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Symbiosis between

Energy Efficiency
&
Production Efficiency

<u>Prestudy</u>

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Abstract

Within the construction industry there are two great areas under development, energy efficiency and production efficiency. These two substantial areas are, however often seen as each others opposites.

The construction sector stands for 40 % of the total energy usage in Europe, of which 15 % is consumed during production and the remaining 85 % is consumed during operation of finished buildings. There is a constant ambition within the construction industry to reduce costs but in contrast to this, energy efficiency often increases building costs.

In this report, the passive house concept and its production is reviewed. A so called passive house is today theoretically not technically different from traditional housing, it simply consists of more insulation in walls, floors and ceilings, more airtight envelope, lower U-values for windows and doors etc but in practise, it is different:

Passive houses require very high accuracy during production. There is a high demand on the building envelope airtightness, in contrast to traditional housing with no specific requirement concerning airtightness. The high demand on airtightness makes it necessary, today, to seal all air barrier joints and nails manually with tape or weld. This is a tricky and very time consuming work that today is not efficient. Even if the exterior walls are prefabricated the producers cannot handle the demands and leave it to the workers on site to perform the task. From a prefabrication perspective this has serious consequences; all installations are placed in a layer (to prevent penetration) on the inside of the barrier and hence they can't be prepared before the barrier is in place. This leaves more work than normal for the workers on site.

Another problem in prefabrication is the fact that the walls, in general, are too thick for automatised machines and hence the wall cannot be produced as one element but has to be produced in layers which requires more lifting operations and assembling work on site.

The "new" problems that have been identified so far only concern the building envelope in different ways. How could we then improve our production in order to solve these problems?

This report presents a survey over today's most common production concepts within construction, in the search for solutions. Production concepts considered here are Partnering, Supply Chain Management, Lean Construction and Industrial Production. After an analysis of the concepts on the basis of the identified problems and prerequisites it is found that an industrial or industrialised production could be the solution to this kind of production. Lessing (2006) suggests eight characteristic areas that represent the industrial house production and two of them are directly related to the problems identified here; "Development of technical systems" and "Off-site manufacturing of building parts". By moving the difficult production operations into factories designed and developed for this production, could that solve the problems? Is it possible to within industrial processes modularise energy efficient technical solutions and hence at the same time reduce costs and increase energy performance?

Contents

1 Introduction

1.1 Background

Two great areas are under development in the construction industry, energy efficiency and production efficiency. Energy efficiency refers to the lifecycle cost of the building and is driven by increased energy prices as well as the changes in climate that are now occurring. Production efficiency refers to decreasing the costs that have been affected by increased material costs and inefficient working operations. These two important areas are however often seen as each others opposites.

During the last decades building costs has increased by an average of 2,5 times consumer price index. At the same time, the building industry stands for 40 % of the total energy usage in Europe, of which 15 % is used during production and 85 % is used operating the final product. To decrease production costs in symbiosis with increased energy performance is hence of great concern to the whole construction industry.

Today in Sweden, energy performance within the production of efficient building systems are only just under the regulations and the gap to the most energy efficient buildings is great. The reason is that a more energy efficient building requires more insulation, a more airtight envelope as well as more transports, which today means increased costs.

In our great and market leading housing companies there are few, if none, persons that possess the knowledge of both these areas and the cooperation over boundaries is weak. Hence, research that considers both these technical areas is needed.

1.2 Purpose and objective

The purpose of this report is to describe current knowledge area regarding production efficiency and energy efficiency, in order to create a platform for further knowledge to be built-up within the area.

1.3 Scope and structure

This report consists of five chapters which are briefly described in this section.

Chapter 1 is an introduction that gives the background to this report as well as purpose and objective.

Chapter 2 contains a literature review in two parts. The first part is a review of the passive house concept, questions like “what is a passive house?” and “what does the current production look like?” is addressed in this chapter. The production section is based on interviews. The second part describes today’s most common production concepts in construction as well as the background to the implementation in the building process.

Chapter 3 discusses how the problems and prerequisites within passive house production can be improved within current production concepts and analysis of respective production concept on the basis of identified problems is made.

Chapter 4 gives conclusions from the literature study and the discussion chapter.

Chapter 5 gives proposals for further research.

2 Literature study

2.1 Passive Houses

The concept was invented by Dr Wolfgang Feist, founder of the Passivhaus Institut in Darmstadt, who built the first passive house, in 1991. Today passive house is a registered trademark which means that there are some requirements that needs to be fulfilled for a house to be built according to this standard. The passive house is actually nothing strange. No new techniques or materials are needed; it's just to apply the best solution on the market.[1]

2.1.1 Definitions

2.1.1.1 Sweden

The following section is a summary of the Swedish demand specification considering passive houses, "Kravspecifikation för passivhus i Sverige – Energieffektiva bostäder[2]".

Due to the colder climate in Sweden in comparison with other European countries a Swedish definition of passive house has been established. The Swedish Energy Agency's program "Forum for energy efficient buildings" (FEBY) management team has been given the assignment, together with the building industry, to develop a demand specification for passive houses and low energy houses in Sweden. The proposal has been out on referral and in the autumn of 2007 the demand specification was finished, version 2007:1. For a building to be referred as the concept "Passive House" there are some fundamental requirements that needs to be fulfilled. In this way the quality will be secured within marketing and communication in the building and operation process. The demand specification has considered the corresponding definition in Germany but deviates because of the Nordic climate. The demands on passive houses aim to minimise the need of contributed effect in buildings so that requisite thermal comfort can be received rationally by heat distribution within the hygiene air flow. Supplementary demands on resource efficiency is put up in order to limit the total bought energy, that is to say operational electricity, hot water, heat and possible cooling. In addition to the demand specification the Swedish regulations (BBR) shall be applied.

Energy and effect demands:

	Climate Zone South	Climate Zone North	Detached houses < 200 m^2, South	Detached houses < 200 m^2, North
Max Effect [3]	10 W/m^2	14 W/m^2	12 W/m^2	16 W/m^2
Max bought energy (excluding household electricity)	45 kWh/m^2,year	55 kWh/m^2,year	55 kWh/m^2,year	65 kWh/m^2,year

[1] http://www.wikipedia.se, *Wikipedia - Den fria encyklopedin,* visited 2007-12-05

[2] FEBY (2007), "Kravspecifikation för passivhus i Sverige – Energieffektiva bostäder" Energimyndighetens program för passivhus och lågenergihus, Version 2007:1, Forum för Energieffektiva Byggnader

[3] Maximum aloud effect at design outdoor temperature and an indoor temperature at 20°C.

Building requirements:

To subsequently be able to verify the buildings technical energy characteristics, the energy usages shall on monthly basis have the ability to be read, household electricity and heat energy separately. In addition, the water volume for heating water and the number of occupants is documented.

The windows in the building shall have a maximum U-value of 0,9 W/(m^2, K), measured by an accredited laboratory working to the standard SS-EN ISO 12567-1. The windows shall have a representative size for example 1,2 x 1,2 m including frames and glass. For other window sizes the standard SS-EN ISO 10077-1 should be used, though the average U-value of the windows, independent of size, shall be a maximum of 0,9 W/(m^2, K). The air leakage through the building envelope shall be a maximum of 0,3 l/(s,m^2) at ± 50 Pa pressure, related to SS-EN 13829.

Demands on indoor environment:
Sounds from the ventilation system shall at least fulfil sound class B, related to SS 025267. The supply air temperature in the final heater shall be a maximum of 52°C in each supply air diffuser when the supply air system is used to supply heat.

2.1.1.2 Europe

For European passive constructions, the prerequisite is an annual heating requirement that is less than 15 kWh/(m^2,a), not to be attained at the cost of an increase in use of energy for other purposes. Furthermore, the combined primary energy consumption per living area for a European passive house may not exceed 120 kWh/(m^2,a) for heat, hot water and household electricity.[4]

PEP, which stands for 'Promotion of European Passive Houses' is a consortium of European partners, supported by the European Commission, Dictorate General for Energy and Transport.[5] Since the climate conditions for building a passive house in northern Europe is not comparable with building a passive house in southern Europe, they have developed an updated definition of passive house[6]:

"The term passive house refers to a specific construction standard for residential buildings with good comfort conditions during winter and summer, without traditional heating systems and without active cooling. Typically this includes very good insulation levels, very good airtightness of the building, whilst a good indoor air quality is guaranteed by a mechanical ventilation system with highly efficient heat recovery. Thereby the design heat load is limited to the load that can be transported by the minimum required ventilation air. However space heating does not have to be carried through the ventilation system. For 40° - 60° Northern latitudes, under conditions specified in the PHPP calculation model:

– the total energy demand for space heating and cooling is limited to 15 kWh/m² treated floor area;

[4] http://www.passiv.de, *Passivhaus Institute*, visited 2007-11-05
[5] http://www.europeanpassivehouses.org, *Promotion of European Passive Houses*, visited 2007-11-05
[6] Kaan, H. (2006) *"Passive Houses Worldwide: International Developments"* Conference Proceeding at the 10th International Passive House Conference, 19-20 May 2006 Hanover

– the total primary energy use for all appliances, domestic hot water and space heating and cooling is limited to 120 kWh/m²

A passive house has a high level of insulation with minimal thermal bridges, low infiltration and utilises passive solar gains and heat recovery to accomplish these characteristics. Consequently renewable energy sources can be used to meet the resulting energy demand.

For 60 degrees and higher latitudes, it's necessary to adjust the figures in order to be able to achieve an ambitious yet realistic solution. Countries who wish to make their national adjustment of the above general PEP approach are free to make proposals, which must be evaluated in a PEP group meeting."

2.1.2 Building envelope

2.1.2.1 Heat transfer

In materials and constructions, there is a heat transfer from parts with higher temperature to parts with lower temperature. The transport of the heat can occur in different ways, which must be considered when thermal relations in materials and constructions are being studied. This concerns calculations and design on new buildings as well as operation and maintenance of existing buildings. The total heat transfer can be separated into three different parts, radiation, conduction and convection. The radiation occurs with difference in temperature as the driving force, which means that heat is transferred from a warm surface to a cold surface. The heat transfer by convection occurs when there is a difference in pressure, the heat then transfers with the air from the side with higher pressure to the side with lower pressure. Heat transfer by conduction occurs when there is a difference in temperature. The heat is then led through the homogeneous material from the warm side to the cold.
In passive houses as well as any other energy efficient building there is an obvious requirement to protect the building from heat transport through the envelope and thus keep the energy usage as low as possible. The building is protected from heat conduction through insulation with good characteristics and the heat convection is stopped through an air tight design.[7]

2.1.2.2 Insulation

Thermal insulation is an important factor for the energy optimization of the building envelope and in achieving thermal comfort for its occupants. A well insulated envelope is necessary to minimize the heat losses and for passive houses it is the most important principle, applied continuously around the building envelope without thermal bridging.[8] In Lindås, the first passive house project in Sweden, the building envelope was highly insulated with 40-50 cm insulation in walls and roof and the floor was insulated with 25 cm insulation. In Sweden, the most common insulation material is mineral wool and expanded polystyrene (EPS) and to use a combination of those isn't rare.[9] The same applies in the rest of Europe. But since energy demands on buildings are getting higher new insulation materials need to be developed and tested. Passive houses force the market to develop new and more effective materials, for

[7] Petersson, B. Å. (2001). "*Tillämpad Byggnadsfysik*" Studentlitteratur, Lund, Sweden
[8] Feist, W., Schnieders, J., Dorer, V. & Haas, A. (2005), *"Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept"* Energy and Buildings 37, 2005, 1186-1203
[9] Wall, M. (2006), *"Energy efficient terrace houses in Sweden: Simulations and measurements"* Energy and buildings 38 (2006), 627-634

example new insulation materials to be able to reduce the thickness of the walls while still retain the same thermal characteristics. Examples of these new materials for the housing industry are vacuum insulation, aerogel and polyurethane.[10]

Vacuum Insulation Panels
Vacuum Insulation Panels (VIP) has a thermal resistance that is about a factor of 5-10 times higher than equally thick conventional polystyrene boards. This opens a new field for slim, energy efficient building envelope design.[11]

VIPs are built from open pore materials like pressed powder boards etc. The core materials are wrapped in a high gas barrier film through a special procedure and after that the air is evacuated and the barrier is sealed.[12] VIPs are however also very sensitive to mechanical damage due to the thinness of the barrier film. Building on site often presents a high risk of damage due to fragility hence they are not so common in Swedish construction. In addition, VIPs can't be cut to the right size on site but must be ordered to fit during the design stage. One option could be to prefabricate the entire insulation façade.[13]

Aerogel (”Silica aerogel”)
Aerogel is an extremely porous material that is directly derived from a wet gel in a process that replaces the entrained liquid phase with air, through a supercritical drying process. In principle aerogel can be derived from all kinds of materials that can take on gel form. The most common, is however, that aerogel is produced from organic silicon compounds that give rise to a porous network of silicon dioxide in the finished product.[14] One form of aerogel is 99,8% air and 0,2% silicon dioxide and hence aerogel is very good as insulation. A typical silica aerogel has a total thermal conductivity of approximately 0.017 W/mK but the thermal conductivity can be reduced by adding an additional component to the aerogel. This has been done with elemental carbon as additive. The thermal conductivity was then reduced to 0,0042 W/mK.[15]

The silicon dioxide composed aerogel is also transparent (90%/cm) and therefore it is used as insulation in windows or skylights. By filling the space between the glazing with aerogel and also evacuating the air to one tenth of the atmospheric pressure the heat transfer coefficient for the glazing part of the window can be reduced to 0,3 W/m^2K.[16]

2.1.2.3 Thermal Bridges

In different interfaces, for different reasons, the same insulation thickness cannot be used everywhere in the walls or floors. It then becomes a thermal bridge. Normally the thermal bridge appears when a material with low heat insulation characteristics breaks through a material with better heat insulation characteristics. Typical places for a thermal bridge to

[10] Feist, W., Schnieders, J., Dorer, V. & Haas, A. (2005), *“Re-inventing air heatin: Convenient and comfortable within the frame of the Passive House concept“* Energy and Buildings 37, 2005, 1186-1203
[11] http://www.vacuuminsulation.co.uk, *Vacuum Insulation*, visited 2007-11-06
[12] Ibid
[13] Grossklos, M. (2006). “*Thermal bridges in prefabricated insulation elements with vacuum insulation used in the renovation of existing buildings”* Conference Proceeding at the 10th International Passive House Conference, 19-20 May 2006 Hanover
[14] http://www.aerogel.se, *Svenska Aerogel AB,* visited 2007-11-07
[15] http://www.eetd.lbl.gov/ECS/Aerogels/sa-home.html, *Silica Aerogels,* visited 2007-11-07
[16] Gudmundsson, K. (2006). ”Byggnadsteknik och design: *Glas i arkitekturen, fönster och glasbyggnadsteknik”, Studentlitteratur, Kungliga Tekniska Högskolan, Sweden*

appear are for example, in the joint between wall and floor, penetrations for various services such as chimneys, ventilation ducts and cables and openings in walls for windows or doors. In a Passive house the heat losses by thermal bridges has to be significantly reduced. The reduction should be made to the degree that the losses through thermal bridges become negligible. A thermal bridge affects the building in many ways but the two most typical are[17]:

- Decreased interior surface temperatures which in the worst cases can result in high humidity in parts of the construction
- Significantly increased heat losses

Both can be avoided in passive houses because the interior surface temperatures are supposed to be so high, that critical humidity cannot occur at any place and the additional heat losses will be negligible.[18]

The thermal bridges can occur in several places in the building envelope and their influence increases with the thickness of the insulation, which of course is the reason that it is especially important in passive houses. In poorly designed interfaces the heat transfer can increase more than 50 %, compared with the heat transfer through the wall itself, thus to avoid a thermal bridge it is important not only to check the drawings but also check the performance on site. If the envelope is not correctly constructed it could mean that a thermal bridge appears. It should however be emphasized that thermal bridges could significantly be reduced by careful and competent planning and building performance.[19]

2.1.2.4 Air tightness

Leakage in buildings affects the indoor environment and also the energy usage since air then easily can move through the envelope along with humid air (diffusion and convection) and heated air (convection). To produce energy efficient houses like the passive houses, an air tight envelope is required to prevent heat losses through leaks. The heat losses through the envelope increase with the size of the leakage but it also needs to be air tight for the ventilation system to work properly. To create this air tight building an air and vapour barrier is used and applied continuously on the inside of the envelope. To seal all the joints, tape or weld is used. The air and vapour barrier is placed on the inside of the exterior wall, roof and floor to prevent moisture from entering the construction. Many accidents have been reported from buildings where the barrier has not been applied correctly and the most common failure is leakage in the barrier joints, interfaces between different building parts, openings for pipes, electricity terminals or ventilation terminals.[20] In a passive house without traditional heating system to back up unpredicted energy losses, it is extra important to succeed with the air tightness. Therefore the barrier often is placed 45-70 mm into the wall so the installations can be applied on the inside of the barrier and no unnecessary penetration of the barrier takes place. An air tight building envelope is also necessary for the mechanical ventilation system with heat recovery, where the exhaust air in a heat exchanger heats supply air. It is then necessary to make sure that the supply air is coming from the supply ducts and not from infiltration through the envelope.[21]

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[17] Abel, E. & Elmroth, A. (2006). *"Byggnaden som system",* ISBN: 91-540-5974-1
[18] http://www.passivhaustagung.de, *Passive House Institute,* visited 2007-11-09
[19] Abel, E. & Elmroth, A. (2006). *"Byggnaden som system"* ISBN: 91-540-5974-1
[20] Anderlind, G & Stadler, C. G. (2004), *"Isolerguiden 04"* ISBN: 91-973761-6-7
[21] Wall, M. (2006), *"Energy efficient terrace houses in Sweden: Simulations and measurements"* Energy and buildings 38 (2006), 627-634

2.1.2.4 Windows

Windows are a part of the building envelope and therefore it is necessary to keep their thermal transmittance as low as possible. To do that there are several ways and one of them is low emission coatings. It is thin layers placed on the pane and the most common is silver or tin oxide. This hinders long wave radiation exiting the envelope through the window, while the short wave radiation from solar radiation can still enter through the envelope via the window. The incoming light is not significantly affected. The most common is to place the low emissivity coating on the inside of the window, one reason for this is simply the mechanical damage when polishing the window.[22] Glazing with low emissivity coating is approximately equivalent to an extra air gap between the glazings. This means that the thermal transmittance for a double glazed window with one side sequestrate, is equal to a clear triple glazed window. Another or complementary way to reduce the thermal transmittance is to replace the air in the sealed gap between the panes with noble air, usually argon or krypton, which has a lower ability to conduct heat.[23]
There have been some comparisons between different window types. To show the importance of the glazing parts the number of low emissivity coatings, the type of gas in the gaps and the number of panes have been studied. The study shows that changing noble gas (krypton/argon) in triple glazed windows with two low emissivity coatings to air in the sealed gaps instead is of minor importance. There was a larger difference when comparing two, one or none low emissivity coatings, but the biggest difference was found when the clear triple glazing was changed to double glazing. This type of knowledge is of great importance considering the passive house concept.[24]

According to the Swedish definition, the maximum thermal transmittance for windows in a passive house is 0,9 W/m^{2}K and according to the German it is 0,8 W/m^{2}K. To meet these demands there are three essentials, triple glazing with two low emissivity coatings, “warm edge”-spacers and super insulated frames. Spacers are basically the material between the two, or in triple glazing three, panes of glass. If the material conducts less heat or cold than conventional (aluminium) spacers, it is said to be “warm edge”. That is a reason why the “warm edge”-spacers thermal characteristics vary. Nowadays, the glass techniques has improved so much that often the frame rather than the glass has the higher thermal transmittance. The thermal transmittance of the frame shall be included in the total when comparing with the threshold value for windows.[25]

2.1.3 Installations

The techniques behind the installations in passive houses are the same as in conventional houses. The only difference is that in passive houses, installations have to be energy efficient, but they could be applied in any other building as well. The electricity installation is just conventional and there is no difference in passive houses. There is, as mentioned, no traditional heating system and hence no radiators etc. The most common and most cost effective method today is to use the ventilation system as transporter for the heat. It’s not a requirement for passive houses but it saves money with the solutions we have today.

[22] Abel, E. & Elmroth, A. (2006). *”Byggnaden som system”* ISBN: 91-540-5974-1
[23] Petersson, B. Å. (2001). ”*Tillämpad Byggnadsfysik*” Studentlitteratur, Lund, Sweden
[24] Wall, M. (2006), *”Energy efficient terrace houses in Sweden: Simulations and measurements”* Energy and buildings 38 (2006), 627-634
[25] http://www.replacement-windows.com, *Replacement-Windows.com,* visited 2007-11-16

2.1.3.1 Ventilation

Ventilation is most easily described as, air exchange in a sealed room. The content of gas and particles in the indoor air, in the room from which they are generated determines, to which extend pollutants must be exported from the room. Ventilation means that the room is supplied with fresh air at the same time as the pollutants are carried off along with the exhaust air. As previously mentioned, ventilation can also transfer heat, in and out of the room, but the primary task for the ventilation system is to keep the indoor air fresh. Concerning heated air supply, exhaust and the export of pollutants the most important factor is air flow.[26] According to Swedish regulations the ventilation system should be designed for a minimum outdoor air flow corresponding to 0,35 $l/(s,m^2)$ for dwellings but when the room isn't used the ventilation rate can be lowered to 0,1 $l/(s,m^2)$ as minimum. There are no special demands concerning the ventilation rate in a passive house comparing to conventional dwellings.[27]
The ventilation system that has been used in passive house projects is mechanical heat recovery ventilation systems with control of both exhaust and supply air, see Figure 1. The reason for that is energy efficiency as previously mentioned, due to the fact that the passive house standard puts high expectations on the building and to have control over the ventilation is an important part of that. Preheating the supply air is important, hence letting cold air infiltrate the envelope increases the energy consumption. Preheating the supply air also means making sure that the air enters in the right place, which is through the heat exchanger and not through infiltration.[28]

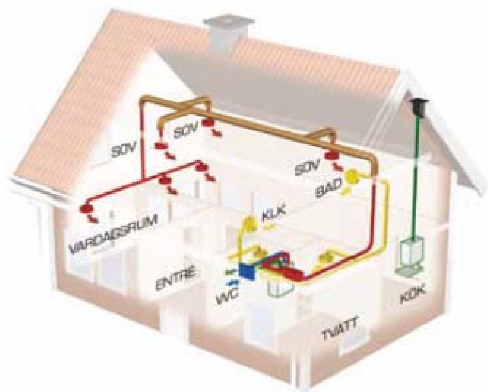

Figure 1: Mechanical ventilation system with heat recovery

If there's no mechanical system it's called natural ventilation which is common in conventional houses. The natural ventilation is driven by pressure differences in the building. There are also mechanical ventilation systems without heat recovery, normally in houses the exhaust air is forced out by fans in the kitchen and bathrooms and the supply air is then taken from ducts behind radiators that preheat the incoming air.[29]

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[26] Abel, E. & Elmroth, A. (2006). *"Byggnaden som system"* ISBN: 91-540-5974-1
[27] Boverket (2006), *"Regelsamling för byggregler - Boverkets Byggregler, BBR"*, ISBN 91-7147-960-0
[28] http://www.passivhaustagung.de, *Passive House Institute,* visited 2007-11-25
[29] Abel, E. & Elmroth, A. (2006). *"Byggnaden som system"* ISBN: 91-540-5974-1

2.1.3.2 Heating system

The difference concerning the heat in a passive house compared to a conventional house is that the heat is transported within the ventilation system, along with the supply air. Today, to meet the passive house standard, mechanical ventilation with heat recovery is used with an efficiency of approximately 85%. Heat recovery is accomplished by exchanging the heat from the exhaust air to the supply air. The heat exchange can be divided into two categories, regenerative and recuperative. In regenerative heat exchange, a body is heated up e.g. by warm air (exhaust air) and then transported to a cold air stream (supply air), where the heat emits. In a recuperative heat exchange the heat is transferred from the warm side to the cold by leading the heat through a wall that separates the fluids.[30] An important difference considering the use in dwellings is the notability to transfer odours. The regenerative heat exchange doesn't separate the fluids to 100% which could be a problem in dwellings. The recuperative heat exchange separates the fluids to 100% and hence no smell from the exhaust air is being transferred to the supply air.[31]

A heat exchanger is a device built for efficient heat transfer from one fluid to another, whether the fluids are separated by a solid wall, so that they never mix, or the fluids are directly contacted.[32]
There are different types of heat exchangers and those can be named after the direction of the air flow. There are cross-flow, counter-flow and parallel flow heat exchangers. In counter-flow the warm fluid is transported towards the cold. This type is one of the most effective ones because it could theoretically transfer all the heat from one side to another and therefore it's the most common one in passive houses.[33]

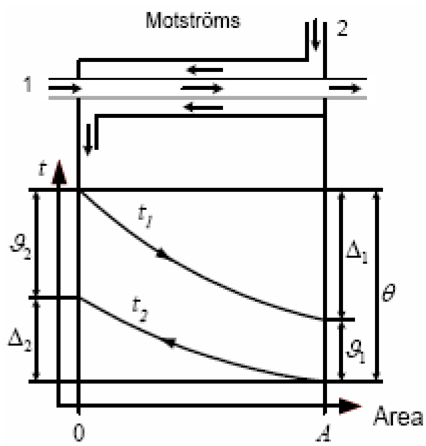

Figure 2: Temperature diagram of counter-flow heat exchangers

The degree of efficiency is defined as the difference in temperature between the supply air and outdoor air divided by the difference between the indoor air and outdoor air.[34]

$$\eta = (T_{\text{Supply air}} - T_{\text{Outdoor air}}) / (T_{\text{Exhaust air}} - T_{\text{Outdoor air}})$$

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30 http://www.av.se, *Arbetsmiljöverket,* visited 2007-11-27
31 Warfvinge, C. (2003), "*Installationsteknik AK för V*" Studentlitteratur, Lund, Sweden
32 Sadik Kakaç and Hongtan Liu (2002). Heat Exchangers: Selection, Rating and Thermal Design, 2nd Edition, CRC Press. ISBN 0849309026.
33 FEBY (2007), *"Marknadsöversikt för passivhus och lågenergihus i Sverige 2007"* Remissversion, Forum för Energieffektiva Byggnader
34 Abel, E., Jagemar, L. & Widén, P. (1997), *"Energiteknik: Termodynamik och värmelära"* studentlitteratur Chalmers, Gothenburg, Sweden

As shown in Figure 2, the temperature of the incoming fluids increases more and more. In very efficient heat exchangers the curve for the incoming fluid can increase more and if the length of the heat exchanger would be extended the efficiency would continue to increase. That is the reason that the counter-flow heat exchanger is called the most efficient. In the parallel-flow heat exchanger the fluids are transported in the same direction. This makes the efficiency lower than for counter-flow. The exchange could be seen as the fluids temperatures are being mixed.[35]

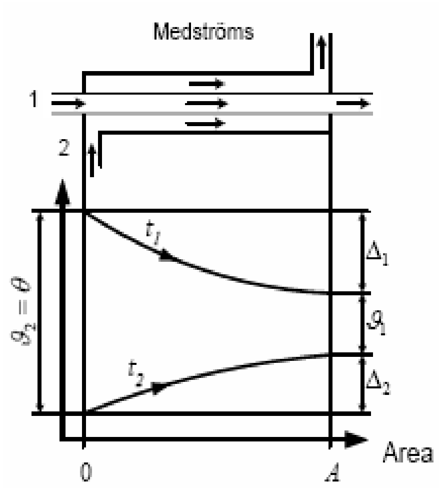

Figure 3: Temperature diagram of parallel-flow heat exchangers

As shown in Figure 3, the temperatures go towards a mean temperature and if the length of the parallel-flow heat exchanger would be extended the result wouldn't be remarkably different.[36]

There are three common devices for heat exchange in buildings:

Plate Heat Exchanger
The plate heat exchanger consists of sheet metal plates, often aluminium, that have been put together alternately so that the supply air and exhaust air passes through every second channel, thus the heat is exchanged, see Figure 4. The plate exchanger is recuperative and therefore it doesn't transfer any odour in the heat exchange. The degree of efficiency is around 60% and it is often a crossed flow. To install this device the ducts need to coincide at the same place.[37]

[35] www.energy.kth.se, *Institutionen för energiteknik,* visited 2007-11-21
[36] Ibid.
[37] Warfvinge, C. (2003), "*Installationsteknik AK för V*" Studentlitteratur, Lund, Sweden

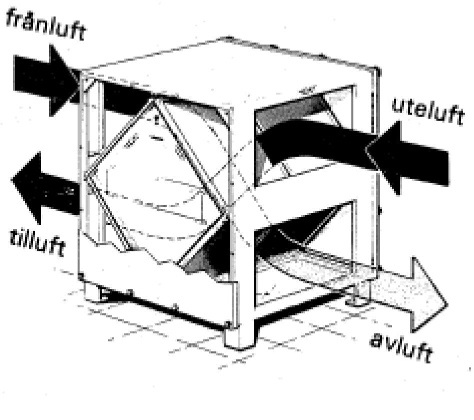

Figure 4: Plate heat exchanger

Rotating Heat Exchangers

In a rotating heat exchanger there is a rotor that is driven by electric power. The supply air passes through half of the rotor and the exhaust air the other half. Thus the same part of the rotor is going to pass by the exhaust air every second time and the supply air every second time and thus the heat is transferred from the warm air to the cold.[38] The rotor consists of a rotor wheel with a large number of small axial channels. The wheel is often made of corrugated metal blade that has been wrapped in several layers, see Figure 5.[39] The disadvantage with this device is the ability to transfer odour, because the same metal surface is in contact with both supply and exhaust air. The rotating heat exchanger is a regenerative exchanger and the degree of efficiency could be up to 85%. Also with this device the air channels must coincide at the same place. [40]

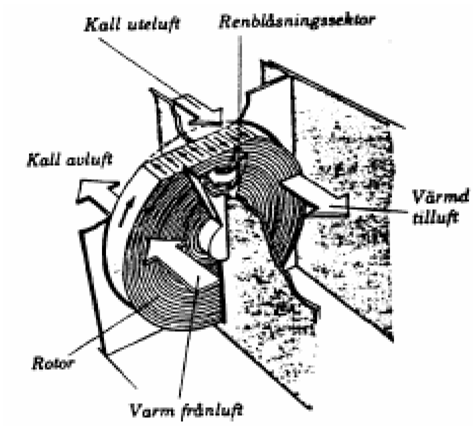

Figure 5: Rotating heat exchanger

Battery Heat Exchangers

In a mechanical ventilation system one battery is placed in outlet air channel and one in the incoming air channel, see Figure 6. By pumping liquid between the batteries the heat is transferred from the exhaust air to the supply air.[41] One benefit with this device is that the air ducts do not have to coincide at the same place, which could be useful in narrow spaces. They

[38] http://energihandbok.se, *Jernkontorets Energihandbok,* visited 2007-11-21
[39] www.av.se, *Arbetsmiljöverket,* visited 2007-11-27
[40] Warfvinge, C. (2003), "*Installationsteknik AK för V*" Studentlitteratur, Lund, Sweden
[41] www.av.se, *Arbetsmiljöverket,* visited 2007-11-27

are also used to add energy recovery to a mechanical ventilation system that doesn't already have heat recovery. The battery heat exchanger is a recuperative exchanger.[42]

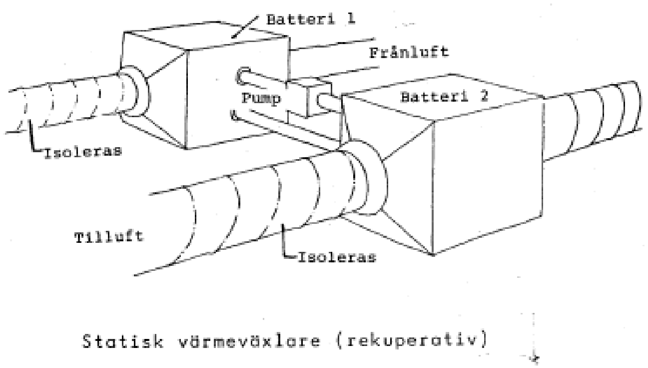

Figure 6: Battery heat exchanger

The air flow in a mechanical ventilation system is forced by fans. There are two different kinds of fans. Axial fan is one of them where air streams in axially and also out axially. By axial it means that the air streams in parallel with the driving fan shaft and the engine is often placed in the fan. In the other one, radial fan, the incoming air streams axially and the outlet air streams perpendicular.[43]

2.1.4 Production

Following section is based on interviews with persons that has good knowledge about today's production, hence the reference to the following is in the appendix. Their knowledge and participation in passive house projects cover almost every project done so far in Sweden.

2.1.4.1 What has been prefabricated and what has been produced on site

The production of passive houses today consists two different methods, one is the use of prefabricated elements and the other one is on-site production. By starting to look at the projects where prefabricated elements have been used it's found that the interior surface isn't in place. The difficulties with air tightness have made the producers leave the vapour barrier installation to the workers on site. This results in further difficulties regarding preparations. Since the air barrier is placed inside the installation space, no installations etc can be preassembled. The finished status of the wall is then nothing else but frame and insulation. Another problem is the fact that passive house walls are too thick for today's factories technical aids. In one case, and probably others, the automatic device that turns the wall element during production was not suitable to fit the elements. This problem comes up already at 300 cm thick walls.

2.1.4.2 Today's interaction between energy efficiency and production efficiency

There is one comment that is shared through all four interviews and that is the fact that energy efficiency and production efficiency doesn't interact today. One general opinion is that passive house building includes too much trickiness and then above all, the work with making the product air tight. One answer to the question how their notions were about the interaction between energy- and production efficiency was;

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[42] http://energihandbok.se, *Jernkontorets Energihandbok,* visited 2007-11-21
[43] Warfvinge, C. (2003), "*Installationsteknik AK för V*" Studentlitteratur, Lund, Sweden

> *"I absolutely don't think that they interact. To exemplify, I can mention today's exterior walls, there are too much trickiness to secure an air tight envelope. It becomes too many working elements that are far from rationalised…"*

One other opinion is the work with the envelope, partly vapour barrier and partly avoiding thermal bridges, that takes time and time is money. One comment was;

> *"Production efficiency is to a great extent to cut costs and to build energy efficient today costs more… Can't say anything else about that…"*

To future integrate energy efficiency within the production efficient projects the general ideas are that there is a need after some kind of prefabricated exterior wall that handles the requirements the passive house standard implies.

2.1.4.3 Are the details adjusted for production?

The details that separate the passive house and the traditional house are the thick walls and the general accuracy during production. A passive house doesn't allow mistakes that affect the energy performance, because of the missing traditional heating system etc. The general thought is that details aren't adjusted to this kind of production. The demand on the air tightness is much higher in passive houses and it leaves too much responsibility to the individual worker. The quality control in these projects is put to a level that no one is used to and we can't use the same techniques and methods when the bar has been raised to higher levels. The need for more robust solutions is obvious.

2.1.4.4 The production efficiency within projects

Since it has been the first time for almost every participant and no one has really known what it will take to carry out the projects, focus has been on the challenge to succeed building a house that's so well built that it doesn't need the traditional heating system. The general thought is that all projects worked out well but has taken too much time and hence not been rationalised. Everybody agrees that with help from adjustments in the factories, new methods and solutions there is a lot of time and money to save.

2.1.4.5 Education for participants within the projects

In all the projects so far there has been education of the participants. The most common method has been to gather all participants for a joint review. There have also in every project been special persons in charge of the air tightness and these persons have received more education. The education has informed participants about the accuracy the project requires and the consequences that follow if everyone does not take responsibility. The general response has been more dedication from the craftsmen side.

2.1.4.6 General thoughts from the passive house production site

In general there has been frustration about the trickiness within the projects. People think it takes too much time. There is also a thought that, the reason why we doesn't build more passive houses or low energy houses in general is just because it's more complicated and

therefore more expensive than traditional houses. One interesting opinion is that people don't see the increased cost caused by more material but rather that the crane needs to do three lifts for an exterior wall instead of one and that it takes too much time because it's hard to work efficiently when details and solutions are so vulnerable.
However, the work with the interior is just like traditional projects.

2.2 Production concepts in construction

2.2.1 Partnering

2.2.1.1 History

The US Army Corps of Engineers started in 1980s to use the concept partnering and hence brought the concept into the construction industry. The reason for implementation and development of partnering into their business was to avoid legal disputes and with that reduce building costs in their projects.[44]

In the middle of the 1990s, in Great Britain, the government appointed The Construction Task Force to cure the construction industry from their lack of commitment and their low productivity. The symptom was insensitivity to customers, low quality and high production costs etc. Every participant was losing within projects. The result from the commission ended up in a report called "Rethinking Construction" in 1998. Rethinking Construction was recommending that reduced building costs, higher quality and shorter building time could be achieved through organisational and logistical means, like partnering. The report emphasizes partnering as one of the most important means to bring construction industry to the desired target. The idea has been developed further in demonstration projects in Great Britain and many companies have taken active interest in the concept. [45]

In Sweden the government appointed a commission 2002, with the assignment to review the construction industry and propose measures to reduce building costs and increase quality. One element in the commissions work was to review other countries situation. The commission then referred to "Rethinking Construction" as a tool to cure one part of the situation.[46]

2.2.1.2 What is Partnering?

There isn't any official definition for partnering and generally partnering isn't seen as a form of contract but more a different way to run projects. Partnering can among others be seen as a system to establish rules for behaviour for such aspects that the contract doesn't comprise. Partnering can then be some sort of guideline in situations where general contract doesn't encourage politeness, common sense, empathy and responsible acting, and a partnering process should break barriers that in other cases should have hindered good work relations.[47]

Thomas Telford defines partnering;[48]

> "*Partnering is a structured management approach to facilitate team working across contractual boundaries. Its fundamental components are formalised mutual objectives, agreed problem resolution methods, and an active search for continuous measurable improvements"*

[44] Kadefors, A. (2002), *"Förtroende och samverkan I byggprocessen – förutsättningar och erfarenheter"* Chalmers Tekniska Högskola, 2002
[45] Andrén, Y. (2004), *"Rethinking Construction ur fastighetsägarperspektiv"* UFOS 2004
[46] Ibid
[47] Kadefors, A. (2002), *"Förtroende och samverkan I byggprocessen – förutsättningar och erfarenheter"* Chalmers Tekniska Högskola, 2002
[48] Telford, T. (1997), *"Partnering in the team"* Construction Industry Board (CIB), London, 1997

Within the Swedish construction company, NCC, partnering is defined;[49]

> *"Partnering is a structured form of cooperation within the construction industry, where the client, the consultants, the entrepreneurs and other key actors jointly solve a building task, based on an open and trusting cooperation where all professionals complement each other through all times during the project."*

Even though the definition of partnering is not unambiguous there are no doubts which parts that are important in a partnering process. It is;[50]

- relation building
- targets in common
- a system for problem and conflict solutions
- a system for follow-up of the objectives and measure improvement

In the report "Rethinking Construction" there are two types defined, project partnering and strategic partnering. Project partnering means cooperation between the client, the consultants and the suppliers as well as the real estate manager and maintenance operator with the purpose to realise a certain project. Strategic partnering is cooperation between the consultants, the entrepreneurs and the suppliers in order to realise several similar projects for different customers.[51] It also involves more long term relationships between companies where customer relations can be developed thanks to the partnership. Strategic partnering can be further separated into two forms. The first form is the traditional between customer and customer and supplier. One example is McDonalds and the construction company Wästbygg. Wästbygg has built 140 restaurants for McDonalds and hence reduced the costs by 20% and the building time from 16 to 8 weeks. The other form of strategic partnering is more long term relations between suppliers in order to offer the customers a stronger team for partnering projects.[52]

2.2.1.3 Partnering according to NCC

NCC is one of the companies in Sweden that have used partnering most frequent within their projects. NCC separates the partnering projects in different phases. The following is a summary of the phases:[53]

Phase 1: Cooperation begins
To begin with, the client must decide his strategy for the project. Which form of cooperation shall he choose and who shall he cooperate with? The right man with the right qualifications at the right place is the foundation of a well working team. The selection of partnering partners should be based on competence.
In this phase common values and targets are explored.

Phase 2: Project design

[49] http://www.ncc.se, *NCC AB,* visited 2008-01-08
[50] Carenholm, S. (2003), *"Vad är partnering?"* Arkitekten, april 2003
[51] Andrén, Y. (2004), *"Rethinking Construction ur fastighetsägarperspektiv"* UFOS 2004
[52] Fernström, G. (2003), *"Blir partnering en framgång i Sverige?"* Väg- och vattenbyggaren 3, 2003
[53] http://www.ncc.se, *NCC AB,* visited 2008-01-08

This phase begins with a workshop, where client, entrepreneur, architects and consultants participate. The purpose is to set common targets and rules for the cooperation and with that create an efficient project team. The purpose is also to get to know each other and the new organisation and establish an effective partnering process within the project. Before exiting this phase everyone agrees about the basis price for the projects realisation. An open economy is very important in partnering projects.

Phase 3: Realisation
Now all details within the project are decided. The production begins and at regular intervals workshops are being held just to make sure that everything is in order. Here it is also important to discuss what's been good so far and what can be done better.

Phase 4: Delivery
In this phase the product is finished and the client gets the "key". At this time there's an evaluation of the entire project. Individual and common targets are being analysed. Were targets reached? How was it to work in a partnering project? What can be better etc? These questions and evaluations can lead to ways to improve and further develop partnering as a form for cooperation.

2.2.2 Supply Chain Management

2.2.2.1 History

SCM is a concept that has its roots in the manufacturing industry. The first visible signs of SCM were in Toyotas production system as part of the "Just In Time" (JIT) delivery system. The JIT delivery system was to decrease the inventories and to effectively regulate the suppliers' interaction with the production line. Another stimulus for SCM originated in the field of quality control, where it was suggested to the Japanese industrial leaders that working with the suppliers in long term relationships would improve the quality and decrease the production cost. After SCM emerged in the Japanese automobile industry, the conceptual evolution of SCM resulted in an autonomous status of the concept in industrial management.[54]

2.2.2.2 Definition

There is no commonly accepted definition of SCM, it means many different things to many different people and numerous, overlapping definitions exists. Christopher, 1992, defined supply chain management as;[55]

> *"the network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in form of products and services in the hands of the ultimate customer"*

SCM views the entire supply chain, see Figure 7, rather than just the next part or level, and aims to increase transparency and alignment of the supply chain's coordination and configuration, regardless of function or corporate boundaries.[56]

[54] Vrijhoef, R. & Koskela, L. (2000), *"The four roles of supply chain management in construction"* European Journal of Purchasing & Supply Management 6, (2000), 169-178
[55] Christopher, M. (1992), *"Logistics and Supply Chain Management: Strategies for Reducing Costs and Improving Service"* Pitman Publishing, London, 1992

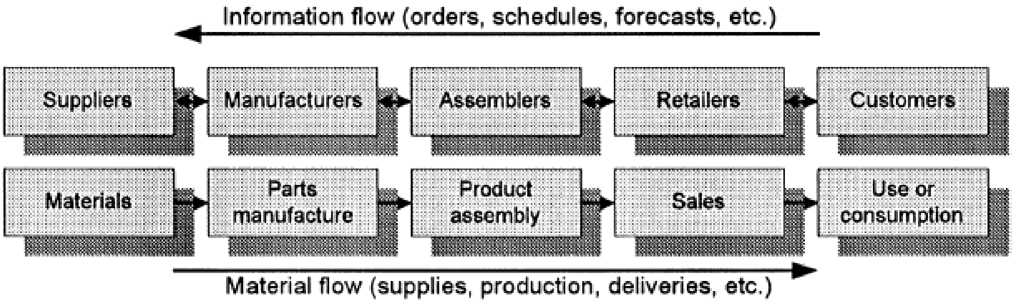
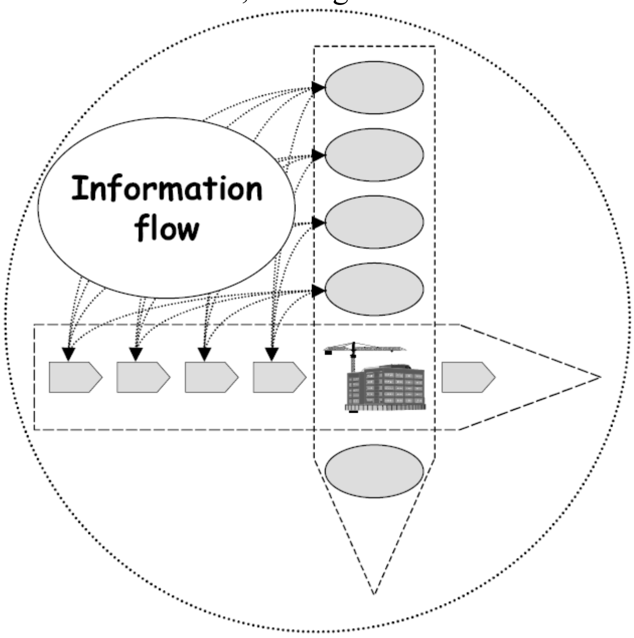


Figure 7: Generic configuration of Supply Chain

2.2.2.3 Supply Chain Management in Construction

Logistics and supply chain management knowledge is in general unknown in construction industry. Competition and consequently customer orientation has for a long time been weak and thus also cost consciousness. This partly explains the lack of developed applied logistical concepts. The construction industry is hence not familiar with flow models and supply chain management.[57] Saad, shows however that the there is a significant awareness of the importance of SCM and its main benefits in construction but he also states that construction needs a better conceptual understanding of it and more systematic approaches to its implementation.[58]

To communicate the possibilities of systematically use of logistics and supply chain idea Olsson presents a model with the purpose to show how the concepts can relate to the existing knowledge among the construction actors, see Figure 8.



Figur 8: The interaction of the supply chain and traditionally modelled construction activities

[56] Vrijhoef, R. & Koskela, L. (2000), *"The four roles of supply chain management in construction"* European Journal of Purchasing & Supply Management 6, (2000), 169-178
[57] Olsson, F. (2000), *"Supply Chain Management in the Construction Industry – Opportunity or utopia"* Licentiate Thesis, Lund University, Department of Design Sciences, Logistics, 2002
[58] Saad, M., Jones, M. & James P. (2002), *"A review of the progress towards the adoption of*

The model describes how the gap between the vertical value chain and the horizontal material supply chain can interact. Further by sharing information from all stages in the two processes new possibilities for using supply chain management opens up.[59]

Vrijhoef and Koskela present four roles of SCM in construction. The roles can be recognised, depending on whether the focus is on the supply chain, the construction site or both, see Figure 9.[60]

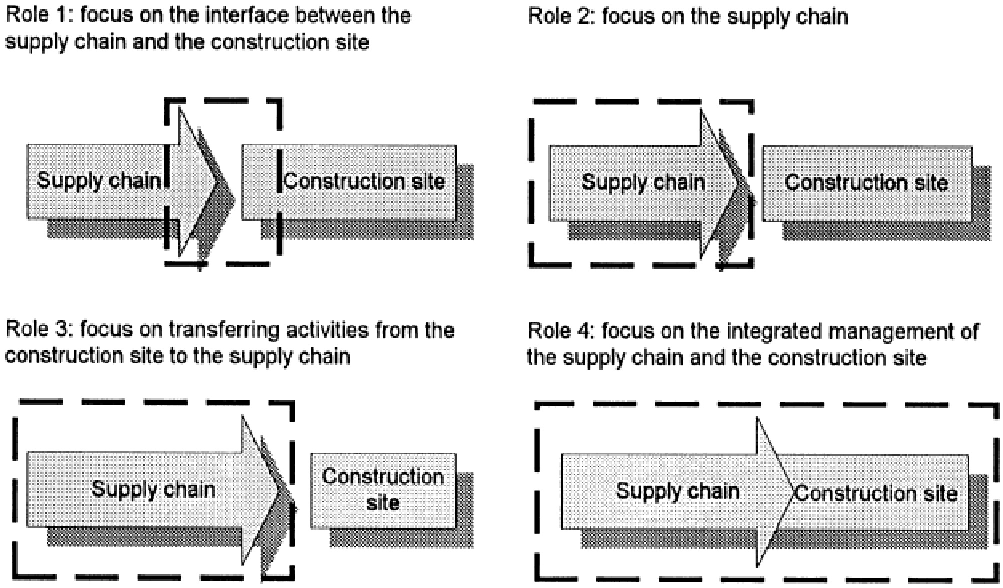


Figure 9: The four roles of supply chain management in construction

Firstly, focus is on impacts of the supply chain on site activities. The contractor who has the main interest in site activities is in the best position to apply this focus. Secondly there is only focus on the supply chain, mainly to cut costs and minimise inventories. Thirdly there is focus on transferring activities from the construction site to earlier stages of the supply chain. This can be adopted by more industrialised construction where on site activities are being moved to factories. Fourthly there is integration of the construction site and the supply chain. There are two approaches to this role. One is sequential procedure where the idea is to structure the site work as successive realisations of autonomous sequences. This can though affect the ability to meet customer demands. The other one is open building, where the basic benefit is in the postponement of the decisions of users regarding the interior of the building.[61]

2.2.3 Lean Construction

2.2.3.1 History

In Japan in 1930, a man called Kiichiro Toyoda started a truck and car production company called Toyota Motor Company. Later World War II disrupted production and the post-war

[59] Olsson, F. (2000), *"Supply Chain Management in the Construction Industry – Opportunity or utopia"* Licentiate Thesis, Lund University, Department of Design Sciences, Logistics, 2002

[60] Vrijhoef, R. & Koskela, L. (2000), *"The four roles of supply chain management in construction"* European Journal of Purchasing & Supply Management 6, (2000), 169-178

[61] Vrijhoef, R. & Koskela, L. (2000), *"The four roles of supply chain management in construction"* European Journal of Purchasing & Supply Management 6, (2000), 169-178

economic hardship resulted in growing inventories of unsold cars, leading to financial difficulties at Toyota. Severe labour disputes in 1950 forced a split of the Toyota Motor Manufacturing and Toyota Motor Sales division, as well as the resignation of Kiichiro from the company.[62] His cousin Eiji became managing director of the manufacturing arm and he went abroad to study how other companies handled their production. Back home from America, Eiji and his mechanical engineer Taiichi Ohno concluded that mass production wouldn't work considering the Japanese market at that time.[63] They had to think differently, instead of Fords heavily specialised machines they had to have more flexibility to quickly and easily be able to change from one element to another. In this way they could combine the cost advantage of industrialisation and the craft productions ability to customize. This much more flexible form of mass production became known as Toyota Production System, and was later dubbed Lean Production.[64] The expression lean was created by Womack, Jones and Roos, 1990, in the book "The machine that changed the world". The authors had studied and compared automobile producing companies and then mostly Toyota, in Japan. The study showed that there were alternatives to mass production that even could be more efficient. They identified and explained how and why Toyotas production system was so superior and translated that into lean production.

Today lean can be interpreted as a system with focus on elimination of waste in order to receive a product and process with the right quality and flexibility that should be continuously improved. The primary objective is to reduce costs and increase the productiveness. The cost is defined widely and is not only created during production but also in sales, administration and finances.[65]

A model with nine variables describing the fundamental principles in lean production that together constitute the production system has been developed[66];

1. Elimination of waste
   Everything that does not add value to the customer is waste and should be eliminated. Important sources of waste are inventory, work in progress, transportation and inadequate quality.

2. Continuous improvements
   Kaizen or continuous improvements is a fundamental principle of lean production. It involves everybody in the company, in all departments and is also often carried out through quality circles, which are small groups where suggestions for improvements are discussed.

3. Zero defects
   In order to attain high productivity it is essential that the processes deliver fault-free parts and products. Quality is everyone's responsibility, not that of a quality controller.

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[62] Holweg, M. (2007). "*The genealogy of lean production*" Journal of Operations Management 25 (2007) 420-437

[63] Hyll, H. & Lessing, J. "*Industrialisering av bostadsbyggandet under1900-talet*". Fyll På

[64] Winch, G. (2003), "*Models of manufacturing and the construction process: the genesis of re-engineering construction"* Building Research & Information (2003) 31(2), 107-118

[65] Sánches, A.M. & Pérez, M.P. (2001), *"Lean indicators and manufacturing strategies"* International Journal of Operations & Production Management Vol. 21 No. 11, 2001

[66] Lessing, J. (2006), *"Industrialised House-Building – Concepts and Processes"* Licentiate Thesis, Lund University, Department of Construction Sciences, 2006

4. Just-in-time
   The goal is that every process should be provided with the right part, in the right quantity at exactly the right time. The vision is to produce a piece at a time, exactly when it is needed. Different types of products and parts require different levels of JIT.

5. Pull instead of push
   Pull is closely related to JIT and means that products are produced as a response to actual customer demands.

6. Multifunctional Teams
   A multifunctional team is a group of individuals who together can perform a wide range of tasks and each team member can do more than one task. This leads to lower dependence on single individuals but requires efforts in staff training.

7. Decentralised responsibilities
   Responsibilities are decentralised to the multifunctional teams and the role of a foreman is not needed since specially trained group members do this by rotation.

8. Integrated functions
   Different functions are integrated in the multifunctional teams and the team's tasks increase to involve not only the isolated production operation but also materials handling, procurement, planning and control, maintenance and quality control. This reduces the need of support functions.

9. Vertical information systems
   Information is important for the teams to be able to perform according to the goals set. Information must be shared and provided directly in the production flow. Information is both on the overall performance of the whole company as well as detailed information about the team's performance.

2.2.3.2 Construction

Lean Construction is to a great extent an adoption and implementation of the Japanese manufacturing principles within the construction process.[67] Areas covered in Lean Construction are, among others[68];

- Lean Supply Chain Management
- Product Development
- IT Support for Lean Construction
- Management of People and Teams
- Production Planning and Controlling
- Prefabrication, Assembly and Open Building
- Flow line
- Safety, Quality and Environmental Management Systems

[67] Bertelsen, S. (2004). *"Lean Construction: Where are we and how do we proceed?"* Lean Construction Journal 2004, Vol 1 #1 October 2004
[68] Lessing, J. (2006), *"Industrialised House-Building – Concepts and Processes"* Licentiate Thesis, Lund University, Department of Construction Sciences, 2006

Lean Construction has a clear set of objectives for the delivery process and it aims at maximising performance for the customer at the project level to design product and process concurrently and it applies production control throughout the life of the project.[69]

The challenge construction faces when implementing the lean production principles is argued by Bertelsen to be met by two different strategies. The first one is to reduce the complexity to a level where the principles from the ordered world of manufacturing can be used as they are. The second strategy is to develop new methods for the management and control of the construction process as a complex system. This can also be explained as one product strategy and one process strategy and in practise the product strategy transfers the construction work to factories and then make the site work an assembly only, while the process strategy aims to develop the on site construction process.[70]

2.2.4 Industrial Production

2.2.4.1 History

In the later part of the 1700s the manual labour based economy of Great Britain began to be replaced by one dominated by industry and the manufacture of machinery. It started with the mechanisation of the textile industries, the development of iron-making techniques and the increased use of refined coal. Once started it spread. Trade expansion was enabled by the introduction of canals, improved roads and railways. The introduction of steam power (fuelled primarily by coal) and powered machinery (mainly in textile manufacturing) underpinned the dramatic increases in production capacity.[71] The industrialisation, during the same period of time, also spread to other businesses and it arrived to Sweden during the 1800s.[72]

1911 the book “The Principles of Scientific Management” was written by Frederick Winslow Taylor. In the book Taylor developed and summarised his thoughts about how companies could make their production more efficient. Scientific Management is more a theory based on four central principles, which are presented below;

1. Standardise the work process
   The works management should replace rule-of-thumb work methods with methods based on a scientific study of the tasks.

2. Right individual/worker at the right place
   Scientifically select, train and develop each worker rather than leaving them to train themselves

3. Company management and cooperation
   Cooperate with the workers to ensure that the scientifically developed methods are being followed.

4. Company management

[69] Howell, G. (1999). *“What is Lean Construction - 1999”* Proceedings IGLC-7.
[70] Bertelsen, S. (2004). *“Lean Construction: Where are we and how do we proceed?”* Lean Construction Journal 2004, Vol 1 #1 October 2004
[71] www.wikipedia.com, *Wikipedia (2007),* visited 2007-12-20
[72] Hyll, H. & Lessing, J. (2004), ”*Industrialisering av bostadsbyggandet under1900-talet*”. Seminar paper, LTH, 2004

> Divide work nearly equally between managers and workers, so that the managers apply scientific management principles to planning the work and the workers actually perform the task.

Henry Ford later implemented and developed Taylor's thoughts in the motor industry.

Henry Ford revolutionised the motor industry business 1908. By then he had achieved two objectives with his car, Model T. The two objectives he had reached were that the car was designed for manufacture and it was user friendly. These two achievements laid the groundwork for the entire motor-vehicle industry. [73]

1910 Ford had 10 % of the entire market. The company put up a price target that was substantially lower then former price target for the production. To reach the new target a new factory was built, Highland Park, the world's first one-type factory within the automobile manufacturing. It was in the Highland factory that Ford implemented and developed the principles from Scientific Management and created a manufacturing system for mass production.[74]
Ford continually developed the assembling process in order to reduce time and the break through, and probably the innovation he is most known for, came in 1913 when he introduced the continuous flow assembly line. But the key to mass production was not the moving or continues or moving assembly line, but rather the complete and consistent interchange ability of parts and the simplicity of attaching them to each other.[75] The mechanization brought higher standard on dimensional accuracy which implied that the different parts could fit in all the cars.[76]

2.2.4.2 Industrialisation of construction

The production has in a historic review been performed at the building site, by craftsmen. But in order to cut costs, reduce time, secure the quality, improve the working environment and increase the profitability the building business slowly has moved towards a more industrialised production where the work on site is moved to factories.[77]

The concept of industrialised house construction was introduced for the first time as the modernisation during the 1920s. One of the most famous early efforts were in Germany, where the large scale construction of "Siedlungen" in cities such as Berlin and Frankfurt was based not upon total systems of prefabrication but rather on highly mechanised and efficient uses of conventional building methods, together with extensive application of factory made components.[78]

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[73] Womack, J.P., Jones, D.T. & Roos, D. (1990), "*The machine that Changed the World*", HarperCollins Publisher, New York, NY, USA.
[74] Berggren, C. (1990) *"Det moderna bilarbetet: Konkurrensen mellan olika produktionskoncept i svensk bilindustri 1970 – 1990"* Student literature, Lund
[75] Womack, J.P., Jones, D.T. & Roos, D. (1990), "*The machine that Changed the World*", HarperCollins Publisher, New York, NY, USA.
[76] Hyll, H. & Lessing, J. (2004), "*Industrialisering av bostadsbyggandet under1900-talet*". Seminar paper, LTH, 2004
[77] Apleberger, L., Jonsson, R. & Åhman, P. (2007), *"Byggandets industrialisering - Nulägesbeskrivning"* Rapport 0701, FoU-Väst 2007
[78] Winch, G. (2003), "*Models of manufacturing and the construction process: the genesis of re-engineering construction*" Building Research & Information (2003) 31(2), 107-118

In the 1930s the development of prefabricated houses began in Sweden and during 1940s and 1950s the production of single-family houses was developed radically as society became more and more industrialised. [79] It was not just a matter of new materials and production methods but also of new technical installations like water, sewage, electricity and central heating, combined with new demands on planning and organisation.[80] But it wasn't until the mid 1960s that industrial production became reality in Sweden. After the Second World War there was a huge housing shortage together with a need for bigger and more modern housing. For that reason a political decision was made in 1964, the so called "Miljonprogrammet", which aimed for one million dwellings to be built in ten years.[81]

The extensive development that took place after the war brought tower cranes, building elevators, machines etc to the building site and therefore the building site started to be more mechanised. During this time the element construction techniques also developed radically regarding manufacturing techniques and methods for assembling. At first hand it was wall and floor elements that were prefabricated and a couple of element plants were established. This was considered as a first real step towards industrial production of buildings where prefabricated elements were the main item. [82]

The same development occurred throughout Europe and the US as well as industrialisation programs based on high rise configurations constructed using large panel prefabrication techniques. The industrialisation of the construction process is widely seen as a failure for a variety of reasons, including:[83]

- Poor urban planning leading to dysfunctional city environments
- Poor structural integrity and thermal performance of some designs
- Lack of management control over site production processes leading to severe quality problems in the final product
- Poor maintenance of the stock once completed
- Breaking up of existing communities during re-housing programmes

In 1971 Sweden was affected by recession and at the same time the need for dwellings was reduced. This combination made the housing market saturated. This saturation led to a certain amount of the new apartments being left empty.[84] The challenge to build 100 000 dwellings per year had directed focus to technique and efficiency in production and the architectural design had been swept aside for standardisation, limited choice and variation etc. Ever since then, industrialised production in construction in Sweden has been associated with the million programs housing environment. The production of apartment houses almost ceased but the

[79] Hallström, J. & Larén-Hallström, K. (2006), *"En idéskrift från Svensk Byggtjänst om; Industrialiserat byggande"* Svensk Byggtjänst januari 2006
[80] Hyll, H. & Lessing, J. (2004), "*Industrialisering av bostadsbyggandet under1900-talet*". Seminar paper, LTH, 2004
[81] Hallström, J. & Larén-Hallström, K. (2006), *"En idéskrift från Svensk Byggtjänst om; Industrialiserat byggande"* Svensk Byggtjänst januari 2006
[82] Apleberger, L., Jonsson, R. & Åhman, P. (2007), *"Byggandets industrialisering - Nulägesbeskrivning"* Rapport 0701, FoU-Väst 2007
[83] Winch, G. (2003), "*Models of manufacturing and the construction process: the genesis of re-engineering construction"* Building Research & Information (2003) 31(2), 107-118
[84] Hyll, H. & Lessing, J. (2004), "*Industrialisering av bostadsbyggandet under1900-talet*". Seminar paper, LTH, 2004

single-family houses continued within the same production rate as before into the 80s and weren't affected by the recession.[85]

In the beginning of 1990s a deregulation in the housing market was made and the public subventions were significantly reduced. This among other things brought a very extensive structural change into the building sector and to the housing market. At the turn of the century (2000) the housing production was very low and the need for dwellings became marked especially in the big cities. At the same time the criticism against high building costs increased. The pressure from the market stimulated methods to produce more dwellings in a more cost and resource efficient way. With this background the interest for industrial production has increased broadly during recent years. There are also new conditions as for example advanced information and communications technologies. The insight into customers needs has also increased a lot in the housing industry and the growing globalisation has significantly influenced the housing market. These new perspectives have changed the view and interest in industrial production, in construction.[86]

In current industrial house construction a key factor is prefabrication, and also advanced IT-solutions, logistics and systematic use of previous experience to create a continuous work flow. This can be achieved when building parts are manufactured by industrial processes, to which inspiration can be brought from the lean production paradigm.[87] When industrialised production in construction is discussed, parallels are often drawn to the manufacturing industry and often different adaptations are taken from the manufacturing industry.[88]

2.2.4.3 Current industrial housing production in Sweden

Definition

Today there are several proposals for defining the industrial housing production. Two suggestions will be mentioned here. The first definition comes from Lessing who has studied underlying production philosophies and concepts like Lean Production, Agile Production, Supply Chain Management, Just in Time principles etc and from that knowledge proposed a description and categorisation of industrial housing production. The second one is coming from a "State of the art" report in industrial housing production written by Apleberger, Jonsson and Åhman (2007). They have discussed different definitions, included Lessing's, and then given their own suggestion.

Lessing has in his licentiate thesis defined the industrial house building as:

> *"Industrialised house building is a thoroughly developed building process with a well suited organisation for efficient management, preparation and control of the included activities, flows, resources and results for which highly developed components are used in order to create maximum customer value."*

Eight characteristic areas have been identified and together they constitute the concept:

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[85] Apleberger, L., Jonsson, R. & Åhman, P. (2007), *"Byggandets industrialisering - Nulägesbeskrivning"* Rapport 0701, FoU-Väst 2007

[86] Ibid.

[87] Lessing, J. (2006), *"Industrialised House-Building – Concepts and Processes"* Licentiate Thesis, Lund University, Department of Construction Sciences, 2006

[88] Apleberger, L., Jonsson, R. & Åhman, P. (2007), *"Byggandets industrialisering - Nulägesbeskrivning"* Rapport 0701, FoU-Väst 2007

1. Planning and control of the processes
2. Developed technical systems
3. Off site manufacturing of building parts
4. Long term relations between participants
5. Logistics integrated in the construction process
6. Customer focus
7. Use of information and communication technology
8. Systematic performance measurement and re-use of experience

There is an important difference between this definition and the historical understanding of industrialised house building where prefabrication was the most central aspect.[89]

Apleberger, Jonsson and Åhman have in their "State of the art" report defined two different types of industrial production:[90]

> *"Industrial building: Manufacturing processes that are performed in a closed industrial environment, only assembly elements are being performed at the building site.*
>
> *"Industrialised building: Building and planning processes are driven according to industrial principles with, among other things, prefabricated components but a predominant part of the construction is performed at the building site."*

Different concepts
Some of the current Swedish industrial/industrialised building concepts are presented in what follows. The facts are summarised from Apleberger, Jonsson and Åhman (2007), state of art report and respective companies' homepage.[91] Other sources are marked with a footnote.

Industrial production is so much more than just prefabrication but the following is limited to the companies' present production methods. The energy efficiency within the concepts is also presented as "Specific energy use" that is equivalent to Swedish regulations. The specific energy use in Sweden means;[92]

> *"The energy that, at normal use, during a normal year needs to be delivered to a building (often called bought energy) for heating, cooling, hot water, installation operations and other electricity to the dwelling."*

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[89] Lessing, J. (2006), *"Industrialised House-Building – Concepts and Processes"* Licentiate Thesis, Lund University, Department of Construction Sciences, 2006
[90] Apleberger, L., Jonsson, R. & Åhman, P. (2007), *"Byggandets industrialisering - Nulägesbeskrivning"* Rapport 0701, FoU-Väst 2007
[91] www.ncc.se, www.finndomo.se, www.boklok.se, www.peab.se, www.openhouse.se, www.lindbacksbygg.se & www.skanska.se
[92] Boverket (2006), *"Regelsamling för byggregler - Boverkets Byggregler, BBR"*, ISBN 91-7147-960-0

Regarding regulations, Sweden is divided into two separate areas, north and south. The requirement for the northern part is 130 kWh/(m^2,a) and for the southern parts it is 110 kWh/(m^2,a).[93]

NCC Komplett

NCC has within their concept been trying to develop a new production technique based on experience from the manufacturing industry. NCC has invested in a new factory to produce modules. In the plant, components and elements are manufactured in an advanced and automatised manner. The structure is made of concrete and steel elements. Three different manufacturing lines are used, floor/ceiling, wall and kitchen. Installations such as electricity, plumbing and ventilation are performed in the factory. In addition, all surfaces, such as wallpapering and flooring, are completed in the factory as well as radiators, windows and doors. A few components such as stairs, balconies and bathrooms (complete) are bought from subcontractors.

The finished modules leave the plant in weather protected truck transports as flat packages to the assembly site. The assembly site is always weather protected by a huge tent that covers the whole site. The truck enters the tent and modules are picked up and put on the right place by a traverse. The team on site consists of four workers from the manufacturing industry, which can assemble up to five apartments per week. The final product can be between four and eight storeys high. The target is to produce 1000 apartments per year.

Alf Göransson, former President and Chief Executive Officer of NCC said;

> "*The construction period is halved and costs reduced. The industrial process facilitates planning and leads to a better work environment, increased efficiency, more efficient logistics, lower purchasing prices and improved quality controls. It is a completely weather-protected process without any risk of moisture-related problems.*"

Specific energy use: The specific energy use is in general just under the Swedish regulation, depending on geographical location etc.[94]

NCC Komplett is the most ambitious attempt in Sweden to industrialise construction, but unfortunately it was decided on 21 November 2007, that the Komplett concept was going to be shut down. The reason for shutting down the pilot concept was because the cost savings were too small and to change the Komplett manufacturing process would have been too expensive.

”Det Ljuva Livet”

"Det Ljuva Livet" (DLL) is based on wood volume element production up to two storeys. DLL is a production concept established through a competition in 2002 in Sweden and it is

[93] Ibid.
[94] Interview with Sverker Andreasson, Product Development Manager, NCC Komponent AB, 2007-12-15

cooperation between NCC and the housing company Finndomo. DLL is a well defined product with an established design, consisting of numerous volumes that can be combined and hence create different apartment variations.
The heating, plumbing, air-condition and electrical installations are installed in the prefabricated base floor unit at the factory.

The modular units are delivered straight from the factory to the assembly site. The remaining work at site is assembly and connection of all installations between modules. The work at site is therefore limited.

Finndomo's part is to manufacture the volumes in their factories and then assemble at site. NCC is in charge of the overall projects, land purchasing and sales. NCC is also responsible for the ground works.

Specific energy use: Just under regulations in those cases district heating is used.[95]

BoKlok

BoKlok is a cooperation between Skanska and Ikea. The concept is focused on lower middle class customers and therefore low price is an important issue. The goal is that as many people as possible shall be given the opportunity too buy themselves a nice and well planned home.

The house is developed as an "L-shaped" house in two storeys and contains normally six apartments. The product is highly standardised and is built of wood volume elements produced in Skanska's factory in Gullringen, which is built just to serve BoKlok projects. The degree of prefabrication is taken far and all installations are being installed at the factory as well as all interior finishing. The time to assemble a house is one day and the time to produce it at the factory is three days.

The house is as mentioned built in 90° angle and can within the same exterior dimension be built with different interior solutions. The size of the apartments can vary between two, three and four rooms and kitchen.

Specific energy use: The specific energy use in the concept is about 105 kWh/(m^2, a) and hence also just under the regulations.[96]

PGS

Peab works with the development of a system for industrial production, and that system is called "Peab Gemensamt System" (PGS).

Peab has been strongly influenced by Toyotas production system hence lean production and its elimination of waste. The first step for PGS was to develop a building structure that could

[95] Boqvist, A. & Akfidan, J. (2005) *"Energy Performance Buildings Directive 2002/91/EG and its consequences"* Institutionen för Byggvetenskap, KTH, 2005
[96] Interview (by e-mail) with Ulrika Nordeborg, Press contact manager, BoKlok Sweden, 2008-01-18

be used in all Peab's buildings. It means prefabricated concrete walls and floors. The interfaces are standardised, allowing flexibility in design, to be able to meet customers' demands.

Peab has today a prefabricated structural system and modules in their production and hence the supplementary work on site is based on traditional methods. Within projects they though develop and make the traditional methods more effective. Their goal is to continue to develop and improve their production system by getting more and more industrialised.

Specific energy use: Unknown

Open House

Open House is a company with a concept based on steel volume modules. The module concept has three fundamental essentials;

- The patent module technology
- The industrialised production system
- The standardised assortment

Open House differs from the other similar systems because of the structure design. The structural frame is a separate steel system. One storey of steel frames is put in place first and then the volume modules are attached by a hanging solution into the structural. This makes a difference since the volumes will only carry their own weight. This makes more open interior solutions possible etc. The system can be built up to eight storeys.

Specific energy use: Unknown

Lindbäcks Bygg

Lindbäck Bygg AB has a production of wooden volume modules that are produced in their factory in Piteå. All installations etc are assembled at the factory so when the volumes have been transported to the site it's just to put them together and connect all joints.

Specific energy use: The specific energy use is just under regulation and if the product for example is placed at the northern part of the southern area the company adds a heat exchanger that normally isn't included.[97]

[97] Lindbäcks Bygg AB, study visit in their factory in Piteå, Sweden, visited 2007-09-17,

Moderna Hus

Skanska has for several years worked on an extensive development program within industrial production. The concept is based on six different types of buildings, all between three to eight storeys. Concrete walls with façade included, floors and bathrooms are being produced in Skanska's factory and brought completed to the construction site. Preparations in walls are being done for installations but the installations itself are done at site.

Specific energy use: Moderna Hus, has a specific energy use, approximately 20 % under regulations.[98]

[98] Interview with Henrik Sundqvist, consultant in building physics, Skanska Sweden AB, 2007-12-21

3 Discussion

3.1 Problems and prerequisites within passive house production

Theoretically a passive house is not so technically different from traditional houses. There are no new materials or techniques needed, it's just a matter of applying the best solutions on the market. The most important principle is to minimise the heat leakage which is done by better insulated envelope together with low U-values for windows and doors. A prerequisite is that the envelope is also air tight, in order to prevent air leakage and thereby let warm air out from the building along with moisture that could infiltrate the construction and cause problems. The envelope requires approximately 500 mm of insulation in family houses and 400 mm in multi-residential houses. That is about twice as thick as normally used today.

Practically, a passive house is technically different from traditional houses. The fact that the envelope must have more insulation, be more air tight and have no thermal bridges causes difficulties in production efficiency.

Today, many factories are not capable of prefabricating walls as thick as passive houses demand and are therefore forced to produce the wall in layers. That often means three times more lifts with the crane to assemble the wall on site and overall doubling the wall thickness means doubling the transport of volumes from factories to construction site, which can be critical if there is a long distance between factory and construction site. If the production is made on site there is still a lot more work with exterior walls, in order to avoid thermal bridges.

Concerning the buildings air tightness a high degree of work quality is necessary. The installation of the vapour barrier requires careful sealing of all joints. To do that today, tape is used and because it is so important that joints are sealed perfectly it is time consuming. The vapour barrier also needs to be placed at least 45 mm into the construction, just to make space for installations etc without being penetrated. This leaves perhaps too much responsibility to the craftsmen, the cooperation between professional groups and also generally caution is not something production participants are known for. Vulnerable solutions on site could be seen as risky and the development of more robust solutions is needed.

The elimination of thermal bridges is not about fragile solutions but more about a smart design. Often walls are built up in crossed layers and hence thermal bridges are minimised. It is however a matter of accuracy and responsibility because mistakes lead to severe consequences. It is also time consuming compared to a traditional wall.

To summarise, the passive house concept production is a matter of high quality in production. The ability to build passive houses is possible with traditional technical solutions but there is a need for more robust solutions and efficient methods. Improvement and development of the product concept is necessary to implement energy efficiency at this level among our largest Swedish construction companies.

3.2 Analysis of respective production concepts

3.2.1 Partnering

Partnering does not solve the problems that have been presented above. Partnering is about facilitating teamwork across contractual boundaries and does not make vulnerable solutions more robust or reduce the number of transports.

Moreover, partnering does not help the participant teamwork on site, so that the electricians help the carpenters etc. But that is exactly what the process needs, a strategy for teamwork for the participants on site that actually carries out the job.

3.2.2 Supply Chain Management

Supply Chain Management does not solve the problem either. The right thing, at the right time and at the right spot is of course a decisive concept for an effective production in all projects. But smarter technical solutions and better systems for production are still needed.

3.2.3 Lean Construction

Lean Construction does not solve the problem, but lets us know that we have problems. Lean is about cutting costs by eliminating waste and waste is something that the construction industry is well known for. So by adding more ineffective elements like those that today's passive house exterior walls require can hardly improve the process.

3.2.4 Industrial Production

A well founded hypothesis is that industrial production can be an effective tool to solve the problems. Industrial production is to a great extent about prefabrication and developing prefabricated solutions could be a good substitute to the present unique, tricky and non-robust solutions on site. The purpose of the construction industries industrialisation is to get a better overview and a better quality control of production and to cut costs through repeating processes etc.

Is it practically possible then, to within industrial processes modularise technical solutions that are energy efficient and by that be able to cut production costs at the same time?

Technical solutions that are difficult to perform on site could be easier in a factory, but the opposite is also possible. In order to answer these questions it is relevant to ask how the passive house solutions would be designed in an industrial manufacturing process. For example, in a total cost perspective it could be better to use more expensive systems or materials in a manufacturing process than in on-site production. The recurrence effect that is achieved within a standardised industrial concept allows that more money can be invested in development and possibilities to reduce the purchase prices increases.

4 Conclusions

Identified problems and prerequisites in current passive house production;

- Time is a problem since the production is not efficient enough compared with traditional housing. The building envelope needs to be improved and developed to reduce time consuming operations.
- Very high quality in workmanship is necessary in passive house construction.
- This is difficult to achieve on site, in an efficient production.

Production concepts that could solve stated problems:

- Industrial production can be an effective tool within energy efficient housing, the product and its design can more easily be controlled. In a concrete manner.

How can the concept solve these problems and improve conditions:

- By taking the production into factories while at the same time solving these problems within an industrial process, will eliminate the necessity for repeated education on site and the waste associated with multiple working operations etc. Time will therefore be reduced.

The hypothesis set up initially in this report was that energy efficiency and energy efficiency can be seen as each others opposites:

- The bigger Swedish companies slowly implement new and more industrialised methods on their way to improve the business, but the strategies do not include energy efficiency. There is a large gap in energy use between current production systems and the passive houses.
- This report confirms the hypothesis, more research is needed to bridge the gap and make energy efficiency an obvious part in our production systems.

5 Proposals

Future research and development

The studies have shown that there is a need for improved efficiency within the production of passive houses today and a hypothesis is that the cure is to industrialise the production. In a standardised industrial concept, efficiency occurs throughout a repeating process. This makes it possible to invest more in the development of products as well as methods.

Today's production of passive houses requires heat recovery with a high coefficient of efficiency which demands high requirements on airtightness. But maybe other technical solutions would be chosen from an industrial manufacturing perspective. Hence today's solutions should not be uncritically integrated within industrial production processes. Instead, the take-off point should be based on the new conditions that occur when energy efficiency is integrated in an industrial production.

The housing industry needs energy efficient solutions that are not more expensive to produce than traditional solutions. If the industry should start this development the suppliers and product developers soon would follow, with new efficient materials etc. Today great companies see energy efficient housings as something vulnerable and insecure and hence they don't want to commit themselves to the concept, yet.

The subject is of great importance and the symbiosis between energy efficiency and production efficiency is a condition for a future sustainable society. Today effective production is about cutting costs, but energy effectiveness as implemented today will increase the production costs. Hence finding solutions for efficient passive house production is of interest for the whole construction industry and for society as a whole.

Proposed future research
The proposals for future research would be to integrate energy efficiency and production efficiency by developing a concept of an industrially manufactured passive house with similar production efficiency as a conventional house.

Guidelines on how industrial manufacturing companies could make their products more energy efficient are needed.

The present report is a first step in a research project, "Energy Efficient Housings – Symbiosis between industrial production and energy efficiency", which will be ongoing for several years.

The project is based on the following questions:

<u>Research question:</u> How could the mechanisms within the interaction of energy efficiency and modern industrial production be understood and utilised in housing production?

<u>Business question:</u> What are the possibilities to reduce production costs at the same time as the energy performance is increased, within housing?

Description of implementation
The research project will be divided into five phases. Every phase has its own milestone.

1. Supplementary Literature Study

A supplementary literature study will be made with the purpose to expand the knowledge about passive houses and industrial production. The survey should focus on factors which are decisive for building energy usage and the most important criteria for a well integrated modern industrial manufacturing process.

Milestone: A compilation of principles, demands and factors that constitute a passive house and industrial production.

2. Interview Study

As focus within the future project is on production it is necessary to realise an interview study with passive house producers and industrial house producers. Interviews with professionals within current passive house production will be made to survey and identify problems and prerequisites throughout the production as well as identify the most critical details and designs. Further interviews will be made with industrial producers in order to find out and confirm which problems would come up in an attempt to produce their product within the passive house standard. Which criteria do they consider as necessary in a well integrated modern manufacturing process?

Milestone: This interview study will result in a description of the conditions for industrial production of passive houses. The demands from industrial manufacturing as well as from the passive house concept will be known. Integration of these will provide the basis for further research within the project.

3. Case Study

In cooperation with an appropriate industrial housing producer a case study will be performed with the purpose to modify their current industrial building system into passive house standard and within that try to solve the problems coming up.

Milestone: The case study should result in that problems and questions are identified, solved and documented.

4. Answer the research question and the business question

Based on the knowledge and experience that has been collected during the project, the questions will be answered.

Milestone: This should result in answered questions and that the answers are documented.

5. Licentiate Thesis

The project documentation is compiled.

Milestone: Approved Licentiate Thesis

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Maria Wall, Researcher, Lector and Manager of the department Energy and Building design at Lund University, Sweden – interviewed 2007-12-21

Per-Erik Bratt, Site Manager at NCC Construction Sweden AB – interviewed 2007-19-21

Svante Wijk, Energy Advisor at NCC Construction Sweden AB – interviewed 2007-12-21

Sverker Andreasson, Product Development Manager at NCC Komplett AB – interviewed 2007-12-15

Ulrika Nordeborg, Press Contact Manager at BoKlok Sweden – interviewed (by e-mail) 2008-01-17

Appendix

Interview questions

1. Which projects have you been involved in and what's been your role?
2. What has been prefabricated and what has been produced on site?
3. How do you see the interaction between energy efficiency and production efficiency, today and in the future and how do you see that we get there?
4. Are the details adjusted to the production or is there much to solve on-site?
5. What is the general thought about the production efficiency within the projects?
6. Has there been any education for the participants within the building process?
7. What is the general thought, out on site, about these kinds of projects?