Industrial Construction Methods for Cost-Effective and Energy-Efficient Multi-Storey Buildings
Industrial Construction Methods for Cost-Effective and Sustainable Multi-Storey Buildings

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Without effort, you will not reach your goal on this path.

Abide by thy tutor, if you seek reward in this life.

Hafez, 14:th century Persian poet
Preface

This thesis is the result of my work at the Division of Building Technology at the Royal Institute of Technology (KTH) in Stockholm. The work has been financed by Hesselmans Foundation and the Swedish Research Council for Environmental, Agricultural and Spatial Planning (FORMAS). Apart from scientific papers, the work has resulted in the construction of a full scale experimental building called the Research Tower. The construction of the Research tower was possible thanks to a long list of corporate sponsors who contributed with both materials and know-how. The following companies have been involved in the realisation of the Research Tower:


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Hanif Pourghazian
Stockholm, September 2008
Abstract

Reduction of the cost of construction is a constant goal for the building industry. One way of reducing the construction cost of buildings is to develop building technologies that will give increased productivity. Reduced construction time at the building-site and waste of materials and resources contribute to further reduction of the costs. This is why the sector is developing towards more industrialized construction methods with prefabricated components. The objective of this thesis is development of industrial construction methods for cost-effective and energy-efficient construction of multi-storey buildings. It is important to highlight the difference between cheap or low-cost and cost-effective production. It is possible to produce buildings to a low-cost at the expense of decreased quality and design. Conversely, cost-effective buildings are buildings that are produced to a low cost while maintaining a high standard of design and comfort. While cost reduction efforts are often made based on a, relatively, fixed building process, this research is focused on reducing the costs by changing the building process with the help of innovative building technologies. The construction of a building is a very complex practice with a wide range of interacting processes. The hypothesis is that a holistic approach is advantageous in order to find effective construction methods. To achieve a holistic view, an interdisciplinary approach to the research is required. By approaching the development of construction methods from the point of view of the entire building process, it is possible to achieve optimizations with synergy effects and by that find solutions that are time-efficient, energy-efficient and cost-effective at the same time.

The work started by analysing the building process and the construction methods currently used in order to; discover the most common problems, gain understanding of the strengths and weaknesses in the conventional construction methods and identify the fields where the largest potential for improvements existed. Based on this analysis, a new building concept for industrial construction of multi-storey buildings is formulated called The Symphony concept. The concept involves a holistic view of the whole building process and is based on a prefabricated heavy structure that is covered with a prefabricated building envelope consisting of large, light-weight elements with a high degree of prefabrication and finished exterior surfaces. The concept required development of new types of building-elements and assembly methods. The technology was first evaluated while still on the drawing table. Some of these evaluations have been of a more detailed character and are reported in scientific papers. Thereafter an experimental building in full scale was erected in order to test the developed technology during production and assembly, while measurements and tests were performed in order to evaluate the performance of the building in operation. Based on the obtained results suggestions for improvements could be given in order to upgrade the concept further.
The economic analysis of the building process showed that the largest cost posts in the construction of dwellings are the climatic shell (24 %), the interior finishing, and the management costs. The construction of the climatic shell is optimized through the use of the Symphony elements while the management costs are reduced through the use of prefabricated elements with a high degree of prefabrication which, substantially, increase the construction speed. Results show that it is possible to reduce the construction costs with about 25 % when constructing according to the Symphony concept compared to conventional construction methods.

The construction of the large light-weight Symphony-elements was possible thanks to the CasaBona system. CasaBona is a building system which integrates the thermal insulation with the structural elements in the outer walls by embedding sheet metal profiles into stiff insulation blocks. The results show that the strength of the profile, when embedded in rigid insulation blocks, is increased between 22 % and 33 % when submitted to bending forces, and between 161 % and 210 % when submitted to compressive forces.

Simulations of the annual energy use of buildings show that the energy performance of buildings is improved with increased effective thermal mass. Increased mass is also beneficial from the acoustic point of view. However, it is important that the interior space is separated from the exterior climate with constructions that have low U-values. It could be concluded that the most beneficial design strategy is the combination of a heavy core-construction (which has a large mass and thermal inertia) and a light-weight building envelope (which yields low U-value without adding to the thickness of the outer-wall).

The construction of the experimental building made it possible to test the technology in an inexpensive yet realistic way. However, it is important to bear in mind that the information which can be gathered from an experimental building can be limited depending on the size of the building and its finishing standard. It could also be noticed that industrial construction benefits from an interdisciplinary design process since this render the increased use of prefabricated components possible.
List of Publications

This Doctoral thesis is a compilation thesis based upon an introductory part and the following research and conference articles.


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1 INTRODUCTION

When the work with this research began in 2003, intensive discussions were taking place in the media about the shortage of housing in Sweden [Dagens Nyheter, 2003-03-19]. At that time, the governing political coalition had promised to build 20,000 apartments per year; however, these promises could not be kept [Dagens Nyheter, 2003-08-14]. The construction of rental apartments, which has always been of great importance in Sweden, was of particular interest. Wide speculations were being made in the media about the reasons for why the demand could not be satisfied. The high production costs of dwellings were seen as the main cause [Dagens Nyheter, 2002-08-27]; this was especially true in the case of rental apartments, for which the rental policies was also a contributing factor. The rent is strongly regulated in Sweden. This means that the rent cannot be dictated by the market, while the cost of production is inevitably decided by market forces. With high production costs, it is difficult for developers to make satisfactory profits from the production of rental apartments. The subject of regulated rent is deeply rooted in the Swedish welfare system and is not easy to change. In this context, a reduction of the production costs is very much sought after.

1.1 OBJECTIVE

There are many possible ways in which the production cost of dwellings can be reduced. One way of lowering the cost is to develop building technologies that will give increased construction efficiency. This was a natural path, given that the research was initiated at the division of Building Technology at KTH. Hence, the research began with the goal of finding cost-effective solutions for the production of multi-storey buildings. By reducing the production costs, the market could be encouraged to increase the production of rental apartments. What is important to highlight here is the difference between cheap or low-cost and cost-effective production. It is possible to produce buildings to a low-cost at the expense of decreased quality and design. Conversely, cost-effective buildings are buildings that are produced to a low cost while maintaining a high standard of design and comfort.

Sweden has a history of industrial construction that spans decades but which had been forgotten during the eighties, this topic was now (during the period when this research started) being brought back to the forefront. Moreover, the building sector was experiencing many problems with inefficiency at the building site, as well as problems with moisture damages. The interest for the energy use of buildings was also increasing with the life-cycle cost of buildings becoming just as important as the actual production costs. This is why the objective of this research very early evolved into the development of industrial construction methods for production of cost-effective and energy-efficient multi-storey buildings.
The construction of a building is a very complex practice with a wide range of interacting processes. The hypothesis is that a holistic approach is advantageous in order to find effective construction methods. Development of a component with a holistic approach of the whole building process implies that consideration is taken to the function of the component in relation to the performance requirements of the entire building. In order to achieve a holistic view, an interdisciplinary approach to the research is needed. A building must be evaluated with respect to a large number of expert fields. The architect decides the architectural design and the spatial functionality of the building while the structural designer evaluates the building from the structural point of view; the building must also be evaluated from the point of view of energy use and interior climate. Furthermore, it must be assured that the building can fulfill fire safety and acoustic demands and, most importantly, any economic limitations. With these conditions, it is obvious that an overall view is required for any kind of optimization of the construction methods.

1.2 COURSE OF WORK AND LIMITATIONS

The intention of this work is not to present a finished industrial construction concept, but to propose a procedure that can be applied in the development of improved construction methods. In this particular case, this procedure has lead to the development of a new building concept called Symphony. The introductory part of the thesis describes the methodology that has been used to find solutions for improved construction methods which have led to the development of the Symphony concept. A holistic point of view with an interdisciplinary approach has been applied, which implies that the concept is evaluated from various aspects. Some parts of the evaluation have been performed in a more general form, while others have been studied in detail. These detailed studies, in particular, have resulted in papers that have been presented at international conferences and submitted to scientific journals. The papers focus on different fields of research, and are presented in the second part of the thesis.

The method has been to begin the work by studying the Swedish building process and the construction methods currently used, followed by a review of existing industrialized construction methods in Sweden (chapter 2). In this way, the fields with the largest potential for improvement can be identified. The limitations and possibilities of existing technologies are then used as basis for optimization of the construction methods on a more detailed level (chapter 3). 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 best possible solution (i.e. minimum or maximum) for a given parameter. It is not possible to find the absolute best way of constructing since there are too many variables involved. This cannot, therefore, be set as the final goal for this work, but more as a compass direction. Optimization – in this thesis
– is defined as taking significant steps in order to improve the efficiency of a product or a process.

Based upon the analysis in the prior chapters, a new holistic building system is formulated (chapter 4), which as much as possible considers not only individual components, but also the way they interact. It is important that the building system is flexible in design and construction, and has a limited impact on the architectural freedom of the building. Concepts with monotonous design can only survive a short period of time before the public - and by that, the market - rejects them. The new building system is then tested through experimental construction; the construction of the experimental building is described in chapter 5. In chapter 6, the building concept is evaluated using test results and measurements that have been performed on the experimental building. The lessons learned, and experiences gathered from the experimental construction and its evaluation, are then used to propose improvements and to formulate an updated version of the building system. In order to perform a complete investigation and evaluation of a construction method, a team of many experts from a wide range of disciplines is required. Due to the fixed time frame of the thesis work, the evaluation has been limited to the fields of economy, moisture in constructions, fire safety, structural engineering, acoustics, and energy performance. Chapter 7 in this thesis is reserved for the author's general remarks and opinions on the subject of industrial construction and its future development.

The outline of this thesis is a combination of a monograph thesis and a compilation thesis. It can be described as a compilation thesis with an extended introductory part. A graphic outline of the thesis is presented on the next page. The research is based on three main components that are developed relatively simultaneously. These are the background research and concept formulation, the experimental building and the scientific papers.

The introductory part of the thesis is based, mainly, on the background research and the concept formulation while large parts from the experiences of the experimental building and results from its evaluation are also included. The conclusions from the papers are, briefly, included in the introductory part while the reader is referred to the papers for methodology and actual results. There are, however, two papers (Paper III and paper IV) which are included in large parts into the introductory part. The introductory part is, thus, an independent document which includes large amount of information that is not found in the papers – which can be regarded as appendixes.
GRAPHIC OUTLINE OF THE THESIS

Research program

Experimental Building
Production Experience
Evaluation

State of the art research + concept formulation

Introductory part

Doctoral Thesis

Paper I
Paper II
Paper III
Paper IV
Paper V
Paper VI
2 OVERVIEW OF THE SWEDISH BUILDING PROCESS

Every country has its own traditions regarding construction methods. These traditions are dependent upon features such as available local construction materials, the local climate, geotechnical conditions, etc. They also rely upon economical and political circumstances of society. In order to improve the construction methods, it is first important to be aware of the construction methods currently being used, and the problems and advantages that these construction methods imply. In this chapter, a short overview of the Swedish building process will be presented: including aspects that have shaped the current building sector, a review of the most common construction methods used for the construction of dwellings, an analysis of the cost of construction, and some of the most common problems connected with the construction of dwellings. Furthermore, a number of industrialized construction concepts which are currently used in Sweden are presented. The information is used to highlight the fields where problems usually occur, and to identify fields in which potential for improvements exist.

2.1 THE MILLION PROGRAM

One particular episode that has had a large impact on the current contours of the Swedish building sector is the Miljonprogrammet (the Million Program in English). This is one of the greatest, and most discussed, achievements of the Swedish construction industry. During the 1960s, Sweden suffered from low supply of housing, and the existing stock was of poor quality and very old. In 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; however, many old buildings were also demolished and, in the end, the net increase of units was only 650,000 [Turington et al., 2004]. Today, the buildings from the Million Program represent 25% of the existing housing stock in Sweden. Building so many units in such a short time in a small country such as Sweden required radical means. It was important to reduce the time, labour intensity, and cost of construction.

Characteristic for the buildings of the Million Program are the high-rise buildings built with prefabricated concrete elements. Large temporary infrastructures were established at the site, along with railroads for the cranes and provisional facilities that produced the concrete elements. The large scale of the projects motivated the cost of this infrastructure. Landscaping with trees and green areas were made after the projects were finished [Arnstberg, 2000]. The buildings were functional; however, very little attention was given to their aesthetics. With time, they have also shown many signs of technical problems. This is easy to understand considering the shortage of time and other circumstances - but the public opinion knows no mercy. These buildings are not very popular among the
inhabitants and have even given a negative tone to the word prefabricated. Although these high-rise 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 controversial program. The same production methods were used later in East Germany with similar results; buildings associated with less attractive townscapes which are not very popular. Although the Million Program left its negative mark on the word prefabricated, it has also benefited it and left behind valuable experience about prefabrication and industrialized construction [Vidén, 1992].

The construction rate had never before been this high in Sweden and will not reach these numbers again for a long time. Industrial construction was at its peak during this period, but dropped at the beginning of the eighties when the main housing demand had been satisfied. The industrial methods developed during this period were designed for high volume monotonous construction and were not useful when solitary buildings with high demands on variety and urban adaptability were required. This, among other reasons, was why the building sector slowly returned to conventional on-site construction.

Due to the high production rate during the period of the Million Program, there were some building companies that grew very large. This is connected to another very important particularity with the Swedish building sector; namely that of poor competition. A few big companies possess the great majority of the Swedish building market, and there are 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, these big companies have large influence on the price of materials and the general cost of production.

Another factor that affects the building sector is the slow planning process and handling of building permits on behalf of the municipality. This process consumes a great deal of time, creates large time delays in the design process, and contributes to higher construction costs. These higher costs are mostly due to difficulties in planning the construction. After a long waiting time, the developer rushes to start the work, this stress is projected by the developer to the design team (the detail design cannot start until the building permits are approved) and propagates down the chain to the contractors and workers, and therefore, counteracting an efficient building process.

### 2.2 CONVENTIONAL CONSTRUCTION METHODS – A SHORT REVIEW

There is a large variety of different construction methods that are currently being used in Sweden. That being said, the definition of conventional construction methods is not a simple one. Regarding the construction of dwellings, there are
three main categories: in-situ construction, prefabricated construction, and semi-prefabricated construction.

The in-situ constructed buildings are characterized by a concrete structure that is casted on site. The concrete slabs are supported by interior partition walls, or by a combination of interior partition walls and steel columns in the façades. The façades are generally not load-bearing, and are built up by light-weight infill elements. The infill elements are semi-prefabricated and are to be fitted between two slabs vertically and two columns or partition walls horizontally (see Figure 1). Hence, these elements are rectangular elements with the approximate proportions of 2,5-3m x 3-4m. The infill elements are built up with metal or wooden studs with a gypsum layer mounted onto the exterior surface. After assembly, the elements are completed with insulation, a vapour-barrier, and internal gypsum boards. The prefabrication degree of these elements varies, and sometimes they are even delivered with installed windows. One thing that these elements all have in common is that they do not have a finished exterior surface. After assembly, the façade is covered with a layer of rigid insulation – that serves as the base for the rendering – after which the façade is rendered. The installations – regardless of the systems used – are distributed from internal installation shafts that run through all floors vertically. There are several shafts in each floor, and each shaft serves a limited number of apartments. The floor-plans of the apartments are designed so that the kitchen and bathrooms are in connection with the installation shafts (see Figure 1). For the interior distribution, the installations are casted into the slabs or built into the walls. The roof of the building consists often of some type of wooden construction that is fabricated on site, while the roof trusses are often prefabricated. Due to bad experience from the first generation of low slope roofs that were built mostly during the 1970s, most roofs are either inclined roofs or ridged roofs.

Figure 1. Infill outer wall elements are usually delivered with a low degree of prefabrication (left). The plan of an apartment building (right); the installation shafts are marked with ellipses. The toilets and kitchens are placed in a way to optimize the number of shafts. Photo credit: Hanif Pourghazian
Prefabricated construction involves buildings that are built up by prefabricated elements for both the load-bearing structure and the façade. These buildings are characterized by concrete façade elements that have the same proportions as the infill elements mentioned earlier. The prefabricated façade elements are delivered with finished exterior surface and mounted windows. Electrical cabling is prepared on the inside of the elements; the interior surface requires only painting. In contrast to the infill elements, these elements are load bearing. Prefabricated concrete slabs (often hollow core slabs) are supported by the outer walls and interior partition walls that also consist of prefabricated concrete elements. The distribution of the installations is done with internal installation shafts, as previously mentioned. This work is connected with a great deal of hole-cutting in slabs and walls, which is a costly operation. Suspended ceilings and raised floors are seldom used in these buildings; the distribution of the installations inside the apartments is done through internal walls and floor slabs. The holes in the hollow-core slabs are often used for the distribution of installations. There is, however, still hole-cutting and filling involved in order to access the holes inside the slabs. On the façade, joints arise between the prefabricated façade elements that are later sealed, but remain visible. The joints have a thickness of approximately 2 cm, running both horizontally and vertically, thus, creating a grid across the façade (see Figure 2). The prefabricated concrete element buildings are distinguished by this façade grid. The roof construction varies: sometimes it is made of a partly prefabricated light-weight wooden construction and sometimes it is made by an upper concrete slab onto which an inclined roof is constructed at the building site. Construction with prefabricated concrete elements is described more detailed in section 2.4.

Semi-prefabricated construction implies buildings that are constructed with a prefabricated load-bearing structure while the rest of the building is completed
with in-situ construction methods. In this case, the prefabricated hollow core concrete elements are supported by steel columns in the façade and internal concrete partition walls. Depending on the geometry of the plan, gable shear walls are built with concrete elements while the rest of the façade is completed with light-weight infill elements.

2.3 CONSTRUCTION COST OF DWELLINGS

In order to optimize the construction cost of dwellings, it is first important to understand the current costs of construction, which is often presented in many different ways in the industry. In TNC 95 [TNC, 95], the production cost is defined as the total production cost for the project including: the price of the property, building permit charges, taxes, fees for connection to the service net for electricity, sewage system and water supply, interest rates connected to the loans that finance the project, and so on. This definition includes a large amount of costs that are not related to the actual construction method used. Furthermore, it includes the price of the property, which is highly dependent on the location. The total production cost include the construction cost, which could be described as the cost for the actual construction of the building: including material, labour, sub-contractors, and the detailed design. The construction cost is directly affected by the construction methods used, and can be optimized by more effective construction technologies.

To obtain comparable numbers, the construction cost is often presented in different types of business ratios based upon the unit square-metre. The amount of square metres is sometimes taken as the gross exterior floor area and other times as the habitable area. These types of business ratios are, however, not useful when working with development and optimization of the construction efficiency. The total cost of a building is highly dependent on the distinctive design and comfort requirements of that building; comparing the total cost of two different buildings can, therefore, be deceptive.

A detailed study was made in order to get a better understanding of the construction costs (see Paper IV). The purpose was to identify the cost for construction of the different building-parts - such as foundation, structure, etc. In this way, the parts of the building with the largest potential for improvement may be identified. For this purpose, a suitable building project was chosen that was recently built and where detailed cost estimations existed. The reference project consists of three buildings recently built in the suburbs of Stockholm. The cost estimation document for this project was very detailed. The buildings were built with an in-situ casted load-bearing structure and the outer-walls consist of one-storey high infill outer-wall elements. The façade is rendered, and the exterior plating is made once the infill outer-wall elements and the windows are mounted. The roof is an inclined wooden roof-construction that is built on site. This project is – in terms of design and construction methods –
representative of the dwellings produced in Sweden today, and gives a relatively
good picture of the costs in housing construction.

2.3.1 THE COST PRESENTATION

In the original documents, the cost calculation was summarized as shown below,
which is a normal way of viewing the costs in the building sector. In this
document, the costs were divided into the following posts (see Figure 3):

- Materials
- Labour
- Sub-contractors
- General expenses – such as establishment, machines, or site
  management
- Technical consultants
- Contractor remunerations – which is calculated as 10 % of the total
  contract sum.

Examining this chart, one can see that the material costs in a building project
amount to only 26 % and that the labour costs represent only 10 %, while the
largest cost is that of the sub-contractors, which totals 38 %. The sub-
contractors’ offers include both material and working hours. If more effective
and industrialized construction methods are being used which reduce the
working hours and the material waste, then these methods will also affect the
offers of the sub-contractors. When viewing the construction from an industrial
point of view, it is the total amount of working hours and material waste that is
interesting. If Figure 3 does, in fact, show the reality, then there is no need to try
to reduce the amount of working hours since they represent only 10 % of the
total cost. The general expenses, as defined in this cost-calculation, are the costs
that make up the actual building activity - such as the rental of cranes,
administration staff, establishment costs, scaffoldings, etc.

![Figure 3](image.png)

*Figure 3. The original cost calculation was divided in the following cost posts where sub contractors are the largest cost post.*
It is obvious that the material costs and working hours represent a larger percentage of the total cost than what is shown in Figure 3. The labour costs and the material costs must be separated from each other in the subcontractor post. For the sake of simplicity, it is assumed that the labour costs covers 40 % of the contract sum while materials cover 60 %. Having said this, a different view of the costs is possible (see Figure 4). Here, the ratio of materials and labour has a totally different scale. The materials represent 47 % of the production costs and the labour costs have risen to a quarter of the total cost. These numbers are in accordance with data given in the publication *Fakta om byggandet* (published by the interest organization for Swedish construction) where the material cost is set to 45 % and the labour cost is set to 27 % (*Fakta om byggandet*, 2005). Figure 4 provides basic information about how improved production methods can affect the total production cost. Reduction of the total working hours will be visible in the labour post, while improved purchasing and reduced material waste can be accounted for in the materials’ post.

![Figure 4](image.png)

*Figure 4. Modified version of the costs in Figure 3, here the sub-contractor post is split up into material and labour costs.*

It is desirable to analyse the production costs in a way that separates the costs for different building parts from each other. In this way, the proportional cost of each building part is more apparent in relation to other parts and to the total construction cost. In order to achieve this, the costs are rearranged yet another time.

When the sub-posts of the cost-post *General Expenses* were studied (see Figure 3 & 4), it was possible to divide them into two separate groups. There is one group that is connected with the establishment of the building site and that involves one-time expenses, such as connection of electricity or establishment of temporary roads. The second group involves costs that are more time-dependent (by time, it is meant the total construction time from the establishment to completion). Examples of sub-post in this group are: the rental of safety equipment and tools, office and changing-room containers, and also building-site management staff. The first group is called *establishment costs*, and the second group will be referred
to as *management costs*. The production is, thus, rearranged into the following posts:

- **Landscaping and Foundation** – This includes everything that is related to the construction of the foundation and the landscaping.

- **Structure** – This pertains to the material and working hours that are related to the construction of the load-bearing structure.

- **The Climatic Shell** – This includes the construction of the roof, the outer walls, and the work connected to the finishing of the exterior façade - such as rendering, plating, and placing of the gutters.

- **Installations** – This includes the plumbing, electrical cabling, and the installation of HVAC systems.

- **Interior finishing** – This includes the construction of bathrooms, kitchen, partition walls, painting, etc.

- **Establishment** – These are one-time establishment costs - such as a security fence around the site or establishment of temporary roads.

- **Management** – These are the running costs during the construction period - such as renting of scaffoldings or cranes, cost of site managers, renting of office, and changing-room containers, etc.

- **Technical Design** – This is not including the architectural design.

- **Remunerations** – These amount to 10% of the contract cost

![Figure 5. Division of the construction cost into the defined posts.](image)

Figure 5 shows the posts of the original cost calculation presented as it was described above. Studying this chart, one can notice that the largest costs during the production of a building are related to the completing of the climatic shell. Thereafter, the interior finishing follows, which is logical due to more expensive surface-materials and electrical house-hold equipment. The third largest post is, in fact, the management cost. The general expenses post (from Figure 3 and 4)
was divided into establishment costs and management costs. It is notable that only a small fraction of the general expenses are made up by the establishment cost; the majority of that post consists of the management costs that are linked to the construction time. The management costs – which represent 14% of the total cost in this case – are reduced, if the production is faster. Prefabrication and industrial construction will have a large impact on this cost post.

2.3.2 VERIFICATION

The cost estimation of one more project was examined to see if there were any general conclusions that could be drawn regarding the proportions of the different cost posts. This project was constructed with prefabricated concrete elements for both the structure and the outer walls. The costs of this project were divided into the same cost posts as the previous one; the results are presented in Figure 6. The documentation for this cost calculation was less detailed than the previous one. As a result of this, it was not possible to divide the posts in exactly the same way. The structure and the outer walls, for example, had been outsourced on sub-contractors and were not specified; this is why the structure and the climatic shell are included in the same post below. Furthermore, the costs related to establishment and management were not specified in detail and it was, thus, not possible to separate them. Therefore, these two posts are also incorporated into one.

Comparing the cost calculations for the different projects, the overall proportions can be recognized although some minor differences do exist. The landscaping and foundation post is slightly bigger in the second project. Project 1 has more apartments than project 2; it is, therefore, natural that the landscaping and foundation cost is less per apartment and, thus, account for a smaller proportion of the total cost. The structure and the climatic shell account for 32% of the total cost compared to the 37% in the first project. The interior
finishing is the same for both projects and the management and establishment costs are comparable.

2.4 GENERAL PROBLEMS IN CONSTRUCTION

Construction faults have occurred, and will always occur, in connection with construction of buildings. It is not realistic to believe that it will be possible to construct without any mistakes. The scale of the construction faults can on the other hand be discussed. The construction faults are obviously connected with costs that are not value adding. With improved construction methods and logistic planning, it will be possible to reduce these costs. In 2002, a government commission report entitled *Skärpning gubbar* was published about the competitive situation in the building sector [SOU 2002:115]. This was a very broad investigation of the sector, and deals with extensive issues - from legal obstacles to the costs of construction faults and the reasons behind them. According to this report, the costs for faults can amount to 10-15 % of the total construction cost. This shows that there is room for improvement and that even small changes in this field will yield large cost savings. The reasons behind why these faults occur and whose responsibility it is will not be treated in this thesis. Instead, it is accepted that problems do happen and, in this chapter, emphasis is put on identifying them. Scientific research in this field is limited; while there exist a large selection of articles published in the technical press and in published technical reports. When reviewing this literature, it is possible to identify some fields where problems frequently reoccur. These fields are presented in the following paragraphs.

2.4.1 MOISTURE DAMAGES

The Swedish climate is characterized by high amounts of precipitation, low external temperature, and high moisture content during large portions of the year. These circumstances increase the risks for moisture damages - both during the construction phase and the service lifetime of the building. One of the components of the building that is often read about in connection with moisture problems is the infill outer-wall elements [Samuelson & Wånggren, 2002]. The majority of the prefabricated infill elements are produced with wooden studs. These elements are introduced into the construction site in an initial phase when the building is not protected, and when it is still exposed to the climate. The infill elements are normally delivered to the site when the load-bearing structure is finished while the roof remains to be constructed. Before the elements are assembled, they are stored at the building site and must be protected from rain and snow. This is the first time they are exposed to the risk of moisture damages. The elements are completed with a gypsum board on the exterior, but are still exposed to moisture damages after assembly. Even if moisture proof gypsum boards are used, there is nothing that protects the joints and the connections to the slabs and columns in the façade. After the assembly, they are covered with a layer of thermal insulation (5 – 10 cm), which also serves as foundation for the
rendering. It can take as long as several months before the façade is rendered and moisture proof. Another common reason for moisture damages of the infill elements is the fact that they are mounted into a concrete structure that is not totally dry. If the connections to the concrete are not properly protected, moisture will have access to the wooden studs and damage them. Hammarby Sjöstad is one of the most famous projects including wooden infill outer-wall elements and moisture problems. This development was widely covered in the media, and a rather profound description of its moisture problems is given in skärpningsgubbar [SOU 2002:115].

In Sweden, it is customary to use a vapour barrier on the inside of the outer-wall. The result is that when a rendered façade is completed, the construction will be tightened both towards the exterior and the interior because of the vapour barrier. As a result, if moisture enters the construction due to leakages, it will be stored there; and, as organic materials are used in the construction, there is a risk for mould growth. This problem was emphasized in a report published by the Technical Research Institution of Sweden (SP) in 2007 [Samuleson et al. 2007]. The report attracted very large attention in the media, advising against the use of these constructions. The research showed that it cannot be guaranteed that the rendering layer will be moisture proof. Moisture will enter the construction from the outside. To prevent conservation of moisture inside the wall, it is advised that the construction should include a ventilated air gap on the exterior side of the wall (behind the rendering layer), which can dry out entered moisture.

Another frequently reoccurring problem is moisture damages related to construction moisture. With construction moisture, it is presumed that moisture is released from construction materials - such as concrete - during the curing process. Due to a tight schedule and negligence in the directions given, surface materials are applied on the concrete before it has sufficiently dried. This includes both organic materials and, for example, plastic floor coatings that are moisture proof. With respect to this problem, there are some people in the industry who conclude that the construction time should be prolonged so that, among other things, problems related to construction moisture are reduced [Byggnads, 02-06-24].

Yet another very typical moisture problem is that of emissions from plastic floor coatings and carpet glues. This problem is also due to the application of plastic floor coatings before the concrete has dried properly [Sikander, 2005].

2.4.2 LOGISTIC PROBLEMS

The logistic planning of a building project is very complicated since a large number of independent actors are involved. Just in time is a logistical term very often used in the field of construction implying that material and deliveries should arrive on site at the exact time when they are needed – and not the next day or a couple of days earlier. This is currently not the reality, and it is not only because of the building project management; it is also due to the transportation
sector. In general, when materials are ordered, the supplier does not guarantee the delivery with more precision than a specified day or even week. Whether or not the delivery is made in the morning or the end of that day cannot be guaranteed. The materials need to be stored in the right order since they must be accessible at the right time. Furthermore, to protect them from precipitation, they must be covered at the end of the day and uncovered the next. This issue is also discussed in *skärpning gubbar* [SOU 2002:115] and *Fel och brister i nya bostäder* [Sigfrid, 07]. Problems associated with the storage of materials on the building site are also valid for projects built with prefabricated concrete elements. Elements are usually large in number and the order in which they can be assembled is very strict. If the delivery of one element is late, the successive elements in the assembly schedule cannot be assembled and, thus, must be temporarily stored on site until the missing element arrives. The building site is usually very crowded and limited in size; temporary storage is, therefore, difficult and very often elements are damaged during this handling.

### 2.4.3 WASTE

Another cost during construction that is not *value adding*, is spillage or waste. Waste includes excessive material that cannot be reused and are thrown away, or materials that are used for temporary construction - such as formworks; this also includes theft of the material from the building site. 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 construction workers on 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 included the handling of equipment and materials on site; temporary works included safety preparations. 14 % of this 45.4 % was spent on the 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, the efficiency of the management, the pure waste of materials, unused equipment at the building site, and much more. The cost for stealing is estimated to be approximately 1 % of the construction cost, while the waste of materials is about 10 % of the material cost. The waste cost for machines and equipment was estimated to be approximately 2-5 % of the construction costs. The writers draw the conclusion that it would be possible to reduce the construction costs by 50 % through waste management, although they add that a realistic goal for the building sector is a reduction of construction costs by one third.

### 2.4.4 THERMAL BRIDGES

Regardless of the construction method used, a thermal bridge is always created at the connection of the outer wall and the intermediate slabs. The fact that the
outer wall is constructed between two slabs shows that the insulation can never be the same in the outer wall as the exterior part of the slab (see Figure 7). Another detail that is well known to create large thermal bridges is the connection of balconies to the façade. This topic has been well examined and solutions and recommendations have been offered for how to prevent the emergence of this thermal bridge. In the Swedish climate, a thermal bridge is not only connected to energy losses. The part of the construction where a thermal bridge exists will have a lower temperature than the rest of the construction. This low temperature can, depending on the conditions, lead to a situation where moisture condenses inside the construction. The condensed moisture can, then, damage the construction and give way to mould growth.

Figure 7. Connection of the outer wall and the intermediate slab creates a thermal bridge.
2.5 INDUSTRIAL CONSTRUCTION

Rising manual labour costs contribute to high construction costs. Apart from the construction costs, the construction time at the site and the waste must be reduced. In the previously discussed report, *skärpning gubbar*, [SOU 2002:115], the matter of how reduced construction time is beneficial for all related parties is discussed. The developers will, for instance, be able to reduce their interest rate costs by selling the apartments quicker, while the urban environment is disturbed during a shorter period of time. Paper IV shows how the shorter construction time also contributes to reduced construction costs. This is why the sector is developing towards more industrialized construction methods. The term *industrial construction* has, to some extent, become a goal that especially larger building companies attempt to achieve. The definition of industrial construction is not fixed and is used in various ways and contexts. Apleberger et al. give a thorough description of the various definitions that are used, and choose to define it themselves as:

“Industrialized construction is the sum of all processes that are required before the final product is manufactured” and,

“Industrial construction is production in an enclosed production environment where everything that is produced is to be delivered to the building site for assembly”. [Apleberger et al., 2007]

This work is based upon a different view of these terms. Industrial construction is a way of thinking that implies highly automated and optimized production processes with a strong reduction of the manual labour. Industrialized construction is the path to this goal. The construction is, thus, industrialized until it reaches the state of industrial construction. In the following section, some of the industrialized construction methods applied in Sweden – and which fit this definition – are described.

2.5.1 OPEN HOUSE

Open house is one of the most famous industrial construction concepts in Sweden. The concept, which is based on volume elements, has been developed by the architect Peter Broberg. The project was initiated in Denmark during 1990 when the architect won an architectural competition. This resulted in a first pilot project which later developed into the concept called *Open House*. The concept took shape during 2001 when Malmö city decided to develop a large part of the city (Brunkeflo) with the Open House concept [Broberg, 2006]. The project implied construction of 1200 apartments, which is a substantial project by Swedish construction measures; it was in connection to this project that the company took over the old Saab factory in Arlöv.

The concept is based upon internally finished volume elements that are mounted together at the building site to form the finished building. The volume elements
are only carrying their own weight. The loads are transferred to the foundation via a grid of columns and beams (see Figure 8). Originally, these columns were made in concrete; however, this was changed to steel columns when problems occurred with the tolerances of the concrete columns that complicated the assembly. The conceptual idea of the Open House system is a contrasting approach compared to the construction concept during the Million Program. The building systems during that period implied prefabricated elements, which gave a finished exterior shape and façade while the interior finishing remained. The idea of the Open House concept is to produce volume elements that are finished on the interior and need to be completed on the exterior. The material chosen for the production of the volume elements was sheet metal profiles. The reason for this was the fact that it is a dead material, as Peter Broberg puts it. By this, he refers to the fact that it does not change its volume due to changed moisture content as, for example, wood does. This gives it very good properties for prefabrication and industrial construction. It was consequently possible to achieve low tolerances with the sheet metal. The volume elements are, thus, constructed with sheet metal studs and beams for the walls and floors, respectively. No particular problems were experienced related to tolerances. The module size of the elements were 3.9 m x 3.9 m; the modules can be prolonged to 12 m with added columns while the width remains the same due to transport possibilities. The system is based on a 36 M +3 M principle. M stands for 10 cm in the Swedish standard.

The Open House factory was shut down in the spring of 2008. The company survived mostly due to the large project in Bronkeflo. The company never managed to reach its initial goals for reduction of the production cost and, until the end, they were not able to lower the production cost below the levels for conventional construction methods [Byggvärlden, 2008-03-10]. The problem was flexibility. The concept is based upon mass production ideology, which is not coherent with the demands on the building market, where variety is vital. The market demands diversity, while the system requires reproduction. In the same article, the vice-president says that he was hired to reduce the number of module-types to 10-15 from the approximately 100 existing different module types. Another problem that the Open House production faced was the synchronisation between the factory production and the assembly on site. They experienced large difficulties in obtaining the time schedules for the assembly. This led to the fact that a large number of modules were delivered, and had to be temporary stored at the building site where they were exposed to the climate. Given that the modules were prefabricated with a finished interior, they were very vulnerable during transportation and assembly. Exterior finishing is not as vulnerable as interior finishing since the exterior finishing is designed to withstand tougher climates and handling. The volumes had also problems with moisture damages due to leakage, during transportation and assembly. This led to the fact that they were designed with a protective roof construction that, in reality, was only useful between the time when the volume element was
transported from the factory until it was assembled. This is a typical waste construction.

The previous vice-president has started working as vice-president for the new company, Bau-How AS. The concept of Bau-How is similar to Open House and based on prefabricated volume units with a finished interior. An interesting remark is that this company will set up its production in the Baltic countries where the labour costs are lower. This could be a sign that the production methods have not been effective enough to reduce the production efficiency and that the production has, therefore, been moved to low-wage countries in order to reduce the production costs.

![Figure 8](image)

**Figure 8.** Finished volume elements are mounted into a load-bearing grid of steel columns and beam. The volume elements have to be weather protected, the corrugated sheet metal roof on the element serves only to protect the element before it is assembled. Photo [Brogerg, 2006]

### 2.5.2 NCC KOMPLETT

NCC is the second largest building company in Sweden. In 2002, the company started a new development project within the field of industrial construction. The concept is based on a high degree of prefabrication, and was inspired by the production methods of the manufacturing industry - especially the car industry. This is also why many of the project staff was hired from industries other than the building industry [Ny teknik, 2006-04-25]. The factory workers were assemblers with no experience from the construction industry. The concept is based on flat elements instead of volume elements. The outer-walls consist of concrete elements with High Performance Concrete (HPC). All of the walls – both interior and exterior - are load-carrying. The wall elements are produced at the factory with detailed finishing on the interior side, while the exterior of the
building is completed post-assembly. Electrical cabling and water pipes are integrated into the walls at the factory where the windows and radiators are also mounted. Even the wall-paper is pasted at the factory. Special kitchen modules are finished at the factory with cabinets and sinks already installed, while the bathrooms are delivered as finished volume elements. The floors consist of lightweight double constructions; whereas, the surface materials and the false ceilings are finished at the factory. The roofs are also delivered as prefabricated elements. At the building site, a huge tent is raised under which the assembly of the elements takes place. The tent is equipped with over-head cranes (see Figure 9) and the assembly team consists of only four people. One of the unique features of the NCC Komplett system is the specially designed push-fit connections. The elements are mounted together with these connection devices in a sort of plug and play system. Just in time delivery of the elements are applied to enhance the logistics during the assembly work. After assembly, the building exterior is finished with conventional methods. The system is highly industrialized and is dependent on very low tolerances. For the elements to click into each other, the parts must be produced with tolerances that are measured in fractions of a millimetre instead of the several centimetres to which the construction industry is accustomed, says company Vice-President, Fredik Anheim.

The factory was inaugurated in April 2006 and was shut down in 2008. The cost of the project amounted to 1 billion SEK. The production never managed to reach the planned production volumes. During the first year, 400 apartments were planned; however, only 50 were built. The second year, 600 apartments were planned; but only about 200 were constructed [Ny Teknik, 2007-11-07]. One of the major difficulties of the production was actually the low tolerances. The concept was based on prefabricated elements with very low tolerances; the problem was that the assembly tolerances were also very low, which created problems at the building site. The system was too fragile for the assembly to work out since the elements had to be produced with the exact measurements and too little space was left for imperfections. The chosen material (concrete) is not suitable for these low tolerances.

NCC Komplett had problems with flexibility as well [Byggyvärlden, 2008-03-10]. The production is standardized towards a special design. The problem is that buildings cannot be mass-produced as cars or toys are mass-produced; buildings need to have unique characteristics. When a production is too standardized, it is costly to create variation, which is why it is important that building concepts are flexible. The NCC Komplett concept was based on a sort of type house with limited architectural freedom. In the brochure for the concept [NCC Komplett] it is stated that the kitchens are performed in standard I or L shapes and that the parquet floors can be chosen from a standard assortment. It is also described how innovative the hidden storages are behind the kitchen sink or the recessed newspaper holds outside the front doors. These are design details that should regard the interior architect, not the building system design.
2.5.3 STRÄNGBETONG

Strängbetong can be described as one of the most experienced and mature industrial constructors in the Swedish market. It is a company with construction methods that have been used since the period of the Million Program. The company was created in 1942 around an innovation within the field of prefabrication. This was a new production method for prefabrication of prestressed hollow-core concrete elements. In 1942, the company established the world's first full-scale concrete-element factory. The core business of the company is prefabricated concrete for both housing and commercial projects, and also for infrastructure projects - such as tunnels and bridges. The image of Strängbetong within the building sector is not the high-tech radical company which is normally given by new players and concepts such as Open House and or NCC Komplett. The products of Strängbetong are very common on the market and frequently used in building projects; it is easy to forget that this is, in fact, industrialized construction. The company has focused on optimization of its production methods and maximized efficiency; it is only during the recent years when the topic of industrial construction has become popular that the company is marketing itself as an industrial constructor.
Strängbetong’s concept for construction of dwellings is marketed under the brand *the Basic Building*. The structure is always based on hollow-core concrete slabs. The vertical loads can be transferred with load-bearing prefabricated concrete façade-elements, internal prefabricated load-bearing partition walls, or with a steel frame with steel beams and columns in the façade (see Figure 10). The façade elements are produced in two different models. The first one is that of sandwich elements with a section of 150 mm concrete, 150 mm EPS, and 75 mm concrete on the outside. These elements are delivered with installed windows and finished exterior surface. On the inside, the electrical cabling is finished and only the painting of the walls remains. The problem with these elements is that they leave visible joints on the façade. To cope with this difficulty, another outer-wall element is developed that consists of an inner 150 mm layer of concrete with 150 mm of EPS as permanent frame work on the exterior. These elements are rendered after assembly in order to leave a seamless façade. The concept is complete with prefabricated stairs and staircases, elevator shafts and balcony elements. They also have prefabricated roof cassettes in wooden constructions that are mounted on top of a last storey of hollow core slabs.

The strategy of the company is to deliver the building with a load-bearing structure and a finished climatic shell. The interior finishing and the installation work are left to the customer. The system is based on an open platform, which means that it can be combined with other building components on the market. Many contractors, therefore, use the load-bearing structure from Strängbetong in combination with light-weight infill elements, prefabricated bathroom units, or other prefabricated and in-situ constructed components.

The challenge connected with this building system is, once again, tolerance problems. The production of the concrete elements cannot be made with low tolerances, the company is fully aware of this, and do not claim to be able to maintain low tolerances. This is, instead, compensated for with increased assembly tolerances, which create difficulties and require post-treatment. It also creates difficulties when combined with other prefabricated elements delivered by other companies. The concept is based on both high-production tolerances and high-assembly tolerances. The transport and assembly of the elements is also costly due to the high weight. Furthermore, it can be mentioned that concrete façades, in general, give higher U-values, which can be lowered only at the expense of increased wall thickness.
Figure 10. The basic building can be constructed with three types of structures: steel framework (up to the left); prefabricated load-bearing concrete partition walls (down on the left); or with prefabricated concrete façade elements (on the right). The slabs are always made of hollow-core concrete elements [Strängbetong].

2.5.4 LINDBÄCKS BYGG

Lindbäcks bygg is one of the success stories in the field of industrialized construction in Sweden. The company was established in 1924 and has, since the beginning of the 1990s, moved towards industrialized construction methods [Apleberger et al., 2007]. The concept of Lindbäcks bygg is similar to that of Open House, with volume elements that are finished on the inside and assembled together at the building site where the roof is mounted and the façades are finished. The main difference between these two concepts is the choice of material. Lindbäcks bygg uses wood-based light-weight construction. The walls and floors are built up by wooden studs and gypsum boards. The finished walls are assembled to volume elements at the factory after which the interior is finished. The interior finishing of the volume elements is performed by craftsmen and is made with conventional methods. The elements are mounted on top of each other at the building site to shape the finished building. The roof is prefabricated at the building site by smaller prefabricated roof elements. This gives a fast finishing of the roof once all the volume elements are mounted. Another difference between the two concepts is that the elements of Lindbäcks bygg are load-bearing; they are, thus, not mounted into a separate load-bearing structure. Since the loads are carried by the volume elements, they can just be stacked on top of each other. This creates an independency of other
imperfections and gives way to reduced tolerances and increased assembly speed. The concept can be used for construction of buildings with up to 7 stories.

2.5.5 PART AB

Part AB is another good example of industrialized construction. The company is focused on industrial production of prefabricated volume elements for bathrooms and kitchens. The production is highly automated with a production line of real industrial standard. The walls are produced from wall cassettes that are manufactured by special bending machines; these cassettes are later put together by robots – guided with optical eyes – into whole walls. The tiles of the walls and floors are glued on by robots, and holes are cut after the tiling is finished (see Figure 11). Computerized water jets are used for the cutting of the holes, which are guided by digital Auto-Cad drawings. All of the bathroom or kitchen furniture are mounted onto the walls in production lines where the walls are moving and the assembler is stationed (see Figure 11). The walls are later put together with floors and roofs to form volume elements. With the help of hydraulic cranes, one man alone can assemble all of the walls of the finished bathroom. Once the volume is formed, the final cabling and plumbing (outside the volume) is done before the volumes are wrapped for climate protection and transported to the building-site. The design of the bathroom for each project is unique and decided by the customer’s architects. Part AB has a successful production, and also exports volume units to other European countries.

Figure 11. Tiles are mounted with a specially made robot that can be adapted to every size of tile and type of pod. (left). The furniture is mounted onto the walls before assembly to volumes (right).
3 STRATEGIES FOR IMPROVED CONSTRUCTION METHODS

In the previous chapter, the building process in general was analysed. In this chapter, construction of the different building parts - such as the load-bearing structure, the outer walls, the roof, etc. - is treated separately. Based on the weaknesses and advantages of the construction methods that are currently applied, conceptual strategies are proposed for each building part. These strategies (which are presented in frames) are meant to serve as basis for further development of new building concepts. The design of the building is also examined and a new design process is proposed, which can contribute to a more efficient construction of buildings.

3.1 BUILDING PARTS

The foundation of the building is not included in the building parts that will be studied in this chapter. The foundation is highly dependent on the site conditions and must be anchored to the subsoil. This implies that the foundation will always require much work on site, and there is not much gain in prefabricating it. Furthermore, the cost of the actual construction of the foundation is rather small in comparison to the total construction cost. The cost of landscaping & foundation is approximately 8 % (see Figure 5), and this post still includes the work for preparation of the ground and the landscaping. It is, therefore, decided not to make any efforts for the improvement of construction methods regarding the foundation.

3.1.1 STRUCTURE

The choice of structure is relevant from both the constructional and the financial points of view. Besides the fact that the cost of the structure is rather large, it is very time-consuming to produce. Furthermore, in-situ casted structures introduce large amounts of construction moisture into the building, as discussed in section 2.4. In Figure 5, it can be seen that the third largest cost post is the management cost, which is related to the construction time of the building. By using a prefabricated structure it is possible to reduce the construction time substantially. A comparison between the production of an in-situ casted structure and a prefabricated concrete structure was performed by Paus [Paus, 2001]. In this study, the construction of two apartment buildings are compared; it could be observed that the prefabricated structure was completed after only 11 days and that the total construction time of the building was 12 weeks faster than the building built with in-situ casted concrete structure. Another benefit with a prefabricated structure is that concrete casting is significantly reduced, leading to reduced construction moisture. Prefabricating the structure will, thus, reduce the construction time since the waiting time for the drying of the concrete is reduced.
The design of the load-bearing structure will also have an impact on the flexibility of the interior plan. It is very complicated to change the position of load-bearing partition walls once the building is completed; hence, they divide the plan into fixed spaces. This creates a limitation for the possibility of future refurbishments and changes of activity inside the building (dwellings to offices or vice-versa). To accomplish maximum flexibility, vertical load-bearing elements should be placed with regard to expected future room combinations [Blach & Kjær, 1987]. Built-in flexibility will reduce the costs for future refurbishments.

This shows that a suitable solution for the structure should be a prefabricated structure with few interior partition walls. Furthermore, the structure should be independent of load-bearing outer walls. A prefabricated structure based upon a steel frame-work and hollow core concrete-elements fulfils these requirements.

3.1.2 ROOF

The roof is a part of the building that is associated with difficult working conditions. Besides working on high altitudes the construction workers are 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 when eliminated. Many problems during the construction phase are related to the weather with wind and precipitation as the main elements. Water damaged materials and constructions cost a great deal, and many efforts have been made to solve this problem. This is also why the report Skärpning gubbar states that infill outer-wall elements should be assembled after the roof is constructed [SOU 2002:115]. One weather-protection method applied in Sweden is to construct the building beneath a tent. A huge tent – slightly larger than the finished building – with an incorporated over-head crane is raised, and the building is constructed beneath it. This is an extraneous cost that is added to the project in order to secure the quality. Inside the tent, a milder climate is created since it is enclosed; the fact that there is no wind and precipitation contributes to improved productivity. The improved productivity does not, unfortunately, correspond to the additional cost for the raising of the tent.

To provide an early protection of the building during construction, it is logical to build the roof as soon as possible. With a prefabricated roof, the weather protection is completed even faster and the amount of working-hours on the roof is reduced. When a load-bearing structure is used with no load-bearing outer-walls, it will be possible to build the roof before the outer walls. This, however, requires that the connection of the outer-wall and the roof is designed in a way that makes it possible to assemble the outer-walls with the roof already in place.
3.1.3 OUTER WALL

The outer-wall normally consists of several layers that are usually produced in various stages of the building process by different contractors – such as carpenters, painters, renderers, etc. 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 unsafe conditions. The construction of outer-walls is in need of many temporary constructions for safety and access reasons. Scaffoldings can be mentioned as one of these temporary constructions. The scaffoldings are built around the building façade only to access the façade for the exterior finishing of the outer wall.

Due to better insulating properties, it is possible to achieve the same U-value for the outer wall with a thinner construction when using light-weight elements instead of concrete elements. Thick outer walls are not economic since they will reduce the rentable floor area. By using non load-bearing outer walls, it is possible to separate the construction of the load-bearing structure from the building envelope. In this way, the structure can be completed independently of the building envelope. Moreover, light-weight elements are easier to handle - both during transportation and assembly. Concrete façade elements can, on the other hand, be delivered with a higher prefabrication degree. The windows are installed and the exterior surface is finished. With these elements, there is also no need for special shear walls. The disadvantage is that the joints between the elements create a horizontal and vertical grid, which is difficult to hide. Another common problem during assembly of concrete wall elements is that the position of the lifting yokes is miscalculated. This implies that the element will not remain straight during the lift, which complicates the assembly and can damage the element [Bajramovic & Bajramovic, 2006]. The lightweight infill elements are also connected with many difficulties as previously explained. They are delivered with a low level of prefabrication, and a great deal of remaining supplementary work. They are also very sensitive to moisture and precipitation during the assembly phase. Another recommendation given in Skärpning Gubbar was that the façade should be covered with weather-proof scaffoldings as soon as the infill elements are assembled.

Both in-fill elements and concrete façade elements result in a broken outer-wall. The elements are placed between two intermediate slabs and are, thus, discontinuous. Due to this feature, no vertical installations can be integrated in the outer-walls. The connection between the slab and the outer-wall is also less insulated, which gives a thermal bridge (see Figure 7).
Light-weight elements are advantageous compared to heavy-weight elements, because of better insulation properties and easier handling during transportation and assembly. Furthermore, it is beneficial if the elements are large and have a finished exterior façade. This will protect the elements and the building after assembly and eliminate the need for scaffoldings. The larger the elements, the fewer elements are required, which gives reduced assembly time and enhanced site-logistics.

3.1.4 INSTALLATIONS

According to the results presented in paper IV, the cost of the installations amount to approximately 10% of the total construction cost (see also Figure 5). There are some studies that show that this cost post is 20% of the total production cost in the case of dwellings [Malmström, 2001]; others estimate a cost that exceeds 20% [SOU 2002:115]. However, it is clear that a reduction in this field will yield large reductions on the total cost of the building. 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, 2006]. This leads to a great deal of ventilation ducts and pipes that need to be incorporated into the building. Installation shafts are used to lead the installations through the different floors. This system requires that all the bathrooms and kitchens are placed above each other, thereby, limiting the flexibility of the interior plan (see Figure 1) [Andersson & Johansson-Seo, 2007].

The assembly of the installations is often outsourced to several sub-contractors; the contracts for electricity and HVAC systems are usually separated. The prices offered by the sub-contractors are difficult to evaluate since they include both material and working hours without specifying the cost of them separately. Furthermore, the discounts that the sub-contractor receives from the detailer are not visible in the offer given by the contractor. 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.

Built up floors create a void between the concrete deck and the floor, this space can be used to place the installations [Sarja & Hannus, 1995]. In this way, the bathrooms do not need to be placed in connection to the installation shafts and the interior plan becomes more flexible. Parts of the installations can be prefabricated to reduce the on-site working hours. Prefabricating parts of the installations could also result in separation of materials and working hours.

3.1.5 INTERIOR FINISHING

The interior finishing represents the second largest cost post for buildings (see Figure 5 & 6). Cost optimisation in this field will, therefore, have large impact on the total construction cost. The kitchen and the bathrooms are the most expensive components in the interior finishing. Many different prefabricated
solutions can be found on the market - both as volume elements, such as PART AB, or delivered as flat elements, such as Societa Sweden [www.societa.se] or Inexa Readymade [www.inexareadymade.dk]. The flat-element systems consist of one floor-element, one roof element, and wall elements. All of the wall and floor elements have a surface of ceramic tiles and connections for water and sewage prepared, as well as connections for toilet seats and sinks. The Director of development at Skanska (the largest building company in Sweden) recounts that the production cost of the bathrooms was reduced by 20 % in a project where they used prefabricated bathroom units delivered by PART AB [Industrialiserat byggande, 2006].

The use of prefabricated bathrooms will contribute to a faster completion of the interior finishing and a reduction of the construction costs. Volume unit elements should be lifted onto the floors during the construction of the structure, while prefabricated bathrooms in flat elements can also be inserted into a finished structure. Volume elements, thus, require better elaborated site-logistics.

3.2 DESIGN PARAMETERS

3.2.1 TOLERANCES

Tolerances are used to compensate for imperfections during the production and assembly of components. In the guide book for construction with prefabricated elements, published by the Swedish Concrete Element Association [Bygga med prefab], the total building-site tolerances are given (based upon the Swedish standards) as a function of production tolerances, staking tolerances and assembly tolerances as:

$$T^2 = a \times T_p^2 + b \times T_s^2 + c \times T_a^2$$  \hspace{1cm} (1)

where $T$ is the building-site tolerances and $T_p$, $T_s$ and $T_a$ are production, staking tolerances and assembly tolerances, respectively. $a$, $b$ and $c$ are constants that vary depending on the component and assembly context. However, these constants can be set to 1 for estimated calculations. The final tolerances are, thus, dependent on the tolerances in previous processes. In the guide book for construction with prefabricated elements, it can be noted that the tolerances used for prefabricated concrete elements are very large. As an example, the building-site tolerances for the position of columns and wall-elements in the horizontal plan can be given, which are set to $\pm 25$ mm. This means that the added misplacement of two elements can amount to up to 50 mm. Working with tolerances of this magnitude is not efficient since the assembly will require too many adjustments while the post-assembly cover up requires too much time. It can be seen from equation (1) that the building-site tolerances can be reduced by reduction of the other tolerances.
Improvement of the marking tolerances is purely a question of using the right equipment given the fact that the technology is highly developed in this field. More advanced and automated production methods for the prefabricated elements, along with the right choice of materials, will render possible a strong reduction of the production tolerances.

The prescribed tolerances are different for different components. The components and materials with the largest tolerances are often the ones that are used earliest during the construction of the building, such as the concrete foundation and the 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.

Tolerance management is of great importance within the field of industrial construction. The earlier in the building process a component is built; the more important is the precision. The general procedure should be to aim at low production tolerances for the prefabricated elements that, along with reduced staking tolerances, will render possible low building-site tolerances and a successful assembly of the building.

3.2.2 ELEMENT JOINTS

The use of prefabricated concrete façade elements leaves visible joints on the façade. The characteristic grid creates association with the buildings from the Million Program, which are not appreciated among the general public. It is not possible to hide these joints; architects are, instead, elaborating with the size of the elements in an attempt to brake away from the grid and create a more irregular pattern on the façade [Bajramovic & Bajramovic, 2006]. Element producers are also offering façade elements with fake joints that could be used to break the characteristic grid [Strängbetong].

The joints are needed due to the tolerances that are required during the assembly. The joints are also needed to leave room for the movement of the outer concrete plate in the sandwich element. The outer concrete plate is exposed to the exterior temperature and moisture variations, and will expand and shrink in response to these variations. Since concrete is a hygroscopic material, much in the same way wood is, it changes its volume due to changed moisture content [Bygga med prefab]. This is why the exterior joint is larger than the interior joint.

The joints are also connected with building physical problems. A study made in 1987 showed that from the 56'000 examined apartments in buildings built with concrete elements, 11,6 % had experienced water leakages in the joints between the concrete façade elements [Jerling et al., 1988] (see Figure 12). When the sealing material in the joints fails, the construction will no longer be air tight. This leads to air leakages that result in increased energy losses [Jerling, 1981].
It is important that the construction of the outer walls, with regard to materials, is designed in a way that minimizes movements in the façade. It is also of great value if the joints between prefabricated façade elements can be made invisible. The air tightness and the durability of the joints are of great importance.

Figure 12. Joints in the façades have been creating building physical problems.

3.2.3 LOGISTICS

An accurate and strictly detailed design is essential for the logistic planning. The work scheme and flow of materials are planned with the production plans as a basis. If problems occur during the production, the work is delayed and the logistic plan cannot be followed, the material flows are interrupted, and temporary material stocks need to be formed on the building site. Problems during the construction are often due to mistakes in the detailed drawings. The logistic planning is facilitated if the amounts of materials that need to be managed at the building site are reduced. High prefabrication level implies that the materials that are normally delivered to the site are instead assembled together into elements. This also reduces the waste management on the site since, except for actual material waste, the wrapping of different material packages add to the waste. The larger the elements that are delivered to the building site, the fewer the number of elements will be and the easier the logistic planning will be. The term *Just In Time* (JIT) deliveries is used more and more in the field of construction. The concept of JIT is very practical and facilitates the material management at the building site. The problem is that the transportation sector has still not adapted its delivery systems to this way of working. This service may cost extra today, although when the whole building sector demands it, it will become standard. Another very important criterion for effective logistics is efficient production spaces and independence of the climate. The weather will always affect the construction and this impact should be minimized.

Normally, several construction activities are in progress at the same time in the same zones. These activities are many times dependent of each other while they are performed by different contractors [Skerfving, 1998]. A simple example is
the construction of gypsum-plasterboard walls. The carpenters finish the wall on one side; they must then wait for the electricians to finish the electrical wiring before they can finish the other side of the wall. If there are any water pipes that are to be integrated, then this is performed by yet another contractor. The separation of these activities needs to be managed both in time and in space. On large building sites, different contractors can be working in different zones at the same time. Efficient computer tools exist for this kind of 4-D planning, where the 4th dimension is the time [Jongeling, 2006]. In smaller sites, the goal is to plan the contracting works in a continuous series and – as much as possible – independent of each other.

Well-elaborated construction plans are of great importance for an efficient logistical planning. One way of creating independence of the climate is to finish the building envelope as fast as possible. A prefabricated building envelope consisting of large elements contributes to this and, in addition, will reduce the material management on the site. It is also important to design the logistic planning with adequate tolerances in order to avoid a too high dependency on JIT deliveries. It is important to design the building components and plan the construction of them in a way that makes it possible for the involved contractors to work independent of each other.

### 3.3 THE DESIGN PROCESS

#### 3.3.1 CONVENTIONAL DESIGN PROCESS

The traditional design process has mainly a linear structure due to the successive contributions of different consultants. The process often begins with the architect and the client agreeing upon a design concept and the architectural shape of the building. The structural, mechanical, and other necessary engineers are then asked to implement the design and to suggest appropriate systems. Furthermore, the construction of the building often starts before the detailed design is finished. In an article regarding the building process in the framework of industrial construction, Carl Jonsson of Skanska says that their industrial concept includes that the detailed design is finished before the construction starts. “It sounds almost ridiculously obvious that the detail design of a building should be finished before the construction starts, but this is not the case in the building sector. We often see projects where advanced detailed design is in progress despite the fact that the fourth floor of the structure is finished”. [Byggindustrin, 2006]

This course of action is possible when on-site construction methods are used since the design and shape of a component is not locked until the component is completed. With conventional on-site construction, the component is shaped after the form of the building while, in the case of industrial construction with prefabricated elements, the form of the building has to be adapted to the component. When industrialized construction methods are used, the shape and construction method of a component is locked when the detailed design of the component is completed.
building is completed. When the construction has started, changes are much more difficult and costly to apply [Paus, 2001].

The production of a bathroom can be used as an example: with conventional on-site construction, the bathroom is built within the limits that are given for the space of the bathroom. If a prefabricated bathroom volume element is to be used, the reserved space for the bathroom must be adapted to this component. The bathroom unit might require a minimum ceiling height in order for the assembly to be possible. The ceiling height cannot be changed once the structure has been completed. This limitation must, therefore, be taken into consideration in the early stages of the design. In fully developed industrial construction, a large number of prefabricated components are used - each with its own limitations and requirements. If the architectural design of the building is prepared with this information in hand, it can be successful. If, on the other hand, the architectural design is finished and afterwards must be changed to incorporate different prefabricated components, revisions (which imply double work) are required, while there is a large possibility that the original architectural expression is lost. The design process in an industrial construction requires a much more close collaboration between the involved consultants.

Another frequently discussed problem is the lack of feedback of experiences and consequences of the design. Consultants are usually disconnected from the project once the detailed design is finished. If any problem occurs during the construction, it is often solved on site by the site manager or by another person who is also on site. Information about the problem is never forwarded to the designer responsible. This gives that the consultants are unaware of the problems that their design have created and cannot improve their design [Skerfving, 1998]. An organized design feedback would benefit the development of improved construction methods.

### 3.3.2 PRODUCT DEVELOPMENT IN THE MANUFACTURING INDUSTRY

Olofsson et al. give a description of product development within the manufacturing industry [Olofsson et al., 2004]. Until the end of the 1980s, the development of a product from idea to market introduction had been characterized by the serial model. The model is reminiscent of a relay race where the baton is handed over to the next runner.

![Serial product development model](image)

**Figure 13.** Serial product development model is similar to a relay race (DP = decision point).

Semi-parallel product development was introduced by the Japanese car industry with the introduction of lean production. The semi-parallel model implies that the next development phase is initiated before the previous phase has been
completed. The waiting time between the activities and the total development time is reduced. The development is more focused on the customer while the product-development and the production-development are more synchronized. The semi-parallel model requires closer contact between the different participants and a larger exchange of information.

![Diagram of the semi-parallel model](Image)

**Figure 14.** The semi-parallel model is more time efficient and requires better communication between the different parts which results in a more customer-adapted product.

Further development of the semi-parallel model is that all phases are performed in parallel mode. With the parallel model, the total development time can be minimized, while the model is expected to lead to reduced conflicts between the involved disciplines and more customer-adapted products. In order to perform all activities simultaneously, it is required that the staff is organized into integrated interdisciplinary teams with close collaboration [Olofsson et al., 2004].

![Diagram of the parallel model](Image)

**Figure 15.** The parallel model is the most effective product development model, but requires interdisciplinary design teams working in close collaboration. Picture: [Olofsson et al., 2004]

Implied in the design process of industrial construction, this model can be translated into a parallel design process where the consultants involved - such as architects, structural engineers, mechanical engineers and others - are working parallel in close collaboration within integrated design teams. These design philosophies are reflected in design strategies, such as *Whole Building Design* [wbdg] and *Integrated Design Process* (IDP).
3.3.3 INTEGRATED DESIGN PROCESS

In 1993, a small Canadian demonstration program for high-performance buildings was initiated with the focus on energy performance, environmental impact, and indoor climate. The program was called C-2000 and was very successful in reaching the preset goals; the involved designers agreed that the main reason for this successful application was the design process prescribed by the C-2000 program. This design process is now called the Integrated Design Process or IDP.

The Integrated Design Process has impacts on the design team that differentiates it from a conventional design process in several respects. The client takes a more active role than usual; the architect becomes a team leader rather than the sole form-giver; and the structural, mechanical, and electrical engineers take on active roles at early design stages. The team always includes an energy specialist and – in some cases – an independent design facilitator. In this way, the skills and experience of mechanical and electrical engineers, and those of more specialized consultants, can be integrated at the concept-design level from the very beginning of the design process. Experience shows that the open interdisciplinary discussion and synergistic approach will often lead to improvements in the functional program, in the selection of structural systems, and in architectural expression. The IDP process is based upon the well-proven observation that changes; and, improvements in any design process are relatively easy to make at the beginning of the process while this becomes increasingly difficult and disruptive as the process unfolds (see Figure 16).

![Figure 16. The horizontal axis represents the project time and the vertical axis represents, on the left side, the impact on the final product and on the right side, the cost and difficulty of implementing changes. It is seen that changes are easy to implement in the early stages of the project, while they will be more difficult and costly towards the end.](image)

“IDP is characterized by a series of design loops per stage of the design process, separated by transitions with decisions about milestones (see Figure 17). In each
design loop, the design-team members relevant for that stage participate in the process” [IDP, 2005]. IDP reformulates the design process with the main purpose of achieving improved energy-optimization and environmental impact.

3.3.4 PARALLEL DESIGN PROCESS

A further development of IDP can be formulated as the Parallel Design Process (PDP). PDP is similar to IDP with some minor differences. Except for energy performance, the focus is also set on cost-efficiency and production optimization. Furthermore, the design facilitator takes a much more central role. The design facilitator is called design coordinator and coordinates the members of the design team. The architect is not a team-leader in the PDP, yet he/she is a team member similar to the other consultants. There are two main reasons for this rearrangement. The decision-making process will not be effective if the team leader is not objective. Moreover, it is required that the design coordinator has interdisciplinary knowledge and a good understanding of the different fields of construction. Another very important member of the PDP design team is a current or former site-manager. The site-manager has invaluable experience of how different material and construction choices affect the assembly work on-site and can predict assembly problems and unforeseen events on site better than any of the other team members. Another important feature with PDP is the follow-up aspect. The design coordinator is the team member who has a total overview of all the information in the project. This is where anyone in the project can turn in order to either obtain information or be forwarded to the member where the

Figure 17: Graphic overview of the Integrated Design Process
requested information can be found. The design coordinator is involved from the beginning till the end of the project and is in charge for the documentation of the progress of the project (see Figure 18). This documentation is of utterly high value at the end of the project and is used as a basis for the knowledge feedback. This feedback is then used in coming projects: the experiences from each project is, in this way, gathered and used in the development of future projects.

![Diagram of the Parallel Design Process](image)

**Figure 18.** A graphic overview of the Parallel Design Process applied on a project built with industrial construction methods.

The design coordinator is directly appointed by the customer and will, thus, govern both the design and construction of the building in the best interests of the customer. In some cases, this can be reduced production costs or short-term gains; in other cases, it can be energy performance and reduced life-cycle costs; sometimes, it is only the design that is relevant and neither the production nor the operation costs are important. The PDP renders it possible for the customer to take control over the building process.

For the parallel design to be successful, it is required that the entire design team works towards the same goal. By performing a stakeholder analysis, it is possible to identify the right type of composition and contracts that will encourage the members of the design team to strive towards the same goal. Normally, the design of the building is made in sequences, while the construction is done parallel. With this building process, the design is made parallel in order to render a sequential construction possible.
4 CONCEPT FORMULATION

In the previous chapter, strategies were proposed for the development of new building concepts. Based upon the analysis of the current construction methods and the proposed strategies, a new building concept has been formulated called the Symphony concept (see paper I), which involves a holistic view of the whole building process. The concept is based on a prefabricated heavy structure that is covered with a prefabricated building envelope consisting of large, light-weight elements with finished exterior surfaces. The building interior is finished with a raised floor and prefabricated bathrooms. It is important to mention that flexibility is a key parameter in the formulation of the concept. The architectural design of the concept is not locked, but left free for the architect to develop. By application of the Parallel Design Process, it is possible to design buildings that can fulfill the requirements of various design and functional programs. In the following chapter, the formulation of the concept is described more thoroughly from the choice of materials to production methods and assembly schedule.

4.1 CONSTRUCTION OF THE SYMPHONY ELEMENTS

4.1.1 CHOICE OF MATERIALS

The conclusions from the previous section proposed that the roof and the outer walls should consist of large prefabricated elements. Outer walls are currently built by concrete façade elements or light-weight infill elements constructed by wooden studs or sheet metal profiles.

The handling of too large prefabricated concrete elements creates difficulties on the building site. Large and heavy concrete elements put special requirements on the crane that is used. Large cranes that lift heavy elements also put great pressure on the ground and, depending on the quality of it the ground, may need to be reinforced [Elwing & Sjögren, 2006]. Bajramovic and Bajramovic wrote a thesis partly based upon interviews with consultants, production, and assembly-personnel involved in the production of a building constructed with prefabricated concrete elements [Bajramovic & Bajramovic, 2006]. The production manager at the concrete factory says that the size of the concrete elements is limited by the production tables that are used, and that too large elements complicate the transportation. The assembly staff complains about large-sized elements because they are heavy and, therefore, difficult to handle during the assembly. They point out especially one element in this project that was two stories high, recounting the problems involved with the assembly of it. They had advised the architect to avoid large elements; this specific element was originally planned to be three-stories high, but the assembly staff had convinced the architect to reduce it to two stories.

Large-sized concrete elements are, thus, considered disadvantageous. Light-weight construction is preferable because of both the low weight and lower U-
values. Regardless of the size of the elements, one side – either the height or the width – is limited because of transportation limitations. This gives that the elements can either be horizontal (one-storey high) or vertical (multi-storey). Vertical façade-elements are chosen, which will yield vertical joints that are preferable from a building physics point of view since water cannot be collected in these joints. This choice eliminates the possibility of using wood as construction material since the length of wooden studs that can be delivered is limited to approximately 5 meters and joints should be avoided due to constructional reasons.

This gives that neither concrete nor wood is suitable for the construction of the elements. The experience from Open House showed positive results in the use of sheet metal profiles regarding tolerance control and precision. Furthermore, sheet metal profiles are not sensitive to moisture damages and can be ordered in the desired lengths. The CasaBona System – which is an integrated building system based on sheet metal profiles – is consequently used for the production of these elements.

CasaBona

During 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 and, thereby, gives the construction a coefficient of thermal transmittance comparable to a wooden-stud construction [Nieminen et al., 1995] & [Jóhannesson, 1999]. The shape of the Z-profile along with the pre-cut rigid insulation blocks offers a very fast build-up of the construction (see Figure 19). The rigid 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 for different material combinations. If required, the polystyrene can easily be exchanged to high-density mineral wool in order to meet specifications on fire safety and acoustics. Experimental houses have also been built with Adobe materials as insulation. The CasaBona profile is currently produced in heights of 100/150/200 mm and the thickness varies between 1,0 and 1,5mm.

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. Both the CBZ-profiles and the insulation blocks are pre-cut with millimetre-precision resulting in a tight fit. Thanks to the design of the construction, the sheet metal is supported by the EPS. This tight support should
strengthen the profile against local buckling. The contribution of the rigid insulation blocks to the buckling stress has been investigated to determine whether it can increase the critical buckling load of the CBZ-profile (see Paper VI). The detailed study shows that the EPS does provide support for the sheet metal, and a method has been developed for calculation of the strength of such constructions. The results show that the strength of the sheet metal is increased substantially when embedded in elastic materials. Calculation of the strength of a CBZ profile with a height of 150 mm shows an increase in strength against bending of between 22 % and 33 % when embedded in EPS (depending on the profile thickness). The increase against compressive forces was much larger: between 161 % and 210 %. The CasaBona construction is, therefore, suitable for construction of large light-weight elements with high strength.

![Figure 19. (Above) Incisions in the insulation blocks made with millimetre-precision yield tight fit. The pre-cut system offers a very fast build-up of the wall construction (4 man-min./m²). (Below) In this photo a single family house is built on site, which is why the wall is produced in a vertical position. Photo credit: Gudni Jóhannesson](image)

### 4.1.2 PRODUCTION METHODS

The core of the Symphony outer-walls is, thus, based on the abovementioned CasaBona system. Both the sheet metal profiles and the rigid insulation blocks are delivered to the factory pre-cut with millimetre-precision. The insulation blocks have incisions for the flange of the Z-profile with which they will be built together (see Figure 19). The width of the blocks automatically shows the distance between the studs, and no measuring is required. The expanded
polystyrene blocks are exchanged for 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 a 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 exterior layers (see Figure 20). Before the turn-over, it is possible to integrate electrical wiring behind the outermost gypsum layer. On the exterior, the element is covered with another layer of 50 mm high density mineral wool before it is rendered. The elements are rendered and painted at the factory before they are transported to the building site. Notice that the walls are rendered 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 element can, therefore, pass by up to 5 floors. All of the doors and windows are installed, and the installations are integrated at the factory. The outer-wall elements will be finished to 95 % when delivered to the building site. Some of the wall-elements will also contain the vertical HVAC and electrical installations needed for the building.

Figure 20. Elements are produced in horizontal position beginning with the inside. They are then turned over to finish the exterior façade.
4.1.3 INSTALLATIONS

The vertical parts for ventilation ducts, piping of the water and sewage, and the main cabling for the electricity - are integrated into the outer-wall elements (see Figure 21). The vertical ducts and pipes have junctions at each floor level to allow for the horizontal connection of the installations from the apartments. 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 metre; therefore, every square metre not sold is an expense. By integrating parts of the HVAC installations into the prefabricated elements, the on-site working hours for this contract are reduced.

Integrating the installations long before the building is finished requires a high degree of planning and a detailed design of the entire building. Here, the benefits of the Parallel Design Process and Building Information Modelling (BIM) are obvious and competitive. Furthermore, it is important to bear in mind and plan for the risks connected with the integration of HVAC-installations into the outer-walls. The placing and fastening of the ventilation ducts and piping in the outer-wall require an elaborate design. Inadequate 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; incorrect fastening and insulation towards the interior of the building can lead to acoustic problems between the apartments.

*Figure 21. The vertical installations are integrated into the outer walls.*
4.1.4 EXTERIOR FINISHING

The purpose of the Symphony concept is to reduce the working hours needed at the building site by the use of prefabricated elements with a high degree of finishing. The outer-wall elements are, therefore, delivered with finished exterior surfaces. It is also important that the joints between the elements are covered in a time-efficient way. The work needed for the finishing of the exterior façade when the building is erected, requires operation on high altitudes, which takes more time and involve special equipment and temporary constructions - such as scaffoldings. Reduction of this type of work will, thus, lead to larger savings than the actual reduced working hours.

The detailed plating work needed around the windows and other openings in the façade is 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. However, this obviously necessitates a greater responsibility in the design phase and the previous production phases. It is vital that all windows are assembled in exactly the right position and angle before the window edge flashings are fastened. The windows need to be mounted in the correct position in correlation with each other and with the outer limits of the element, since the whole outer-wall element can be adjusted, while one specific window cannot. Normally, when a window is installed in the outer wall, it is adjusted both horizontally and vertically before the details around it are finished. It is much more costly and time-consuming to adjust an incorrectly mounted window in a prefabricated element (where all the details around it are finished) after assembly. Corrections of errors when constructing with prefabricated elements are much more costly than for on-site construction [Elwing & Sjögren, 2006]. This is why quality control in prefabrication is extremely important.

4.2 ASSEMBLY

4.2.1 THE STRUCTURE

Based upon the conclusions drawn from the previous chapter, a prefabricated structure is advantageous regarding the construction time, cost of construction, and the reduction of construction moisture. The type of structure chosen for the building concept is, thus, based on hollow-core concrete floor slabs and a steel frame-work (see chapter 2.5.3 and Figure 10). The hollow-core concrete elements are pre-stressed and are lighter compared to a solid concrete deck. This gives the possibility to span the floor slabs over larger distances. In this way, no interior load-bearing partition walls are required which, in-turn, will give a freer disposition of the interior plan.

The columns will be situated in the façade and built into the outer walls so that they are not visible from the inside. The type and dimension of the columns and the thickness of the slab will depend on the building geometry and the 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 (see Figure 22). Both the frame work and the floor slabs are, thus, prefabricated and assembled on the building site. This will yield a short production time for the load-bearing structure. Components such as lift and stairway shafts will also be prefabricated and assembled at the same time as the structure; this will contribute to the horizontal stabilization of the building. Further stabilizing elements, such as shear walls, can be required depending on the geometry.

Figure 22. Hollow-core concrete decks rest on horizontal steel beams that are supported by steel columns in the façade.

4.2.2 THE ROOF

In the framework of this concept the roof consists of prefabricated elements, with a high degree of prefabrication, that are assembled before the outer walls, see Figure 23. By building the roof with light-weight technology it is possible to integrate the thermal insulation into the rest of the construction. It is not economical to design light-weight low-slope roof elements that span over the whole building without load-bearing partition walls. The large span can lead to complex and expensive solutions when excessive deflection of the roof is to be avoided [Lundgren, 2005]. The roof elements are therefore mounted on to a primary roof construction which transfers the loads to the load-bearing structure. The primary construction consists of different types of roof trusses. The roof elements are flat elements with a limited width that is dependent on the transportation possibilities (3.6–4.1m), while the length can vary. The size and shape of the roof elements will vary from project to project; however, the design concept will always remain the same. By changing the design of the primary construction, the building can be designed with both low-slope or inclined roofs. The roof elements are assembled onto the primary construction with cranes. The procedure significantly reduces the need for workers on the roof. To further reduce the working hours on the roof, the elements will be delivered with finished exterior surface and prepared water drainage system. The surface material of the roof covering is dependent on the roof inclination and, thus, also
on the architectural design 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. The roof will not be completely finished when mounted; however, the working hours on the roof are substantially reduced. The construction of the roof, and its various layers, is limited to the fastening of the roof elements; the finishing of the roof covering is limited to the covering of the joints between the elements. The larger the elements are, the fewer joints will be created. It is clearly seen that larger prefabricated elements will yield a reduction of the on-site working hours.

Figure 23. The roof is constructed before the outer walls

4.2.3 THE OUTER WALLS

The Symphony concept is based on light-weight outer-wall elements that are not load-bearing. In this way, the roof can be mounted independent of the outer-walls, while the outer walls will have good thermal properties. The one-storey high infill elements are exchanged with larger full-height multi-storey cover-elements. These outer-wall elements are not mounted between two slabs; instead, they are mounted outside the structure and run past the slabs (see Figure 24). The large size of the elements implies that the total number of outer-wall elements decreases (about one-fourth compared to one-storey infill elements). This also reduces the number of joints on the façade. Furthermore, fewer elements on the building site will give less storage and enhanced logistics. The width of the elements is 3,6 – 4,1 m and is dependent on transportation limitations, while their length can be adjusted to cover 3, 4, or 5 stories with a maximum limitation of 15 m. Longer elements will be too fragile and difficult to handle during the assembly. The elements are delivered to the building site with installed windows and finished exterior façade. The large building elements reduce the production time and give an easier quality control. The quality control on site is reduced to inspection of the correct mounting of the elements. The quality control on site is always more difficult than that at a factory. Furthermore, the prefabricated outer-wall elements with finished façades will
eliminate the need for scaffoldings, and will save both money and work-related injuries.

The outer-wall elements will be mounted following the roof (see Figure 24). 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, which will create good working conditions inside the building. The wall-elements will arrive at the building site on trucks that are horizontally loaded. 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 must be mounted in the correct vertical position from the start. Therefore, adjusting possibilities for the outer-wall elements is of great importance. Even small angle deviations will cause inclining windows, which will be difficult to adjust afterwards.

Figure 24. The prefabricated full-height cover elements are assembled after the roof and can cover up to 5 stories vertically.

4.2.4 ELEMENT JOINTS

The full-height vertical outer-wall elements eliminate the horizontal joints and break the grid by leaving only vertical joints. In order to hide the joints in the façade, they should be wider; this enhances the post-rendering of the joints. In the Symphony concept, the distance between two façade elements is approximately 20 cm, which makes it possible to post-render the joints in a way that do not make them visible. 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 (see Figure 25).

Aesthetically, the joints can be treated in different ways. Depending on the architectural design, they can be either exposed or totally hidden to create an even façade. When exposed, the exterior surface material of the joint-elements is simply applied before assembly. The joint element will, in this execution, have
bands of expanding polyurethane attached to it before assembly. After application, these bands expand in an irreversible process and no post sealing is required. These elements will be mounted by crane and fastened from the inside at each floor level; this results in a finished façade instantly. The same type of joint-element is used when the joints are to be hidden. The only difference is that these elements must be rendered after the assembly (see Figure 25).

Figure 25. Joint-elements are mounted as full-length elements and rendered after assembly.

4.3 INTERIOR FINISHING

For the interior finishing of the buildings, traditional methods are used with conventional techniques, with the exception of the bathroom where prefabricated bathrooms are used. A point worth mentioning is that the outer wall elements are prepared with most of the electrical cabling integrated on the inner surface and that the rest of the internal installations are collected under a raised floor. Raised floors create an air gap between the floor and the concrete slabs (see Figure 26). This gap can be adjusted between 20 and 400 mm depending on model and manufacturer. Hollow-core concrete slabs are very bumpy and rough on the surface. To even out the floor surface, a layer of 20 to 50 mm of concrete is usually poured over the slabs. When using a raised floor solution as previously described, trowelling of the floor is not required. This will speed up the production since the drying time of the concrete is eliminated, while no additional moisture is built into the building. The created air gap is used for placing the installations - such as water pipes and electrical cables. The horizontal connection of the installations is enhanced since the distance between the actual device and the connection to the vertical ducts are substantially reduced. The installations of each apartment are connected to a connection point somewhere in the outer-walls of that apartment. This will not only facilitate the actual connection work but will also require less internal space inside the building reserved for installation shafts.

With the use of raised floors, the cables are able to run to the connection points directly the shortest way, and do not need to follow the internal walls. This leads to installation-free partition walls that are produced quicker than partition walls that contain installations. The procedure will not only reduce the amount of
metres cable needed and facilitate the work; it will also give a more flexible building. Renovation of an apartment will be much easier when non load-bearing walls with no hidden electrical cables inside are to be moved. The same discussion is valid for the water and sewage pipes. Sewage pipes that are not cast into the concrete slab create entirely different possibilities when it comes to changing the place of a floor drain. With the sewage pipes being placed under the raised floor, the original floor plan of the apartments becomes much more flexible since the bathrooms and kitchens can be placed individually in each apartment independent of the position of installation shafts.

The partition walls divide the plan into spaces; there are, 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. There are also higher demands on the acoustic insulation of these walls since they separate various apartments.

4.4 HVAC-INSTALLATIONS

The symphony concept integrates part of the HVAC-installations into the prefabricated elements as described earlier. In this way, the work of inserting the installations into the finished building is reduced. This is not to be underestimated since this type of work very often includes opening of holes in structures, such as load carrying walls or floor slabs, which is costly. In reality, every hole made in a building is a waste of resources since effort has been made to create the solid material and more effort is needed to remove the same material in less favourable circumstances.

No specific ventilation system or heating system is prescribed by the concept. The purpose is to offer the possibility for the customer to choose systems based
upon his or her own experience. The system, however, is well suited for the use of airborne heating systems – where ventilation and heating is combined – such as TermoDeck [Strängbetong] & [Barton et al., 2002]. The TermoDeck system uses the holes in the hollow core slabs for distribution of the ventilation air. The air is preheated and, in this way, also heats up the floor-slab, which results in low temperature heating of the building. The same system is changed during the summer to provide cooling. This also offers the possibility of using the cool air during the summer nights for night ventilation (see paper V).

4.5 FIRE SAFETY

According to the Swedish building codes, prescribed fire resistance class regarding load-bearing capacity for walls in multi-storey buildings is: R 60 for buildings with 2 – 8 stories and R 90 for buildings with more than 8 stories, regarding isolation of the fire, the requirement is EI 60 [Fallqvist et al., 2002]. R stands for load-bearing capacity; E stands for separation; and I stand for isolation: The latter implies prevention of the average temperature on the non fire-exposed side to rise above 140 °C. The numbers indicate minutes.

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; vertically, it is isolated by the concrete slab. The concrete slab provides good fire protection; the partition walls are designed according to standard solutions which fulfil these requirements. However, at the outer border of two apartments, fire can spread via the outer-walls - both horizontally and vertically. Normally, the outer walls are broken by the floor slabs; however, the Symphony outer wall which continues pass the slab, can contribute to the spread of fire between different apartments. With reference to the abovementioned, the construction of the non load-bearing outer-wall elements must separate and isolate the fire during 60 minutes. To accomplish this, the insulation blocks are exchanged for stiff mineral-wool at the border of the two fire cells - both horizontally and vertically (in order to prevent the fire from climbing up the façade).

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 is important to protect these components from the fire during a longer period of time in order to prevent the building from crumbling. Concrete constructions have a natural fire protection because of the material. The protection of the steel framing and the metallic joints is 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.
5 THE PILOT PROJECT

In 2005, theory was put into 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 metres, it has the proportions of a tower. Construction of the Research Tower was the result of co-operation 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 reserved for the production of the building elements. The four outer wall elements, the roof element, and the four joint elements were produced inside the factory and transported out to the yard where they were mounted on the steel frame structure (see Figure 27) – with hollow core concrete slabs – that was delivered by Strängbetong, similar to the structure in section 2.5.3 (see also Figure 10).

Due to the small area of the building, four outer wall elements were enough to cover the façade. Two elements contained windows and doors, one element was an installation element containing all the vertical installations of the building and the fourth element was a solid element. The assembly was designed to start with the erection of the primary structure followed by the assembly of the Symphony elements, starting with the roof element. With the roof in place, the work would be continued with the assembly of the outer-wall elements.

Figure 27. 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 metres, it has the proportions of a tower. The Z-beams for the standard formulation of the structure had to be exchanged for L-beams (see left picture).
5.1 PRODUCTION OF THE ELEMENTS

5.1.1 THE OUTER WALL ELEMENTS

The sheet metal profiles and the rigid insulation blocks for the CasaBona construction were pre-cut with millimetre-precision and delivered by different companies to the factory. The insulation blocks were cut with the same thickness but with different heights. The incisions for the flange of the Z-profile was also prepared (see Figure 19). The CBZ profiles and all other sheet metal profiles were delivered in full lengths with exact measurements. Only one of the suppliers’ many factories could produce the CBZ-profiles in full length (11.2 m). The delivery time was, therefore, one week longer for these profiles. The sheet metal profiles were delivered with millimetre-precision, while some difficulties were experienced with the delivered EPS blocks. In the first delivery of the EPS blocks, the incisions for the flange of the CBZ-profiles were not totally straight. The factory was contacted and it appeared that the reason had been carelessness from the workers side. This was probably not deliberate; the workers were probably not used to this level of precision in their production. Once the matter had been rectified, the next batch was delivered with perfect results. The width of the EPS blocks automatically provided the distance between the studs, which substantially increased the production speed. The line of expanded polystyrene blocks was broken by blocks of stiff mineral wool alongside the connection to the intermediate floor slabs for fire security and acoustic reasons, (see Figure 28). The intention had been to receive the stiff insulation blocks pre-cut as well; however, this was not possible since the order was too small. The pre-cut components significantly increased the production time; as soon as measuring, cutting, or sawing was involved in the production, the speed was reduced. The elements are designed to be produced in horizontal position beginning with the inside and starting with the CasaBona construction. Before the dry sheets are screwed onto the element, it is important that the element has the correct proportions and that the angles are perpendicular. This was very difficult to achieve due to the absence of appropriate facilities and the large size and weight of the element. In the future, this problem could be solved by using custom designed production tables. Once the core construction was finished, the work continued with the fastening of the gypsum boards and the horizontal studs, and placing of the additional inner insulation-layer before the element was turned over. The proposed production table should also be capable of turning around the element. This technology already exists, but was not used in the project because of financial reasons. The turn over of the elements was made with overhead cranes, which was extremely time-consuming and required too much preparation work. On the exterior, the element was covered with another layer of 50 mm insulation before it was rendered.

Rendering is the most used façade material for multi-storey buildings in Sweden, particularly in Stockholm. Outer wall elements with a rendered façade are fragile
and difficult to handle. The rendering layer is sensitive to movements due to bending of the elements and, therefore, it can easily crack. Render was, thus, chosen as façade material in order to extend these subjects. For the sub-base of the rendering, both EPS and high-density mineral wool is normally used.

A detailed investigation was made to study the moisture properties and movements in the rendering layer (see Paper II). The drying out of the outer wall after several days of rain was modelled. The rendering will expand and shrink in response to moisture and temperature variations in the rendering layer. The conclusions made from this study were that the temperature and moisture variations in the rendering layer are strongly dependent upon the thermal inertia of the wall construction. Light-weight elements have a low thermal inertia. To avoid high temperature variations, the thermal inertia of the construction can be increased. To avoid damages in the rendering layer, the rendering material on light-weight elements needs to be more elastic in order to not be damaged by the temperature movements. Based upon these conclusions and consultation with the rendering producer, a rendering material was chosen that was very elastic. For the sub-base, high-density mineral wool was chosen instead of expanded polystyrene. The high-density mineral wool has a slightly higher thermal inertia, while it has better fire resistant properties. The high-density mineral wool would also give the outer-wall better acoustic properties for the reduction of traffic noise.

Based on the experience from the experimental construction, it is estimated that, with the use of the correct equipment, the production time of the elements - excluding the rendering - can be reduced to 8 hours per element.

Figure 28. The CasaBona construction is seen up close - to the left and to the right an outer wall element during production is visible. It is also visible how the EPS-blocks are exchanged to high-density mineral wool at the connection of the floor slabs.

5.1.2 INSTALLATION ELEMENT

All of the vertical installations were integrated into the installation element (see Figure 29). Ventilation ducts were built in, along with the pipes for water and sewage. The electrical wiring was also built in. All the ducts had horizontal
connections at the correct level on each floor. As a result, after the assembly of the installation element, what remained was only to connect the local installations on each floor into the installation element. 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. Conversely, the vibrations from the ducts 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 installation element needed also to be covered with gypsum boards, but had many protruding junctions. One of the most time-consuming tasks during the entire production was to cut out holes in the gypsum boards for the junctions of the installations. Large tolerances were required for the holes in order to render the fitting of the gypsum boards possible. These large tolerances created voids that had to be filled afterwards. With the correct type of equipment, it is possible to screw on all the gypsum boards and cut out the holes afterwards, as done in the Part AB factory (see section 2.5). With more detailed planning, the pipes and ducts used inside the installation element can be delivered pre-cut and easily fitted into the element. This would speed up the production of the installation element, which was the most time-consuming element to produce.

Figure 29. All the vertical installations were integrated into the outer-wall.

5.1.3 THE ROOF ELEMENT

The roof element was rather small in this project, which enhanced the production. The element was finished with roof covering and roof drain (see Figure 30). A low slope roof was designed with an inclination of 1:60. A PVC roof covering was used which is suitable for low slope roofs. The PVC sheet is mechanically fastened onto the roof, while the joints are welded with hot air to ensure water tightness. At the borders of the roof, larger pieces of the sheeting were used. After the assembly, these pieces would be used to cover the joints between the roof and the internal side of the outer wall (see Figure 30). In this
way, the roof can be finished very fast once the outer wall elements are assembled.

Siphonic full-flow systems were used for the roof water drainage [Arthur & Swaffield, 2001]. The system sucks the water of the roof by the use of the gravity force at full flow. The system requires drainage pipes with a small dimension (Ø = 45-55 mm) for the pipes of the drainage system, which can easily be hidden inside the construction. The roof drain was also mounted onto the roof at the factory with a piece of drainage pipe connected to it (see Figure 30). This pipe would be connected to a drainage pipe that was integrated into one of the joint elements. During the assembly of the joint element, the protruding pipe of the joint element was to be connected to the pipe of the roof drain. The purpose was to achieve a completed water drainage system when all the elements were assembled. The roof element was, thus, completed with insulation, roof covering, roof drain, and drainage system.

Figure 30. The roof element was finished at the factory with PVC-covering and roof gully mounted. The pipes for the roof drainage were integrated into the construction of the joint element.

5.1.4 THE JOINT ELEMENTS

The joint element was designed as a T-section, which would incorporate the steel column of the structure when assembled (see Figure 31). These elements were also produced as full-length elements with a core construction of EPS and sheet metal profiles. The flanges of the element cover the opening of the joint in a better way and provide better protection against penetrating water. Bands of expanding polyurethane were fastened on the inside of the flange just prior to assembly. After application, these bands expand in an irreversible process; when expanded, they will tighten the space between the surface of the wall and the inside of the flanges of the element providing water and air tightness. Thus, it would not be necessary to access the joints from the exterior side of the building in order to seal them. The joint element was prepared with connections and was to be screwed onto the outer wall elements from the inside. In this way, the elements could be assembled by the crane and fastened from the interior side on each floor.
Inside one of the joint-elements, a drainage pipe was built-in with connections at the bottom and at the top for connection to the day-water drainage system and the roof drain, respectively. This resulted in full-length insulated joint elements with prepared connections, a built-in drainage system, and a finished exterior surface (see Figure 31).

The production of the element required a great deal of screwing, which should be reduced in the future. Also, the design of the element should be modified. Once assembled, in its present form, it creates cavities around the load-bearing columns of the structure. These cavities are difficult to tighten afterwards. In this project, it was chosen to enhance the joint by revealing it more at the façade with stainless steel as finishing material.

![Figure 31. 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 a crane.](image)

### 5.2 THE LOAD-BEARING STRUCTURE

Some minor changes were made to the standard formulation of the prefabricated structure. The Strängbetong system is adapted to construction with infill outer-wall elements, while the Symphony outer-wall elements are continuous. The beams carrying the concrete slabs were, therefore, changed from Z-beams to L-beams. The flange of the Z-profile would have gotten in the way of the outer walls that pass by the floor slabs (compare Figure 10 & 27). 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 shafts, elevator shafts, 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.
5.3 ASSEMBLY OF THE BUILDING

The prefabricated structure was mounted in one day by the supplier. Before the assembly of the building envelope began, the structure was controlled to ensure that the tolerances were within the prescribed ranges. During this procedure, it could be stated that the tolerances of the structure were very large. It was also discovered that the space between the steel columns were not correct. In the drawings that were given to the supplier of the structure, the position of the columns was marked with the outer distance between two columns since this distance was important for the assembly of the outer-wall and joint elements. The supplier, on the other hand, was used to centre-positioning of the columns. The structure had been assembled according to this principle resulting in a too little distance between the columns. It was possible to assemble the wall elements; however, the joint element would not fit since the space was too small. The joint elements had to be modified to compensate for the incorrect structure. Although this modification worked, it substantially complicated the assembly and the fastening of the joint elements.

Once the primary structure was erected, the assembly of the climatic shell continued starting 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 began. 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 slightly complicated the assembly.

For the assembly, a challenge had always been the lifting of the outer wall elements from horizontal to vertical position. 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 small during this phase, it can damage the construction materials such as the gypsum boards and the rendering. Calculations showed that the deflections would not be hazardous due to the use of the CasaBona construction, while the forces imposed on the bottom of the element would be too large. Consequently, it was decided to lift the element in two points and turn it into vertical position in the air. The wind forces during the lifting of the elements needed also to be considered. The wind has a strong impact on these light-weight elements because of the low ratio between weight and surface area. Calculations were made to determine the limiting velocities of the wind in which the assembly could be performed without any risks.

The elements were lifted in two points by two cranes and raised from the ground to the level were they could be turned to almost vertical position. At this point, the elements were put on the ground on an approximate 85 degree angle, while the bottom-lifting yoke was removed (see Figure 32). Now the element could easily be lifted and transported to any point by one crane. 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 was 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, and was made from the inside of the building at each floor level.

When the assembly of all four outer-wall elements was finished, the work continued with the assembly of the joint elements. Just before the joint elements were mounted, bands of expanding polyurethane were fastened on the flanges to achieve automatic tightening post-assembly. The elements were easily lifted by one crane at the top and guided by one person at the bottom. During the assembly of the joint-elements, no complications – due to the tolerances – were encountered. The pre-emptive measures taken had been successful. When the joint element that contained the roof drainage pipe was to be mounted, precision was of utmost satisfaction. 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 point, the façade of the building was finished and tight. The next move was to go on the roof and unscrew all the lifting eye bolts. The only work remaining on the roof was to insulate the joint between the roof and the interior side of the outer-wall elements, to fasten the roof covering – which was bigger than the roof area – onto the outer-walls, and to 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 in two days from a steel frame structure to a building with totally finished exterior - without the use of any scaffoldings.

Figure 32. Assembly of the outer wall elements; the elements were put on the ground on an approximate 85 degree angle, while the bottom-lifting yoke was removed (left picture). The revealed joint elements can be seen in the picture on the right.
5.4 INTERIOR FINISHING

The outer-wall elements were produced with the innermost layer of gypsum boards mounted on the interior side of the outer-wall element. Due to the tolerances needed for the assembly, the gypsum boards were cut shorter and did not reach the floor and ceiling when the outer-wall element was assembled. This created a gap that needed to be covered afterwards. There were also gypsum boards that became moist after a couple of days because of the change in the 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 dry sheets mounted at the factory. It would be better not to screw on the last layer of gypsum boards until the outer-wall elements are mounted.

The inaccuracies of the structure created problems during the sealing of the joints between the outer-wall elements and the concrete slabs. This connection must be airtight because of fire safety, acoustic, and comfort reasons. These joints were too large and irregular, and were very difficult to seal. The point of intersection between the joint elements and the slab was especially difficult. The design of the joint-elements created vertical cavities that were very difficult and, in some points impossible to access. The steel beams and columns were painted with fire protective paint before they were built-in behind the gypsum boards. The walls were covered with gypsum boards but not sealed or painted. The raised floor was constructed, but not covered with surface materials and not sealed along the walls.

The building is heated with the TermoDeck system. A heat exchanger is installed in the first floor. The preheated supply-air is led through the installation element to each floor were it is directed into the holes of the hollow-core elements. The air runs through the elements and is let out into the room through the floor. The return-air is collected below the roof via inlets in the installation element. The supply air and exhaust air of the system is also collected through ducts in the installation element that run all the way to the roof.
6 EVALUATION OF THE BUILDING CONCEPT

In this chapter, the objective is to evaluate the Symphony concept. During the construction of the Research Tower, the different technical solutions were applied in practice; it could be discovered that some of the technical details needed to be further elaborated upon. Measurements and tests performed on the Research Tower were used to evaluate the performance of the building. The construction of the Research Tower also provided information that could be used as basis for an assessment of the production time of the various parts and the total construction costs of future buildings. Based upon these evaluations, proposals are given for changes in the building concept, which would yield increased efficiency.

6.1 ELEMENT PRODUCTION

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 these tasks have one thing in common: they all require preparatory work. The measuring involves holding the measuring tape, which often required two persons (due to the large size of the elements), reading off the measurement, marking - and sometimes even transferring - the measurement to another point. Cutting involves a great deal of measuring, while performing the actual cut along a straight line also requires preparation. Mistakes were very easily made during these tasks, such as wrongly remembering the measurement and, therefore, cutting something too short. The turning around of the elements also required a great deal of preparation. However, it must be mentioned that the production facility was not fully adapted to this task. There were only two overhead cranes that were available and could be used to turn the elements around. Lifting straps and protective constructions had to be placed on the element prior to turning. Mistakes during the turning could damage the elements.

The elements could be produced with low tolerances; measured differences for the length and width of the element were about 0,05 %, which is equivalent to the tolerances of the measurement itself. The largest tolerances during the production were found on the diagonal of the elements, and were about 0,08 %. With the right type of production table, this could be reduced below 0,05 %.

The production of the joint-elements required a great deal of screwing, which should in the future be reduced. The design of the joint-element should also be modified since it, in its present form, creates cavities around the load-bearing columns of the structure after assembly. These cavities were very difficult to tighten post-assembly, and there were some areas that could not be reached at all from the inside.
6.2 ASSEMBLY

During the lifting to vertical position, the rigidity of the elements was very satisfying in the sense that it resulted in smaller radius of deflections than what was estimated. When the elements were in horizontal position and resting upon supports with a distance of 9 m, the maximum deflection was 8 mm. This led to the rendering not being damaged during the assembly (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 preliminary results show that elements up to 15 m long could be produced and assembled. For the actual lifting, simple devices could eliminate the need for the second crane, and speed up the assembly substantially. In the future, the elements will be lifted directly off the truck, thus, requiring only one crane. By optimizing the lifting and the mounting of elements, the assembly time for each element can be reduced to 30 minutes per element with three workers.

The experience from the assembly of the elements showed that it is possible to work with low tolerances. The mounting of one of the joint elements that contained the piping for the siphonic water drainage system can be taken as an example. The roof was prefabricated with the roof drain mounted. The roof drain would be connected to the water drainage system through a horizontal pipe – 45 mm in diameter – to which it was connected. This pipe would be connected to a drainage-pipe which was integrated into the joint-element and connected to the ground. The pipe that was integrated into the joint-element also had a horizontal connection at the top. The roof element was mounted on top of a four-storey steel frame. For the assembly to be successful, it was of utmost importance that these two horizontal pipes would meet in the zx-plane when the joint-element was mounted. This means that the adjustment possibilities of the pipes (5-10 mm) had to correspond to the added tolerances of the assembly of the structure and the roof element. The mounting of the joint element was successful, and the pipes could be connected with minor adjustment.

6.3 ENERGY

Evaluation of the energy performance is important for the estimation of the life-cycle cost of the building. Regarding insulation, the outer-walls in the Research Tower have a U-value of 0,14 W/m²K. The insulation layer is evidently thinner where the ducts are built in and could, thus, create thermal bridges; this could possibly result in energy losses from the installations integrated in the outer-walls. Measurements made in the Research Tower during operation, however, showed a temperature fall of 1 °C for the air-supply temperature between the first floor and the last floor (9 m) with a difference between the exterior and interior temperatures of 32 °C.
A thorough study of the building parameters that affect the energy use of buildings was made in paper V. Among other findings, the conclusions from this research were that increased thermal mass contributes to reduced energy use of a building. The thermal mass of the building must be in contact with the interior space. This can either be in the form of interior structural elements, or by placing the thermal mass on the interior side of the outer-walls - with as little insulation as possible towards the interior. For the Symphony concept, this increased thermal mass can be added by building the partition walls between the apartments with concrete walls, instead of light-weight constructions.

6.3.1 AIR TIGHTNESS

During the construction of the Research Tower, it was noted that there were some problems with the air tightness between the outer wall and the slab. It is very important that the separation of different apartments is air tight - both horizontally and vertically between two stories. Air leakages increase the spread of odours between apartments, while they also reduce the acoustic insulation due to the increased spread of sound. The leakages are furthermore a path for the smoke to spread between fire cells. The outer-wall element passes the slab, which implies that this connection must be properly sealed. The sealing material used here needs to be elastic since the outer wall will be submitted to horizontal movements due to the wind loads. These movements are very small; however, if the sealing is not elastic, it will be damaged by these movements. The problem with elastic-sealing materials is usually their long-time performance since the elasticity of the material is usually reduced with time.

The detail which is even more difficult to treat is the connection between the slab and the joint element. The joint element is a continuous element which, after assembly, leaves vertical cavities parallel with the outer-wall elements. These cavities run pass the slabs as well, and are very difficult to tighten. The design of the joint-element must be revised in order to enhance the tightening of this connection which, today, consumes too many working hours. The measured values for the air tightness of the Research Tower showed very high values for the air leakage: a mean value of 2,6 l/sm² for 50 Pa overpressure and negative pressure. This could be compared to the Swedish regulations that prescribe 0,8 l/s,m² [BFS 1998:38].

6.4 FIRE SAFETY

It has been noted that the fact that the outer-walls are constructed with insulation blocks of EPS is raising concerns among developers regarding its fire safety properties. It is, therefore, important to design the outer-wall so that the core of EPS is protected against fire. A study of the Symphony outer-wall was made to evaluate the fire-safety properties [Hoseini, 2007]. The construction was simulated with a heat load corresponding to the standard ISO fire curve. These simulations showed that the construction can uphold segregation of the fire up
to 50 minutes, provided that the gypsum boards are intact. It is difficult to
exactly predict the failure time of the gypsum boards. Solutions are needed that
protect the core construction of the outer walls from the fire for at least 60
minutes. In the current construction of the outer wall elements, the core of EPS
is exchanged for rigid mineral wool at the border of the fire cells. The rigid
mineral wool is fire-resistant and will, thus, prevent the spread of fire between
fire cells. With regard to this discussion, it can be concluded that the outer wall
fulfils the requirements. However, a thorough discussion with fire-safety
engineers combined with fire tests is required in order to classify the outer-wall
elements from the point of view of fire safety.

6.5 ACOUSTICS

The sound insulation performance of external walls of course determines the
extent to which dwellings will be isolated from intrusive sounds as traffic noise.
However, even the airborne and the impact-sound insulation between dwellings
can be affected by the design of the external walls, as these can also transmit
sound. This phenomenon is referred to as flank transmission and can be described
as the sound that reaches a receiver room via alternative paths through connecting
constructions (see Figure 33). Flank transmission is of special interest in the
present case since the outer walls are continuous, and pass by the intermediate
slabs vertically and the partition walls horizontally.

In Sweden, dwellings are classified with regard to their acoustical properties.
According to enforced building regulations [BBR, 2006], the minimum
requirement is that, at least, sound class C according to SS25267 [SS 25267,
2004] must be fulfilled. The requirements for sound-class C is a minimum of 53
dB for the airborne sound insulation and a maximum of 56 dB for the impact
sound insulation. However, when planning new dwellings, real-estate developers
often adopt sound class B, which corresponds to a better acoustical standard.

To study the acoustical properties of the external wall design, field
measurements were performed at the Research Tower. The following properties
were measured:

- façade sound insulation;
- vertical airborne sound insulation between dwellings; and,
- vertical impact sound insulation between dwellings.

The airborne sound insulation was measured, according to the method described
in ISO 140-4 [ISO 140-4:1998] and rated, according to ISO 717-1 [ISO 717-
1:1996]. The façade sound insulation was measured on one outer wall at a time,
according to ISO 140-5 [ISO 140-5:1998] and rated, according to ISO 717-1
[ISO 717-1:1996]. The measured façades were the north-façades (the ones with
the installations integrated) and the east façade, which is totally blind. The
impact-sound insulation was measured, according to ISO 140-7 [ISO 140-7:1998] and rated, according to ISO 717-2 [ISO 717-2:1996].

The measurement results obtained at the Research Tower are presented in Table 1. No difference in sound insulation properties of the façade was found between the blind wall and the installation wall. The measurements show that the Research Tower does not fulfil the demands for sound class C: neither with regard to airborne nor impact sound insulation. However, it is difficult to draw conclusions from the measurement on the role the external wall played in the sound transmission. A major problem during the measurement was that the interior of the building was not finished to normal standard levels and that the joints between the floor and the walls were not properly sealed. These joints were temporarily sealed with mineral wool; however, this measure was not completely satisfying. The cavities in the joint elements, as previously described, also contributes to increased sound leakage. Moreover, the installations that were integrated in the north wall should also have been equipped with sound attenuators. All of these facts lead to a great deal of sound leakage. Measurement data exists for the floor type used (FBS) in combination with hollow-core slabs. These values show that FBS-floor, combined with hollow-core slabs of 265 mm, fulfils the requirements for sound class B. With respect to the measured impact-sound insulation, it should be noted that the floors did not have any surface materials or impact-sound attenuation-carpets at all.
However, one should bear in mind that the Research Tower differs from a normal building due to the ratio between floor area and outer wall area. A standard room in an apartment normally has one outer wall, while the rest of the walls are interior partition walls (see Figure 33). The rooms in the Research Tower have four outer walls in each room. In a real apartment building, only a fraction of the flank transmissions will be transferred through the outer-wall. The rest of the sound will be transmitted through the slab and the interior partition walls. The concrete floor slab provides fine acoustic insulation because of the high density of the concrete. How much it can absorb is dependent on the mass of the slab. When the thickness of the slab is uniform its size will affect the mass. The walls connected to the slab will interact with it and contribute to the total mass of the slab. Therefore, when designing the partition walls, it is important to bear in mind that they will not only have an effect on the horizontal sound insulation between two apartments; the vertical sound insulation is also affected. Flank transmission is very much dependent on the construction of the wall and its connection to the slab. By a correct design of the partition walls and their connection to the slab, it is possible to greatly reduce the flank transmissions. Adding internal partition walls of concrete would have a positive effect on the acoustic performance of the building.

Table 1. Measured acoustic values for the Research Tower

<table>
<thead>
<tr>
<th>Acoustic Insulation</th>
<th>Sound</th>
<th>$R_w$ (dB)</th>
<th>$R_w + C_{50-3150}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne</td>
<td></td>
<td>52</td>
<td>50</td>
</tr>
<tr>
<td>Façade</td>
<td></td>
<td>44</td>
<td>34</td>
</tr>
<tr>
<td>Impact</td>
<td></td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

6.6 ECONOMY

The construction of the Research Tower was financed, in large part, by corporate sponsors. Furthermore, the proportions and the interior design are not representative of ordinary dwellings: the floor area is only 13 m² on each floor; there are no kitchens or bathrooms; the walls are not painted; and, the floors are not covered with surface materials. These facts make it difficult to estimate any realistic construction costs for the Symphony system based on the experimental building. Conversely, the cost for production of the elements and the required time for the assembly were experienced during the experimental construction. With the use of this information, a more detailed cost estimation for the construction of Symphony buildings was performed where the production cost of construction according to the Symphony concept is compared to conventional construction methods. The construction costs are divided into different cost posts that are then compared and put in relation to the entire
construction costs. In order to obtain a detailed description, the reader is referred to paper IV.

Figure 34 shows the production costs of the different posts for the conventional alternative and the Symphony alternative. The chart offers the possibility to directly detect and compare the pure economic consequences of the two production methods. In this case, the total production cost is reduced with about 12% when the same project is constructed according to the Symphony concept.

A closer examination of Figure 34 shows that the costs for the climatic shell and the management costs are reduced by almost 50%. The installation costs are also substantially reduced, while the cost for technical design is increased. In addition, it is notable that the cost of the prefabricated structure is raised by approximately 43%. We are left to ask the reasons why.

The cost for the prefabricated structure was based on the offer received by a local prefabricated concrete element producer, and was rather expensive. The price for the in-situ casted structure that was available in the original cost calculation was approximately 1500 SEK/m² including the partition walls that separate the apartments. This can be compared to the price for the prefabricated structure of approximately 2500 SEK/m², which was given in an offer received by a local producer of such constructions. To add to this, was also the total cost of 1.7 million SEK for construction of the light-weight partition walls that separate the apartments. It could be that the offer given by the manufacturer of the prefabricated structure was simply too high. Another reason could be that the structure was based on a steel frame-work that the producer needs to buy from a third party and, which increases the price. Another possible explanation could be that the prefabricated structure does not compete on the basis of the
price, but on time-efficiency so the company can, therefore, charge more for a product that saves time.

The use of symphony outer-wall elements does not require that the structure is a prefabricated steel structure with hollow-core concrete elements; it could just as well be used together with a standard in-situ casted structure. By placing the load-bearing partition walls in the correct way, it is possible to achieve limited restriction of flexibility of the interior plan. Dwellings contain many small fire cells (one per apartment) and the walls that separate them have high design requirements that will automatically be fulfilled when constructing these partition walls in concrete. Furthermore, since the walls are load bearing, the slabs need to span shorter distances. This implies an easier design and reduced production cost of the slabs, while the future flexibility of the floor plan is reduced since the load-bearing partition walls cannot be removed.

Based on the above discussions, a second alternative was examined that is a combination of the Symphony concept and conventional construction methods. In this version, the climatic shell is built up by the Symphony elements, while the structure remains an in-situ-casted concrete structure since this solution proved to be more economical. In this way it is possible to benefit from the advantages of both previous alternatives.

The foundation, climatic shell, and interior finishing are not affected by this change; whereas, there is an impact on the management post. The in-situ-casted structure takes longer time to complete and requires a great deal of formwork and temporary safety constructions. Fans and heaters are required for the drying of the casted concrete which adds to the costs. Consequently, the management costs will be higher than they would be for the pure Symphony version.

![Figure 35. Comparison of the cost for the different posts for the conventional construction method, construction according to the Symphony concept, and a mixed version.](image-url)
Figure 35 shows the production costs of the different posts for the three alternatives. It can be seen that the cost for the structure in alternative three is the same as in alternative one, while the climatic shell and the installations are the same as in the Symphony version. Furthermore, it is visible that the management costs in the mix version are lower than the original version since large parts of the building are prefabricated, yet they are higher than the Symphony version. This is due to the fact that, in the Symphony version, a prefabricated structure is used, which increases the construction speed substantially. When adding up all the costs, it is noted that the production costs for the mix version are 23% lower than the production costs for the original version.

6.7 SUGGESTIONS FOR IMPROVEMENTS BASED ON THE EVALUATIONS MADE

Interior partition walls should be exchanged for concrete walls regardless of whether or not they are prefabricated. It is visible that this will have an economic impact on the construction cost since the slabs will have a shorter span, which implies that the thickness is reduced and, by that, economic savings are made. Concrete partition walls will also give a better acoustic protection and are advantageous from a fire safety point of view as well. The concrete partition walls will also add to the interior thermal mass of the building, which gives way to reduced energy use (see paper V). The structure should, thus, be changed to a prefabricated structure based on hollow-core slabs and interior partition walls of concrete (see Figure 10). This would give the same cost for the structure as the in-situ-casted version, while it would still reduce the management costs; and, in doing so, the total construction cost would be further reduced by more than 23%.

The connection between the outer-wall and the intermediate slabs should be further examined, and sealing methods should be identified that are elastic and have adequate life-time performance. The methods chosen should also be quick in application so they do not slow down the assembly process. The production of the Symphony elements at the factory should be further developed towards pure assembly with more pre-cut components that speed up the production. Standard solutions for balconies should also be developed. This is a field of great importance, but has not been explored during this work. Furthermore, the interior finishing of the building should be developed towards an industrial production. This is a large cost post that has substantial potential for improvement (see paper IV). It is not necessary to prefabricate the entire interior space at the factory as is done with volume elements; however, the mere use of prefabricated components speed up the production – as is displayed with prefabricated bathroom units and partly prefabricated kitchen units.

The Symphony concept can be summarized as a strategy for industrial construction of buildings where the PDP is applied so that an increased use of
prefabricated building components is possible. This concept is based on an open platform, and the Symphony elements can be used – in combination with any structure – to form a prefabricated building-envelope with integrated installations.

Buildings constructed according to the Symphony concept will, preferably, be constructed with a prefabricated load-bearing structure consisting of: hollow-core concrete slabs and concrete partition walls between apartments; a prefabricated building envelope with integrated installations consisting of Symphony elements; prefabricated bathrooms; as well as raised floors. The Symphony elements can, however, be used in any other building concept to complete the entire, or parts, of the building envelope.
7 REMARKS ON THE FUTURE DEVELOPMENT OF INDUSTRIAL CONSTRUCTION

The definition of industrial construction is not an obvious one; the term is used in a variety of ways and in somewhat different contexts. What is clear though is that the interest for industrial construction is increasing on a global level as a way of reducing costs and increasing production speed. In this chapter, the subject of industrial construction is discussed from the point of view of the author.

7.1 INDUSTRIAL CONSTRUCTION PHILOSOPHY

There is a tendency of connecting industrial production with automated machines as a substitute for workers. This 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. Optimization of the construction has been going on during a long period of time; 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. According to the author, the key words for success in industrial construction are: optimization, control, and precision.

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 moving while the production equipment is not, it is possible to use larger and more powerful equipment. Controlling this movement is the reason for the success of the manufacturing industry - not mass production - as we are often incorrectly led to believe. Mass production is only a result of the optimization of the use of this equipment. Ergonomic studies of the human body along with psychological analysis of the workers’ mind can be used to find the optimized conditions for production. A great part of those conditions are found in a controlled environment such as a factory. Factory production gives an overall more regular working speed that result 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.

Furthermore, the tasks of workers need to be optimized. Measuring can be given as an example, which is a very time-consuming task that has a serious effect on the product. Optimizing this task will save a great deal of time while, at the same time, it 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.

The problem of the construction industry is the lack of refinement. In the manufacturing industry, the product is refined by a step-by-step process until it
takes its final form. Construction companies – even when using in-situ construction methods – use prefabricated components, such as windows or infill outer-wall elements. Large parts of the material processing, however, are made by the construction company. 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 car production. The car is produced by the assembly of various components. Each component is, in turn, a product of other components assembled together – and so forth.

The use of the CasaBona system is a step in this direction. The CBZ-profiles are delivered pre-cut with millimetre precision; it is the same for the horizontal sheet metal studs. The insulation blocks are also delivered pre-cut with the correct length and width; therefore, the work in the factory is limited to assembly. The pre-cut components are assembled together to form the building elements which, in turn, are assembled together to form the finished building. Furthermore, the CBZ-profile is a suitable example for how synergy effects can be achieved with a holistic point of view on the development. The sheet metal profiles currently available on the market are mainly optimized from the point of view of structural efficiency. This is why they are provided with many flange stiffeners and web stiffeners. This design complicates the insulation of the construction whereas cavities are created around the stiffeners. The CasaBona system integrates the insulating and constructive properties of the construction. The rigid insulation blocks provide support for the profile and strengthen it against local buckling, while the straight design of the flanges and the web increases the production speed and results in perfect insulation of the profile.

7.2 HOW CAN INDUSTRIAL CONSTRUCTION BE ACHIEVED?

The production methods of companies such as Strängbetong AB and Part AB can be defined as industrial since they change the production process and, in that way, speed up the production. This is done by application of new technology. The production lines for Hollow-core concrete elements and battery moulds for production of prefabricated concrete walls are examples of this type of technology that strongly reduce the need for manual labour [www.precastfountain.com]. In the factory of Part AB, the tiles are glued to the walls and the procedure is automated. Prefabrication in the building industry is normally limited to using traditional methods and materials to build (inside a factory) components or full modules very similar to the ones done on a traditional construction site (Richard, 2005). It is not enough to move the construction inside in order to improve it, if the work is more or less performed in the same way as on the building site. This type of production is similar to a workshop rather than a factory. There is a big difference between a factory and a workshop. Apart from the larger factories, workshops were the only places of production in the days before industrialisation.
Industrial construction methods do not only give a faster and more effective production of the building elements; they will also make it possible to produce different parts of the building at the same time. With traditional construction methods, the building must be constructed in a specific order. It is not possible to build the outer walls until the foundation is finished, or to construct the roof until the outer walls are finished. Industrial construction renders it possible to have parallel construction of the building elements. The outer walls and the roof can be constructed before the foundation is finished; it is only the assembly that remains on the building site. Industrial construction concepts should, however, be flexible with the goal of creating minimum limitations for the architectural design of the buildings.

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. Improved building-site logistics will increase the construction speed. To enhance the logistic planning, the amount of materials and components received on the building site should be reduced. Prefabricated elements reduce material deliveries to the site, while the waste that needs to be transported from the site is also reduced. The fewer the elements that are to be mounted together at the site, the faster the assembly will proceed. This gives that the prefabricated elements must be large. Large prefabricated elements contribute to an effective building-site logistics and material management on the building site. The larger the elements are, the fewer elements are required. Of course, this must be balanced with the cost and possibilities for transportation and effective logistics, crane capacity, etc.

JIT deliveries speed up the production because it reduces the material management on the building site. The materials received do not need to be stored, protected from the weather, and then recovered again. They are directly transported to the correct place for immediate use. Unfortunately, JIT deliveries do not function properly today since the transport sector does not prioritize it. The main reason for this is that the building sector does not currently demand this service. The logistical planning should, therefore, be performed with adequate tolerances in order not to create a dependency of the JIT deliveries. In the near future, and with the development of industrialized construction methods, the demand for JIT deliveries will increase and the transport sector will adapt to it by making JIT deliveries standard.

The building sector should not focus upon developing building concepts that produce turn-key buildings. The key to industrial construction is stepwise processing of the final product and specialization. This is a strategy applied by companies such as Strängbetong AB or Part AB. They have specialized in the production of a limited part of the building. In order to reach industrial construction, the sector needs to move away from construction and develop towards assembly. The main activity of construction companies during the industrial-construction era will be assembly of various prefabricated components.
that are delivered by other companies. The assembly will not, therefore, be outsourced, but will be in-house.

Industrial building concepts should, furthermore, be based on open platforms! This means that the building components of one company should be compatible with the building components of other companies. In this way, different components can be freely combined with each other, according to customer choice and in order to create variation. Strängbetong’s Basic Building is based on an open platform, while the concepts of Open House and NCC Komplett are based on closed platforms.

The general goal should be to approach the development of new solutions and products within the framework of industrial construction. With this collective goal, the products developed by the building sector will all be part of a shared catalogue of prefabricated components that can be combined in different ways to form various building types and to bring the sector closer to the era of full industrial construction.
8 CONCLUSIONS

By approaching the development of construction methods from the point of view of the entire building process, it is possible to achieve optimizations with synergy effects. The holistic view is necessary in order to identify details that can improve the whole building process when they are optimized. In this way, it is possible to achieve solutions that are time-efficient, energy-efficient and cost-effective at the same time. The level of synergy effects depends upon the knowledge and experience that are available during the early stages of the development. During the development of the Symphony concept, only basic knowledge of the acoustic and fire protective properties of constructions was available. This is also why these fields are the least optimized.

The largest cost posts in the construction of dwellings are the climatic shell (24 %), the interior finishing, and the management costs (which are proportional to the construction time at the building site and represent about 14 % of the total construction cost), see Figure 5. The construction of the climatic shell is optimized through the use of the Symphony elements. The management costs are reduced through the use of industrial construction methods – such as the Symphony concept – with a high degree of prefabrication. The results show that, all together, it is possible to reduce the construction costs with about 25 % when constructing according to the Symphony concept compared to conventional construction methods (see Paper IV). The interior finishing can also be optimized through the use of prefabricated components - such as prefabricated bathrooms. However, being the second largest cost post with 17 % of the total construction cost, there is large potential for optimization and cost savings within this field.

Industrial construction requires interdisciplinary design processes, such as the Parallel Design Process since they render the increased use of prefabricated components possible. This calls for a close collaboration between the different consultants (engineers and architects) and will yield more effective solutions, which can solve several problems at the same time. The design time of the building may be increased, while the construction time is reduced substantially.

Tolerance management is of very high importance and can have a great impact on the success of a building system. The conclusion from the experimental building is that it is possible to produce large elements with a tolerance of 0,05 %. Production tolerances should be kept low, while assembly tolerances need to be slightly larger to prevent complications during the assembly. The assembly tolerances should not, however, be too low since this can complicate the assembly; whereas, they cannot be too high either since this will lead to extensive post-treatment of the element joints.

Integrating the thermal insulation with the structural elements as the CasaBona system does, improves both the production efficiency and the material use. The
strength of the profile, when embedded in rigid insulation blocks, is increased between 22 % and 33 % when submitted to bending forces, and between 161 % and 210 % when submitted to compressive forces (see paper VI). This shows that profiles with a reduced thickness can be used to achieve the same strength. This effective use of materials provides both financial and environmental profits. The CasaBona construction renders the construction of large light-weight elements with high rigidity possible.

The experience from the experimental building shows that the production of the Symphony elements through assembly of pre-cut components give both increased production speed and reduced waste at the factory. Furthermore, it is shown that large full-height light-weight cover elements give increased prefabrication degree, improved thermal insulation, and enhanced building-site logistics, thus, reducing the total construction cost. The concept of cover-elements that pass by the edges of the floor slabs will, however, affect the acoustic properties. The acoustic evaluations showed that the flank transmissions can be increased if the design of the elements and their connections to the structure is not made in the correct way.

Simulations of the annual energy use of buildings show that the energy performance of buildings is improved with increased effective thermal mass (see paper V). To increase the effective thermal mass of the building, it is important that materials with high thermal inertia are placed towards the interior side of the building with as little insulation as possible between the construction and the interior space. Increased mass is also beneficial from the acoustic point of view. However, it is important that the interior space is separated from the exterior climate with constructions that have low U-values. It is also important that the outer walls are not too thick since this will occupy valuable living space. The strategy should, therefore, be to design the buildings with a core of heavy construction (which has large density and thermal inertia) and a building envelope of light-weight construction.

The production of the Symphony elements showed that it is possible to prefabricate elements with pre-cut components that are delivered by totally different companies. For the experimental building the production of the Symphony elements were produced in a “primitive” production line with simple hand tools. However, many modifications of the production line could be identified with which the production line could, step by step, be upgraded to a highly automated production line, requiring very little manual labour. The development of a production line should be an iterative process and based on experiences gathered from actual production. There is a large risk that a too hastily developed production line will yield inefficiencies as the volumes increase.

The construction of the experimental building made it possible to test the technology in an inexpensive yet realistic way. Possible complaints from dissatisfied tenants did not need to be considered since the building would not
be inhabited. The fact that the building has been empty has also enhanced the evaluation process with measurements and tests. However, it is important to bear in mind that the information that can be gathered from an experimental building is limited. It could, for example, be seen that the results from the acoustic measurements were not realistic; this was the same for measurements of the energy use. It is, therefore, important to design the shape and form of experimental buildings based on the tests and measurements that are planned.

The most valuable experience that was gathered in connection with the experimental construction was the evaluation of the construction methods - during the production of the elements and the assembly of the building, as well as the remaining post-treatment. Details may appear logical on the design table; however, only when they have been implemented can the efficiency be evaluated. The purpose of experimental construction is not to prove that the technology is working, but to test the technology and identify the means by which it can be improved. This shows that the development of the technology cannot be regarded as finished when the experimental construction has begun.

The results of the evaluation of the Research Tower showed that some parts of the initial concept formulation of the Symphony concept gave inefficiencies and had to be reformulated. For example, the steel frame construction of the structure with columns in the façade and no load-bearing partition walls was changed to a prefabricated structure with hollow-core concrete slabs and prefabricated concrete partition walls between the apartments. This was because the latter solution proved advantageous from the point of view of acoustics, fire safety, energy use and economy. The objective of any evaluation during the development work must be to find the best solution for the problem - not to prove that the “invented” solution is the best.
9 FURTHER RESEARCH

This research has raised some questions and identified fields in which there are potential for further research, which could favour the further development of effective construction methods.

- Current detailed studies of the productivity of the construction of different building parts do not exist. These types of studies are of high value for the detection of production inefficiencies and identification of improvement potential.

- Regarding the construction costs, it must be said that the construction costs that are available for researchers today are actually not costs but, in fact, the prices given by the building companies. The real cost of construction of different parts are not given out by the companies [SOU 2002:115]. Research within this field is also of great interest for the development work of improved construction methods.

- The exterior rendering of outer-walls is an operation widely executed and connected to large costs. While a large variety of various rendering systems with different properties exist, the actual application of exterior rendering of outer walls is still performed by semi-automated methods, which requires many working hours. Research and development, with the aim of finding improved methods for application of rendering, would yield economic savings and increased productivity within the building sector.

- Another aspect of the building construction that still demands a large amount of working hours, and is performed by highly manual production methods, is the various operations for the interior finishing of the building. This is a field with large potential for improvement and, as shown in paper IV, represents 17% of the total construction costs.

- In paper VI, it is shown that the strength of sheet metal profiles is greatly increased when embedded in an elastic medium - such as EPS. Further research is required to study the more detailed effect of this type of embedding upon the sheet metal strength: not only for the CBZ-profile, but also for other type of profiles in general. This includes the testing of different combinations of profiles and elastic mediums and studies of their behaviour under different loading conditions.
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