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Industrialised Building Systems

Vertical extension of existing buildings by use of light gauge steel framing systems and 4D CAD tools

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Susan Bergsten

Stockholm, April 2005

Abstract

Extending buildings vertically is fraught with technical and managerial problems. Inevitably, many of these types of buildings will be located in areas with access restrictions and other physical constraints on the movement of materials, components, operatives and equipment.

Industrialised construction methods and prefabrication could be a practical alternative to traditional construction methods for vertical extension projects. Industrialised construction methods are not much used in refurbishment projects and in this research project a case study with five vertical extensions projects is made. In this case study the extent of usage of prefabrication in these projects is studied. How these vertical extension projects have been conducted as regards to material handling and logistics planning are also studied.

Furthermore, the potential for utilising light-gauge steel framed system and its industrialised construction methods in Sweden is evaluated. This has been done by studying two projects, in which industrialised construction methods have been used. The use of light-gauge steel framed systems represents a practical and cost-effective solution to the problems created by these buildings. However, material handling and other logistical problems mean that the construction process is less than certain. A part of the study aims to understand the benefits from 4D CAD.

This research has three main areas, industrialised building methods with light-gauge steel framing system, vertical extension of existing buildings and 4D CAD. The results will include experiences from the studied cases and a comparison of the benefits over more traditional means for design and construction management when erecting vertical extensions to existing buildings.

Sammanfattning

Genom införandet av den nya lagen om tre dimensionell fastighetsbildning i januari 2004 har möjligheterna för påbyggnad av befintliga byggnader ökat. Behovet av centralt belägna bostäder är idag stort i storstadsområdena. För att möta den efterfrågan och bibehålla en hållbar stadsutveckling kan lokaler med attraktiva lägen utnyttjas mer effektivt genom om-, till- eller påbyggnader.

I detta forskningsprojekt har byggsystemet lättbyggnad med stål med särskild fokus på påbyggnader i kombination med industriellt byggande och 4D modellering studerats. Vidare har lättbyggnad med avseende på stålets utförbarhet för industriella produktionsmetoder utforskats. I två projekt, där lättbyggnadssystemet använts, har de använda industriella produktionsmetoderna studerats. Forskningsprojektet har också undersökt fem påbyggnadsprojekt. Problem uppkomna under produktionen relaterade till påbyggnadsprocessen har beaktas och de industriella byggmetoder som har använts i påbyggnadsprojekten har studerats. För att öka nyttan för inblandade parter har forskningsprojektet vidare haft syftet att utvärdera moderna projekteringshjälpmedel för informationshantering, såsom 3D CAD och 4D CAD. Inom ramen för projektet har 4D CADs möjligheter för att förenkla och förbättra denna process iakttagits.

De industriella byggsystemen och produktionsmetoderna i de undersökta projekten var koncentrerade till fältfabrikproduktion snarare än helhetslösningar för hela leverantörskedjan och värdekedjan för byggprocessen. Många uppkomna problem under produktionstiden hade inte sin grund i själva byggsystemet och dess möjligheter för industriell produktion utan till hur man implementerade de förändrade krav som ett industriellt byggande medför. Lättbyggnad med stål har med sin lätta egenvikt samt smala toleranser stora möjligheter för industriella produktionsmetoder. Många av de upptäckta problemen i fallstudierna är relaterade till avsaknad av kunskap för planering och utförande av industriella produktionsmetoder samt bristande koordination mellan projektering och produktion på byggarbetsplatsen. Här har 4D CAD stora möjligheter att förenkla integreringen av projektering och produktion men också byggarbetsplaneringen. Med tanke på att vid påbyggnader är byggarbetsplatsen en av de viktigaste restriktionerna, måste byggarbetsplatsens aktiviteter beaktas. Logistikplaneringen på, till och från byggarbetsplatsen i alla de undersökta projekten kunde ha utförts mer koordinerat och därmed hade materialhanteringen till och från arbetsplatsen men även på byggarbetsplatsen effektiviserats mer.

List of publications

This thesis is based on the following papers.

Paper I

Bergsten, S., (2002), Using 4D CAD in the Design and Management of Vertical Extension of Existing buildings with Light-Gauge Steel. *Construction Process Improvement*, Blackwell Science, Oxford.

Paper II

Bergsten, S., (2002), Vertical extension of existing buildings by use of the Light Steel Framing, Steel in sustainable construction, conference Proceedings, International Iron and Steel Institute World Conference 2002 15-17 May Luxembourg, 49-54.

Paper III

Bergsten, S., (2005), Industrialised construction for vertical extension of existing buildings (to be printed).

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1 Introduction

1.1 General

The demand for apartments situated in the city centres is presently high in attractive regions and is likely to increase. One way of meeting this demand has been extending existing buildings vertically and horizontally which has frequently been undertaken over the centuries (Bergenudd, 1981). An important feature of extending existing buildings vertically is the possibility to use already developed land and resources such as existing buildings, roads, telecommunications and sewerage systems. By integrating residential houses, workplaces, recreational areas and shopping centres, the city becomes more active all day round and a safer street environment will be created. Moreover, vertical and horizontal extensions of existing buildings are a natural way of the urban development and rebuilding process. During the last years, vertical extensions of existing buildings have attracted a great interest in Sweden. This is related to a new law valid from January 2004, which made possible the division of an existing building's ownership into separate ones. The law change enabled land and buildings thereon to be subdivided into common property areas and lots, with separate title and ownership of the lots. The traditionally defined ownership of a building in which the building belongs to a lot, is extended to a three dimensional definition of title and ownership of buildings (prop. 2002/03:116). This has been welcomed by the industry because the owners received their title deed to a unit where e.g. the existing buildings have mixed use as retail, commercial activities and residential areas. The new law and the need for housing provided a good opportunity for vertical extension projects using an efficient construction process and adequate building systems. Extending buildings vertically is however fraught with some specific technical and managerial problems (Wall, 2001) (Bergenudd, 1981). Inevitably, many of these buildings are located in areas with access restrictions and other physical constraints such as movement of materials, components, operatives and equipment. Thus, the construction processes for these buildings are considered to have more constraints than for those in traditional housing projects. One way to meet these constraints is to use an industrialised production more extensively.

The ideas of industrialised production methods for the construction industry have been discussed during many years. In the sixties the production of the structural components of buildings was industrialised and the material used was often concrete. The structural components were erected on the site and afterwards interior work, service and installation were installed on the site. Concrete and steel were the main materials used in the elements and the components. Concrete slabs and columns result in heavy elements, which require a large crane to handle these elements at the construction site.

Moreover, transporting heavy structures is less cost-efficient compared to transporting lightweight structures. Effective design and site control is essential for any construction work. Small tolerances for assembly of components are vital in order to ease fit-out, sizing and positioning in a production environment. A common comment from practitioners within the construction industry is that the significant disadvantage of concrete elements for industrialised construction is its dimensional inaccuracy. Wood, an organic material, is also less suited for large-scale industrialised construction due to shrinkage and shape distortion. Warsawski (1999) points out some reasons behind the failure of the industrialised building process in the period following the late seventies. They are summarised below.

- The failure of designer and producer to think in systems rather than in individual elements resulted in less attractive buildings and less efficient building systems.
- The fragmented and diversified demand of that time made prefabrication less competitive than existing methods. Methods and tools for the automation of the building process were not yet developed.
- Lesser demand, lack of system approach and lack of efficient management resulted in a higher unit cost than that of traditionally constructed ones.

An industrialised building process requires the industrialisation of both the design and the production process. The industrialisation of a process is an investment in equipment and technologies with a purpose to increase the productivity and the output using less manpower. An additional purpose of the industrialisation is to improve the quality of the product. Industrialised design in the building industry can be defined as the art of utilising the resources of technology to create and improve productions and systems which serve human beings, taking into account factors such as building performance, safety, economy, and efficiency in production, distribution and use. Such design may be partly expressed in external features but is predominantly expressed in integrative structural relationships responding to the demand and a meaningful form (a problem solving method) (Haris, 1975). Industrialisation of the production mainly concerns production planning, prefabrication and assembly processes. However, to some the term industrialisation means especially prefabrication and the role of factory production and to others rationalisation and automatization of the production process.

A building system could be defined as all components necessary for a particular building together with the execution process or any assembly of integrated building subsystems satisfying the functional requirements of the building. An industrialised building system can be described as a building system where the design, production, and assembly are strongly interrelated as an integrated process. Moreover, the industrialised building system has been developed in order to increase the productivity of the production by using prefabricated assemblies with minimum site works (jointing and finishing work on site). Furthermore, on site handling of material and components are rationalised and mechanised in order to simplify the logistics to, from and on the site. Important components of an industrialised building process for building systems can be summarised as follows:

- Flexible design of a building system is associated with the financial side of the system and how its subsystems are associated to the degree of variability, irregularity in the different subsystem and the prefabricated elements. However, flexible design, cannot affect the economy of the system if enough production units are produced.

- Lightweight building components in order to minimise the need for heavy cranes and machines and to ease the transportation of the elements from off-site factories to the construction site.

- High level of prefabrication to minimise the work at the construction site. Off-site, factory production can also guarantee a higher quality of elements.

- Simple erection with developed jointing methods on site to obtain higher productivity at the site.

- Small tolerances to ease the production at the construction site.

- Accurate planning of the construction process and coordination between the design (the design process of the specific project and also the design and development of the building system) and the production process, (accurate planning of the plant and off-site factory as well as the construction site).

- Developed logistics between the different suppliers in the supply chain in order to recognise redundant parts in the chain. Developed logistics at the construction site allows having a satisfactory workflow and a high productivity at the construction site. Just in time deliveries, delivering of elements to the construction site, as they are required by their erection schedule, will enable minimisation of waste in work and material flow to the construction site.

A frequent classification of systems used in construction is based on the used structural materials as timber systems, steel systems, precast concrete and cast in site concrete systems. This research concentrates on a building system using light-gauge steel. Light-gauge steel framing mainly compromises three different materials: thin steel, mineral wool and gypsum boards. Research on light-gauge steel framing has shown that the construction time can be significantly reduced by an industrial production of building elements and a fast erection on the building site. Moreover, the significant elements of industrial production are realised in this system (Hiraga, Furukawa, 1966) (Sand, 1998) (Cederfeldt, 1996) (Lessing, 2003). The use of light-gauge steel framed systems represents a practical and cost-effective solution for apartment buildings (Andersson, Borgbrant, 1998) as well as for vertical extension and over-roofing (Toma, 1999) (Verburg, 2000) (Hiller, et al, 1998).

Light-gauge steel framing results in a lightweight building. For example it has been shown that the weight of such a building is only one-fifth of one made of traditional material like concrete (Burstrand, 2000). Therefore the need of reinforcing the existing building will be minimised when vertical and horizontal extension are considered. Consequently, the cost of the extension of the building will be reduced. Accordingly, the light-gauge steel framing system is suitable for vertical and horizontal extensions of existing buildings. Furthermore, the steel is inorganic and hence the risks for moisture and mould problems are very small. With a suitable production method and production management the materials will remain dry during the construction time. In addition this building system has a relatively low use of resources and the materials have an established recycling loop (Adilstam, 1997) (Burstrand 2000). The building systems with light-gauge steel can fulfil the requirements regarding acoustics and thermal comfort (Burstrand, 2000).

Material handling and other logistical problems mean that the construction process is less than certain. The concept of 4D CAD, a 3D model extended with a time dimension, is being considered for applications in the building sector in order to overcome the shortcomings in traditional non-visual and 2D CAD processes, in regard to construction methods, resources and schedule reviews. The enthusiasm for 4D CAD's capabilities comes mainly from academic research units and some pilot projects, which have been undertaken by the industry.

1.2 Research objectives and positioning the research in a larger context

An overall goal of this research is to meet the demand for apartments by ensuring a good balance between social, economic and environmental needs. As a result of the mentioned background the capabilities of vertical extension with the light-gauge steel building system for residential use will be examined. The research concerns three main areas, illustrated in figure 1-1, where light-gauge steel framing, 4D CAD as a managerial tool and vertical extension of existing buildings are the topics. Each of the research subjects has a broad context and could contain several independent research projects. However, in this research project these subjects have been put together in order to find a common denominator of the three subjects**.** The research focus is to find and evaluate the potential both for this building system and the 4D CAD tool in order to improve the construction process for *on-top construction*. One way of doing this is to use the 4D planning process in combination with the industrialised production of building components.

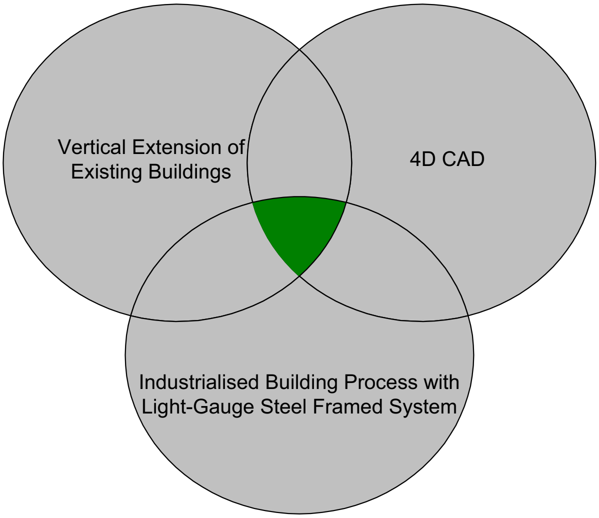

Figure 1-1: The main area of the research project

2 Research question

The underlying hypothesis of this research is that the industrialised building methods of light-gauge steel framing and the 4D tools have the potential to improve the integration of new apartments within existing buildings. The hypothesis is based on a “how” question. However, the lack of projects, where a building is vertically extended with light-gauge steel and 4D CAD has been used, made the evaluation more complicated. However, it is possible to investigate the possibilities of industrial building of light-gauge steel processes by studying how traditional construction processes for vertical extension projects are and how these processes meet the demand for fast and high quality vertical extension projects. The research is focused on contemporary events in a construction project and involves social and organisational behaviour. The investigator has no control over the events in the construction project. The goal of the research is to develop relevant hypotheses and propositions for further investigation of the three main subjects of the research, industrialised building with light-steel framing, vertical extension, 4D CAD tool. The research question can be stated as *if industrialised building methods using light-gauge steel systems and 4D tools can improve the construction process for vertical extension projects.*

The research question is explorative and the research type is related to change in management and evaluation involving many parameters. In order to verify the hypothesis and answer the research question, the following sub-questions are defined.

- How and to which extent an industrialised building process is used in vertical extension projects.
- What is the potential for the industrialised building process for vertical extension projects.
- What potential 4D CAD has to improve design and construction processes and increase the productivity of the project.

These sub-research questions are explorative. By stating these sub-research questions and answering them the aim is to obtain a picture of the state of today’s construction process and understand the industrialised building process and its application to vertical extension projects. The usage of 4D CAD tool in the construction industry is studied in order to understand its advantages and disadvantages.

3 Research method

This section will discuss the implication of the different methodologies available for this research. The methodologies used in previously related research are identified. Furthermore, the method of research and the research process are described in this chapter.

The idea of 4D analyses is not new and the first related research dates from the late fifties. Early research regarding the 4D CAD has been based on models in which information coordination and construction management in projects could be made and research for software development was performed. Later 4D CAD research has been based on feasibility studies of 4D CAD tools and the different software packages' impact on the construction process. This has often been done with qualitative research methodology.

Research about the technical and the managerial impacts of vertical extension have been relatively limited. On the other hand the industrialisation of the construction industry has been extensively researched. Research regarding the industrialisation of the construction process can be divided in pre sixties and after sixties. Definitions and approaches differ in many aspects. In these research both quantitative and qualitative approaches have been used and interesting facts have been found. In this research project, in order to understand the light-gauge system and the industrialisation of the system the two projects Näktergalen and Open House were studied in detail.

During the literature review and the state-of-the-art review phase of the project, no research project, which considered these topics together, was found (as: the usage of 4D CAD in industrialised building process or industrialised building process for vertical extension projects or 4D CAD tool usage in vertical extension projects). However, examples of researches based on case studies, in which the use of 4D CAD has been analysed in projects with a high level of restriction have been made by other reserchers.

The purpose of this study is not to produce statistical data for the measurement of the efficiency of the industrialised building methods of light-gauge steel framed system for vertical extension. Hence quantitative research methods have not been used. The research has been limited to understanding the construction process for vertical extensions and the possibility for building systems such as the light-gauge steel frame. An additional purpose is to understand the capabilities of the 4D CAD tool for usage in industrialised building processes.

3.1 Research design

Defining the three sub-research questions has been an important step in the research process. Each sub-research question was considered independently. The research method chosen for each sub-research question is based on the type of the question. To begin with, the research project was concentrated on literature study and previous research about the subjects of vertical extension and 4D CAD modelling tools.

The research method for the third sub-question, has 4D CAD the potential to improve design and construction processes and increase the productivity of the project?, has been mainly literature study. The researches made related to 4D CAD is studied in a literature review. Thereafter follows a discussion about the possibilities of using the 4D CAD as a managerial, control, and steering tool for vertical extension projects. However, this is based on previous researches and literature studies and is by no means directly validated in this research project. As in the Swedish construction industry no 4D CAD tools have directly been used, it has been difficult to study the advantages and disadvantages of the tool in a case study.

The answer to the other sub-questions has been searched by a study of five different vertical extension projects. Case studies have been chosen as the method to answer the explorative sub-questions of the research. The design of the research is illustrated in figure 3-1. In the first phase of the research projects five different vertical extension projects were identified. These projects were observed and a semi structured interview was made in order to understand the projects' problems, restrictions, structural systems and building methods. In the second phase, three of theses five vertical extensions were chosen for further investigation. In this study, industrialised construction have been studied from the point of view of two characteristic and related subjects:

- Grade of prefabrication and the relevant decision process.
- Use of logistic strategies in the construction process and the material handling process.

The reason for choosing these three case studies was the willingness of the project managers to share information.

3.2 Limitation of the study

This research project is characterised by the vertical extension projects, which has been available for studying during the research period and also the projects partners' volition for sharing information regarding the construction process to the researcher.

One major challenge of vertical extension is the integration of the services. This was concluded from the first phase of the research project but it was not studied further. The reason behind this decision was the lack of ability to involve the actors in these projects after the end of the project time. In the second phase of the case studies the industrialised building process was extensively studied. This could be continued in a third phase with a more narrow perspective of the most important outcomes of the second phase. However, this has been omitted due to lack of time and has been left to the next research project.

The interviewees were the contractors' construction managers and the clients' construction managers. Only interviewing managers at high level in the project organisation can obtain different perspectives of experienced problems in the projects. However, the managers of high level could have more holistic views on the project and the construction process, which gave a more valuable input. The experiences of the interviewees and their understanding of the researcher have influenced their answers and the aspects and topics that were discussed. These can clearly be seen in the interview protocols where the different interviews are in some aspects different. The results from the qualitative analysis are limited to the interviews and the persons who were used as sources.

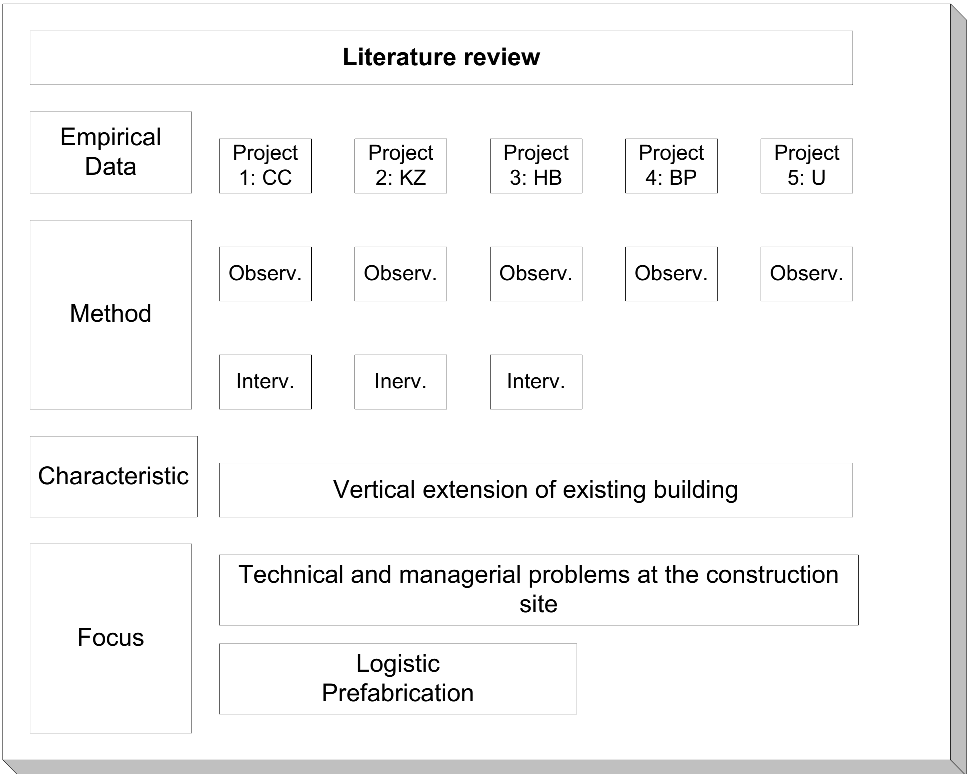

Figure 3-1: Overview of the research design.

CC: Citv Cronan. KZ: Klara Zenit. HB: Husbv. BP: Berzelii Park. U:

3.3 Case studies

Parallel to the literature study five vertical extension projects were chosen to be studied. Bergsten (2005) contains a complete description of those construction projects and cases studies including the case studies protocols. These case studies are the main part of the research and have provided rich and plentiful materials for understanding the construction process of vertical extensions. Figure 3-1 shows the overview of the design of the research. These cases have been selected with regard to industrialised building methods and traditional construction methods for vertical extension projects. At that time, late 2001, these projects where the ongoing vertical extension projects in Stockholm.

During the execution of the projects several site visits and structured interviews were made in order to understand the problems related to vertical extension projects. The focus was on the structural solution for vertical extension, integration of the new structure to the existing structure and restrictions, which the restrictions could be, inferred on the construction site and also the extension of services, sewerage and elevators. The second phase of the research was concentrated on only three of these projects and was carried out when the projects were finished. The open interviews were concentrated on process related parameters and managerial aspects of the construction process of vertical extension of existing buildings. The subjects, which have guided the preparation of the second phase of the case studies, are the following.

- Level of prefabrication.
- Logistics organisation and coordination.
- Material handling at the construction site.

The fact that the second phase of the case studies was conducted retrospectively gave the possibility to compare the change of attitudes between the first phase and the second phase.

4 Vertical extension of existing buildings- case studies

An on-top building project has more constraints compared with building project in areas, which are not as much exploited as city centres. The complexity of an on-top building project depends not only on the usual factors in all building projects but also in factors as follows:

- Lack of space for material handling on site
- Inner city traffic and its effects on deliveries to the construction site
- Disturbance to the surroundings and to the existing activities in the already existing buildings due to construction activities
- Need of more understandable communication between those involved in the project and the tenants in the existing building.

These factors compel that an on-top building project is more critical. Vertical extension projects have often been highly on-site constructions and prefabrication has not often been used. Usually vertical extensions have a lot in common with refurbishment projects.

In the following sections the five case studies will briefly be presented. All these cases were in Sweden and during an economic upswing. The complete case study report is presented in Bergsten (2005).

4.1 City Cronan

At the time the project was one of the big ongoing projects in central Stockholm and comprising 50 000 m^2 refurbishment and extension. This vertical extension project was performed under the design and build contract model. However the client organisation and the contractor organisation were in the same combined business group, which facilitated the communication between the organisations. The project was highly focused on the tenants. A fast construction process was desirable and the construction time was during the years 2000 to 2003. The construction system was prefabricated steel columns and pre-cast concrete slabs. The existing building was built in the seventies and its structural system is site cast concrete slabs and columns. Two houses in the block were merged together by the extension. The buildings were vertically extended with two and four floors (figure 4-1). The project was characterised of high complexity e.g. two tunnels were located under the building. The complication of the foundation resulted in many uncertainties in the construction process. The just-in-time production philosophy was used in the project.

Figure 4-1: KV. City Cronan after reconstruction

4.2 Klara Zenit

The existing building is from the late sixties and was built with site cast concrete slabs and pre-cast concrete columns. The buildings in the block were extended with one floor and with two storeys detached houses on top. The extra floor was built with site cast slabs and the houses were made of prefabricated timber elements. Also refurbishment of the existing building was a large part of the project. The total area involved were 68 000 m^2. The project was carried out under the design and build contract model. The client organisation was a joint venture between the contractor, an investment company and a property company. This resulted in a close collaboration between client and contractor organisation through the design and construction processes. The needs and the wishes of the tenants were central in the design and construction process of the project. Therefore, the design team and the client organisation were placed at the construction site in order to integrate the production and design processes and minimise the construction time with maximum tenant flexibility. The just-in-time concept was applied for the production. A fast construction process was desirable for the client organisation and the construction time was between 2000-2003.

4.3 Husby

The existing buildings were built during the seventies. The buildings had five floors and its structural system is site cast concrete slabs and pre-cast concrete columns. The project involved vertical extension of three buildings and each building was extended with one-storey volumetric student study bedroom apartments. The project comprised 35 new apartments (figure 4-2). There existed a written agreement between the client and the contractor for vertical extension in the area. This agreement was based on an old relationship and experiences in earlier projects. The project was performed with the design and build contract model. The client organisation was a municipal housing company. The existing building was from the early seventies with concrete structural frame.

Early in the project the client decided to use a highly prefabricated building system in order to minimise the disturbance to the surroundings. Characteristic of this vertical extension project was its high level of prefabrication. The project had to be finished before the start of the academic year, but due to the failure of the suppliers in delivering modules on time, it failed to do so. The total construction time was nine months.

Figure 4-2: Husby project after reconstruction

4.4 Berzelii Park

The building in the project Berzelii Park is placed in an area with many hotels, theatres, restaurants and commercial buildings in the Nybro bay in Stockholm. The vertical extension was on a theatre hall, built at the beginning of the last century, which had already been extended with five floors during the late sixties (figure 4-3). The project included demolition of three floors, refurbishment of the existing building and vertical extension with four floors. The theatre and the original façade were to be conserved. The vertical extension's structural system was a combination between light slabs, steel columns and slabs with precast concrete elements. The construction time was during the years 2000 to 2002.

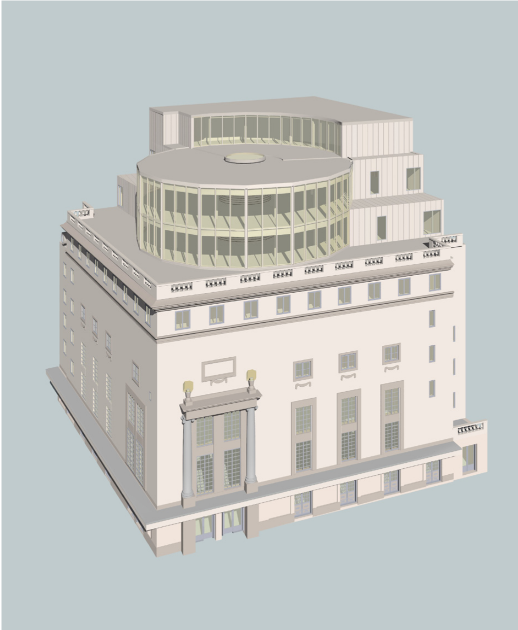

Figure 4-3: Outline of the Berzelii Park project after reconstruction

4.5 Unionen

The buildings in the project Unionen were placed in central Helsingborg, near the old town and the university. The project contains several phases. The first phase was the refurbishment of an office building and the second phase was vertical extension of an existing parking house with four floors. The vertical extension contained 60 student flats. The second phase of this project was included in the case study. The existing parking house's structural system was site cast concrete from the early sixties. The project was carried out under the design and build contract model. The construction site was very limited and in consequence one of the roofs of the buildings was used as field factory where exterior wall elements were assembled. The vertical extension's structural system was light-gauge steel framed together with hot rolled steel columns and slabs. The construction time was during the years 1999 to 2001.

5 Industrialised Building

Industrialised building has been defined as “the term given to building technology in which modern systematic methods of design, production planning and control as well as mechanised and automated manufacture are applied” (Sarja, 1996). The industrialised building process requires industrialisation of both the design and the production process. The industrialised building process has for a long time been about prefabrication of components and elements of a building. Prefabrication can be defined as a building production wherein the components or assemblies are manufactured fully or partly (composites) in factories and thereafter assembled on-site. In the building process different levels of prefabrication are used. Prefabrication has often been used as a solution for a particular kind of building such as industrial storage, holiday homes, detached houses and temporary shelters. In order to use the same technology in certain respect, for increasing efficiency in refurbishment of commercial buildings and housing projects in the city centre as well as vertical extension projects, new ways of thinking of prefabrication have to be developed. Prefabrication and off-site production is not often used in refurbishment projects (Gibb, 1999). Different types of buildings require different building systems.

A building system and its sub-systems consists of several components each one with a defined design, function and production method, figure 5-1. In all buildings some components and/or sub-components are industrially manufactured e.g. doors, steel floors, or cladding sections. The level of industrialisation is thereby varying a lot between different projects. Prefabrication of sub-systems e.g. slabs, external walls, structural frames etc is not unusual. The building system’s flexibility is related to the adaptability of the production methods and to different architectural design with reserved economy. The building system should give the architecture maximum design freedom but some restraints are inevitable.

Prefabrication constituents are standardisation, pre-assembly of components and sub-systems of a building system and modularisation of building systems. In an industrialised building process it is necessary to define a complete system for planning, production, managing and controlling as well as designing, assembling and manufacturing the products. This means that not only the design of the product should be defined but also its supply chain including logistics, material handling and assembly technology. Prefabrication as well as on-site construction must focus on quality, economy, aesthetics and give the architectural design reasonable freedom. Cost-efficiency of a building system with a high level of prefabrication is mainly related to the adaptability of the components and the sub-systems to different design.

Standardisation is not about building standard houses but to bring certainty into the process. It is about improving the physical, organisational and the contractual interference as well as standardisation of components, dimensional standardisation of elements and standardisation of production methods. Standardisation will also give better predictability and higher quality to the product and the process. Design rules for both designer and producer, such as norms in different fields of engineering, are commonly used. These commonly used design rules and norms are important for the development of industrialised building processes.

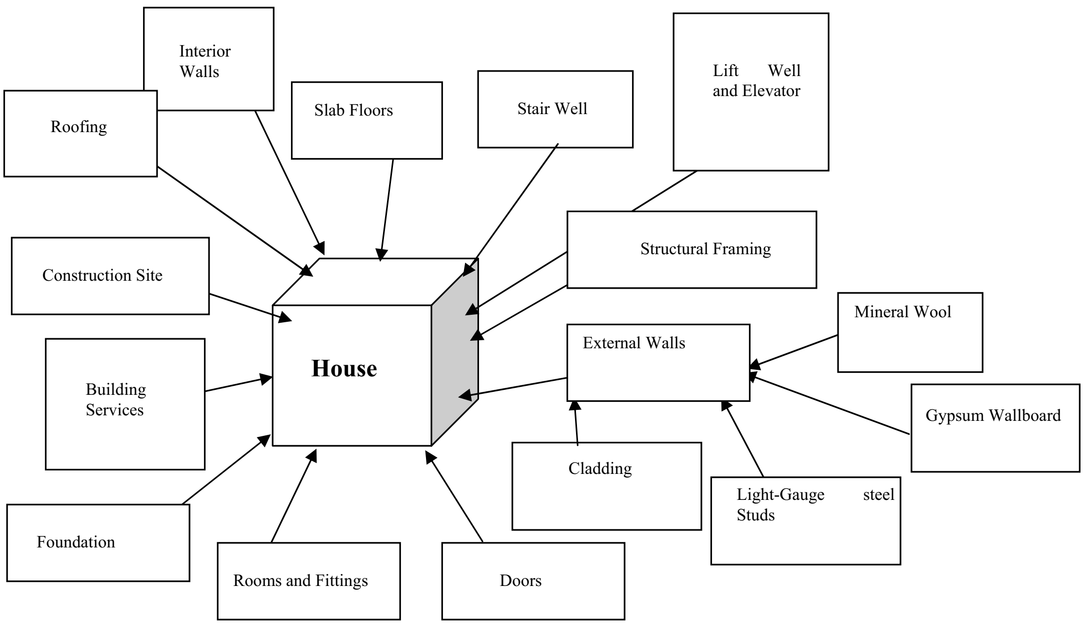

Figure 5-1: A typical building consists of a system with many different components and sub-components. The total or parts of the building system can be produced under industrialised production conditions.

From the technological perspective, almost any architectural requirements can be related to prefabrication but it might be costly. The benefits of standardisation is obvious, such as higher production series, better utilisation of plant investments, higher standardisation of the labour, however it is not possible to adopt it fully. Standardisation within a building system can be realised but for a building system to be adaptable to shifting demands, it has to be adaptable to other building systems. The demand for buildings is not standardised and thereby the product meeting this demand cannot be standardised either. Therefore, standardisation has to be sensitively performed. Hitches of interchangeability of different components and sub-systems of different building systems can be due to the nature of connections and joints of the building systems and also due to non-modular and non-uniform components and elements, such as slabs' and walls' thickness (Warskawski). Buildings have an extremely long life. During the standardisation process the life cycle of the building has to be well thought-out. In the future when functional changes of a building are required, the adaptation could be even harder.

Pre-assembly is a process by which various materials, prefabricated components and/or equipment are joined together at a remote location (plant off-site or in a plant on-site) for subsequent installation as a unit at a construction site. Pre-assembly gives the opportunity for decoupling sequential activities into parallel activities. Modularisation is a particular form of pre-assembly in which volumetric units are manufactured off-site. However, pre-assembly and modularisation increase the risks of damage during transport and handling.

In an industrialised process the design and the production are more integrated and the construction process resembles a manufacturing process. Industrialised processes are related to the relationship between the different actors in the construction process and the supply chain, see figure 5-2. In an industrialised construction these relationships are recurring in different projects. Moreover, the industrialised processes are related to a defined method of work within prefabrication, pre-assembled components or modular systems. Industrialised processes imply new approaches for construction process monitoring and control as well as complex requirements for procurements.

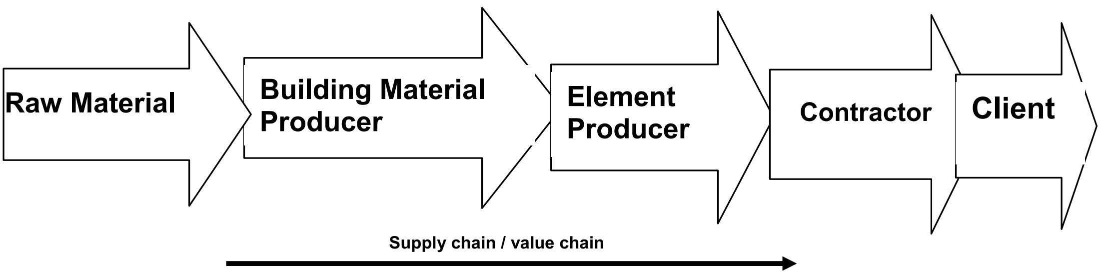

Figure 5-2: The supply chain or, as it is sometimes referred to, the value chain.

A standardised building system is related to its own sub-system and its own supply chains, thereby, these are the bases for industrialisation. The processes of the supply chain of the building system are dynamic and changeable from project to project. However it has to be well defined, standardised, and measurable.

5.1 Industrialised building with light-gauge steel framing systems Practical examples

This research has studied the experiences from the Swedish industrial building process with light-gauge steel. In the following section two examples of projects using an industrialised building process with light-gauge steel will be briefly described.

5.1.1 Kv. Näktergalen

As part of a research project the Näktergalen project was studied (Persson,1997) (Andersson, Borgbrant, 1998). Its aim was to compare different building systems and processes with each other. The Näktergalen project (kv Näktergalen phase II) consists of three different phases. During the planning of the second phase, it was decided to build two identical buildings. Two different building systems were used whereby an analysis and comparison between the two building systems were possible to complete. A traditional concrete building system was compared with the industrialised building method of light-gauge steel framing. In addition, in the Näktergalen project, the new method of collaboration between the designer, the contractor and the manufacturer by using a 3D modelling tool and light-gauge steel building system was evaluated. This was then compared to traditional methods of work between the actors of the process and a concrete based building system. Due to the use of a new production system with light-gauge steel and the use of a 3D model, the actors of the project had to work and collaborate closely. Consequently, this led to a working model with a high level of collaboration both at a strategic level and on an operative level (Cederfeld, 1997) (Andersson, Borgbrant, 1998). Also in the production phase a great effort was made to educate the actors and to improve workmanship. Moreover, production planning through collaboration seemingly had a very good effect on the project performance (Cederfeld, 1997) (Andersson, Borgbrant, 1998) (Persson, 1997).

The result of the Näktergalen research project agrees with that of Puse (1996). In order to gain efficiency and improve productivity by using a prefabrication process, decisions should be taken early in the design process and the stock level should be high. It is important to design for prefabrication. The consequences of changes in the design or mistakes are higher in projects with a high level of prefabrication than those with a high level of on-site construction (Puse, 1996) (Persson, 1997). Both prefabricated production and the technical performance of light-gauge steel framed system were good. Moreover, the production costs were lower than the average production costs (Andersson, Borgbrant, 1998). However, no analysis regarding the actual logistical management within the supply chain or at the construction site has been undertaken. The Näktergalen project was the first project in Sweden, where 3D modelling was used for a light-gauge steel structure. The purpose was to investigate how 3D technology could contribute to a greater efficiency and quality assurance in the construction process. The building consists of a semi-basement storey of in situ concrete. Above the basement storey, four stories were built with light-gauge steel framing. The potential of the 3D technology was confirmed in many ways:

- The total quality of the project was improved by better project planning.
- By using the 3D model the order of the assembly had been visualised.
- By a better planning process the construction of the building was smoother because of less changes and ad hoc solutions for problems. This radically reduced the total project time, (Cederfeldt, 1996).

Figure 5-3: Kv. Näktergalen phase II

5.1.2 The Open House system

The inventor of the Open House system, Peter Broberg (director of Landskrona Arkitekterna AB), has the aim to build dwellings at a price, which is affordable, resource-efficient, environmentally and culturally suitable as well as correctly designed. By combining the modules differently it is possible to build buildings with both an individual interior and an individual exterior in a neighbourhood with a characteristic appearance. The Open House system has been used in many projects. One of these projects is the kv Ridskolan (figure 5-4). The modules have the maximum width of 3.6 m normally allowed in Sweden. Six columns support each module and any combination of the walls within each module is possible, see figure 5-5. The Open house system has shown very good performance regarding fire protection and building physics. The modules are produced at a factory in Skåne, Sweden. The light-gauge steel profiles are delivered with adjusted lengths to the factory. Thereby, work on cutting and adjusting the profiles will not be needed. The same applies to the other materials. In consequence the material waste is minimised as well. The profiles are then put together to elements and then to modules. The vision is to deliver complete modules to the construction site, though this is not the case yet.

The level of completion could be different between different projects. Doors and windows are assembled, indoor walls and roofs are painted and tiled where needed, sanitary and electrical installations are prepared. However, façades are not put in position. Balconies and stairs are installed after the façade is assembled. The transportation company is specialised in transporting housing modules. The assembly contractor takes over the responsibility from the transport company and has responsibility from the unloading of the trucks to the end of the installation process. The weight of a module is 5-7 tons and a large mobile crane is needed at the site. The same contractor is responsible for assembling the steel columns and then installing the modules. The different sub-contractors manage their own material supply and logistical work at the site. Logistical work coordination at the site has not been considered much in early planning or during the production planning consequently the result is a messy construction site (Lessing, 2004).

Figure 5-4: The Open house system used in kv. Ridskolan

5.1.3 Industrialised building process with light-gauge steel framing system

The previously mentioned projects, a design concept for a building system for housing, are well defined. The Open House system has a high level of off-site production where Näktergalen is more about prefabrication of elements on a field factory beside the construction site. A system with components and sub-components is designed for manufacturing and assembling. Conversely, an efficient supply chain for design and manufacturing is missing. In the Open House project the aim is to establish an efficient supply chain where this supply chain is the same in the different housing projects. The two building systems are compared in the Table 5-1 with respect to the important factors of industrialised building processes.

On the other hand, those involved in the project decide on the construction process, methods of work and functions. Prefabrication has an important part in these projects and its process is decided during the design phase. In order to bring about an industrialised process for the construction of a building, there must be a well-defined construction work as for instance on site activities should be well coordinated and site work that should entirely consist of assembly work. Also, the volume of the production has been small which makes the project less economical. In neither Näktergalen nor Open house has much coordination effort been made for construction site management, which has resulted in messy construction sites.

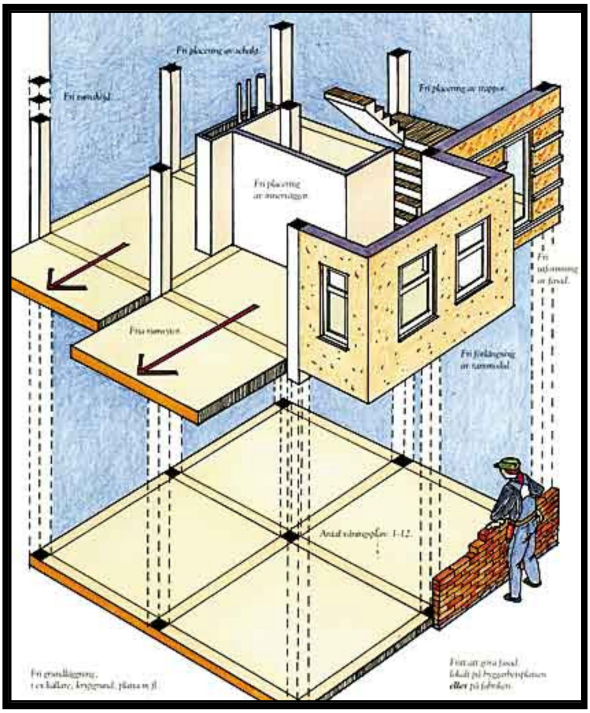

Figure 5-5: Structural system of the Open House system

Table 5-1: The comparison between the Näktergalen and ridskolan, Open House

Important components of industrialised building	**KV. Näktergalen**	**KV. Ridskolan** **The Open house system**
Flexible Design	The connections and the joints have to be considered. There has been problem with the connections.	The steel columns have the same dimensions The connection points are designed identical
Lightweight	Each element weighs 9-116 kg- The roof elements: 121-157 kg	A module weight=5,5 ton
Level of prefabrication	Exterior wall elements, slabs and the roof structure were off-site assembled	The steel columns were assembled at the construction site. Modules delivered to the construction site
Simple erection	Despite the problems regarding the connection the erection was simple due to the low weight and the element accuracy	The low weight means for easy handling
Tolerances	For the elements: +/- 10 mm	For the system +/- 2 mm
Accurate planning	Not design for prefabrication. 3D model gave an opportunity for better planning	Design is integrated to the production. No 3D model used in design or production
Logistics	Not coordinated	Not coordinated
Supply chain	Not coordinated	The aim is to be the same between different projects. Not well developed yet

6 Construction information management through 3D and 4D modelling

6.1 3D modelling

Common for all parts in the building process is the extensive use of information. The 3D model based on sharing a common database will provide the last versions of the design and information will be available from the database to all different players in the construction process, figure 6-1. All types of documents can be produced by this database, for example different 3D perspectives, material specifications and 2D drawings for manufacturing and assembling. The database can also produce data for cost calculations, time scheduling and very important data needed for the client and the future tenants (Cederfeldt, 1998).

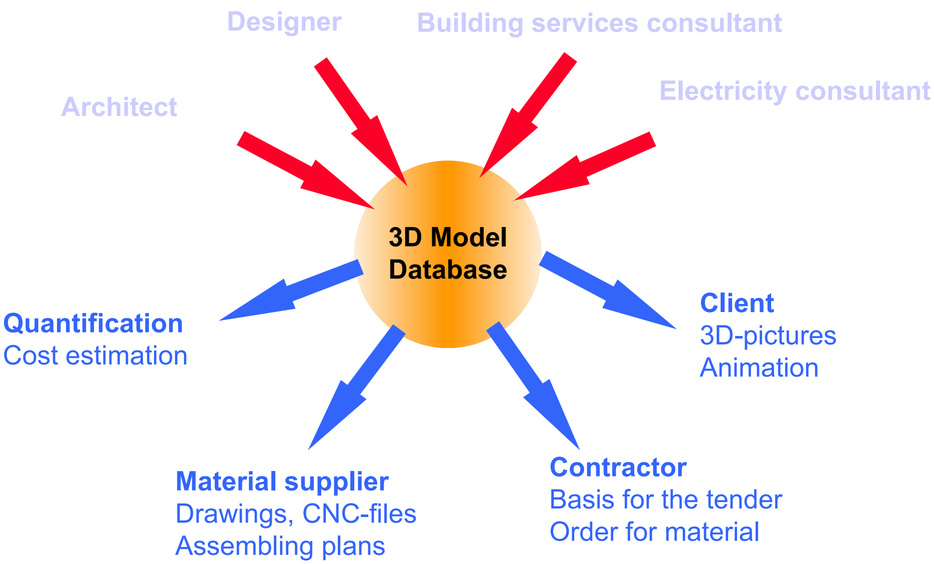

Figure 6-1: The 3D database model for construction

In the Swedish construction industry Microsoft Project and AutoCAD are the most common tools used for planning and designing of construction projects. In the early stages of a project, the architects use 3D modelling for producing 2D and 3D perspectives and not the shared database being described above. Structural engineers use 3D modelling for e.g. steel structures analyses during the design phase. However, in general, 3D modelling is not used to any great extent in Sweden. Two dimensional CAD (computer aided design) software has been used in the design phase since the eighties and has been steadily increasing (Fridqvist, 2000). According to a survey in 2000 (Samuelson, 2000), the usage of the 3D modelling tool in the construction is increasing. 41% of the Swedish construction industry has access to CAD tools and 15% of the architects in the construction industry use 3D modelling tools. However, this figure is almost nill for the other actors in the construction industry (Samuelson, 2000). The evolution of the usage of CAD tools in construction is illustrated in figure 8-1.

The 3D design model focuses on the design of the building, its spatial construction, material and its manufacture. The 3D model is a static model, built in the computer for representing the physical building. This could be seen as a drawback for the construction process since the construction process is a dynamic process and needs a dynamic presentation. The three most important obstacle for increased IT-tools usage in construction industry are summarised by Samuelsson (2000), as high investment costs and the need for increased knowledge. Hinders and potential threats for the application of the modelling systems are discussed in many research projects. Some of those mentioned in earlier research is summarised as (Blokpoel, 2003):

- Incompetence of the workers in the sector;
- Too complex, not flexible and too closed systems for the construction process and everyday usage in construction work;
- The lack of measurable benefits, costs and effects of systems;
- The lack of a good collaboration between the different actors in construction projects and lack of strategic collaboration for 3D modelling implantation between different actors of the construction process;
- Unclear ownership of the information produced within the 3D model through the construction phase;
- Unclear decision making process;
- Existing forms of project contracts are not always best suited for 3D modelling through out a construction process;
- Unclear and neglected model errors in computer files and error handling process;

However, many of the mentioned barrier for 3D modelling are not roadblocks and more related to implementation strategies and change management within the different organisations than technical matters of the 3D modelling.

Both in Sweden and elsewhere there are many examples of 3D modelling usage where efficiency in the project has been gained. Gibb (1999) mentions several examples where CAD data are used in both design and production of highly industrialised construction processes. One of these is the digitally controlled manufacturing process by Rowen Structures, Nottingham (Gibb, 1999 pp204:205) where designer, producer and fabricator create design information with the help of AutoCAD and Microstation, STRUCAD and XSTEEL. Also material handling is driven from the site with CAD information produced. According to the site requirements the buying department can order and call-off materials. This eases steel material handling on site and optimises transportation.

6.2 4D Modelling

4D CAD is a concept, which combines an object oriented 3D CAD model with time. 4D CAD is a kind of information visualisation that is easier to understand than traditional methods, such as 2D drawings and time schedules, which are used to manage construction projects. 4D CAD is a logical way of imagining the construction. The 4D modelling tool is conceptually much closer to an intuitive picture of a construction process than 2D drawings and time schedules. Often 4D systems rely on accurate information which links an object oriented database to 2D and 3D model elements. The 4D concept visualises the dynamic process of the construction process and as a result the information will be more comprehensive. The 4D model simulates the construction progress. By integrating a fifth dimension, such as cost, the static 3D model could be integrated with the dynamic process of the construction process.

To understand and evaluate the 4D concept researchers at Stanford have developed a prototype that has been used in some complex construction projects in California. Research results show that using 4D concept can improve the construction information flow between the partners of the construction project. The use of visualisation and the 4D concept enables the partners to focus on the relevant information and to interact productively. By the use of a 4D tool more time could be spent on performing predictive tasks. Moreover, design, buildability and construction scheduling (Liston, Fischer and Knutz, 2000) could be evaluated with high efficiency. In this way the design and construction phase can be integrated properly resulting in a more efficient construction process, (Fisk, 1997).

In fact the 4D concept, by visualisation of the construction process, is an efficient planning tool to organise the logistic of the site during the planning phase instead of as today during the production. The site layout can be simulated and visualised with a 4D CAD tool for the different actors in the project which will help, in particular the site engineer, to organise the activities, the material flow and the site logistics.

The use of 3D-4D modelling has many benefits for owners, architects, engineers, contractors and subcontractors. The overall benefits of 3D-4D modelling are summarised in the main points below, (Staub and Fischer, 2000):

- Better coordination of subcontractors,
- Clear communication of the project schedule within the team,
- Visualisation of the work flow,
- Efficient identification of buildability factors,
- Showing the status of the project at any time.

The pedagogic benefits of the 3D model with a linking to time dimension, has been proven in projects like Krympmåttet, Sweden (Bengtson and Bergstrand, 1999), where a simple visualisation of the construction process has been used to describe the process for the contractor and the site workers. By visualising the different time steps in the production process of the building, the production process was presented for the site workers and site managers early in the production phase. The main purpose with the visualisation was to visualise and clarify the structure of the building and the erection of the structure. The visualisation was also used for describing the project process to the owner and the contractor. The aim was also to use tools, which are used in the Swedish construction industry such as AutoCAD R14 and Microsoft Project for linking the time with a 3D model.

The method for the visualisation in this project was to build a 3D model in AutoCAD. Different time steps in the production process were laid in specific layers, and thereby by lighting and shutting down layers, different time sequences of the model were visualised. The model was primarily defined by solid elements. These solid elements contain more information e.g. volume and centre of gravity, than the elements combined of areas and lines. The use of the 4D thinking in this project was very simple although it proved the advantages of using 4D modelling. The method has of course many shortcomings, both technically and theoretically. However, the aim was to use the visualisation for pedagogic usage of 4D modelling at the project team meetings and for presenting information to the contractors and the subcontractors during the production planning process (Bengtson and Bergstrand, 1999).

However, as stated in a paper (Ganah et al 2001), an industry survey on the use of computer visualisation to communicate design information as part of a project was done in 2000. The aims were to demonstrate how computer visualisation could be used in clarifying design details and buildability problems. The survey shows that traditional tools are not adequate to communicate design information. Clarification of information regarding buildability analysis was mainly done by using 2D drawings, written statements and face to face meetings. Physical 3D models and perspective images were very rarely used. In the same survey the use of 4D CAD tools for clarification of problems related to the production has not been found. Moreover, the same survey shows that 46% of the respondents thought that computer visualisation might have little effect on communication during the construction stage. Eighteen percent of the respondents thought that visualisation could improve communication. The later were those respondents who have used computer visualisation tools at some stage of the design. This survey was done in March 2000 and contractors were selected randomly from the top 100 UK contractors.

Rönnberg (2003) in his licentiate thesis evaluated how a 4D modelling tool can be used for planning the production of the factory and the benefits of implementing a 4D modelling system in a precast concrete factory. The 4D model include planning and following up administration for the precast concrete element factory (Rönnberg, 2003). As technologies develop further, 3D-4D modelling tools become more sophisticated and user friendly for production planning, installation and erection planning as well as logistics planning for on site and off-site production (Gibb, 1999) (Blokpoel, 2003) (Staub et al 2001).

7 Summary of the papers

The papers together with the previous chapters have the aim of describing and illustrating the state of the art of the Swedish Construction Industry regarding the main research areas. However, the main research areas are self-standing subjects for further research. The relationship between the research areas and the papers are presented in the Table 7-1, that shows the main research areas, vertical extension, industrialised building process with light gauge-steel framing and 4D CAD and the papers where these subjects are discussed.

Table 7-1: The relationship between the research areas and the papers

The subject of the research	Paper 1	Paper 2	Paper 3
Vertical extension	Partly State-of the-art	Partly Case Study	Mainly Case Study
Industrialised building process with light-gauge steel framing		Mainly Case Study	
4D CAD	Partly State-of-the-art		

Paper I:

The paper presents a literature review and a state-of-the-art description regarding the three main subjects of the research as well as tentative results. One main part of the state of the art review was to follow five different vertical extension projects with different structural systems and building methods. The aim was to understand the different problems related to vertically extending buildings in city centers. These problems are summarised below.

- Durability of the existing structure and the quality of the existing building.
- Moisture control and weather-tightness of the existing building during the construction of the extension.
- Working space and the strict boundaries of the site.
- Logistic planning from, to and on the site and the impact of the site activities on traffic around the site.
- Communicating the construction plan to affected people.

There are many indicators found in the literature study showing that 4D CAD raises the productivity in projects. 4D CAD's possibilities for steering the prefabrication plan or the control of the construction process have been discussed in many different researches. 4D CAD modelling to support production planning would provide greater certainty of success for projects involving vertical extensions. The extra time for 4D analyses and simulation could be of interest when the restrictions of vertical extension result in difficulties in the process and the simulation will give opportunities for better planning and control. 4D CAD possibilities for being used in an industrialised building system have not been discussed and nor had discussions been found in the literature study.

Paper II:

In this paper, two housing projects with a high level of industrialisation are compared. In both projects two different light-gauge steel framing module systems were used.

These two cases showed the capability of the system to produce affordable housing as well as to reduce the production costs of housing projects. Moreover, the low weight of the light-gauge steel framing system makes it appropriate for vertical extension and building on land with low bearing capacity. Also, in both cases, site activities were minimised by the industrial production process.

Paper III:

In order to understand the relationship between the industrialised building process and the modern vertical extension construction process, three vertical extension projects were studied. The subjects such as prefabrication and supply chain and their relation to the project restrictions of on-top constructions were intended to be illuminated. Subjects such as prefabrication level, construction site planning and supplier relationship at the site were studied in depth interviews. The questions used in the interviews were based on results from paper I, the first phase of the case study. Different levels of prefabrication and building methods were used in these three projects. The paper discusses the different approaches for handling restrictions regarding the vertical extension projects, used in the different projects, and how they are implemented.

8 Findings

The results of this exploration of on-top constructions; industrialised construction process of light-gauge steel framing and 4D CAD are considered as the initial stage for further investigation within the subject of how to make the construction process more productive and industrialised and also with more customer focus. It has to be remembered that in these case studies actors active in the projects, such as site managers and project managers were interviewed, and that the research was concentrated on individual projects.

Generalisation of qualitative case studies results is difficult. However, some conclusions could be taken from the five vertical extension projects. The case studies show a pattern in how vertical extension projects are planned and executed. Thus far, other refurbishment projects are not differing much from this pattern (Engwall, 2001). However, the insight for vertical extension project restrictions, during the construction time, exists. Yet, many times these problems are discovered and resolved at the site and not, as they should be resolved, in the earlier stages.

The interviews showed that the customer orientation as well as the market sensitivity of these projects were the most important factors for the project, although, in one case, the total construction costs were of greater importance than the customer orientation (vertical extension of an existing building with student study homes). In the projects where the builder had a well-developed building system, that system was used. However, the level of prefabrication was less than normal due to the site construction and the existing building limitations. In other cases where the builder did not have a building system, best price and supplier relationship were of importance when the building system was chosen. In two cases, as often is the case, refurbishment and vertically extending the existing building were executed at the same time, which resulted in more complicated construction processes (Engwall, 2001) (Gibb,1999). In neither case, a building system for vertical extension was developed.

Although research both in Sweden and elsewhere indicates the capabilities of 3D-4D CAD modelling for improving the construction processes, none of the studied cases used 3D models or 4D models. 2D drawings together with descriptions were used for exchanging the design information. All project documentation is backed up with 2D CAD drawings. 3D models are sometimes used to analyse difficult parts of the project during the design of steel structures. Critical Path management schedule was used for communicating the construction time and the construction process during the production phase. 2D drawings were used for planning the construction site and were updated a few times during the construction. Additionally the approach within the interviewed team in these case studies where negative to this kind of tools, which indicates problems with the implementation of new technology. However, it is important to find a way for measuring the increased efficiency when 4D modelling is used. The evolution for CAD tools is illustrated in figure 8-1. The complexity of the system increases with 3D CAD and 4D. At the same time the opportunity of using the information is increased. In these vertical extension projects the grade of using the CAD tool did not go further than to the second box, figure 8-1. In order to be able to implement 4D modelling the usage of 3D models must be more common Moreover, in all studied projects, industrialisation of the process has been wished for, though not much implemented.

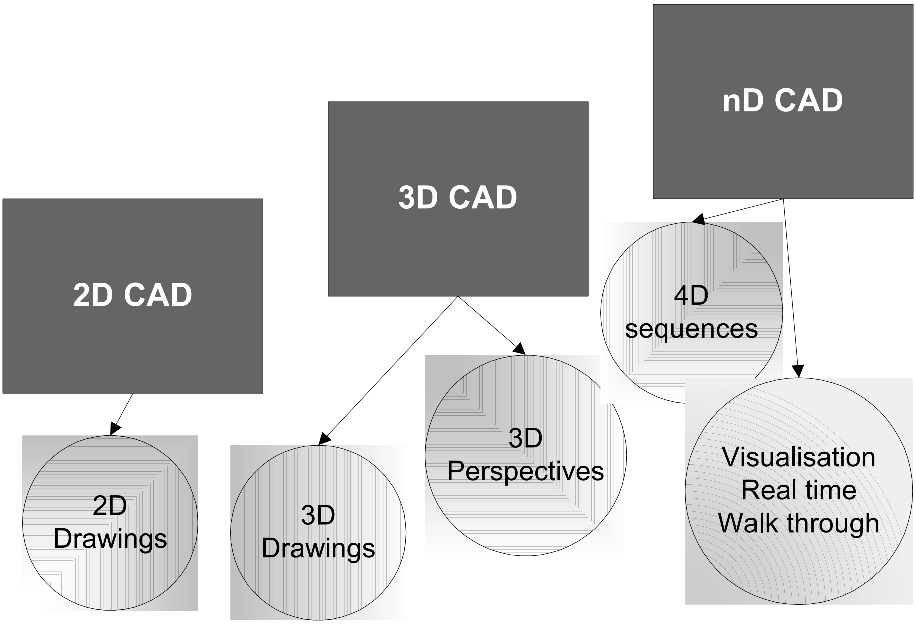

Figure 8-1: Evolution of the CAD application

The evidence so far collected would seem to confirm that the industrial production of the light-gauge system for vertical extension, albeit its possibilities, is undeveloped in Sweden. The pros and cons of the system for vertical extension have not been verified or dismissed. However, the possibilities for further developing the existing building systems to a higher degree of industrialisation and for vertical extension were observed in one of the case studies. Developing a building system only for vertical extension may not be efficient, but by recognising the factors differing the vertical extension from normal construction, a suitable building system could be adapted to the specific case. Some factors in vertical extension projects which have to be considered during design and production are presented in the case studies report (Bergsten 2005).

As mentioned earlier the building systems using light-gauge steel have good quality and well-developed industrialised production. However, in the vertical extension project where light-gauge steel system was utilised, the problems were related to the construction process rather than the building system as well as the not well organised supply chain in that project. The reasons behind this could be that the partners did not have the experience of working in an industrialised building process or/and the project was a pilot project for the used building system. The low weight of the light-gauge steel framing system makes it appropriate for vertical extension and building on land with low bearing capacity. One-storey volumetric student study bedroom apartments were specially designed for this project with respect to restrictions as transport to the site and location of the modules. The modules arrived at the site in two parts and were then assembled at the site. The assembly process together with the erection was made in front of the building. The design of the volumetric modules was made in collaboration between the main contractor and the designer and also the manufacturer. The project was carried out under the design and build contract model. However, problems relating to the project could be induced from the lack of analysis of the production planning and the relationship between the actors in the supply chain. Mainly because of not recognising any value in having a main contractor sign a Design and Build contract, the client stated that in the future they would rather work in a project organisation such as in the Open house model (figure 8-2). Vertical extension with light-gauge steel in both Unionen and Husby was possible without any reinforcement of the existing buildings, which was a very important factor for minimising the construction time, disturbance to the surroundings and the construction costs.

The case studies showed that instead of implementing the industrialised building process and solving the related problems it is easier to deal with the problems, which one is used to. In the case studies, a high degree of prefabrication was desired by contractors and clients. However the uncertainties in the implementation of new materials and a new process suppressed the way forward to a more industrialised construction process. In all the studied projects the industrialisation grade decreased during the execution of the projects. The motive behind that has in all cases been unsolved problems. These problems have often been understood already during the start of the production at the site. In one case, the project manager points out, that one of the reasons behind the low prefabrication grade was lack of suppliers on the market at that time. Industrialisation of vertical extension projects is not a general solution. One-off projects with little repetition is not expected to gain much benefit with a higher degree of prefabrication. However, in projects like Husby, part of Klara Zenit and Unionen, with a higher level of repetition, the opportunity for a higher degree of industrialisation was greater.

Summarising the findings from the case studies could be stated as due to the many restrictions standardised building systems are not very suited for vertical extension projects. In addition, in these case studies industrialised production methods were not enough developed in order to be able to be adopted in an efficient way in vertical extension processes. The larger amount of construction site restrictions within the refurbishment and the horizontal and vertical extension projects makes the industrialisation of these projects more proactive. At the same time 4D CAD can make the analysis and planning of these restrictions more straightforward and thereby the adjusting and industrialising processes become easier.

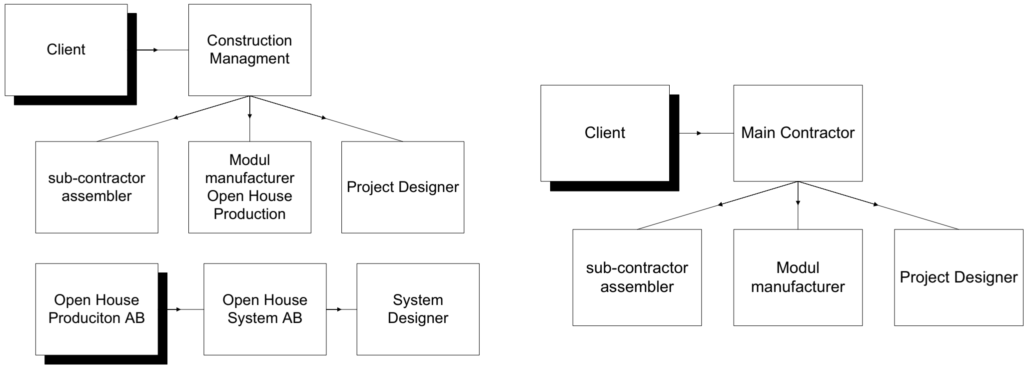

Figure 8-2: Project organisations for the Husby project and for the Open house building system

9 Discussion and further research

The qualitative study aims to explore the vertical extension of existing buildings using an industrialised building method such as the light-gauge steel framed system. This qualitative study has improved the understanding, the mechanisms and the motivations for industrialised vertical extension projects. Productivity measurements are one way to quantify the improvements of the processes when new technology is developed. The need for research regarding appropriate productivity measurements is high.

The industrialisation of a process is an investment in equipment and technologies with the purpose to increase the productivity and the output by using less manpower. In order to be able to do that and implement new technologies, measurements of productivity are important. Efficiency and effectiveness of a building system such as light-gauge steel together with 4D CAD can only be measured within its own context and project. However, construction projects are far too complicated to be easily compared with each other in efficiency studies. Clearly, the use of 3D models and CNC machines and 4D modelling of production data increases the productivity of the steel production and assembly in projects. During the productivity discussion it must be taken into account that productivity measurements within the industrialised construction could include the productivity of part of a process off and on site or the manufacturing process or on site assembly work. But measurement of the whole process is complicated. For instance Gibb (1999) mentions as an example that by adjusting the fabrication of columns for a project to the delivery and erection requirements the manufacturing process was made less efficient while the need for off-site and on-site storage was reduced, which increased the productivity at the construction site.

Efficiency means doing things right, which must logically be relevant to all production processes. With the right processes and by producing the right products, a high level of efficiency will be reached. Thereby high efficiency in a project will result in a high level of productivity in a project. Total productivity is defined as output value of all products divided by all inputs such as labour, capital, material, energy etc (Johansen, 2003) (Borgbrant and Lidén, 2000). Johansen (2003) presents different groups of productivity measurements in the manufacturing industry. Total factor productivity could be defined as value added/labour capital input and partial productivity is the ratio of one single out put. Total productivity and total factor productivity is more suited for management level and partial productivity for operation level and shop floor. The productivity measurements goal may involve increasing quality, decreasing defects and waste in workflow, transportation, keeping high customer service and shortening construction time.

Jonsson (1996) summarises the problems of implementing manufacturing industry productivity measurements in construction as the difficulty of measuring the output before the project is finished. However, this is a concern in large projects as airplane manufacturing too. Borgbrant and Lidén (2000) discuss the productivity measurements as external and internal. These measurements, which have been developed specially for the construction industry, show low increment of the productivity rate in Sweden. The internal perspective on productivity measurements´ starting point, used in Puse (1996), is that a higher rate of industrialisation will give a higher productivity. Also, Andersson and Borgbrant (1998) state that a starting point for external productivity measurements is that low average rent and production cost result in a higher productivity. A more system orientated approach for productivity measurements are discussed by Cheung and Jönsson (2002). In a productivity measurement system for construction there will be an opportunity to get an understanding of where to find the deviations. Furthermore, Cheung and Jönsson, 2002 present a measurements system for construction industry with proposed key performance indicators, which covers all the key processes in a construction project and can be used for comparison between the different projects or for improvement of the measurements in a project.

Defining the goal for productivity measurements is important. Implementation of the industrialised building system with IT-tools increases the need for education and a high competence level within the production team, which means the need of new productivity measures. The main idea of productivity measurements should be to recognise a partial measurement of a specific ratio of input and output and also to consider the competence within the teamwork.

Comparing different vertical extension projects without a well-defined quantitative measurement is difficult. Moreover, as mentioned earlier comparing two different projects with different qualities, circumstances and methods of work is not always objective. Also measuring the pros and cons of tools such as 4D CAD in qualitative measurement is not always enough for productivity studies. In the first place further research should concentrate on defining partial productivity measurements which could consider values such as raised competence and quality as well as higher rate of input and output ratio. However, these kinds of measurements are usually process orientated and difficult to use for comprising different projects, but measurements could make it possible to study a process within its context in order to perform the right processes in the right way. Additionally this will give the opportunity to different businesses to measure different investments in new technology and tools.

10 Conclusion

At the moment industrialisation is concentrated on products rather than looking into the industrialisation of the construction process. By industrialising the construction process, the supply chains have to be involved in a more integrated way. The construction site coordination and planning is often forgotten during the planning of the production and during the execution of the projects. The building system light-gauge steel framing is suitable for industrialisation and vertical extension, which is shown by many projects. Vertical extension will happen all the time and due to the many restrictions, not always very suited for industrialised production. However a 4D CAD tool could ease the planning and analysis of restrictions, difficult work processes, activity orders, construction site planning and workflow planning. Also, a 4D CAD tool could be used for planning of elements or modules at the site plant in order to get the most efficient production line.

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Fastighetsbildningslagen, FBL (SFS 2003:628)

Lagen om förvaltning av samfälligheter (SFS 2003:629).

Paper I

4D CAD IN THE DESIGN AND MANAGEMENT OF VERTICAL EXTENSIONS TO EXISTING BUILDINGS

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Paper I

4D CAD IN THE DESIGN AND MANAGEMENT OF VERTICAL EXTENSIONS TO EXISTING BUILDINGS

ABSTRACT

Extending buildings vertically is fraught with technical and managerial problems. Inevitably, many of these types of building will be located in areas with access restrictions and other physical constraints on the movement of materials, components, operatives and equipment. The use of light-gauge steel framed systems represents a practical and cost-effective solution to the problems created by these buildings. However, materials handling and other logistical problems mean that the construction process is less than certain. The concept of 4D CAD, which has emerged from the process-engineering sector, is being increasingly considered for applications in the building sector where data regarding construction methods, resources and time are integrated with 3D design information. A major case study is being used to evaluate the potential for utilising light-gauge steel framed systems, with support from 4D CAD. Results will include a comparison of the benefits over more traditional means for design and construction management when erecting vertical extensions to existing buildings.

1. INTRODUCTION

The demand for apartments situated in city centres is presently high and is likely to increase. Extending existing buildings vertically and horizontally has been a frequently adopted approach over the centuries in older cities. In some cities, apartments have been added to existing buildings such as shopping centres, offices and multi-storey car parks by vertical and/or horizontal extensions or conversions. However, poorly constructed vertical extensions have led to buildings collapsing and hesitancy by owners to contemplate such developments. Traditional methods of construction are generally used for vertically extending buildings, but are often not cost-effective (Andersson and Borgbrant, 1998). Further development within larger and more compact cities must therefore make use of lighter building materials, novel building techniques and more efficient production processes. Even so, there is bound to be concern over the certainty with which newer materials, techniques and processes can provide an adequate and safe solution.

Designers are used to producing mock-ups of the end product for communicating their ideas and, perhaps later, for production planning and control. Usually, these mock-ups are physical scale models, but increasingly 3-

D CAD systems are used to portray the end product. 3-D cannot, however, take account of the production process without extensive adaptation. The 4D concept represents geometrical product (3D CAD) information together with process information (time) and offers a way forward for owners and designers who are considering complex additions to existing buildings.

This paper describes the potential for the industrial production of light-gauge steel framing systems coupled with the use of 4D CAD. This is seen as a potentially cost-effective alternative for the vertical extension of existing buildings.

2. STATE-OF-THE-ART REVIEW

2.1 Vertical extension of existing buildings

In most capital cities, and Stockholm is no exception, one of the most coveted places to reside is in the city centre. A consequence of this interest is the creation of more densely populated areas, where every possible space for accommodation is considered. In fact, many buildings in the historical parts of European cities have been extended once or even several times over long periods, as figure 1 shows. Berglund (1981) gives many examples of the vertical extension of buildings.

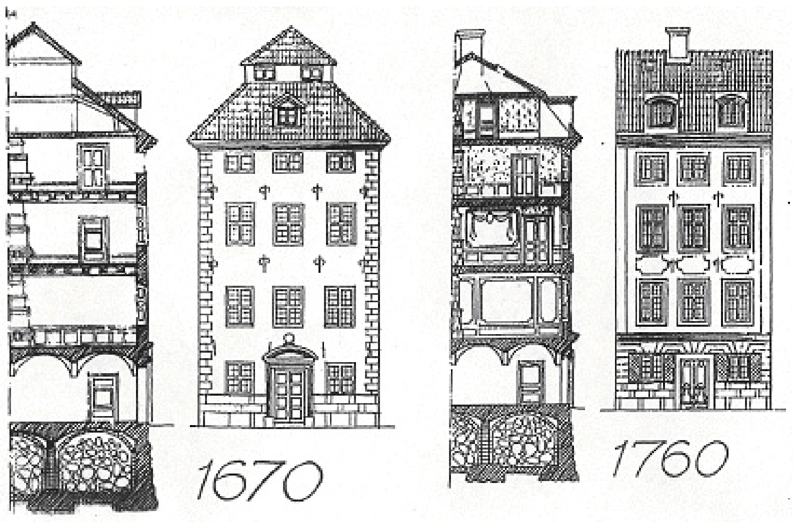

Figure 1: Vertical extensions in the 17th and 18th centuries (Berglund, 1981)

More recently, conversions and extensions to existing buildings have been successful in several countries, for instance the United Kingdom, Netherlands and Sweden (Verburg, 2000; Hiller *et al*., 1998). Another example is that of The Robert L Preger intelligent workplace, which has received an award for innovation under the auspices of IDEAS (Innovation Design and Excellence in Architecture with Steel Award 2001[1]). This particular building is a one-storey extension of an existing university building in Pittsburgh, USA.

A survey by Bergsten and Wall (2001) on the vertical extension of existing buildings in Stockholm was undertaken during 2001. The results of the survey show that for vertically extended buildings, no special construction process or building methods were used. Many of these projects have been expensive and only made possible because of a local boom in the construction sector. Three vertical extension projects have been studied in detail in this survey. The projects are: Klarazenit with steel column and cast-in-situ concrete slabs; CityCronan with steel column and pre-cast concrete slabs; and Berzeliipark with a combination of concrete slabs, steel columns and light concrete and steel slabs. All these extensions offer between three and five additional storeys. In all cases, the existing building is of reinforced concrete. Studies of these projects have revealed many common problems as summarised below.

- The durability of the existing structure and foundation is a very important consideration during the design of the new structure. On site tests are needed to confirm the quality of the construction. It is necessary to check carefully the local strength of attachment points between the existing building and the extension and, if necessary, strengthen them.
- Moisture control and weather-tightness (rainwater disposal and water-tightness) are essential requirements for reducing the risk of moisture problems during production and later in the use phase of the building. During the construction of vertical extensions some parts of the existing building will be exposed and therefore vulnerable to the weather.
- Working space allowances on the construction site must be planned before work commences in order to minimise problems from the lack of space due to the strict boundaries of the site.
- The construction plan must be communicated to the people affected by the work. It is not only for the benefit of those managing and working on the side: there are neighbourhood responsibilities too.
- Logistics planning from, to and on the site is very important. Also, the impact on traffic around the site, especially in city centres, has to be considered. At the same time the overall lack of space on the site leaves

[1] http://www.arc.cmu.edu/cbpd/html/iw/iw.index.html

little space for storing materials. Properly planned logistics on, to and from the site are vital for efficient working.

As seen above, the problems related to vertical extensions are not uncommon problems in construction generally, but are perhaps more acute in these circumstances. Constraints on construction are often site and geometry related, such as in the vertical extension of existing buildings, where access and movement restriction and other physical constraints imposed by the existing building make the production process more complex. This implies that these constraints must be carefully considered during design decision-making.

In vertical extension projects, it is also important to minimise disruptions and eliminate hazards for neighbouring properties and legitimate activities especially in the vicinity of the site. When altering the existing environment, several aspects must be considered and must be taken into account in the planning process:

- Influences that the extension will have on the existing building
- Influences of the extension's activities on existing activities
- Influences of production activities on the everyday activities of the existing building and its environs.

The trend in the 1960s and 1970s for flat roof construction has left its mark on the townscape. In many cities, there are large areas of flat roof, underneath which the existing structure has the ability to bear the extra loads from additional storeys. To make the best use of these areas, it is essential to develop building methods, which are practicable, cost-effective and appropriate.

Figure 2: Modern vertical extension in central Stockholm

2.2 Light-gauge steel framing for vertical extensions

The main structural component of the light-gauge steel framing system is galvanised cold-formed steel sections. The system has been tested and is suitable for up to five storeys. Research and application have confirmed many benefits from the use of light-gauge steel framing in housing, some of which are mentioned below (Burstrand, 2000; Gorgolewski *et al.*, 2001; MacCarthy, 1998):

- Structural performance
- Ease of construction and deconstruction
- Lends itself to pre-fabrication
- Re-use and recycling of material
- Good level of sound and thermal insulation
- Dry construction process
- Improves the chances of consistent quality.

Light-gauge steel framed buildings with their lower weight, when compared to other traditional buildings, have been recognised as suitable for vertical and horizontal extensions to existing buildings (Peterson and Öberg, 2001). They outperform similar concrete buildings in terms of their weight by a factor of five (Burstrand, 2000). Other experiences confirm the suitability of this method for vertically and horizontally extending existing build (Tomá, 1999).

Another important attribute, as mentioned above, is its industrialised production method. The design and manufacture of light-gauge steel framing lends itself to pre-engineering for off-site assembly of elements, tight tolerances and simple site erection of the elements (MacCarthy, 1998) (Grogolwski *et al*., 2001).

2.3 Information management and 4D CAD

The use of 3D modelling is an important aspect of the industrial production of light-gauge steel framing systems. In the past few years, the use of 3D modelling in design and the procurement of light–gauge steel framing systems has increased. The 3D model defines the product and shares a common database. This common database generated the latest version of drawings and information for use by different actors. Many kinds of documents can be generated from the model; for example, perspectives, material specifications, workshop drawings and assembling drawings. The database can also produce data for cost estimating, time scheduling, manufacturing and contract tenders (Cederfeldt, 1997). The product and the production process must be considered during planning and scheduling. Linking a 3D model to the process is currently undertaken with the use of, for example, critical path method (CPM) schedules.

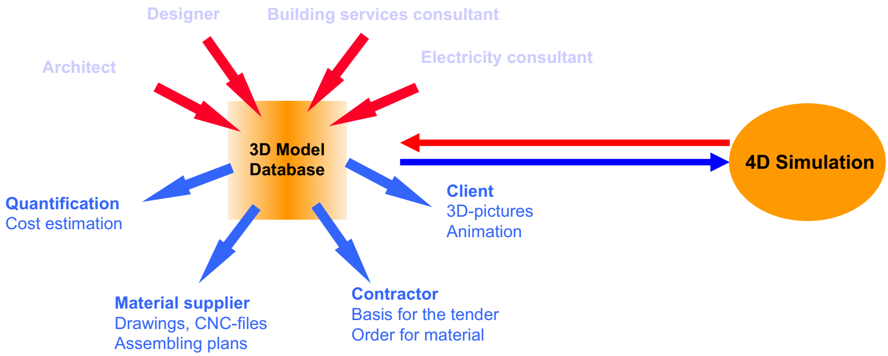

Figure 3: 4D CAD concept

The existence of the 3D model and visualisation techniques are effective tools for representing production information in detail in order to shorten overall time and increase project productivity (Koo and Fischer, 2000; Akbas, 2001; Webb, 2000; Leiononen and Kähkonen, 2000).

The 4D-concept can be described as a matter of connecting the 3D model to the production process and trying to visualise the production through the use of different colours – see figures 3 and 4. By visualising and building the structure in the computer, prior to work on site, the 4D model can help identify constructability and sequencing problems. Other benefits from 4D CAD are: better communication and coordination between project actors, conveying the spatial constraints of a project, foreseeing hazard situations and safety matters. A 4D model also assists in visualising workflow on the site and the allocation of resources and materials (Koo and Fischer, 2000; Staub-French and Fischer, 2001).

The results of a case study by Staub-French and Fischer (2000) show that today's mechanism for 4D model generation, adjusting the 3D model and linking it with the schedule, is too complicated for everyday use. Furthermore, many constraints are overlooked during detailed production planning. The time taken to create a model depends upon the application of the 4D method, the level of detail provided in the 3D model and the user's knowledge. A vital consideration for the project's design is how work is organised on the site, especially in the early phases. Also important is how work is brought on to the site and controlled. Attention to these matters during the design helps to avoid conflicts (Howell, 1999). Currently, research is being conducted into the automatic generation of construction zones from 3D models to assist in construction planning and scheduling (Akbas, 2001).

Despite the enormous benefits promised by 4D modelling, Koo and Fischer (2000) discuss some limitations in the method. Although 4D models can help relatively inexperienced users to identify problems in construction projects, they cannot convey all the information required for evaluating schedules and activities. Users can easily infer physical constraints from the 4D model, but non-physical constraints are harder to establish. Using different colours for showing different activities can mean that models become quite cluttered, leading to a loss of detail definition. Also, generation of rapid alternative scenarios is difficult and labour intensive. Besides, it is important to specify the types of operation and the level at which detailing a 4D concept provides the most benefit. Many contractors assume too quickly that the cost of CAD operators on top of 3D and 4D modelling system is prohibitive. Research has shown that by using 4D CAD in design and construction, overall productivity in the project will rise and many other benefits will accrue to the actors involved (Staub-French and Fischer, 2001).

Researchers who target the technical problems in 4D CAD often forget the impact and difficulties of softer parameters. Problems related to implementing *4D thinking* in the construction sector have been reviewed by Barrett (2001) and can be summarised as low organisational readiness, tacit-tacit emphasis, high action and reactive orientation and economic turbulence in the sector. In fact, these factors should be considered during the work of 4D CAD implementation. The efficient use of 4D CAD implies that the 4D concept and software are implemented correctly. Targeting the technical aspects and not the user aspects will result in disappointing experiences and a lack of realisation of the primary benefits of 4D modelling.

2.4 4D CAD practice in construction sector

Today, there are many examples where virtual reality and simulation techniques have been used successfully as, for instance, in the shipping industry. The product model is used throughout the design, fabrication and assembly phases and 3D/4D simulations with connections to numerous databases (including those for cost and time) have shown themselves to be a reliable way for increasing productivity and competitiveness (Douglas, 1994). Other examples in the heavy engineering and process industries can be found.

The most frequent use of visualisation and 4D CAD in construction has been in the marketing and pre-construction phase. Some attempt has, however, been made to facilitate visualisation during the construction process. An early attempt by Bengtsson and Bergstrand (1999) to apply the 4D method in the construction phase was by manually connecting different layers in a 3D model to a time schedule. Different time sequences in the production process were introduced to different layers. By revealing or suppressing layers, various sequences of the production could be visualised.

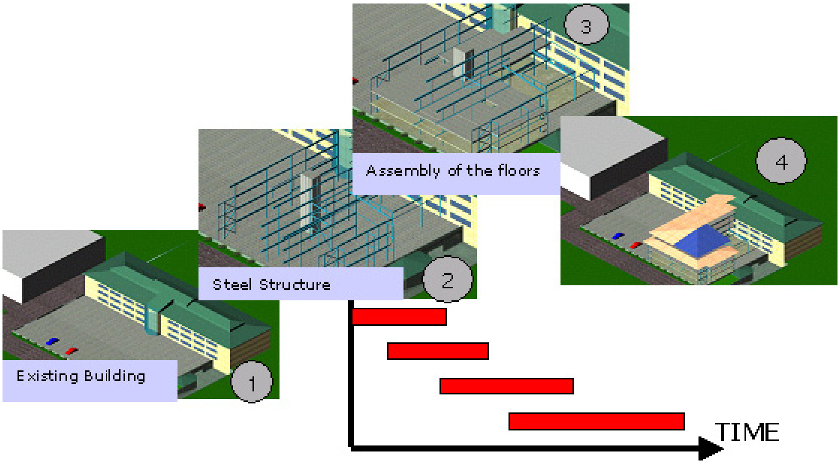

Figure 4: Example application of 4D in construction

More sophisticated attempts to implement the 4D concept in the construction phase have been undertaken by the Center For Integrated Facility Engineering (CIFE) at Stanford University in the US and have attracted industrial interest.

Today, there are several 3D and 4D modelling tools on the market that have been used by contractors (e.g. Bovis and Bentley) in pilot projects or case studies (Webb, 2000; Leiononen and Kähkonen, 2000). In Norway, a 4D model has been used for the project, Pilestaedet Park2, using a 3D model and time planning program. Other attempts at realising 4D methods have been seen in the integration of life cycle data with building and visualisation (Linnert *et al.*, 2000).

2.5 Using 4D CAD in the design and management of vertical extensions

Research indicates that the light-gauge steel framing system is a cost-efficient alternative for multi-storey housing projects. Using 3D modelling systems for design and production planning, in the industrialised production of light-gauge steel framing systems, increases productivity in the project (Burstrand, 1998; Cederfeldt, 1997). Case studies reveal that light-gauge steel framing, together with 3D modelling, have reduced production costs by approximately 20% for multi-storey housing projects and increased overall project productivity (Andersson and Borgbrant, 1998). Usually, contractors want to accelerate the

2 http://www.pilestredetpark.no/

on-site works. In order to minimise construction time, industrial production methods can be used (Fernström and Kampe, 1998), although accurate planning of resources, space and activities should be done early in the project and not, as often is the case, for overcoming delays. By using 4D models and increasing the reliability of the project schedule, an efficient route to more productive and efficient construction process can be found (Akinici *et al.*, 1998).

Combining the use of light-gauge steel framing with 4D modelling also succeeds in bringing a degree of coordination and integration to the design and production process that might otherwise be absent. 4D methods enable the design team to simulate the coordination of the extension with the existing structure. By considering constructability, production methods, interdependency of tasks and matching manpower to available work in the design phase, changes and inaccuracy can be minimised. This will also minimise some of the disturbance caused to the surrounding area. Visualisation also assists the project team by showing the status of the project at any time. For example, the project can be simulated for the benefit of neighbours of the site in order to inform them about the progress of the project and how the project will affect them during different periods. Alternative designs for the extension can be simulated in order to determine the most process-efficient solution. Logistical considerations, such as access to the site for delivery vehicles and materials handling on the site, can be introduced and different scenarios tested. Finally, the impact of on-site works on traffic flows can be investigated in order to minimise disturbance in the vicinity of the site.

3. RESEARCH PROJECT

3.1 Project description and objectives

Extending buildings vertically, especially in city centres, is fraught with technical and managerial problems. Many of the problems have been mentioned earlier and are particularly worrisome with respect to apartment buildings. Since apartments, as compared with commercial buildings, have the highest requirements for sound insulation and fire protection, they provide a demanding test-bed. The results of the research could also be applicable to other building systems used for housing and commercial and industrial buildings. Against this background, the aim of the research is to identify cost-effective production methods for the vertical extension of existing buildings. The industrial production method of light-gauge steel framed systems, together with the use of 4D CAD, is being investigated in order to support the achievement of this objective.

Another aim is to produce guidelines for integrated design and production methods when industrialised building methods are used. These will be based on the most appropriate means for simulating industrialised production methods and the implications of a given design.

Josephson (1994) found that the majority of the defects in construction could be ascribed to design, site management, sub-contractors, materials and execution of the work. This research project will therefore determine if the 4D concept can help in minimising defects and thereby increasing a project's overall productivity. The productivity of the project will be measured using the method discussed by Jansson (1996).

3.2 Research methodology

Case studies will be used as the primary approach for investigating new methods and new design and management tools. A study of the design and production planning process within the respective projects will be carried out in close co-operation with the owners, designers and contractors. One case study is being undertaken with respect to a highly industrialised construction process using light-gauge steel for the vertical extension of an existing building in Stockholm. This study will also evaluate the design and the planning process and the physical result with respect to quality, cost and customer satisfaction. The usefulness of applying 4D modelling will be determined from this work and can be summarised as:

- evaluating 4D modelling in comparison with the actual procedures for design and planning
- drafting guidelines for implementing *4D thinking* in the Swedish construction sector.

4. RESEARCH RESULTS AND INDUSTRIAL IMPACT

4.1 Tentative results

The expectation is that the results of the case studies will largely confirm the utility of applying 4D modelling, especially to the problem of the vertical extension of existing buildings. This will be based upon industrial production methods using light-gauge steel framing. It is further expected that the case studies will provide hard evidence of the extent to which this approach is able to minimise the duration of work done on the site and disturbance to the neighbourhood. Evidence of a lower than normal requirement for storage space on site will also be expected to emerge.

4.2 Implementation and exploitation

The application of the approach outlined in this paper will also be considered for application to other types of building. Moreover, it is expected that the results of the research will spin-off into other areas of construction activity. There appears no reason why 4D modelling could not be deployed on other kinds of building and construction problem. Other uses for light-gauge steel framing systems are likely to receive some measure of support from the successful completion of this project.

5. CONCLUSIONS

The problem of extending existing buildings vertically, especially to provide space for apartments, has been discussed in this paper. Two strands of research are being pursued and attention has been drawn in the earlier sections to the current state-of-the-art in the application of 4D CAD modelling. This has been set against the background of the availability of light-gauge steel framing systems that potentially offer an attractive and speedy solution for added accommodation in city centres and other densely populated areas. The evidence so far collected would seem to confirm that the industrial production of the light-gauge system, together with the use of 4D CAD modelling to support production planning, would provide greater certainty of success for projects involving vertical extensions. The case study method adopted in the research is expected to provide specific evidence of the practical use of the approach as well as highlighting changes that are needed within the construction sector for it to gain acceptance.

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<u>Paper II</u>

Vertical extension of existing building by use of Light Steel Framing

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Paper II

Vertical extension of existing building by use of Light Steel Framing

Abstract

The number of people living in the urban areas is very high today, and will in all probability increase in the future. City centres are the most coveted places to live in and this entails an increased interest for creation of more densely populated cities. One possibility to meet this demand is to add apartments to existing buildings, such as shopping centres, offices or multi-storey parking house by vertical extension. An important feature of extending existing buildings vertically is the usage of already developed infrastructure, land, resources such as existing buildings, roads, telecom infrastructure, sewage etc.

When converting an established infrastructure, several constraints have to be considered in the planning process in order to minimise the disturbance on existing activities and to surroundings. The disturbance on existing activities and buildings can be minimised by shortening the construction time, using suitable materials and production methods.

Light-gauge steel framing results in a very lightweight building compared with those of traditional materials. Thus, this makes Light-gauge Steel Framing suitable for vertical extensions of existing buildings. Further, the materials used in the system, steel, plaster boards and mineral wool, are inorganic and hence the risk for problems with moisture and mould is very small. This paper has the aim to describe how vertically extending buildings with light steel framing can open new ways for sustainable urban development.

INTRODUCTION

It is important to develop and construct buildings with a high level of environmental performance, durability, healthy indoor air, quality through integrated design and with social and cultural aspects taking into consideration. Emerging technologies can be means for this. This paper has the aim to describe the state of the art and the achievements of light-gauge steel framing in Sweden. Also, this paper will argue for vertical extension with light-gauge steel framing. Mainly, two projects will be described in this paper, the Husby project in Stockholm and the Open House system in Skåne.

Light-gauge steel framing in Sweden

Year 2005, 75% of the population of the earth is believed to be willing to live in cities. It is important to use the sustainable resources in order to supply future needs. From a global perspective, the quantitative need for housing in the cities is very important. The raw resources of timber are needed for the paper industry, for interiors and furnishing and for e.g. the traditional Swedish timber façade, where the timber has a function as a cultural element. Concrete construction results in heavy constructions, which are usually labour- and site work-intensive and do not result in an efficient construction method. Steel constructions are resource efficient as seen in figure 1; the material content of a framework with concrete is much higher than light-gauge steel framing system. Moreover, every material used in the light-gauge steel framing system is recyclable [1].

From a local perspective, a Scandinavia perspective, the need for affordable housing for all citizens is a social and political issue. There is a big need for affordable homes for students, elderly people, and other groups of citizens who are not well off. Production costs for dwellings in Sweden increased rapidly during the economic upswing in the 80s and the costs levelled out during the economic recession in the beginning of the 90s. However the production costs have once more started to increase faster than inflation, see figure 2.

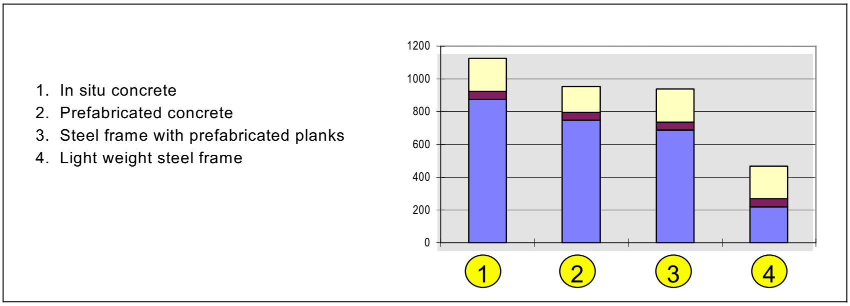

Figure 1: Raw material use. Description of the columns from bottom: a: Manufacturing, b: maintenance, c: use and demolition [8].

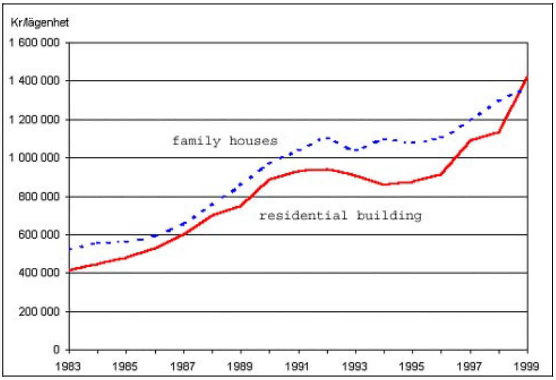

Figure 2: Average production costs for apartments and single-family houses during 1983-1999. Source: Statistics Sweden (SCB). (1€~8.9SEK)

The ideas of industrialised production methods for the construction industry have been discussed during many years within the industry. During the 60s the structural components of the buildings were industrialised and the material used was often concrete. The structural components were installed on the site and afterwards, interior work, services and installation where done on the site. Concrete slabs and columns are large and heavy, thereby a larger crane is needed to handle the elements. Moreover, these elements require more space. Also, transporting heavy structures is less cost-efficient compared to transporting light-weight constructions. The industrialisation of the construction process with concrete had many disadvantages. The most significant disadvantage of concrete elements is the dimensional inaccuracy. Small tolerances are an important fact for industrialised production in order to ease fit-out and sizing and positioning in a production environment. Wood, an organic material, is also inappropriate for industrialised construction. Until the 90s appropriate construction material for industrialised construction has been limited. Light-gauge steel framing and the industrialised production methods of light-gauge steel framing give the opportunities for [2]:

- Lightweight building components
- High level of prefabrication
- Simple erection
- Small tolerances
- Accurate planning
- Developed logistics
- Just in time deliveries

Case studies has been made where the light-gauge steel framing system's industrialised building method together with the modern 3D modelling tool have reduced the production costs with approximately 20% for multi-storey housing projects and have increased the project productivity [3]. Service and installation works are labour and time-consuming in traditional construction. The idea of the industrialisation of the construction is to move expensive activities from the site to the workshop environment. Thus the quality of the end product will increase, costs will be minimised and the construction time can be reduced. By modular construction the site logistics will be more effective and minimised. Thereby the disruptive work on the site can also be minimised.

By moving construction work from the site to a factory the work environment will be much better for the workers. Also, construction workers will be more like manufactures workers, more specialised. This entails opportunity for better construction quality and quality control. The construction process is under more control in the manufacturing environment than on the construction site. The modules will reach final destination on the site with the just-in-time principle and will be lifted to the final position from the lorry. However, the industrialised construction process will change the roles of the partners in the construction process and also the activities.

There are several systems for light-gauge steel framing that include products and detail solutions for interior walls, exterior walls and floors and these systems fulfil all the requirements of the building regulations as well as users' requirements regarding building physics, structural performance and acoustics insulation on the market today [1]. Light-gauge steel farming's advantage has been proven in many case studies and research projects. Experiments in full scale have shown that the use of steel stud instead of wood stud will increase the moisture safeties in external walls. Moreover, building elements under safer condition as in an indoor workshop will reduce the risk of moisture problem in the future [5]. In Borås (Sweden) two elementary and intermediate schools had ”sick house” problem. Consequently, the average absence of students and teachers was very high. During an inspection, mould problems in the timber construction were found. After several investigations, it was decided to build new school buildings with inorganic materials in order to prevent developing of mould and other allergens. SP, the Swedish National Testing and Research Institute assisted the council in the investigation process in order to find the best solution for creating a safe indoor environment. In year 2000, the new schools were constructed with light-gauge steel framing system [4].

The Open House system

An industrialised building process is the vision of Peter Broberg, the inventor of the Open House system and the director of Landskrona Arkitekterna. The main vision of Peter Broberg is to build dwellings at a price, which is affordable, recourse-efficient, environmentally and culturally suitable as well as correctly designed. In the construction process of Open House, architects will have a role more like industrial designers rather than the role of the traditional architect. They will have to put the standard module volumes together in order to create an appropriate living space, residential district and sustainable urban environment. They have to consider social and cultural needs of the area and combine the standards modules in order to assemble a suitable house. Structural engineers will construct the structural frame and how different modules will be placed together so that the load path is robust and stable. Structural engineers' work will decide how different modules will be placed together and the units' horizontal and vertical attachments are be tied together correctly to satisfy the structural requirements. Partnering and long term relationship develop between the module manufactures, and material suppliers must be considered in order to make efficient the industrialised construction process. Factory production will need a stable and qualified workforce. Today there are several obstacles, which result in, retarding the acceptance of the use of industrialised construction with light-gauge steel framing in Sweden. Some are mentioned below [11].

- Regulation made by the councils
- The strong timber tradition in Sweden
- The Industrialised building process is associated with the impersonal looks of the sixties and seventies suburbs and today’s social problems
- Lack of manufactures and assemblers

Fulfillment of the customers’ requirements is a basic objective. Also, design and plan for a sustainable urban environment. By combining the modules differently it is possible to build buildings with an individual interior and exterior and a neighborhood with a characteristic appearance, se figure 3. The Open House system has been used in many projects. The modules have the maximum width of 3.6 m normally allowed in Sweden. 6 columns support each module and any combination of the walls within the each module is possible, se figure 4.

Figure 3: Examples of dwellings with the Open House system. The dwellings are placed around a yard and the parking places are placed under the yard.

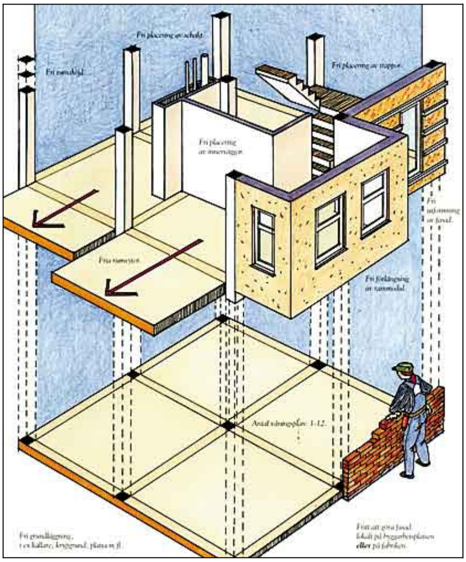

Figure 4: Structural model of Open House system

The Open house system has shown very good performance for fire protection and building physics. Acoustics insulation has been shown to be much better than many traditional constructions. An air gap between the modules, because of the structural frame, results in 15% better acoustics insulation of the construction (se table 1).

Table 1: Acoustics performance of walls and floors of the Open House system

		Figures for Open House system	Swedish recommendation for residential buildings class A
Airborne sound	Floor	R'_w=63 dB	≥ 52
	Wall	R'_w=58 dB	≥ 52
Impact sound transmission	Floor	L’nw=49dB	≤50
	Wall	L’nw=45dB	≤50

Sustainable urban development with vertical extension of existing building and industrial construction process

As modern industry and workplaces are less noisy today it is easier to integrate residential housing and offices. City centres are the most coveted places to reside in. Over time, vertically or horizontally extending has been efficiently used in the cities. Conversions and extensions of existing buildings have successfully been used in several countries, for example: the Netherlands and *Sweden [10] [9*]. A more integrated city with shopping centres, recreational areas, residential areas and workplaces can be created by vertical extension and conversions. Office and workplace areas gets empty during night time which make a good environment for unwanted activities as prostitution and drug dealing. By integrating residential, workplace, recreational areas and shopping centres the city gets more active all day round and safer street environment can be created. Stockholm is constantly changing and developing and with 20 000 annually moving to the city the need for new residential areas is very high. As a consequence the city needs to create new residential areas. One possibility to meet the demand of new apartments in the city centre is by converting city centre areas, which have been primarily office and workplace areas to more integrated areas. By vertical extension of existing buildings in city centres, new apartments and offices will be created. At the same time the city environment has become safer and more active 24 hours a day. The city centre in Stockholm can be divided in two major areas with the western part very active during all hours of the day and the eastern part active during office time. By integrating residential apartments, offices and shopping centres the eastern part has become more active and many unwanted activities has been minimised [7]. A study of 3 vertical extension projects in Stockholm in 2000 shows that most construction firms have not developed special construction methods for vertical extension. If vertically extending buildings should be applied widely the specific requirements and the high level of constraints should be considered in the design and construction process. By putting a major part of the production process away from the site the actual work done on the site can be reduced. By modular construction, where modules are assembled in the factory, and the installation of services, which is a major work in the construction process, are done in the factory, time on the site will be reduced [9].

Advantages of vertical extensions of existing buildings:

- More efficient use of exploited land means that the use of new land can be minimised.
- Exploitation is made in the areas where the need is high.
- Infrastructures for i.e. sewerage, water, telephone, schools, streets etc, already exist and have been developed.
- Vertical extension and over-roofing can be combined with renovation and conversion of the existing building.
- The bearing capacity of existing buildings can be used more efficiently.

- Vertical extension is a cost-effective method to increase the exploited level.

Light-gauge steel framing results in a light-weight building compared to one made of traditional materials, e.g. compared with a concrete building the weight is only one fifth. The technique has the highest strength -to-weight ratio of any structural frames assembly [1]. Therefore the need of reinforcing the existing building will be minimised. Consequently, this will reduce the cost of the extension of the building. Therefore the Light-gauge steel framing building system is suitable for vertical and horizontal extensions of existing buildings [12]. When converting an established infrastructure, several problems have to be considered in the planning process in order to minimise the disturbance on existing activities and to surroundings. The disturbance on existing activities and buildings can be minimised by shortening the construction time, using suitable materials and production methods.

Figure 5: Modular over roofing, the Husby project. Before and after one floor extension is placed on the roof of the existing building

An example of a vertical extension is the Husby project. Husby is an immigrant suburb in Stockholm with some social problems. Husby is located near the telecom valley of Stockholm, Kista. In connection to Kista there is need for hotels, student residences and apartments. Modules manufactured in Nora (200 km from the site) and assembled on the roof on the same day of arrival. The modules were delivered in two parts, the roof structure and the modules. It was possible to assemble a module per day.

Conclusions

The low weight of the light-gauge steel framing system makes it appropriate for vertical extension and building on land with low bearing capacity. Also by the industrial production process the production costs can be minimised which will give an opportunity for affordable housing.

Research and case studies in Sweden have shown the possibility of using this material and building system for a sustainable urban development. The experiences from the recent projects in Sweden and research and project around the globe show, that by building dwellings and houses with light steel framing and specially by using industrialised building methods, the life quality of today and future generations will be improved and a balance between social and economic elements and environment will be achieved.

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Paper III

Industrialised construction for vertical extension of existing buildings

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Paper III

Industrialised construction for vertical extension of existing buildings

Abstract

Industrialised building processes in todays Swedish construction industry has been studied in three vertical extension projects. Vertical extension projects are fraught with both technical and managerial problems, which may be solved with an more industrialised building process. In fact each of these extension projects has its own prompts and opposing for industrialised building process, however, the implementation in construction industry is far more complicated than is recognised by the industry. This has been experienced in this research project as well as in other studies.

In this paper the idea of an industrialised building process is divided in two main areas prefabrication and logistic strategies in construction. With this starting point, the implementation of industrialised thinking in Swedish construction about vertical extension projects will be reviewed. Based on experiences from three vertical extension projects in Stockholm, the prefabrication level and the strategies for supply chain management and the logistical activities are studied.

Key words: Construction Logistics, industrialised building methods, JIT, prefabrication, supply chain management.

Introduction

Prefabrication

In manufacturing, the design and production processes are more closely aligned because they are typically undertaken by the same organisation. The organisation seeks to control the entire process, because it sees this as a way to better meet the needs of the customer and to produce a product required by the market. In construction, the design and production process could look different. However, one of the prime examples of the integration of design and production in construction is when prefabrication is applied. In a literal sense, prefabrication is about making buildings under factory conditions and then transporting them to the project site for final assembly.

Experiences from several projects in Sweden indicate that the production costs can decrease 20-50 % depending on the prefabrication level and the volumes (SOU 2000:44). This has been one of the main reasons behind prefabrication. Another motivation for prefabrication is that it can be seen as a way to minimise work on the site, which will enable better quality of the construction elements and better work environment for the workers. Prefabrication could then be seen as moving activities from the site to a factory and then transport elements or modules for installation without any changes in the actual construction process. Also, prefabrication can be a solution for the lack of skilled labour as it give less reliance on site labour. High quality of the products is easier to achieve and the weather dependency is minimised (Gibb, 1999). There are many aspects, which have to be considered when high prefabrication level is implemented. The design and decision process for choosing a prefabrication level, buildability studies and the logistics of the construction process are some key aspects, which differ the traditional construction process form the construction process using high prefabrication level. Buildability (refereed to as constructability in US literature) is about buildable design, design for efficient and safe construction, in order to reduce waste and rework in construction. Prefabrication requires detailed buildability studies before any production activities start. Thereby, a more integrated design planning and production planning will be required. A buildability study is a tool for increasing productivity in the production and has to be considered early in the process before the manufacturing of components starts. The problems, which the contractor is involved in at the site, have to be considered in the design. Previous studies on buildability show that interfaces between components and difficult assembly especially for cladding, services installations, roof and stairs are widely experienced and these could delay projects up to 21-30 % (Ganah et al., 2001).

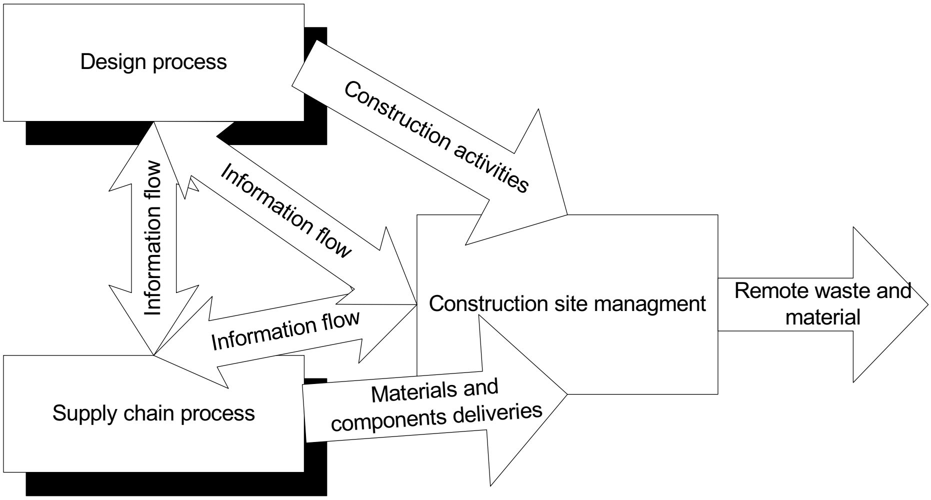

Figure 1: Logistic activities in the construction process. Logistic activities can be spilt in two main groups: logistic

By off-site factory based production the operational rules of construction will be changed and new methods for planning the construction process and controlling the production and assembling processes will be needed. When a high level of prefabrication is used in the construction process the organisational, managerial, contractual and physical interface between the trades can be reduced. The activities on the site will change and be more about assembling than construction, which will simplify the construction site management. Moreover, prefabrication and factory manufacturing construction impose their own conditions for the supply chain relationship.

Logistics strategies in the building process

Logistics can simply be described as the art of efficient material flow and was originally the art of moving quartering troops. Logistics is now the process of planning, implementing and controlling the flow and storage of raw materials, in process inventory, finished goods, services and related information from point of origin to point of consumption for the purpose of conforming to customer requirements, (Council of Logistics Management (2000), *"1999 Year end revie*w"). Logistics activities in the construction industry are seen as operational activities and are often managed ad hoc on the site. The construction industry unlike the manufacturing industry lacks a general strategy for logistics management, however this seems to be changing (Berteslen et al.,1997). Construction logistics can be split into logistics to and from the site and also logistics activities on the site, figure 1. The design process controls which activities are going to take place on the construction site. The supply chain process is depends upon the design and vice versa. Nevertheless, the supply chain activities (procurement) and design process controls the supply of materials and the components and also the equipment required to support construction work.

Construction site logistics plans are the prime control and steering tool in Swedish construction. Seventy per cent of the Swedish construction companies make construction site plans before the actual work on the site begins. Twenty per cent make these plans during the first bidding calculations and 11% just before the establishment of the construction site. However, around one third of these plans will never be updated or revised (Hanson, 1999). Construction site logistics management can be divided into three different parts before, during and after the production phase. Before the production phase, site logistic management is about previewing the production process and to see the potential problems that can occur during the project execution. By implementing the philosophy of design for production, site logistic aspects of the production will be considered early in the construction process. At the production and during the production time a logistics pole or routine for logistics coordination should be installed on the site. After the production phase the experiences should be documented and feed back of mistakes and deviations should be done (Bertelsen, Neilsen, 1997) (da Silvia, Cardoso, 1999). Logistics cost analyses and productivity studies can give valuable information to the involved companies (Bertelsen and Neilsen, 1997).

Logistics to and from the site is about the process of supplying resources to and removing waste from the site. A resource could be anything from construction equipment to construction component, construction materials, information or workforce. Production can be organised in two ways, producing on demand (pull system) and producing on forecast of demand (push system). The client's real demands are the steering factor for the production of products. The pull system, often mentioned as the Kanban system (Ohno, 1978), could be compared to an information processing system for providing production scheduling to all processes and suppliers (Yuan and Low, 1992). Supplier relationship is an important factor in order to be able to implement a working pull system and an efficient supply chain management. Structural changes in the supply chain will result in cost savings for the construction project and the construction industry (Olsson and Larsson, 2000) (Bertelsen and Neilsen, 1997).

The Case studies

The method of exploration

Three vertical extension projects in Stockholm have been studied. All three projects involve extension of an existing building with one or several extra floors. Vertical extension projects are, among others, characterised by minimal construction sites and restricted vertical and horizontal movements at the site. Exploratory case studies have been done in order to be able to answer the question if or how the industrialised building process has been applied in these projects and to identify those factors that have played a role in the construction process of vertical extension projects in city centres. Undertaking these case studies and analysing their findings will identify problems for further studies. In this study, industrialised building have been studied from the point of view of two characteristic and related subjects:

- Grade of prefabrication.
- Use of logistics strategies in the construction process and the material handling process.

By stating these subjects the attention will be focused on the theoretical issues examined within the scope of the study and in order to simplify the explorative study several sub-units have been chosen (see Table 2). These units will also help to identify problems relating to the vertical extending of buildings on today's Swedish market. The overview of the research method of the study is shown in Figure 2. After deciding relevant parameters for the study and choosing three ongoing projects several interviews were made. Findings from the interviews are listed in en the different organizations.

Table 4.

Table 2: The units used in the interviews

Subjects of the case study	Units
Prefabrication	Prefabrication level
	Buildability studies
	Decision process and design process for prefabrication

Logistic organisation and coordination	Deliveries to the site
	Planning methods of the deliveries on the site
	Material handling on site and the planning of site areas
	Logistics coordination
	Client satisfaction
Material handling at the construction site	Total customer focus
	Main contractor and supplier relationships
	Client and main contractor relationship
	Methods and IT- tools used

Data collection

The data collection method in the case studies was open interviews. The interviews have been explorative with the goal to find as much information as possible with focus on the units of the proposition. Detailed notes from the interviews are found in Bergsten (2004). The interviewer approached the informants with the aim to discuss the topics of the case study units. The starting point for the interviews were to understand the project members` perspective on the project planning and execution. The interviewed persons are presented in

Table 3. Each interview took approximately two hours. Moreover, study visits to the sites have been made and documents have been studied in the pre-case study phase.

Table 3: The informants of the interview

Project 1	Project 2	Project 3
Project manager	Client	Client
Site manager- steel structure	Project manager	Project manager

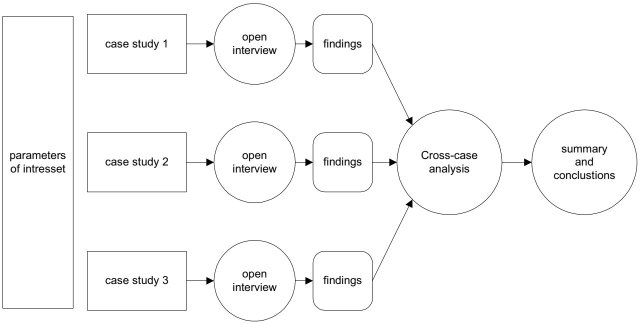

Figure 2 Overview of the study method

Vertical extension projects used in the case studies

Project 1

At the time the project was one of the big ongoing projects in central Stockholm, comprising 50 000 m^2 refurbishment and extension. This vertical extension project was performed under the design and build contract model. However the client organisation and the contractor organisation were in the same business group of companies, which facilitated the communication between the organisations. The project was highly focused on the tenants. A fast construction process was desirable and the construction time was during the years 2000 to 2003. The construction system was prefabricated steel columns and pre-cast concrete slabs. The existing building was built in the seventies and its structural system is site cast concrete slabs and columns. Two houses in the block were merged together by the extension. The buildings were vertically extended with 2 and 4 floors. The project was characteristic of high complexity amongst other factors e.g. two tunnels were located under the building. The complication of the foundation resulted in many uncertainties in the construction process. The just-in-time production philosophy was used in the project.

Project 2

The existing building is from late sixties and was built with site cast concrete slabs and pre-cast concrete columns. The buildings in the block were extended with one floor and with two storeys detached houses on top. The extra floor was built with site cast slab and the houses of prefabricated timber elements. Also refurbishment of the existing building was a large part of the project. The project was carried out under the design and build contract model. The client organisation was a joint venture between the contractor, an investment and a property company. This resulted in a close collaboration between client and contractor organisation through the design and construction process. The needs and the wishes of the tenants, were central in the design and construction process of the projects. Therefore, the design team and the client organisation were placed at the construction site in order to integrate the production and design processes and minimise the construction time with maximum tenants flexibility. This caused major problems at the site. The just-in-time concept was applied for the production. A fast construction process was desirable for the client organisation and the construction time was between 2000 and 2003 and the total area involved was 68 000 m^2.

Project 3

The existing buildings were built during the seventies. The buildings had five floors and their structural system is site cast concrete slabs and pre-cast concrete columns. The project involved vertical extension of three buildings and each building was extended with one-storey volumetric student study bedroom apartments. The project comprised 35 new apartments. There existed a written agreement between the client and the contractor for vertical extension in the area. This agreement was based on an old relationship and experiences in earlier projects. The project was performed with the design and build contract model. The client organisation was a municipal housing company. The existing building was built with a concrete structural frame.

Early in the project the client decided to use a highly prefabricated building system in order to minimise the disturbance to the surroundings. The characteristic of this vertical extension project was its high level of prefabrication. The project had to be finished before the start of the academic year but, due to the failure of the suppliers in delivering modules on time, it failed to do so. The total construction time was nine months.

Summary

Svanerudh (1998) has stated that the higher the level of influence of the user in the design the more integration of the design and production phases is needed. This is related to the time the user can wait for the end product to be delivered. As seen in these cases, the relationship between the prefabrication level and the influence of the end users is that a higher prefabrication level means less users influence. This is because of the existing building systems, construction processes and the time when the tenants are allowed to enter the process in order to be able to influence the outcome of the process. In the project in which the tenant's orientation was high the contractors found the project more complicated due to constant changes based on the tenant's needs. The main contractors in these projects had different strategies for dealing with client satisfaction and different strategies for understanding the level of client satisfaction have been considered by the contractors. But only in project 1 actual measurement were done.

In table 3 the findings from the open interviews are summarized. The table shows the different studied units in relation to the different case projects. A market pull-system was considered in all three projects although only in two of the projects tenants were involved in the process. The desire to have a considerable client focus in project 2 resulted in many changes in the design during the production. The detailed design was not completed before actual work at the site began. In project 2, the combination of user involvement and the integration of the design and production phases and also the lack of appropriate manufacturer for the building system resulted in a lower prefabrication level. Minimizing the disturbance to the surrounding housing area was the main reason behind the client's wish for a high level of prefabrication in project 3.

Usually design and build contracts give the constructor more freedom to choose the structural frame, prefabrication level and other design decisions. In project 1 the main contractor organization used their in-house developed structural frame for the project. In project 1, site conditions and the difficulties of integrating the vertical extension with the existing building resulted in a lower prefabrication grade. However the project managers in project 1 and 2 stated that the uncertainties regarding site restrictions was too high to be able to apply a high prefabrication level. The interviews show that the reason that in the first place prefabrication was chosen both in project 1 and project 2 was that a high level of prefabrication was believed to result in a shorter construction time. Moreover, at a strategic level it is agreed on that handling elements on site instead of materials will give more flexibility to the construction site as well as less workflow conflicts. But this was not validated at the construction sites due to changes made at the construction sites or in the detail designs in project 1 and 2. In project 3 the construction process was well defined before the actual start of the manufacturing of the modules and the on site construction work. Also, project 3 was much smaller in size and less complicated in comparison to project 1 and 2.

Several of the informants commented that the knowledge existing in the head of the project participants is the most important tool in order to plan activities and buildability studies. This could also be confirmed by other studies (Ganah et al, 2001). In projects 1 and 2, the buildability studies were performed before the actual production team was involved. However, in these two projects the attitude was that the complexity of the projects made it necessary to consider and reconsider many things at the site after the work had started. Other explanations to why at the detail design phase the prefabrication level was reduced in both project 1 and 2, could be the lack of strategic buildability studies and workflow planning.

Some aspects of site logistics were considered at the design stage and early in the production planning but far from enough. Examples of these considerations were site condition studies and design descriptions, also validating technical solutions. The site layout planning was done late in the process, often just before the production. For vertical extension projects one of its most significant restrictions is the site location. This means that they have to put site layout planning much more in focus at the detailed design phase. In these projects the capacity of the site layout plans was not used and not often updated when changes during the production were done. In all three projects information exchange with the surroundings was important in order to minimise the disturbance to the surroundings and the tenants. In project 1 regular meetings and 3D models where used for information exchange. In project 2 a call centre was established in order to give service to existing activities during the construction time and also to answer questions regarding problems.

Uninterrupted workflow entails a highly planned production. This should be done in close relationship with the suppliers and the different workforces at the site early in the process. During the construction period, meetings were regularly made with suppliers and subcontractors. At these meetings subcontractors and suppliers were involved in the detailed workflow planning. Informants have commented that they did not directly work with minimizing non-adding value activities. Each trader had a goal to perform within the limits of the contract agreement. The main contractors could have had the role of minimizing non-value adding activities on site but as seen in these projects, construction managers have not considered this during the workflow planning. To minimize disturbance to the neighborhood environment was important. Implementing a pull-strategy for the deliveries to the site will requires a minimisation of storing and handling of materials on the site (Yuan and Low, 1992). All deliveries to the sites in these projects were restricted. In project 1 and 2, deliveries to the site and to the stores around the construction site could not be made at the same time. However, there was not any direct coordination between the deliveries to the site and to the stores around the construction site. If clashes happened the vehicle had to drive around the city until a more appropriate time. Deliveries on trailers had to be repacked on smaller vehicles outside the city center in order to be permitted to drive in the city center. Although there was a high level of restriction for deliveries to the construction site, special arrangement for delivery management was only made in one of the three projects. In project 2 a logistic co-ordination organization was put up. The co-ordination organization's responsibility was to coordinate the JIT deliveries to the site. Each activity manager gave information regarding the delivery needs and the coordinators responsibility was to plan the schedule for delivery, reception, unloading, lifting devices and also storage and handling on the site.

As the delivery of materials was not integrated in the building process schedules in the two other projects, each delivery was pointed out on a white board on the construction site. This white board was used for planning, scheduling and controlling all logistical activities to and from the site. Each responsible receiver, who could be a subcontractor or manager, wrote down the weekly plan of coming deliveries. Each receiver of the delivery was responsible for planning the delivery, reception, unloading, lifting devices, storage and handling on the site and also for safety arrangements. Mobil phones and personal contacts are other important tools for delivery planning. However the builder agreed that construction site layout plans should be used more for planning of deliveries to the site and on movements of workflow and materials on the site.

These projects were completed under the design and build contract system. The client appoints the main contractor for the project and the contractor takes responsibility for the construction process. The design and building method of procurement integrates the design, supply and construction phases. Contracts between contractors and subcontractors and suppliers are often based on best price (or best value for the price) and the relationships are characterized as highly social. In these projects the relationship is not based on technical improvement, building system development or standardisation. The supply chain activities in these case studies were not analysed by the contractor in order to dismiss non-value adding activities. This could be related to lack of iterative communication between the procurement team, production team and design team. In one of the projects a written agreement between the client and the contractor existed for vertical extension in the area. This agreement was based on an old relationship and experiences form earlier projects. However, for the next step the client would prefer to have a Construction Management procurement system instead of continuing the next phase of the project with the same contractor. This was because the client did not find any added value in the project with that contractor and the design and build procurement. Thereby, there was a desire for the module manufacturer to take more responsibility for the overall construction process. In project 1 the client organization and the contractor belonged to the same business group, which resulted in improved communication and experience exchange between the organizations. In the project 2 the client organization was a joint venture of the contractor and the owner of the building. In the same project the client representatives and the design team was placed near the construction site in order to smooth the communication between the different organizations.

Table 4: Cross-case analysis

	Case studies	**Project 1**	**Project 2**	**Project 3**

Project characteristics	**Project time**	2000-2003	2000-2003	Jan 2001- oct 2001
	Total project cost	>1 000 M euro	>1 000 M euro	2,8 M euro
	Procurement	Design and build	Design and build	Design and build
Subjects of the case study	**Units**			
Prefabrication	**Grade of Prefabrication**	Low	Low	High
	Buildability studies	No defined strategies Design meetings prior to the start of production	No defined strategies Design meetings prior to the start of production	No defined strategies The client wished for a high prefabrication solution early in the process
	Decision process and design process for prefabrication	**No**	No	Initiated by the Client
Logistic organisation and coordination **Material handling at the construction site**	**Deliveries to the site**	Partly JIT	Partly JIT	Partly JIT
	Planning methods of the deliveries	Ad hoc	Logistic coordinator	Ad hoc – depending on the module manufacturer
	Client satisfaction	Measurements have been done with positive	Near and daily contact with the client	No

		results	organisation	
	Total customer focus	Partly	Yes	No
	Main contractor and supplier relationship	Social and adjusted to the conditions of the market	Social and adjusted to the conditions of the market	Social and adjusted to the conditions of the market
	Client and main contractor relationship	Same company	Joint venture	Social and adjusted to the conditions of the market
	Methods and IT-tools for production planning and controlling	CPM schedules 2D CAD drawings Project database Meetings Informal personal contacts	CPM schedules 2D CAD drawings Project database Meetings Informal personal contacts	CPM schedules 2D CAD drawings Meetings Informal personal contacts

2D drawings were used for communicating design information together with descriptions. CPM (Critical Path Management) schedules were used for communicating construction time plans but also for the construction process. Project databases were used for document sharing and distribution in the two larger projects. Also in the two larger project web sites for information sharing were made. Mobil phones and personal contacts were pointed out as the main important information exchange tool. Formal and informal meetings were an important tool for controlling the progress of the production and planning activities. In one project the design organization and the production organization were placed at the same location near the construction site, resulting in a better information exchange and communication between the design and production organizations. At the same time the design and the production of the project were highly integrated.

The Just-in-time (JIT) concept could be seen both as part of the logistic strategy and as a production planning strategy which was used in all three projects. JIT is about minimisation of waste in the construction process and prefabrication will enable waste minimisation in the process. Also, JIT is applicable to construction by eliminating the uncertainties in the workflow and supply chains, which cause variation and disruption in the construction process. Ballard and Howell (1995) suggest that the implementation of JIT to construction differs from its application in manufacturing due to the fact that manufacturing and construction are different types of production. Construction is more complex, the process is more uncertain, in the construction process each product of the process is produced once and it is important to minimise the production time. Also flexibility is needed through the processes in order to respond to the customer's requests and late changes. In these projects the JIT strategy for the deliveries to the site was chosen but no strategy for waste minimisation in the supply chain or material handling on site was recognised. Some of the difficulties of applying JIT to the construction industry are described in the literature. These could be estimating the exact requirements for materials, well coordinated site work, changes in the client's requirements, unexpected shortage of materials, waste (in time, workforce, material), management on site. These difficulties could more or less be identified in these case studies too.

The industrialised building method used in project 3 was successful and was suitable for vertical extension. Also the basic conditions of the projects 1, 2 and 3 are very different from each other and thereby it is difficult to discuss the level of the prefabrication effect. One problem has been to define the prefabrication level and what should define the grade of applied industrialised building methods in these projects. The just-in-time concept has not been applied efficiently or has not been possible to implement completely in these three projects. The prefabrication level in project 3 was high. However, lack of experience of co-ordinated production planning and of the industrialised building process by the module manufacturers and the contractors was the main reason for the failures of the project 3.

Conclusion and further studies

The case studies have shown the different aspects of implementing the industrialised building methods for projects with a high degree of restrictions in vertical extension projects. The two parts: grade of prefabrication; logistics strategies in the construction process, defined for industrialised building process in this paper, are highly intertwined and must be considered at the same time. The focal point of the case studies shows that there is a wish for a higher prefabrication level and an industrialised construction process among clients and contractors, however the uncertainties in the implementation of new methods and processes impede the way forward to a more industrialised building process.

These projects have been highly customer focused and at the same time the construction time had to be minimised. By starting the construction work before the design work been finished and also being customer focused complicated the projects. Also, buildablilty studies regarding the site restriction were not satisfactory and resulted in that the prefabrication level had to be decreased. From the interviews it could be concluded that defining the client wishes and project characteristics are two important factors in planning a construction process and thereby not directly important for the prefabrication level and the decision process of the prefabrication level. However site restrictions are an important factor of for the prefabrication level and the decision process of the prefabrication level, which needs buildability studies. Changes in the design and construction methods in late phases and minimising the design time reduce the advantages and the motivations for prefabrication as seen in these projects.

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