering it could help to have a thinner and more elastic plastering layer. In this way the plastering layer itself would store less moisture and at the same time be able to dry out much faster.

4.8 Interior finishing

The climatic shell of the building is finished very fast. This will create good working conditions inside the building. By planning the order for the rest of the work in an efficient way and to prevent different contractors from working at the same time, a controlled production space can be created to optimize the production. For the interior finishing of the buildings traditional methods are used with conventional techniques. Worth mentioning is that the outer wall elements are prepared with most of the electric cabling integrated on the inner surface and that the rest of the internal installations are collected under the raised floor. This leads to installation free partition walls which are produced quicker than partition walls that contain installations. The raised floor creates an air gap between the floor and the concrete slabs (see figure 11). This gap can be adjusted between 20 and 230 mm. The gap is used to put installations such as water pipes and electrical cables. Hollow-core concrete slabs are very bumpy and rough on the surface. To level out the floor surface, normally a layer of 20 to 50 mm of concrete is poured on the slabs. Using the raised floor solution as described above the floor does not need to be poured with concrete. This will speed up the production since the drying time of the concrete is eliminated at the same time that no additional moisture is built into the building.

The purpose of the partition walls is to divide the plan into spaces. There is however some special requirements for the walls that divide different apartments. These walls are dividing fire cells which put special requirements on them regarding the fire safety. Furthermore there are higher demands on the acoustic insulation of these walls since they divide apartments.

When designing the partition walls it is important to bear in mind the fact that they will affect not only the horizontal sound insulation between two apartments but also the vertical sound insulation. The sound that is released in one apartment will get to the above one through the floor slab and through the walls. The concrete floor slab provides fine acoustic insulation because it absorbs a great deal of the sound waves. How much it can absorb is dependent on the mass of the slab. When the thickness of the slab is uniform the size of it will affect the mass. The walls connected to the slab will interact with it and contribute to the total mass of the slab. This is of course very much dependent on the construction of the wall and its connection to the slab.
4.9 Fire safety

The fire protection of the building is divided into two parts, fire protection of the primary constructions and fire protection of the secondary constructions. The primary construction includes the steel framing and the hollow core concrete elements. These are the skeleton of the building and carry all the loads. It’s important to protect these components from the fire during a longer period to prevent the building from crumbling. Now the concrete floor slabs and shear walls have a natural fire protection because of the material. The steel framing and the metallic joints need to be protected. This is done mostly by embedding the steel frame into the rest of the construction but has for the remaining parts to be met by using fire-resistant paint and protective sheeting. The steel frame is painted before delivery and does not need to be treated at the building site.

The secondary constructions being the Symphony outer-wall and roof elements do not call for the same strict fire protection since they are not load-bearing. These elements are protected according to the Swedish building code during 30 min. The fire protection needs to prevent the spread of fire and the transmittance of high temperatures. This could be achieved with the combination of a double layer of dry sheets and mineral wool insulation (see figure 7). Each layer of gypsum board corresponds to ca. 15 minutes of fire protection according to the producers [Gyproc, 2003].

4.9.1 Regulations

The CasaBona construction is normally used in two different ways. In small houses it is used as load bearing outer walls since the loads are relatively small. In high-rise buildings on the other hand it is used in non bearing outer wall elements. These elements are hanged outside the floor structure and carry only their own weight.

During a fire the Swedish building codes require [Fallqvist at al., 2002]:

- Regarding the load-bearing capacity
  - R 60 for BR1 and R30 for BR2
Regarding segregation of the fire

- EI 30 for BR1 and EI 30 for BR2

R stands for load-bearing capacity, E stands for separation and I stands for Isolation which implies prevention of the average temperature on the non fire-exposed side to rise above 140 °C [Fallqvist et al., 2002]. The numbers indicate minuets and BR1 and BR2 are high-rise buildings and small houses respectively. With reference to the above mentioned the construction in the outer-wall elements must separate and isolate the fire and maintain its structural properties during 30 minuets.

4.9.2 Spread of fire between different fire cells

Each apartment is regarded as one fire cell. The fire can spread from one fire cell to another when the constructions that are separating them fail. The fire cell needs to be isolated both horizontally and vertically. Horizontally the fire is isolated by the partition walls. The symphony concept does not prescribe any special construction for the partition walls hence the choice of construction is made by conventional procedures. At the outer border of two apartments the fire can spread via the outer-walls. To hinder this, the insulation blocks must always be exchanged to stiff mineral-wool at these points. The same goes for the vertical border of two apartments. The insulation blocks alongside the floor slabs need to be exchanged to stiff mineral wool to prevent the fire from “climbing” up the façade.

4.9.3 Fire modelling of the outer walls

The use of Expanded Polystyrene is favourable because of its high ratio between E-modulus and density and its moisture proof properties. The disadvantage with the EPS is its sensitivity towards high temperatures and its flammability. Due to this fact the material needs to have a thorough protection when used as insulation in outer walls. It is of great value to find cost-effective methods for protecting the CasaBona construction against fire and developing models that can predict the fire resistance. Full-scale fire tests are very expensive to carry out and avoided if possible. The goal is to create a model that can predict the behaviour of the construction with satisfactory accuracy. The behaviour of the construction will be examined protected by a double layer of 12,5 mm thick gypsum boards.

4.9.3.1 Modelling of the fire

The temperature development of the fire is not linear and very difficult to predict as it depends very much on present conditions. To be able to compare results and tests on an international level a common “fire” is needed. The Iso-834 standard fire curve is often used in fire modelling and full-scale fire tests. The ISO fire curve consists of a logarithmic, time dependent function

\[ T_f = T_0 + 345 \times \log_{10}(480t + 1) \]  

(14)

where \( T_0 \) is the ambient temperature and \( t \) is the time. During a fire the temperatures can rise well above 1000°C. In these temperature ranges the material properties such as heat capacity and thermal conductivity will no longer remain constant but vary non-linearly. The material properties of most of the materials used in construction will change at higher temperatures. This creates difficulties during modelling and requires a model that can consider the temperature dependent variations of the material properties.
4.9.3.2 TASEF-software

TASEF is a software distributed through SP (the Swedish Testing Institute), and stands for Temperature Analysis of Structures Exposed to Fire [Wickström, 1979]. The program is based on the Finite Element Method and developed for temperature analysis of two dimensional and axisymmetrical structures. The software has a number of features that makes it particularly suitable for calculation of temperatures in fire exposed structures.

- Structures may contain materials with thermal properties varying with temperature, latent heat for instance may be considered in this way.
- Heat flux boundaries by convection and radiation from fires may be specified.
- Heat transfer across internal voids by radiation is calculated considering view factors.

4.9.3.3 The finite element approach

The transient two-dimensional heat transfer equation

$$\frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) - \frac{\partial e}{\partial t} + Q = 0$$

(15)

- $x,y$ = coordinates [m]
- $T$ = Temperature [$^\circ$C]
- $k$ = thermal conductivity [W/m K]
- $e$ = specific volumetric enthalpy [J/m$^3$]
- $t$ = time [s]
- $Q$ = internally generated heat [W/m$^3$]

is solved with the finite element method. The body to be analyzed is divided into elements and the internal temperature of each element is approximated by its nodal temperatures. In general several small elements yield high levels of accuracy. Small elements are needed where non-linear temperature distributions are expected, e.g. near boundaries.

![Figure 12. Section of the simplified construction used in the model. The mesh is divided in 19 columns and 27 rows with a total of 513 nodes. Node 17 is the interface between the inner layer of the gypsum boards and the EPS.](image-url)
4.9.3.4 The model

Because of the limitations of the software the model used has been simplified. The software allows a total of seven regions, this has led to simplification of the wall. The outer flange of the CBZ-profile is removed and the layers outside the profile are simplified to one layer of high density mineral wool (50 mm). Furthermore the effects of moisture migration are ignored and the initial inside and outside temperatures are set to 20 °C. The boundary-nodes on the gypsum side are regarded as very small surfaces completely surrounded by the fire and the resulting emittance $\varepsilon_{12}$ is set to the emittance of the surface. The convection properties $\beta$ and $\gamma$ depend highly on local conditions and can vary a lot. Exact modelling of the convection properties is time and power consuming. Further on it can be noticed that as the temperature rise the heat transferred via convection becomes very small compared to that transferred via radiation (see figure 13). The values are chosen as constants as follows.

- Fire exposed side: $\beta = 1.0, \gamma = 1.33$
- Not fire exposed side: $\beta = 2.2, \gamma = 1.25$

The Profile has a slotted web in order to reduce the thermal bridge. The slots of the web will consequently contain air but are not treated as voids in this model. The web is regarded as a different type of steel in the model. The thermal conductivity of the entire web including slots is calculated with a finite difference software called GF2-Dim. The value was calculated to 29 W/mK in room temperature. The thermal conductivity of structural steel is reduced linearly with 55% up to 800 °C after which it remains constant [Wickström, 1979]. The thermal conductivity of the web is assumed to have an equal development.

The Expanded polystyrene is assumed to have constant thermal conductivity (0.036 W/mK) and heat capacity (1000 J/kgK), consideration has consequently not been taken to the glass-transition phase of the material.

![Figure 13](image13.png)

*Figure 13.* The upper and lower curves show the heat transferred through radiation and convection respectively during fire. Notice that temperature rises with time.
4.9.3.5 The gypsum board

The software has a limited number of predefined materials that can be used in the model but gypsum is not one of them. Thus the material properties of the gypsum board had to be analyzed and inserted to the software. The temperature dependent thermal conductivity of the gypsum board is identified, the variation of the volumetric enthalpy on the other hand is a more complicated matter.

Gypsum boards are made up of calcium sulfate dihydrate, \( \text{CaSO}_4 \times 2\text{H}_2\text{O} \), that contains about 21% by weight chemically-combined water and additionally relatively small amounts of absorbed free water [Cooper, 1997]. The gypsum boards also include a 0.4 mm layer of paper covering on the surfaces. The model used will ignore the effects of such surface-mounted papers. When the temperature is raised above approximately 80°C, the chemically-bound water begins to be released in a two stage process. Most of the water is released in the first stage as the calcium sulfate dihydrate becomes calcium sulfate semihydrate, \( \text{CaSO}_4 \times \text{1/2H}_2\text{O} \) also called plaster of Paris. This stage is usually completed by the time the material reaches 125 °C. As heating is continued the rest of the water is released and the remaining material goes to anhydrous calcium sulfate, \( \text{CaSO}_4 \). This process is referred to as calcination and requires absorption of relatively large amounts of energy. This large energy consumption is what restraints the heat to pass through the material and gives the gypsum board its fire-protecting qualities. The energy is thus consumed in the layer that is being calcinated and the temperature flow through the material is obstructed. Behind the calcination front, temperature is supposed to rise insignificantly (~100°C) [Gyproc]. It’s also important to remember that moisture migration must occur before the steam released can reach the surface of the board. In this model, the effects of moisture migration have not been considered.

4.9.3.6 Results

The duration of the fire has been set to one hour and the results of the calculations can be seen in figures 14-17. The x-axis represents the nodes parallel to the normal of the wall with node 1 on the inside and node 27 on the outside. Node number 17 on the x-axis is the intersection between the gypsum boards and the EPS. The y-axis represents a section of the wall which is 600 mm wide with the sheet metal profile in the centre while the z-axis represents the temperature. Following the calcination front, it can be seen that it reaches the surface of the second gypsum board after approximately 14.5 min. It can also be seen that the temperature of the EPS and the CBZ-profile surpass 100 °C after 30 minutes. This means that both gypsum layers have calcinated after approximately 30 minutes.

Additionally it can be noticed that the temperature of the polystyrene will surpass 110 °C after 32 minutes. This is the melting point of the polystyrene. As the Polystyrene melts it will create a kind of melt-front that will with time move away from the gypsum board towards the centre of the construction. This will create a gap between the EPS and the gypsum board. The polystyrene will not have direct contact with the flames as long as the gypsum boards do not crumble. The flame temperature of the EPS when not exposed to direct flames is 500 °C. Oxygen is required for the EPS to burn. It is assumed that as long as the gypsum boards are intact, the amount of air available in the gap will not be sufficient to generate burning. The low heat conductivity of the EPS creates a barrier that stops the heat. This barrier will on the other hand lead to the fact that the temperature rises in the gypsum layer and speeds up the calcination process.
The effect of the thermal bridge that is caused by the CBZ-profile is clearly demonstrated. The high heat conductivity of the steel has a cooling effect on the construction and it can be seen that the gypsum layer in contact with the metal profile has a lower temperature than the gypsum layer which is in contact with the EPS. This difference is more obvious when the temperatures rise. Still it can be seen that the node-temperatures of the CBZ-profile never exceed 450 °C during the hour long simulation. This is the critical temperature after which the metal will start to flow.

The time of calcination is proportional to the density of the gypsum board. The energy consumption of the gypsum can be divided into three parts, calcination, heating of water and evaporation of the water. With higher density follows automatically higher amounts of water to be heated and vaporized. Furthermore, the energy required for the calcination - \( h_{\text{calc}} \) is 16.3 kJ/mol. Consequently the calcination energy \( Q \) is

\[
Q = \rho \cdot \frac{h_{\text{calc}}}{M} \quad [\text{kJ/m}^3] \quad (16)
\]

where \( M \) is the mol-weight [kg/mol] and \( \rho \) is the density [kg/m³]. As can be seen in equation 16 the calcination energy is directly proportional to the density.

4.9.3.7 Conclusions

Studying the temperature distribution in the construction (see figure 18 & 19) one can clearly see a resistance in the gypsum board behind which the temperature does not exceed 100 °C. This is compatible with the manufacturers’ assertion [Gyproc]. Directions from manufacturers regarding segregation of the temperature recommending one gypsum board for every 15 minuets can also be seen in the results. When analyzing the calculation results it can be seen that the temperature can rise unobstructed after the calcination front has passed. But the construction as a whole can maintain segregation of both the fire and the temperature during one hour as long as the gypsum boards stay in place. The question remains, when do the gypsum boards collapse? The calcination process of the Gypsum boards is an energy dependent process and is thus strongly dependent on the heat flow through the gypsum board. This can explain the fact that there exists a large variety of researches that all show different temperatures for which the calcination process starts. To determine the calcination rate, the nodal temperature is not important. What matters is the energy content of the node which is dependent on the heat flow through the node. The EPS behind the gypsum boards creates a heat barrier which will reduce the heat flow through the gypsum boards. This creates heat storage in the gypsum layer and accelerates the calcination process. In these circumstances the gypsum board will calcinate after approximately 15 minuets. The question is if the 15 minuet limit would be valid for a similar construction with less insulation. The energy input to the gypsum board can be calculated and the calcination process can thus be modelled. Furthermore it can be stated that the strength of the gypsum board is purely dependent on the calcination rate since water is the binding material of gypsum. If the relation between calcination rate and the strength of the gypsum board was known it could be possible to model the falling off of the gypsum board.

During the fire, large temperature differences occur between the inner and outer flanges of the CBZ-profile which will yield bending of the profiles. The bending of the studs can be of such extent that it will however give rise to fractures in the gypsum board. Temperature differences of such magnitude will occur after 50 minuets of fire. The construction should therefore be able to resist the fire during at least 50 minuets.
Figure 14. 3-dimensional temperature gradient of the outer-wall construction after 15 minutes. The x-axis represents the nodes parallel to the normal of the wall.

Figure 15. 3-dimensional temperature gradient of the outer-wall construction after 30 minutes. Node 16 starts to rise above 100 degrees Celsius.
Figure 16. 3-dimensional temperature gradient of the outer-wall construction after 36 minutes. The effect of the thermal bridge is becoming more obvious.

Figure 17. 3-dimensional temperature gradient of the outer-wall construction after 60 minutes. Even though the gypsum boards are calcinated the construction can still maintain segregation of temperature and fire.
Figure 18. Temperature distribution in the gypsum boards after 14.4 min. Temperature is kept below 100ºC behind the calcinations front. Notice that node number nine is the limit between the first and the second gypsum board. Node number 17 is the limit between the second gypsum board and the EPS.

Figure 19. Relation between the node temperatures after 14.4 min. T-net is the ratio between the temperature of the actual node and the foregoing node, 100% occurs when the temperatures are the same. T-net drops with almost 40% at node nr.9, this is the calcinations front behind which the temperature is kept below 100 ºC.
5 THE PILOT PROJECT

In 2005 theory was put to practice, when – with the help of corporate sponsors – an experimental building called the Research Tower was raised according to the Symphony concept. The building consists of a load bearing steel structure with hollow core concrete elements and a climatic shell of lightweight prefabricated roof and outer wall elements. With a building area of 13 m² and a total height of 11.4 meters it has the proportions of a tower. The research tower is a co-operation project between the “Symphony” project and the “Termodeck revisited” project [Karlström, 2005].

The research tower was raised in the factory yard of an old concrete element factory near Stockholm. One of the factory halls was also reserved for the production of the building elements. The four outer wall elements, the roof element and the four joint elements were produced there and were later transported out to the yard where they were mounted up on the steel frame structure with hollow core concrete slabs that was delivered by Strängbetong.

![Image](structure.png)

Figure 20. The four outer-wall elements are mounted on to a steel-frame structure with hollow core concrete slabs to form the research tower. With a building area of 13 m² and a total height of 11.4 meters it has the proportions of a tower.

5.1 Design of the building

The load bearing structure is a conventional system that is used a lot in Sweden today. A steel frame carries hollow core concrete slabs that are prefabricated in specified lengths. Some minor changes were however made to the standard formulation. The beams carrying the concrete slabs were changed from Z-beams to L-beams. The flange of the Z-profile would have gotten in the way of the outer walls which are continues and pass by the floor slabs (compare figure 2 & 20). The horizontal positioning of the columns was also adjusted to fit the Symphony elements. The proportion of the building makes it very slender. Normally a building contains stabilizing elements such as stair-case shaft, elevator shaft or shear walls. The small building area did however not permit such elements in this building. Stabilisation against horizontal forces was therefore achieved with Cross tensors integrated in the outer walls.

Because of the small area of the building four outer wall elements was enough to cover the facade. Two elements contained windows and doors while one element was a so called...
installation element containing all the vertical installations of the building and the last one was totally blind. Integrating installations into the outer walls should be done with precaution. Heat transfer towards the exterior from the heated air and water in the ducts can result in energy losses. The vibrations from the ducts on the other hand can result in acoustic inconveniences inside the apartments. The design of the connections of the ducts and pipes inside the element are therefore just as important as the depth in which the installations are placed. The elements were designed to be produced in horizontal position beginning with the inside and starting off with the CasaBona construction. Once the core construction is finished the work continues with the fastening of gypsum boards and horizontal studs and placing of the insulation before the element is turned over. On the outside the element is covered with another layer of 50mm insulation before it is plastered. Notice that the walls are plastered in horizontal position facilitating the procedure and lowering the amount of working hours.

A low slope roof was designed with an inclination of 1:60. The low slope of the roof required a type of roof covering that is suitable for lower inclinations. A roof covering of PVC material was used in this project and for the roof water drainage a siphonic full-flow system is used. This means that drainage pipes with a smaller dimension can be used which are easier to integrate into the construction.

The assembly was designed to start with the erection of the primary structure followed by the assembly of the Symphony elements which would start with roof element. The purpose of this is to create a climatic protection as early as possible. With the roof in place the work would be continued with the assembly of the outer-wall elements. The lifting of the outer-wall elements to vertical position needed to be designed in detail. When the element is lifted at the top while the bottom is resting on the ground it can be regarded as a simply supported beam with a span corresponding to its length. If the radius of deflection is too high during this phase it could damage the construction materials such as the gypsum boards and the plastering. Calculations showed that the deflections would not be hazardous in this case but the forces imposed on the bottom of the element on the other hand would be too large. Consequently it was decided that the elements should be lifted in two points and turned vertical in the air. Also the wind forces during the lifting of the elements needed to be considered. The wind has a strong impact on these light weight elements because of the low ration between weight and surface area. Calculations were made to determine the limiting velocities of the wind in which the assembly could be performed without risk.

With the outer-walls mounted remained only the mounting of the joint elements which were also designed as rigid full length elements built up by sheet metal profiles integrated with expanded polystyrene. The elements were to be mounted with the crane and fastened from the inside at each floor level. The exterior finishing of the joint element has no restrictions. In this project it was chosen to enhance the joint by revealing it extra at the façade with stainless steel as finishing material.

The climatic shell of the building could be finished very fast. This would create a climatically controlled space inside the building. By planning the order for the rest of the work in an efficient way and to prevent different contractors from working at the same time, a controlled production space could be created which could optimize the production. Traditional methods with conventional techniques were to be used for the interior finishing. The floor would be a raised floor which creates an air gap between the floor and the concrete slabs. This gap can be adjusted between 20 and 230 mm. The gap could be used to put installations such as water pipes and electrical cables. For the electrical installations plug-in connections would be used which means that cables can be plugged in
to the distribution box in one end and the wall socket in the other end. This will save large amounts of time for the electrical work.

5.2 Production of the elements

5.2.1 The outer wall elements
The production of the elements in the factory showed good results. Both the sheet metal and the stiff insulation for the CasaBona construction were delivered to the factory pre-cut with high precision. The insulation blocks had incisions for the flange of the Z-profile with which they were built together (see figure 21). The width of the blocks gives automatically the distance between the studs and no measuring is required. The line of Expanded Polystyrene blocks were broken by blocks of stiff mineral wool alongside the connection to the intermediate floor slabs for fire security and acoustic reasons (see figure 21). The pre-cut components were really a time saver. As soon as measuring, cutting or sawing was involved production speed was reduced. Activities such as cutting of the gypsum boards were really time-consuming. Large efforts were required for adjusting the outer wall elements to get exact perpendicular edges. This could be speeded up remarkably with a simple table of the same size as the elements. The table should have two perpendicular sides in rigid steel against which you could adjust the element components. Since the building components are pre-cut it’s enough with two guiding sides. The table should have a third steel beam that can compress the element in its plane perpendicular to the direction of the sheet metal studs. Further should the table be able to turn the element around, this technology already exists. It was not used in the project because of financial reasons. The turn over of the elements was made with overhead cranes which was time consuming and required too much preparation. In general the production of the elements could be made automated to a great extent and in this way decrease the amount of workers.

![Figure 21. The CasaBona construction is seen in close up to the left and to the right can be seen an outer wall element during production.]

5.2.2 Installation element
All the vertical installations were integrated into the installation element (see figure 22). Ventilation ducts were built in, together with the pipes for water and sewage. The electrical wiring was also built in. All the ducts had horizontal connections at the right level on each floor. As a result, after the assembly of the installation element it would only remain to connect the local installations on each floor into the installation element. With more detailed planning the pipes and ducts used inside the installation element can be delivered
pre-cut and easily be fitted into the element. This would speed up the production of the installation element which has been the most time consuming element to produce.

Figure 22. All the vertical installations were integrated into the outer-wall.

5.2.3 The roof element

The roof element was easy to produce and to assemble in this project because of its size. The element was finished with roof covering and roof drain (see figure 23). The PVC roof covering was mounted and welded on at the factory. It was mounted in bigger pieces than the roof, enough to make it possible to cover the joints between the roof and the internal side of the outer wall elements after assembly. In this way the roof covering could be finished fast and easy after the assembly of all the elements since it only needs to be complemented. The roof drain which sucks the water off the roof was also mounted at the factory and connected to a drainage pipe. This pipe would be connected to the rest of the drainage system once the joint elements were mounted. The roof element was thus completed with insulation, roof covering, roof drain and drainage system.

Figure 23. The roof element was finished at the factory with PVC-covering and roof gully mounted.
5.2.4 The joint elements

The joint element was successful to produce and to assemble. Inside one of the joint elements a drainage pipe was built in with connections at the bottom and at the top for the connection to the day water drainage system and the roof drain respectively. This led to full length, insulated joint elements with prepared connections, built in drainage system and finished exterior surface (see figure 24). The production of the element required a great deal of screwing which should be reduced. Also the design of the element should be modified. In its present form it creates cavities around the load bearing columns of the structure after assembly. These cavities are difficult to tighten afterwards. The same joint element can also be produced to not be visible after assembly. This is very important for the esthetical flexibility of the building.

![Image](image_url)

Figure 24. The joint element is a rigid construction with a finished surface. It has the same length as the outer-wall elements and is mounted with crane.

5.3 The assembly

Once the primary structure was erected the assembly of the climatic shell started with the roof element. In this project the roof element was very light and rather small and thus easy to assemble. After the roof the assembly of the outer walls started. As much as the size of the building area facilitated the mounting of the roof element it also complicated the assembly of the wall elements. The integrated cross tensors in the outer-walls made the assembly a bit problematic.

For the assembly, a challenge had always been the lifting of the outer wall elements from horizontal to vertical position. The elements were lifted in two points and raised from the ground to the level where they could be turned to almost vertical position. Then they were put down on the ground in an angle of about 82 degrees where the bottom lifting yoke was removed (see figure 25). Now the element could easily be lifted up and transported to any point. The outer-wall elements were assembled in a two step process. In the first step a preliminary connection was made to the structure with adjusting possibilities. Here the deviation of the elements from the plumb-line is controlled. After this step the crane could be disconnected and start with the lifting of the next element. The second step involved permanent connection to the structure that could be made from the inside of the building at each floor level.
The rigidity of the elements was high as predicted, and resulted in smaller radius of deflections than estimated at the time of lifting to vertical position. This led to the fact that the plaster was not damaged at all (which was one of the main challenges from the start). The rigidity of the element is a direct consequence of the strength of the Z-profiles in the CasaBona construction. The results preliminary show that elements up to 15 m long could be produced and assembled. For the actual lifting simple devices could eliminate the need of the second crane and speed up the assembly remarkably. In the future the elements will be lifted directly off the truck with only one crane needed.

After the mounting of all four outer wall elements the mounting of the joint elements proceeded. Just before the joint elements were mounted, bands of expanding polyurethane were put on the flanges to achieve automatic tightening after assembly. The elements were easily lifted by one crane at the top and guided by one man at the bottom. During the assembly of the joint-element no problems due to the tolerances were encountered. All four joint elements could be fitted in place without any problems. When the joint element that had the roof drainage pipe built in was to be mounted, precision was very satisfying. Only a slight twitch was enough to fit the pipe projecting out from the joint element into the pipe connected to the roof drain.

at this moment the façade of the building was finished and tight. The next move was to get on top of the roof and screw off all the lifting eye bolts which was done easily. The only thing remaining on the roof was to insulate the joint between the roof and the internal side of the outer-wall elements and to fasten the roof covering (which was bigger than the roof area) on to the outer-walls and weld the edges. After this stage the top-flashing of the outer-wall elements were mounted and the exterior work of the roof was finished. The building was finished from a steel frame structure to a building with totally finished exterior in less than three working days without the use of any scaffoldings.

![Figure 25. Assembly of the outer wall elements, the revealed joint elements can be seen in the picture to the right.](image)

### 5.4 Interior finishing

The outer-wall elements were produced with the final gypsum board mounted on the inside. Because of the tolerances needed for the assembly the gypsum boards were cut shorter and did not reach the floor and the ceiling. This created a gap that needed to be covered afterwards. There were also gypsum boards that were moist after a couple of days
because of the change in relative humidity of the air and others that were physically damaged during the assembly and needed to be replaced. This has raised the question of the actual gains of having the exposed gypsum boards mounted at the factory. In some situations it would be better to not screw on the last layer of gypsum board until the elements are mounted.

The fire protection that needs to be done on the interior could be optimized as well. The beams and the columns of the steel structure could for example be delivered painted with fire protective paint and the joints tightened with sprayed sealing compound. The experience shows that fire safety engineers are needed in the initial design team. In this way optimal solutions for the fire safety could be integrated in the initial design of the building.

The problem with the plug-in electrical cables was that the connections as they are produced today are too big and result in unattractive big wall sockets and similar. The systems are furthermore not fully developed today which results in a mix of traditional connections and plug-in connections.

5.5 Observations

During the design phase all the drawings were discussed with all the participating engineers and even the workers such as the crew from the crane company. The purpose of this was to use their experience to discover details in the components that would in some way complicate the assembly or the long time performance of the component in question or the adjacent components. This shows the great strengths of an integrated design team who design the entire building in close collaboration with total transparency and sharing of information.

Regarding the production of the elements it could be observed that the most time consuming tasks during the production of the elements were the turning around of the elements and tasks that involved measuring and cutting. All of these tasks are in need of preparation, the measuring involves holding of the measuring tape which often required two persons, reading off the measurement, marking and transferring the measurement to another point. One of the reasons why cutting is so time consuming is that it involves a great deal of measuring. To perform the actual cut following the line also requires preparation. Mistakes are very easily made during this task, such as remembering the measurement wrong and cutting something to short. Regarding the turning around of the elements it needs to be mentioned that the production facility was not adapted to this task. There were only two overhead cranes in disposition. The turning of the elements was done with these cranes and with the help of straps. In a production space that is adapted to this kind of activities the turning time of the elements can be substantially reduced.

The methods used by construction workers today can be compared to iron smiths two hundred years ago. The problem of the construction industry is the lack of refinement. In the manufacturing industry the product is refined piece by piece until it takes its final form. If the person who is going to screw something has everything prepared for him the process will be much quicker. The process of refinement can be improved significantly in the field of construction. This can be compared to the outsourcing methods used by high-tech companies or production of a car. The car is produced via the assembly of various components. Each component is in turn a product of other components assembled together and so forth. When a task is specific the possibilities of developing tools to perform it will increase and it can be more automated.
Moving around of equipment is another task that consumes a lot of time. Several different tools are often needed for one station. Separating the tasks will lead to the fact that one person does only one task and thus needs only one tool. To be able to do this it is of course important that the precision is increased which requires that the methods for staking are improved. By improving the techniques for staking it is thus possible to achieve higher precision. Improved precision will give the possibility separating the tasks and in that way increase the efficiency which in turn will decrease the production time.

It was seen during the mounting of the elements that it is possible to work with low tolerances. The mounting of one of the joint elements that contained the piping for the syphonic water drainage system can be taken as an example. The roof element had the roof drain mounted with a horizontal pipe connected to it. The roof element was to be mounted on top of a four story steel frame. The centre of the pipe connected to the roof drain needed to be situated at an exact point in the zx-plane after assembly. Into the joint element a water pipe with a diameter of 45 mm was integrated. The pipe had a horizontal junction that was to be connected to the pipe linked to the roof drain. For the assembly to be successful it was of outer most importance that these two pipes would meet when the joint element was mounted. The mounting of the joint element was successful and the pipes met perfectly.
6 CONCLUSIONS

There is room for large amounts of improvements regarding optimisation of the production of high-rise buildings. To be able to find methods for production of sustainable, cost-effective and attractive high-rise buildings it is necessary to have a holistic view. A holistic concept that takes into consideration the whole building process will yield time- and cost-efficient production while it will also make it possible to achieve better quality. The symphony concept can be a competitive alternative for industrial production of high-rise buildings. The experiences from the research tower show that:

- Thanks to the fact that the whole building was designed by one team with one person being the leader of that team with information about all details. It was possible to foresee many problems. Necessary means could be taken and the problems could be avoided.
- The production of elements even in the temporary experimental production facility proved to be fast and economic, even with untrained labour force.
- The most time consuming details were those who involved measuring and cutting.
- The problem of the construction industry is the lack of refinement in the production chain. It is not said that it does not exists but it can be improved significantly.
- By improving the techniques for staking it is possible to achieve higher precision. Improved precision will give the possibility to divide the construction tasks and in that way increase the productivity which in turn will decrease the production time.
- When a task is specific the possibilities of finding tools to perform it will increase and it can be more automated.
- It was seen during the mounting of the elements that it is possible to work with low tolerances.
- The elements could be plastered at the factory and then mounted without the plastering layer being injured at all.
- The windows and doors could be mounted at the factory without any problems related to inclination after the assembly of the outer-wall elements to the floor structure. These components were always kept parallel to the edges of the element. When the outer-wall elements were to be mounted, there were no problems getting them to follow the plumb line.

Detailed research one showed that embedding of the sheet metal profiles in the rigid insulation blocks would increase the buckling load of the stud. By establishing the relation between the thickness of the profile and the modulus of foundation for the insulation, optimum material combinations could be found for different fields of application.

Detailed research 2 showed that the thickness of the plastering layer and the material properties of its substrate would affect the strains in the plastering layer and the moisture stored in it. Once again this knowledge will be useful in the choice of materials. Together with the economic factors regarded, optimum material combinations can be made without surprising affects.

Detailed research 3 showed that a double layer of gypsum board is enough to protect the construction up to 60 min in case of a fire as long as the gypsum boards do not crumble. In the research tower the two layers of gypsum boards were mounted on both sides of the
horizontal studs. The horizontal studs are screwed on to the vertical studs and will keep one of the gypsum boards in between them in place for a longer time than if the gypsum board was only attached to the studs with screws.

6.1 Further work

This is a licentiate thesis which implies that the work on the project will continue. The remaining topics to be addressed in the further work are

- Economics and logistics
- Acoustics
- Further development of the buckling strength

A detailed research will be performed to examine the real economic and logistic benefits of the concept. A virtual Symphony project will be compared to a similar existing project where conventional construction methods have been used. Furthermore acoustic measurements will be made in the research tower. These measurements will then be processed to evaluate the acoustic properties of the Symphony concept. The goal is to identify the weak parts and propose possible solutions. Finally a deeper investigation in the field of buckling strength will be made with the objective of developing the theories that were presented in this thesis.

The ambition is to achieve real project implementation after the project is finished. Work will naturally continue with the development of a complete design and production process while at the same time trying to find cooperation partners on an international level.
7 REFERENCES


Duškov, M., EPS as a Light-Weight Sub-Grade Material in Pavement Structures, Delf University, Netherlands, 1997.


FBS, website of the Swedish floor manufacturer FBS, [www.fbs.se](http://www.fbs.se)


Josephson, P.E., Saukkoriipi, L., Slöseri i byggprojekt – Behov av förändrat synsätt, ISSN 1402-7410, Sveriges Byggindustrier, Göteborg, 2005.


Strängbetong, the website of the Swedish producer of prefabricated concrete elements, [www.strangbetong.se](http://www.strangbetong.se).


