Saimaa University of Applied Sciences
Technology, Lappeenranta
Double Degree Programme in Civil and Construction Engineering

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COST OPTIMIZATION OF PASSIVE HOUSE EXTERNAL WALLS

Bachelor’s Thesis 2010

ABSTRACT

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Cost Optimization of Passive House External Walls, 86 pages, 10 appendices
Saimaa University of Applied Sciences, Lappeenranta
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The purpose of this thesis was to optimize the costs of Passive House external walls, using ISOVER insulation materials. The aim was to compare 5 different timber structures and 2 main ISOVER insulation products: KL-33 and KL-37. Thus, 10 wall structures were studied in this thesis.

The methodology is based on Life-Cycle Cost analysis. It consists of material costs calculation (initial costs) and energy losses' costs calculation (life-cycle costs). Material costs were calculated for thermal insulation, vapor barriers and gypsum boards. Energy losses' costs were calculated for 3 cases: 50 years study period with 2% annual energy price increase, 20 years study period with 2% annual energy price increase and 50 years study period with 5% annual energy price increase. The sum of material costs and energy losses costs shows the total costs for the structure during its life span.

Each structure has 6 variants with different thickness of thermal insulation. Thicknesses were chosen in such a way to provide U-values of structures from 0.07 W/m^{2}K to 0.13 W/m^{2}K. Calculations were made for 1 sq. m. of investigated structures. This method allows to find out the best solution (type of structure, insulation material and thickness of this material).

For calculation of technical characteristics of structures, DOF-THERM software and manual calculations were used. For cost calculation and cost optimization, Excel tool was used. All calculations were done according to Finnish and European building codes and standards.

The results show that in all cases Double timber frame structure with total insulation thickness 525 mm is the most economically advantageous solution.

One more important aspect revealed by the results is that the usage of cheaper insulation with higher thermal conductivity is more profitable when the study period is short and energy price increase is small.

Keywords: Passive House, External Walls, Heat Losses, Life-Cycle Costs

CONTENTS

APPENDICIES

1 INTRODUCTION

Around the world, the challenges regarding energy policy issues are almost the same. The supply of energy should be safe, environmentally friendly and supplied at a decent cost. Taking measures towards more energy efficient solutions and making investments in renewable energy sources have the potential to conduce to all these three goals. (Janson 2008)

Construction of energy efficient buildings contributes to the environmental goals by considerably decreasing the energy use for heating. In this way, the use of fossil fuels decreases and the emissions of carbon dioxide, air borne particle contaminations, sulphur dioxide, etc are reduced. (Janson 2008)

The idea of developing the Passive House concept originally came from Professor Bo Adamson at Lund University. Inspired by building techniques from a study trip in China, he, together with Dr. Wolfgang Feist, developed the Passive House concept. (Janson 2008)

A well insulated, airtight construction with mechanical ventilation is the basic idea of a Passive House. Building components which are necessary in any case; the building envelope, the windows and the ventilation system, are optimized to reduce the need of energy for space heating to the lowest possible level. Thermal bridges must be avoided, as must infiltration through the building envelope. Detailed planning is necessary to achieve a well functioning Passive House of sufficient airtightness. These improvements result in a building that works almost like a thermos. (Janson 2008)

Wall structures take a very important place among other envelope constructions of Passive House, because the total area of walls is quite large. Thus, big percentage of Passive House energy losses is related to wall structures.

This study concentrated on cost optimization of Passive House external walls with timber load bearing structures. Passive House as an investment project should be investigated taking into account not only initial costs, but also life-cycle costs. For this purpose Life-Cycle Costs analysis method was used. This method allows to check structure costs on its life span. The normal life span of house with timber structures is 50 years, according to Erocodes. However, investigation of a shorter study periods is also useful, as customer can sell his/her house. For this case, 20 years study period is investigated.

To narrow down the scope of this thesis, only 5 different structures and 2 types of insulation: ISOVER KL-33 and ISOVER KL-37, are studied.

2 PASSIVE HOUSE CONCEPT

2.1 Definition

Passive House or PassivHaus (German) refers to the voluntary standard for energy use in buildings. It results in very low energy buildings that require little energy for space heating or cooling. The Passive House standard requires that the building fulfills the following requirements:

- The building must not need more heating energy than 15 kWh/m² per year
- With the building de-pressurized to 50 Pa (N/m²) below atmospheric pressure by a blower door, the building must not leak more air than 0.6 times the house volume per hour ($n_{50} \leq 0.6$ / hour)
- Total primary energy consumption (primary energy for heating, hot water and electricity) must not be more than 120 kWh/m² per year. (ISOVER 2008).

However, Passive House constructions used in Central Europe cannot be assumed to work unconditionally in other parts of the world. It is important to develop passive house solutions for each location, suitable for the actual climate and geographic conditions (Table 2.1). Local building traditions as well as national/local building regulations must also be considered.

Table 2.1 Definitions of Passive House in different parts of Europe (Nieminen, Holopainen, Kouhia, Saari 2008)

	Heating energy kWh/m^{2}a	Cooling energy kWh/m^{2}a	Primary energy kWh/m^{2}a
South Europe	15	15	120
Central Europe	15		120
Nordic Countries (above 60^o latitude)	20-30 depending on the building's location		130-140

In all climates, the air leakage rate of the building is $n_{50} \le 0.6$ / hour (Nieminen, Holopainen, Kouhia, Saari 2008).

2.2 History

The Passive House standard originated from a conversation in May 1988 between Professors Bo Adamson of Lund University, Sweden, and Wolfgang Feist of the Institut für Wohnen und Umwelt (Institute for Housing and the Environment), Germany. Their concept was developed through a number of research projects, aided by financial assistance from the German state of Hesse. The eventual building of four row houses (also known as terraced houses or town homes) was designed for four private clients by architects professor Bott, Ridder and Westermeyer. (Feist 2006).

The first Passivhaus buildings were built in Darmstadt, Germany, in 1990, and occupied the following year. In September 1996 the Passivhaus Institut was founded in Darmstadt to promote and control the standard. Since then, thousands of Passive Houses have been built, most of them in Germany and Austria, with others in various countries worldwide. (Feist 2006).

After the concept had been validated at Darmstadt, with space heating 90% less than required for a standard new building of the time, the “Economical Passive Houses Working Group” was created in 1996. This group developed the planning package and initiated the production of the novel components, notably the windows and the high-efficiency ventilation systems. Meanwhile further passive houses were built in Stuttgart (1993), Naumburg, Hesse, Wiesbaden, and Cologne (1997). (Cox 2005).

The products developed for the Passivhaus were further commercialized during and following the European Union sponsored CEPHEUS (Cost Efficient Passive Houses as EUropean Standards) project, which proved the concept in 5 European countries over the winter of 2000-2001.

2.3 Technology

2.3.1 Heating energy requirement

A passive house is defined based on its heating energy requirement. The heating energy requirement is lowered by reducing the heat losses of the exterior shell and ventilation.

Various factors have an effect on the ability to achieve the heating energy requirement specified in the definition of a passive house: the thermal insulation of the exterior shell and its parts, the air-tightness of the structures, and the annual coefficient of the efficiency of the ventilation heat recovery system. The annual coefficient of efficiency in ventilation heat recovery should be at least 75% so that the insulation of the exterior shell structures does not have to be unreasonably thick. Managing the cold bridges of structures and their joint solutions becomes a key design principle for exterior shell structures. (Passive House concept)

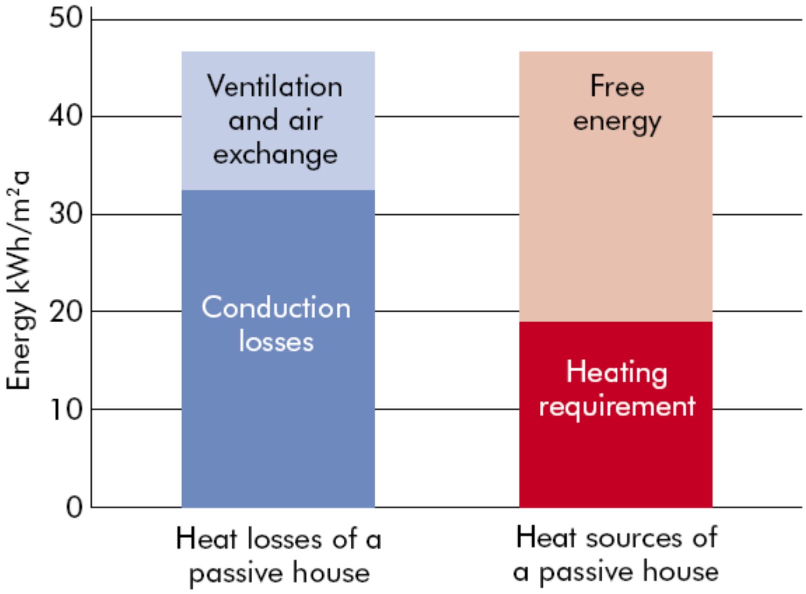

Chart 2.1 Heat losses and heat sources of Passive House (Passive House concept)

A majority of a passive house's heating energy requirement can be covered by so-called free energy, i.e. internal heat sources and solar energy. Chart 2.1 shows that passive house utilizes free energy, i.e. heat released by the occupants and appliances.

2.3.2 Building design

Building a passive house is not tied to certain materials – the building's framework can be made of wood, concrete, blocks or steel as long as the thermal insulation of the structures is high enough – nor does it depend on the utilization of solar energy. Good thermal insulation, an air-tight exterior shell, low energy windows and doors and heat recovery from ventilation exhaust air form the cornerstones of the concept. Orienting the building to the south provides energy benefits, especially during the beginning and end of the heating season in the autumn and spring. However, experience from passive houses in Central Europe shows that the concept also works rather well in northwards oriented building sites. The concept does not place any limitations on the building's location at the construction site, allowing the designer to take full consideration of the scenery. (Passive House concept)

2.3.3 U-Values

The low energy requirement for heating of a passive house requires a thermal insulation level that is considerably higher than normal. Table 2.2 below lists the target values for the thermal transmittance coefficients of the exterior shell components.

Table 2.2 Target values for thermal transmittance coefficients of the exterior shell components (Passive House concept)

Exterior wall, base floor and roof	0.06 – 0.12 W/m^{2}K
Window	0.70 – 0.90 W/m^{2}K
Fixed window	0.60 – 0.80 W/m^{2}K
Entrance door	0.40 – 0.70 W/m^{2}K

For instance, according to the National Building Code of Finland, for heated, especially warm or cooled cold space abuts the outside air , unheated space or the ground, reference U-value of exterior wall should be 0.17 W/m^{2}K. (C3 National Building Code of Finland 2010).

2.3.4 Air tightness

The limit value for the air leakage rate of a passive house's exterior shell has been set at $n_{50} = 0.6\ h^{-1}$, which must be verified through measurement. When the air leakage rate is low, the building's location and the surrounding wind conditions will have no major effect on the building's heating energy requirement. (Passive House concept)

In order for the air barrier to be effective, it must be continuous and its permeability may be 1×10^{-6} m^3/(m^2 s Pa) at a maximum. The seams of plastic sheeting acting as an air barrier inside the thermal insulation must be sealed, and the air barrier must be continuous over the entire area of the exterior shell. The seams of window and door joints must be thermally insulated and sealed on both the exterior and internal sides. (Passive House concept).

2.3.5 Wind shielding

Wind shielding protects the thermal insulation layer from cold air currents in the outside air. In principle, all thermal insulation which arrives in the form of slabs or which is sprayed or blown needs wind shielding, which may have an air permeability of 10 x 10^{-6} $m^3/(m^2$ s Pa), including seams, at a maximum. (Passive House concept).

2.3.6 Ventilation heating

A passive house is air-tight and requires a functional and correctly designed ventilation system. Improvements in energy efficiency are not sought through reductions in the ventilation volume. The target level of ventilation depends on the purpose of a room. A passive house does not require a traditional heat generation and distribution system such as radiators or floor heating. Ventilation heating is a sufficient heat distribution method. The basic principle of ventilation heating system is described on the Figure 2.1.

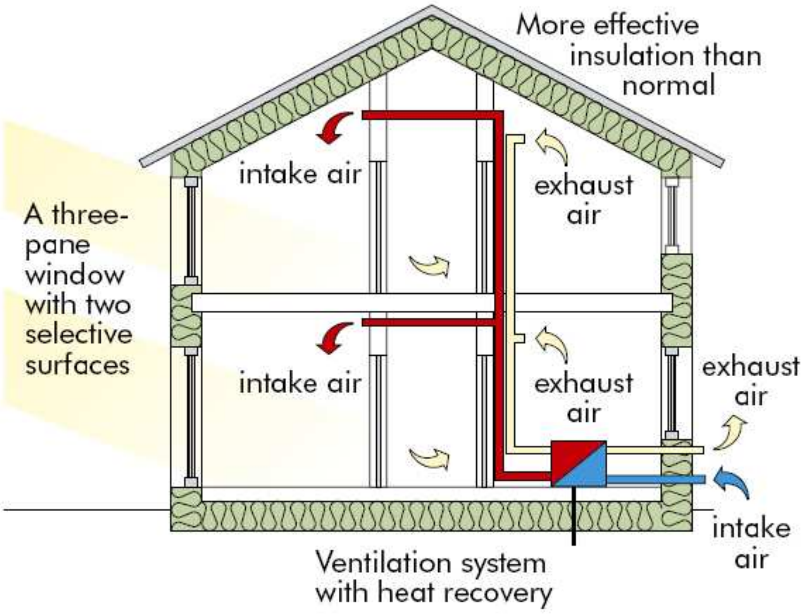

Figure 2.1 Ventilation heating system of a one-family house (Passive House concept)

There are two alternative solutions for a ventilation heating system. The intake air can be either heated in a centralized manner immediately after the ventilation machine, or room-specifically at the terminal ventilation equipment. The former alternative generates constant-temperature air for all spaces, while room-specific temperature control allows varied temperatures but requires heating the intake air either at the terminal equipment or in the ducts before the terminal equipment. Overheating may occur due to the thermal load from the sun, even during early spring, so it must be possible to bypass heat recovery in order to avoid the need for cooling. (Passive House concept).

A high annual ventilation heat recovery coefficient (at least 75 %) can reduce the heating requirement and temperature of the intake air. The temperature of the intake air must be below 50℃. A typical problem of ventilation heat recovery systems is their poor efficiency, caused by the need to melt the ice forming in the recovery system. One new way of improving the efficiency is to preheat the fresh air using piping with fluid circulation, located underneath or next to the building. The piping can also be used for cooling the intake air. (Passive House concept).

2.3.7 Lower operating costs

The initial investment in a passive house may be larger than that of a conventional house, but its operation and lifecycle costs are significantly lower than a conventional house, like it is shown on the Chart 2.2.

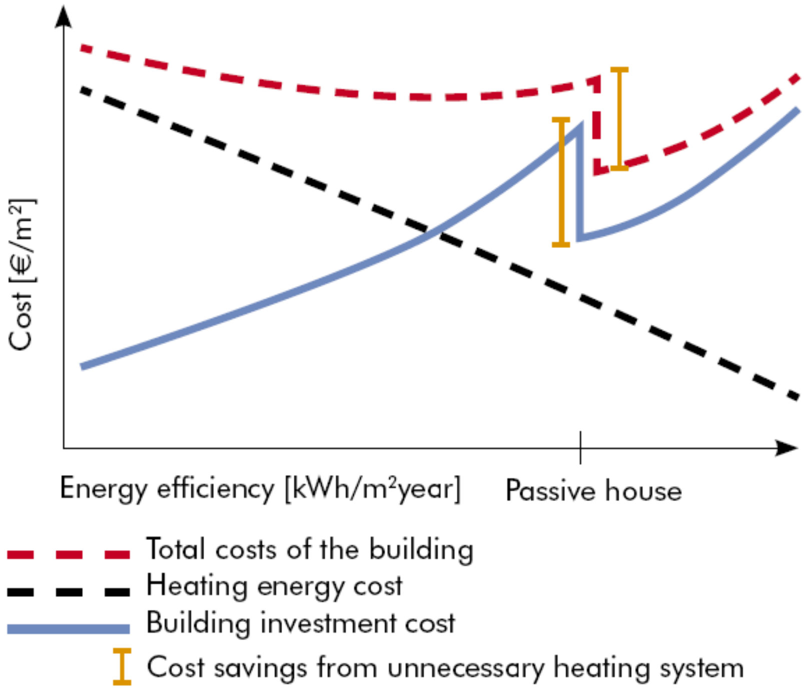

Chart 2.2 Building investment and lifecycle costs (Passive House concept)

The goal of a passive house is to minimize lifecycle costs through energy saving and simple and high quality technology. When the heating energy requirement is low, the heat distribution system can be made simpler. This reduces both the investment costs and the lifecycle costs. (Passive House concept).

A passive house provides the developer with lower operating costs. The low energy consumption and low power required from the power grid reduce fixed energy costs and provide savings in the purchase costs of heating systems. A smaller size and power and a lower amount of heating equipment reduce service and maintenance costs. (Passive House concept).

2.3.8 Thermal comfort

Thermal comfort and indoor air quality require that the intake air is mixed well with the indoor air. Mixing reduces the vertical thermal gradient in the air inside room spaces. The velocity of air from terminal equipment placed high up must be sufficiently high in order to achieve effective mixing, while in the living zone, the speed must be low, at most 0.15 to 0.20 m/s, so that the airflow does not reduce comfort. (Passive House concept).

Floor heating is justified in humid spaces to speed up the drying of the floor, but the temperature must be set lower than regular floor heating, only 1 to 3 ℃ above air temperature. A higher temperature may cause overheating. The vertical thermal gradient in a room space must be under 2 ℃ from a sitting person’s ankles to his or her neck, i.e. between 0.1 m and 1.1 m. Window height should not exceed 1.8 meters unless air blowers are placed in front of them. (Passive House concept).

The thermal properties of a passive house’s exterior shell are good, so the maintenance of small temperature gradients is easy and the heating period is short compared to a conventional house. A fireplace can cause overheating and reduce thermal comfort in a well-insulated house. Because the heating energy requirement of a passive house is small, the heat output of a fireplace must be low. This should be taken into consideration when selecting a fireplace. (Passive House concept).

2.4 Wall structures

While designing Passive House envelope, such as wall structures, a lot of terms should be taken into account. As it was said in previous chapters, envelope should be air tight and well insulated, insulation should be protected from cold wind and moisture.

To implement all these requirements in life plenty of solutions can take place. One of the most common of them is shown in the Figure 2.2.

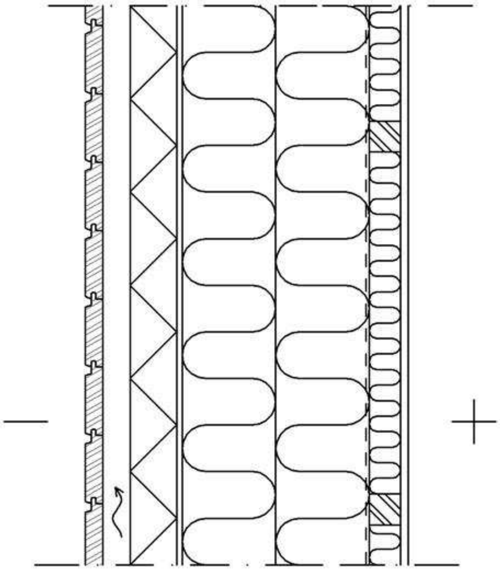

Figure 2.2 Passive House external wall with crossing frame

This structure has timber frame. It is a very good solution, as it is easy to erect, it is environmental friendly. One more advantage is that large amounts of thermal insulation can be installed between timber studs. In case of Passive House this requirement is necessary in order to achieve low thermal transmittance of the structure. For the same purposes thermal bridges should be avoided. This can be done, for instance, using I-joist timber studs (Figure 2.3) and no crossing frames (Figure 2.4). To decrease the thickness of the whole structure, insulation with low thermal conductivity, λ, is used. U-value requirement of Passive House exterior walls differs from 0.6 W/m^{2}K to 0.12 W/m^{2}K depending on the location.

If electricity conduits are installed within the exterior walls, the use of installation spaces between the air barrier and internal cladding is recommended. As it is shown in Figure 2.2, Figure 2.3 and Figure 2.4, between air barrier and internal surface is installed a 50 mm insulation layer. This solution provides continuous air and vapor barrier of structure.

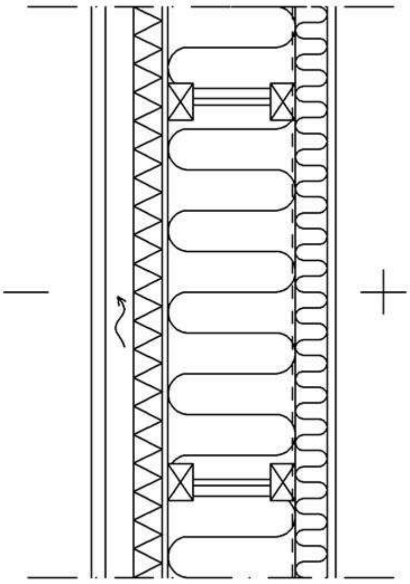

Figure 2.3 Passive House external wall with I-joist frame

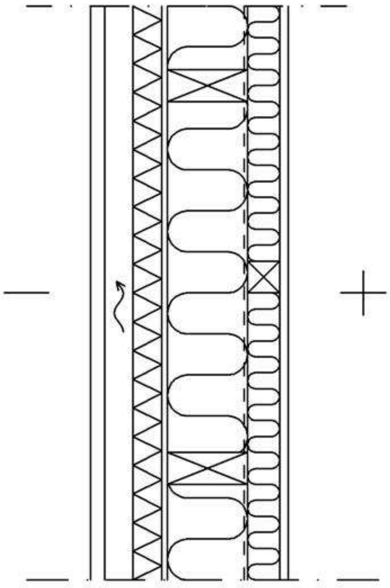

Figure 2.4 Passive House external wall with no crossing frame

A correctly functioning air and vapor barrier is particularly important when there is too much pressure indoors. This occurs nearly always at the top of the building during the winter. Moisture convection, moisture that accompanies air when it penetrates into a structural component, is much more dangerous than moisture diffusion, that is moisture which is transferred due to differences in vapor content. (PAROC 2003).

Airtightness is therefore very important. But the barrier should also prevent vapor diffusion into the structure. Otherwise water vapor can condense and cause damage. The driving force for diffusion is highest during the winter, since moisture will flow into the building from people and from activities. The barrier must then be placed on the inside in order to be effective. If it is placed on the outside, it will have almost the opposite effect to that intended. In this case the moisture will condense on the barrier. It is sometimes stated that a vapor barrier on the inside can cause damage during warm, rainy summer days when the diffusion drives the moisture from the outside to the inside of the structure. However a large number of investigations show that these fears are exaggerated. It is the driving forces during the winter that must be guarded against. (PAROC 2003).

A structure that is not airtight will result in higher energy consumption and there will be a risk of damage due to damp and mould within the structure. Four factors together can cause mould: temperature, moisture, organic material, time. Critical values: RH>80% and temperature 0-50^{o}C.

Wind shielding can be built from fiberboard, gypsum board or other board material with sealed seams. Wind shielding can also be attained by plastering on top of the thermal insulation layer or using mineral wool insulation with air-tight coating and sealed seams.

Behind the facade layer and under the roof coverings there should be a ventilated air space. The purpose of an air space is to ventilate (and in walls also to drain) away any rain water that has penetrated and to prevent it from reaching other moisture sensitive construction components. Furthermore, the space must ventilate away any moisture that comes from within the building. The air space should be at least 20 mm wide and must not be packed with lath or mortar remains. (PAROC 2003).

3 PASSIVE HOUSE IN EUROPE

3.1 Promotion of European Passive Houses (PEP)

It is generally recognized that, within the housing sector in Europe, many building activities can be expected over the coming decades. The old building stock will need to be renewed or, in many cases, even demolished and new buildings erected. Since many houses will be renovated and many houses will be newly erected in the near future the chance is offered to improve the energy efficiency in the housing stock. The basic idea of a passive house is to minimise the heat demand for space heating so that the necessary heat can be supplied by additional heat to the ventilation air. An average energy reduction of 50% to 65% can be obtained per house compared to the business as usual. Chart 3.1 illustrates the energy saving potential of a passive house compared to the average existing building stock and newly built houses per country. (Elswijk, Kaan 2008, p. 5)

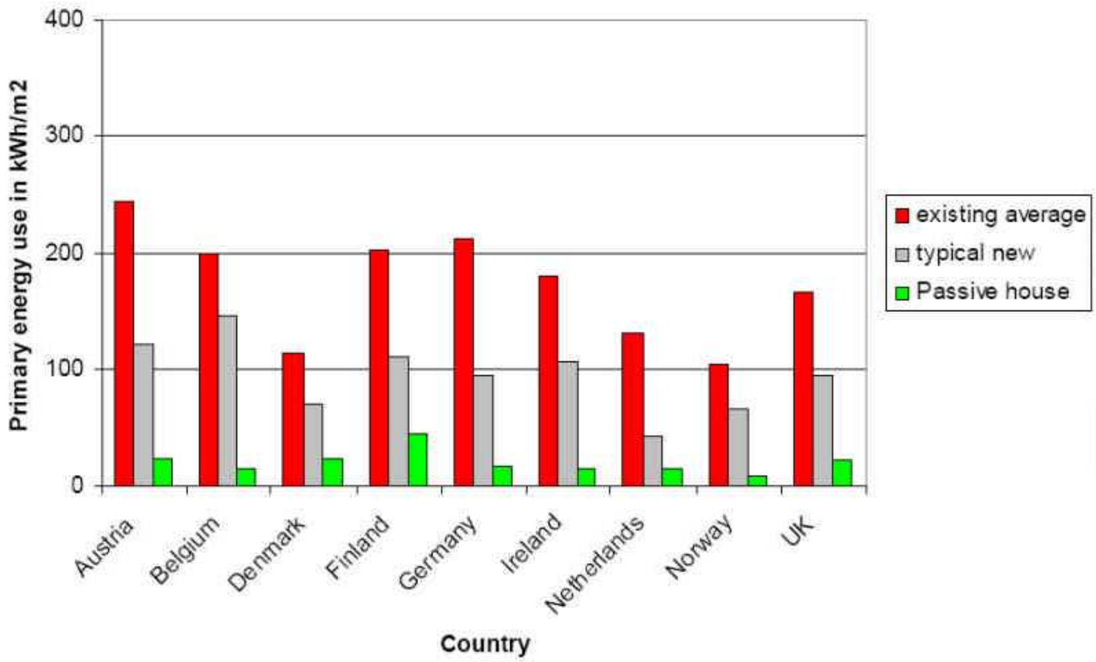

Chart 3.1 Yearly primary space heating energy uses per dwelling, per existing, typical new and passive house (Elswijk, Kaan 2008, p. 5)

Most European countries have made large progress in reduction of energy consumption in the housing sector during the last two decades. However, much more can be achieved, as has been shown with building and renovating according to the passive house standard in Germany and Austria. In order to investigate how the experience and knowledge about passive houses can be used, and how the principles of passive houses can be linked to the information and awareness strategies that are intended by the EU Directive EPBD (Energy Performance of Buildings Directive), nine cooperating European countries (Ireland, UK, Netherlands, Belgium, Norway, Denmark, Finland, Germany and Austria) started a project: Promotion of European Passive Houses (PEP). The project was financially supported by the EC, within the framework of the Intelligent Energy for Europe - programme. The project started in January 2005 and completed in January 2008. (Elswijk, Kaan 2008).

3.2 Passive House in Germany

According to the main definition of Passive House and Table 2.1, requirements to Passive Houses in Germany are as follows:

- The building must not need more heating energy than 15 kWh/m² per year
- With the building de-pressurized to 50 Pa (N/m²) below atmospheric pressure by a blower door, the building must not leak more air than 0.6 times the house volume per hour ($n_{50} \leq 0.6$ / hour)
- Total primary energy consumption (primary energy for heating, hot water and electricity) must not be more than 120 kWh/m² per year.

To achieve these characteristics different methods can be used. For instance Germans were the first who implemented the Passive Houses estate with terraced buildings. The idea was to build them in such a way, that they would have the common walls. Thus, the total area of external walls of all buildings was less than it would be if they were separate. Therefore the energy losses were also less. This concept helped architects and engineers to obtain Passive House standards. Estate with the same idea is shown in chapter 3.2.6.

3.2.1 National policy

The German government agreed on a national energy and climate programme which includes strengthening of building regulation concerning energy efficiency. The requirements were strengthened by 30 % in 2008 and will be strengthened by another 30% in 2012. Occasions for retrofit building envelope or service systems will be imposed. The current resolutions will shorten the distance between building regulation and passive house standard. (Elswijk, Kaan 2008).

3.2.2 Barriers

In the long term (5 years) it is important that the passive house standard becomes the ‘normal standard’. Existing DIN-standards (e.g. DIN EN 12831 for heat load calculations) form a barrier for passive house dissemination and should be updated as well as the current requirements for energy efficiency of buildings. (Elswijk, Kaan 2008).

In the short term the training/education of planners, building companies and developers should be improved. The number of experienced passive house planners is still too small. In 2007 the Passivhaus Institute started an examination for planners concerning passive houses. In case of passing the exam the planner gets the title ‘certificated passive house planner’. Training courses will be offered in whole Germany.

3.2.3 Passive House certification

A certification system for passive houses and passive house suitable components was established in Germany in 1997 by the Passive House Institute Darmstadt. Certification of products facilitates finding and comparison regarding energetic qualities. (Elswijk, Kaan 2008).

The certificate ‘quality proofed passive house’ confirms the ‘as built’ design of a building in accordance with the Passive House Planning Package. It will be assessed if the values for total energy demand, total primary energy and air tightness fulfill the passive house requirements. In future the certificate for passive house planners will make it easy to find a planner with substantiated knowledge regarding passive houses.

3.2.4 Implemented Passive Houses

Approximately 8,000 passive house dwellings have been built in Germany until now. However, passive houses have still a very small market share of about 1% in Germany. Regions with an active passive-house-supporting policy achieve higher market shares. (Elswijk, Kaan 2008).

3.2.5 Project in Hannover-Kronsberg

The Passive House estate lies in the „Kronsberg“ district, southeast of the Hannover centre. Figure 3.1 shows the south view of the houses with the large window surfaces.

Figure 3.1 Passive Houses in Kronsberg, Hannover (Feist 2001)

Three house sizes were built in Kronsberg:

- House type „JDL: Jangster de Lüx“, the widest house with an inner dimension of 6 m and a "Treated Floor Area" of 119.5 m²; a total of 22 houses, of which 8 are end houses. (Feist 2001)
- House type „J: Jangster“ with an inner dimension of 5 m and a Treated Floor Area of 97.3 m². 9 houses of this type were built. (Feist 2001)
- House type „123“ with an inner dimension of only 3.80 m and a Treated Floor Area of 75.1 m²; only one house of this type was built. (Feist 2001)

The non-basement terraced houses with gabled roofs and external storage rooms are built using a mixed modular system: ceilings, partition walls between homes, gable walls and remaining load-bearing structures consist of prefabricated reinforced concrete slabs; the highly insulated facade and roof are lightweight prefabricated wood elements. In addition, triple-glazed windows with specially insulated window frames as well as a home ventilation system with a high efficiency heat exchanger were installed. The U-values of the envelope structures are shown in the Table 3.1. (Feist 2001)

Table 3.1 U-values of the building envelope parts (Feist 2001)

Building envelope	U-value, W/m^{2}K
Floor slab (Middle houses)	0.125
Floor slab (End houses)	0.091
Exterior walls (south and north facades)	0.126
Exterior walls (gable facades)	0.097
Roof	0.095
Windows, average	0.83

The roof is built from prefabricated lightweight wood elements with 400 mm high I-beams, which span from one partition wall to the next. An internal polyethylene foil forms the airtight layer. (Feist 2001)

The outer wall elements for the north and south facades are also built using prefabricated lightweight wood elements. So-called half box beams are used as shafts. An internal polyethylene foil forms the airtight layer. (Feist 2001)

The outer wall of the gable sides is, like the house partition walls, built from load carrying reinforced-concrete slabs. This is protected on the outside against heating losses by a 400 mm polystyrene external thermal insulation compound system. The concrete itself forms the airtight layer for the gable wall. (Feist 2001)

The floor slab consists of 240 mm prefabricated steel-reinforced slabs, which is insulated underneath by factory-made 300 mm polystyrene external thermal insulation (420 mm for the end-of-terrace houses) . The concrete floor itself also forms the airtight layer. (Feist 2001)

Each of the 32 Passive houses has its own independent ventilation system with built-in heat exchanger to recover heat, which can be operated by the occupants. The system is located in the building services room under the roof; supply and exhaust air are aspirated or blown out directly above the roof. The ventilator control is clearly located in the windscreen area of each house. (Feist 2001)

The measurement values of the air-tightness tests produce, despite small defects, optimal results of n_{50} = 0.17 to 0.4 h^{-1}, the average value for all houses produces the exceptionally low value of $n_{50\ Avg.}$ = 0.29 h^{-1}. The limit for Passive Houses of n_{50} = 0.6 h^{-1} is thus clearly above the maximum measurement values. (Feist 2001)

The total construction costs per m² living area for this project, were:

- House type „Jangster de Lüx final house“ 951.02 €/m²
- House type „Jangster de Lüx middle house“ 885.48 €/m²
- House type „Jangster middle house“ 987.94 €/m²
- House type „123“ 1,089.91 €/m²

The construction costs were thus in the lower half of the typical construction costs for similar terraced houses at the construction site. The proportionate extra costs in comparison with a building built according to the insulation ordinance were between 11.6% and 13.7% of the pure construction costs. (Feist 2001)

However, the benefits also took place. Due to the increased insulation on the north and south facades, heating energy savings of 14% compared with the heating energy requirement of the insulation ordinance reference case are achieved. The extra investments, for 64.8 m² of construction element surface area, are 1,159 €. Costs for the kilowatt-hour of saved energy equal 4.1 Eurocent/kWh. (Feist 2001)

3.3 Passive House in Sweden

Requirements to Passive Houses in Sweden are as follows:

- The building must not need more heating energy than 15 kWh/m² per year
- With the building de-pressurized to 50 Pa (N/m²) below atmospheric pressure by a blower door, the building must not leak more air than 0.6 times the house volume per hour ($n_{50} \leq 0.6$ / hour)
- Total primary energy consumption (primary energy for heating, hot water and electricity) must not be more than 120 kWh/m² per year. (Janson 2008).

But it is very important to remember that Passive Houses which will be built in the northern part of Sweden (above 60^{o} latitude) should satisfy Nordic Countries' requirements (Table 2.1).

3.3.1 National policy

The Swedish ratification of the Kyoto Protocol and the United Nations' Framework Convention on Climate Change are used as a basis for decisions regarding the Swedish climate strategy. The goals for the Swedish energy policy were provided in 1997, when a strategy for the continuous work on the modification of the energy system was also compiled.

The total energy use in the Swedish industry and building sector today is almost at the same level as in 1970, even though the total heated area has increased, the total population is 11% more and industrial production is much higher than in 1970 (Elswijk, Kaan 2008).

3.3.2 Barriers

The key barriers hampering market penetration and growth have been primarily related to lack of coordinated information, knowledgeable passive house construction experts and uncertainty of future energy efficiency requirements. While the overall policy mixture in Sweden (including environmental taxes on electricity and heating oil, construction standards, financial incentives, public procurement and R&D efforts) has provided a sufficient framework for breaking the barriers, the market pull has been created by proactive forerunners from local level, cities, municipalities as well as private citizens and bigger construction companies raising to the challenge. An active dialog (facilitated by the by "Bygga-Bo-dialogen, launched 2003) between communes, construction companies, property owners, banks, insurance companies and the government has been an important part of providing the required knowledge base and coordination for a more sustainable construction and building sector in Sweden. (Gaia Consulting Oy 2008).

3.3.3 Passive House certification

Sweden's first certified passive house will be the Skogslunden passive house pre-school in Åkersberga. At the moment, certification proceeds formally through the Passive House Institute in Darmstadt, Germany. However, a Swedish certification body will soon be taking over.

3.3.4 Implemented Passive Houses

In Lindås, south of Gothenburg, lie the first Swedish houses with a modern Passive house standard. The twenty terrace houses were completed during 2001. The second Passive house project was built in 2003 – 2004 and are rental apartments located in Glumslöv, Landskrona in the south of Sweden. In

May 2009, about 700 apartments with a Passive house standard had been built in Sweden. (Goksöyr, Tärnås 2009).

3.3.5 Project at Oxtorget in Värnamo

At Oxtorget in the centre of the town Värnamo, five multifamily houses were built with passive house standard (Figure 3.2). The client Finnvedsbostäder is the public housing company in Värnamo.

Figure 3.2 Passive Houses at Oxtorget in Värnamo (Janson 2008)

The five houses consist of 40 rental apartments in 2.5 storeys with apartments with 2 to 5 rooms. The tenants moved in during June – July 2006.

The load bearing structure is made of concrete and cast on site. The external wooden frame walls are also put together on site. The building envelope is highly insulated. U-values for the building envelope are shown in Table 3.2. The part of the floor facing ground right under the apartment walls has a total U-value of 0.15 W/m2K excluding foundation .

Table 3.2 U-values of the building envelope parts (Janson 2008)

Building envelope	U-value, W/m^{2}K
Ground floor (excl. foundation)	0.09
Exterior walls	0.095
Roof	0.07
Windows, average	0.94
Door	0.60

To reduce the moisture content in the concrete the apartments were ventilated until the required moisture content of maximum 85% was reached. The concrete used for all constructions has a w/c ratio of 0.6. Additional measurements of the RH content in the concrete construction were performed before the walls were mounted, to ensure that the moisture content was low enough.

To protect the wooden construction from the moisture in the concrete slab, there is a metal sheet placed on the concrete slab that breaks the capillary suction. A small spacer block made of plastic is also put under the wooden beam for additional moisture reduction. The steel strip construction has been tested to make sure it will not cause a thermal bridge

The exterior walls were made as wooden frame construction and mounted on site. From the outside, the walls consist of a façade material, wooden studs with mineral wool, expanded polystyrene, plastic foil and on the inside wooden studs with mineral wool and gypsum board.

The contractor was not sure if they would be able to make the building as airtight as stated in the requirements for the project; 0.4 l/s,m2 at 50 Pa (n_{50} = 0.6 / hour). They had never built this airtight before and it was important to discover in an early phase if they were building with the right method to achieve the airtightness required. One apartment was measured at an early stage when the walls were mounted and holes for doors and windows were covered with plastic, to measure any air leakage in the construction. The measurement showed that air was leaking between the inner walls and the slab. The air was leaking through the expansion joint, but it was easy to seal with a sealant. In a second measurement the results were much better and the contractor now could finish all apartments. The final measurements showed an average air leakage 0.2 l/s m2 for all buildings (n_{50} = 0.3 / hour).

All apartments have their own air-to-air heat exchanger placed next to the bathroom. To avoid spread of noise from the fans into the rooms through the ventilation system, two silencers are mounted on the supply air duct directly after the heat exchanger unit and one silencer is mounted on the exhaust air duct. The drainage pipe from the heat exchanger is led to the bathroom. Space heating is supplied by an electric heating battery on the supply air side in the heat exchanger unit.

The calculated total cost for the client was SEK 50,243,000 (about 5,170,000 €). The final cost for the client was SEK 55,700,000 (about 5,732,000 €). The gross amount per square meter, subsidies not subtracted, ended up at SEK 17,898 /m^2 (about 1,842 €/m^2). The total cost for the contractor was SEK 36,700,000 (about 3,776,000 €), VAT not included; approximately SEK 11,800 /m^2 (about 1,214 €/m^2). In these prices, the cost of the piece of land is included as well as costs for electricity- and water connections. For building a regular house just meeting the building code requirements, the cost would probably be around SEK 15,000 /m^2 (about 1,543 €/m^2).

3.4 Passive House in Finland

According to the main definition of Passive House and Table 2.1, requirements to Passive Houses in Finland are as follows:

- The building must not need more heating energy than 20-30 kWh/m^2 per year
- With the building de-pressurized to 50 Pa (N/m^2) below atmospheric pressure by a blower door, the building must not leak more air than 0.6 times the house volume per hour ($n_{50} \leq 0.6$ / hour)
- Total primary energy consumption (primary energy for heating, hot water and electricity) must not be more than 130-140 kWh/m^2 per year.

The floor area is calculated as treated floor area in the international Passive House definition and as gross floor area in the Finnish Passive House definition. (Lylykangas, K. 2009)

3.4.1 National policy

Finland's building energy use related legislation used to be one of the tightest in the world 20 years ago. Since then, only minor adjustments have taken place. The present government aims at a new approach in 2010. The new code of 2010 aims at 30 – 40% reduction in energy demand of buildings compared to 2008 regulations. (Elswijk, Kaan 2008).

3.4.2 Barriers

Three kinds of barriers were identified at the beginning of the project PEP: technical, market dependent and institutional barriers. The main barriers solved during the project are user expectations (technical barrier), unclear benefits (market barrier), and attitudes towards passive houses and signal to change (institutional barriers). The passive house definition for the Nordic countries is now well known among building professionals. The key problems in the present construction process are the architect's poor knowledge on energy related issues, and the chained process itself. Input into the beginning of the process is required. This also includes the use of energy calculation tools even in the draft design phase. The process should be able to allow feedback from different stakeholders. (Elswijk, Kaan 2008).

On a short term, the most important steps in the implementation path are evoking investments into energy-efficient construction, break the industry's conception of perceiving passive houses as expensive, and improving the coordination of the process towards a win-win situation between clients and producers by value added with high quality products, change from products to solutions, including services to solutions and building on user demands. (Elswijk, Kaan 2008).

3.4.3 Passive House certification

VTT is an accepted certification body, and VTT has developed a passive house certificate for whole building solutions. (Elswijk, Kaan 2008).

3.4.4 Implemented Passive Houses

Approximately 10 passive house construction projects have been started in 2007 in Finland. One of them is an apartment housing project of 20 dwellings. The market potential for passive houses increases. New single-family and row houses are the predominant market. The estimate for 2010 is 500 – 1000 new dwelling units. (Elswijk, Kaan 2008).

3.4.5 Project in Nummela, Southern Finland

Multi-Comfort is a concept by Isover Oy for new constructions. It sets a requirement for the energy performance of a building in accordance to the Finnish Passive House definition. (Lylykangas, K. 2009)

The heating energy demand of a Multi-Comfort house is max. 20 – 30 kWh/(m^{2}a) according to the location, as in the Finnish Passive House definition. As the national primary energy factors are not confirmed, the Multi-Comfort concept does not at this stage set any criteria for the total primary energy demand, but the calculated total energy consumption should not exceed 130 kWh/(m^{2}a). In addition, the Multi-Comfort concept gives recommendations for air-tightness (max. 0.6 1/h) and maximum heating power (20 – 30 W/m^2 depending on the location). The calculation tool is not specified by the concept. (Lylykangas, K. 2009)

Table 3.3 The Passive House definition and the criteria of Multi-Comfort concept (Lylykangas, K. 2009)

Climatic zone		The Finnish Passive House definition			The Multi-Comfort concept			
		South	Middle	North	I	II	III	IV
Heating energy demand	kWh/(m²a)	20	25	30	20	22	25	30
Heating power	W/m²	no requirement			20	22	24	28
Total primary energy demand	kWh/(m²a)	130	135	140	no requirement			
Total energy consumption	kWh/(m²a)	no requirement			130			
Air-tightness	1/h	0.6			0.6			
Internal heat load	W/m²	not specified			3.1			
Floor area		gross floor area			gross floor area			

The first project targeting to meet the criteria of the Multi-Comfort concept is a single-family house located in Nummela, 50 km North-West from Helsinki center. In the Southern parts of Finland the Multi-Comfort house criteria for the heating energy demand is max. 20 kWh/(m²a), and in addition the Multi-Comfort concept recommends the heating power of max. 20 W/m².

Figure 3.3 Multi-Comfort pilot project in Nummela, Southern Finland (Lylykangas, K. 2009)

The Multi-Comfort pilot project is a single-family house, 179 m^2 in gross floor area, characterized by the large north-facing windows, which the client family wanted to have for the lake view on the northern side of the house. The rooms are organized in one storey for functional reasons, leading to a relatively high shape factor (A/V) of 1.3 m^2/m^3. The recommended shape factor of a single-family Passive House is max. 0.8 m^2/m^3. (Lylykangas, K. 2009)

The architectural design was an interactive process with the energy simulation. The early simulation results of the sketches indicated that the heating energy demand would be too high, about 27 kWh/m^2a. The architect listed changes, which would decrease the heating energy demand. The changes were simulated and applied in the plan in the order of the client family priorities. The target value for the heating energy demand was achieved by reduction of the window surface area and the room height, improvements of the U-values and introduction of the occupancy-time-based control in the ventilation. (Lylykangas, K. 2009)

The mechanical ventilation has a heat recovery system with a regenerative heat exchanger and the annual efficiency of 74 %. Heat is distributed through floor heating and ventilation. The heating energy for the domestic hot water and the floor heating is generated by an air-to-water heat pump with the COP of 2.6. (Lylykangas, K. 2009)

The load-bearing exterior walls are constructed of prefabricated wall elements with LVL (laminated veneer lumber) frame. The facade materials are oak panelling with white translucent finish and plaster rendering on ventilated plasterboard. The thermal insulation for the roof and for the floor was installed on site. The ventilated floor structure consists of hollow concrete slabs with thermal insulation on top. (Lylykangas, K. 2009)

The U-value of the relatively large window surface area was improved by using sealed quadruple glazed units fixed onto the wall frame. This solution was applied wherever an opening window is not necessary and the glass surfaces can be easily washed on both sides. The price per square meter of this 4K-glass unit filled with Argon is less than half the price of a regular Passive House window. (Lylykangas, K. 2009)

Table 3.4 U-values of the building envelope parts (Lylykangas, K. 2009)

Building envelope	U-value, W/m^{2}K
Exterior walls	0.083
Roof	0.053
Floor	0.098
Windows, average	0.800
Door	0.700

The energy consumption of the Multi-Comfort pilot building was simulated by Equa Simulation Finland with the dynamic simulation software IDA – Indoor Climate and Energy 4.0 using the climate data of Helsinki. (Lylykangas, K. 2009)

The terrace roof provides shading for the south-facing windows. The simulation results showed, however, that the summertime room temperatures would be relatively high due to the large windows in the west facade. Thermal comfort was improved by adding external blinds on the west-facing windows. This decreased the percentage of hours when the operative temperature is above 27℃ from 25 % down to 13 %. The simulation model did not include the trees, which will provide some extra shading from the low sun angles from west. (Lylykangas, K. 2009)

The total primary energy demand was calculated as an indicative value, though the Multi-Comfort concept does not set a requirement for the total primary energy demand and the Finnish primary energy factors are not defined yet. With the factor of 2.3 (for electricity) the primary energy criteria of a Finnish Passive House (max. 130 kWh/(m^{2}a) in the Southern Finland) could still be met. (Lylykangas, K. 2009)

The energy performance criteria of the Multi-Comfort concept were proved to be viable for an average-sized single-family house in Southern Finland. Despite the relatively high A/V ratio, large window surface area and the north orientation of the windows, the criteria for the energy performance can be met. With higher U-values or less effective heat recovery the target level would not be achieved, and the compensation would probably require reduction of the window surface area and compromising the wishes of the client family. (Lylykangas, K. 2009)

The simulation results also show that the thermal comfort of the interior spaces would be poor without the external shading of the west-facing windows. In the buildings with high level of thermal insulation, extra attention must be paid to the thermal comfort and shading of large windows. Mechanical cooling of spaces would increase the annual energy consumption. (Lylykangas, K. 2009)

4 COST OPTIMIZATION METHOD

As it is shown in previous chapters the main idea of Passive House as an investment project is to reduce costs for energy by accomplishment specific conditions. For optimal solution obtaining it is necessary to estimate not only initial costs such as material costs, but also costs for energy consumption, maintenance, etc. In this study the Life-Cycle Costs Analysis method is used.

4.1 Life-Cycle Costs analysis

Life-Cycle Costs Analysis (LCCA/LCC) is a technique for analyzing the cost of a product or a system over its entire lifespan. During an LCC study it is important to define the elements to be included in the product or a system, then attribute the various cost components via a series of calculations.

To make LCC analysis several steps should be done:

- Study period choice
- Life-Cycle Costs formula
- Time adjustments
- Calculation

- Final result

In case of this research, LCC shows the cost effectiveness of different kinds of Passive House external walls in long term perspective.

4.2 Study period choice

Frame solutions of studied wall structures are limited by usage of timber constructions. The design working life of building with timber structures corresponds to Category 4 “Building structures and other common structures” and is equal to 50 years. (EN 1990:2002 Eurocode: Basis of Structural Design).

The most favorable insulation must be also calculated based on a particular lifetime for the building. The insulation does not wear out, does not require maintenance and does not require replacing. A lifetime of 50 years is normally reckoned for insulation that is to match the estimated working life for the building. Thus, the study period of LCC is 50 years. (PAROC 2003)

One more investigation is done with a study period of 20 years. This value can be also interesting for a customer if he/she is not going to live in this house for the whole life.

4.3 Life-Cycle Costs formula

In order to find the best alternative among different options, in general case, three components are important to include into calculation. Those are: the energy costs during the life-cycle of the structure, the investment cost of the structure and the maintenance cost for the structure, as it is shown in Formula 4.1 (Energimyndigheten. 2009).

$$LCC = C_i + C_m + C_e \qquad (4.1)$$

where

C_i	investment costs (initial costs), €/m^2;
C_m	maintenance costs, €/m^2;
C_e	energy costs during life-cycle, €/m^2.

However, in this research there is no need to take into account the maintenance costs (repainting, facing replacement, etc.), as all kinds of wall structures need the same inputs. One more assumption is that energy costs are not taken into account, but costs of life-cycle energy losses through the sq. meter of wall construction. Thus, the LCC formula is as follows:

$$LCC = C_i + C_e \qquad (4.2)$$

where

C_i	investment costs (initial costs), €/m^2;
C_e	energy losses' costs during life-cycle, €/m^2.

The final conclusion about effectiveness of each wall construction is based on the results of this sum.

4.4 Time adjustments

The purpose of such an adjustment is to take into account changes which are taking place through the whole study period. In this study it is important to consider changes of energy prices. This factor plays a rather influential role, because even a 2% annual price increase results in a huge rising of energy losses' costs after 50 years.

One more adjustment which is always considered in LCC calculations is money inflation. However, it is not necessary in this study, because current (nominal) costs are enough to compare different structures.

4.5 Calculation

4.5.1 Wall structures' design

The first step of wall optimization is structures' design. The main idea of designing Passive House envelope is to achieve low values of thermal transmittance and high values of air tightness.

Five different types of wall structures are investigated in this thesis. Also these structures are studied with usage of different insulation. Thus, 10 wall models are studied:

- ISOVER materials (including ISOVER KL-33), Timber frame (ISOVER Passive House structure library: PAUS1001), code in this thesis: US1;
- ISOVER materials (including ISOVER KL-33), Crossing timber frame (ISOVER Passive House structure library: PAUS1005), code in this thesis: US2;
- ISOVER materials (including ISOVER KL-33), I-joist timber frame, code in this thesis: US3;
- ISOVER materials (including ISOVER KL-33), Double timber frame, code in this thesis: US4;
- ISOVER materials (including ISOVER KL-33), No crossing timber frame, code in this thesis: US5;
- ISOVER materials (including ISOVER KL-37), Timber frame (ISOVER Passive House structure library: PAUS1001), code in this thesis: US6;
- ISOVER materials (including ISOVER KL-37), Crossing timber frame (ISOVER Passive House structure library: PAUS1005), code in this thesis: US7;
- ISOVER materials (including ISOVER KL-37), I-joist timber frame, code in this thesis: US8;
- ISOVER materials (including ISOVER KL-37), Double timber frame, code in this thesis: US9;
- ISOVER materials (including ISOVER KL-37), No crossing timber frame, code in this thesis: US10;

All these structures are designed in such a way to decrease thermal transmittance (by usage of modern insulation materials with low thermal conductivity factor), to decrease the amount of thermal bridges and their thicknesses (by usage of special timber frames), to allow usage of internal insulation layer for communication installations without breaking of vapor insulation layer.

4.5.2 U-value calculation

Calculation of U-value is made with DOF-THERM software, which follows the EN ISO 6946:2007.

The calculation method is based on the appropriate design thermal conductivities or design thermal resistances of the materials and products involved. (EN ISO 6946:2007)

The method applies to components and elements consisting of thermally homogeneous layers (which can include air layers). (EN ISO 6946:2007)

The standard also gives an approximate method that can be used for inhomogeneous layers, including the effect of metal fasteners, by means of a correction. (EN ISO 6946:2007)

The principle of the calculation method is to:

- obtain the thermal resistance of each thermally homogeneous part of the component;
- combine these individual resistances so as to obtain the total thermal resistance of the component, including (where appropriate) the effect of surface resistances.

Thermal resistances of individual parts are obtained as follows:

$$R = \frac{d}{\lambda} \qquad (4.3)$$

where

d is the thickness of the material layer in the component;

λ is the design thermal conductivity of the material, either calculated according to ISO 10456 or obtained from tabulated values.

Design thermal conductivity is a value of thermal conductivity of a building material or product under specific external and internal conditions, which can be considered as typical of the performance of that material or product when incorporated in a building component. (EN ISO 10456:2007).

Measured values of thermal conductivity or thermal resistance shall be obtained using the following methods:

- guarded hot plate, in accordance with ISO 8302 or equivalent national method;
- heat flow meter, in accordance with ISO 8301 or equivalent national method;
- calibrated and guarded hot box, in accordance with ISO 8990. (EN ISO 10456:2007).

The values of surface resistances R_{si} (internal) and R_{se} (external) are taken according to the table in EN ISO 6946:2007. All structures in this thesis have well-ventilated air layer: the openings between the air layer and the external environment exceed 1500 mm^2 per meter of length in the horizontal direction. Thus, the thermal resistance of the air layer and all other layers between the air layer and external environment should be disregarded. The value of R_{se} is taken the same as R_{si} and is equal 0.13 m^{2}K/W.

The resistances of the layers are combined as follows:

- components consisting of thermally homogeneous layers;
- components having one or more thermally inhomogeneous layers;
- components containing a tapered layer.

For structure with thermally homogenous layers, total thermal resistance is calculated as follows:

$$R_T = R_{si} + R_1 + R_2 + ... + R_n + R_{se} \qquad (4.4)$$

where

R_{si} is the internal surface resistance;

$R_1, R_2, ..., R_n$ are the design thermal resistances of each layer;

R_{se} is the external surface resistance.

As walls consist of inhomogeneous layers (because of load bearing timber structures), then total thermal transmittance is calculated as follows:

$$R_T = \frac{R'_T + R''_T}{2} \qquad (4.5)$$

where

R'_T is the upper limit of the total thermal resistance

R''_T is the lower limit of the total thermal resistance

Calculation of upper and lower limits shall be carried out by considering the component split into sections and layers in such a way that the component is divided into parts, which are themselves thermally homogeneous. (EN ISO 6946:2007)

When calculating the upper limit of thermal resistance, the building element is considered to consist of two thermal paths (or sections). The upper limit of resistance is calculated from:

$$\frac{1}{R'_T} = \frac{f_a}{R_{Ta}} + \frac{f_b}{R_{Tb}} + \ldots + \frac{f_q}{R_{Tq}} \qquad (4.6)$$

where

$R_{Ta}, R_{Tb}, \ldots, R_{Tq}$ are the total thermal resistances from environment to environment for each section, calculated using equation (4.4);

$f_a, f_b, \ldots, f_q$ are the fractional areas of each section.

When calculating the lower limit of thermal resistance, the resistance of a bridged layer is determined by combining in parallel the resistances of the unbridged part and the bridged part of the layer. The resistances of all the layers in the element are then added together to give the lower limit of resistance. The equivalent thermal resistance, R_j, for each thermally inhomogeneous layer is calculated as follows

$$\frac{1}{R_j} = \frac{f_a}{R_{aj}} + \frac{f_b}{R_{bj}} + \ldots + \frac{f_q}{R_{qj}} \qquad (4.7)$$

Then the lower limit is determined using equation (4.4):

$$R''_T = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \qquad (4.8)$$

Thermal transmittance is calculated as follows:

$$U = \frac{1}{R_T} \qquad (4.9)$$

Finally, corrections are applied to the thermal transmittance, to allow for the effects of air gaps in insulation, mechanical fasteners penetrating an insulation layer, and, in roof cases, precipitation on inverted roofs. (EN ISO 6946:2007)

4.5.3 Natural convection calculation

Natural convection is a type of heat transport, in which fluid motion is generated by density differences, occurring due to temperature gradients. The onset of natural convection in an insulating material with an open structure depends on permeability, thickness and temperature difference. The driving force for natural convection is described by the dimensionless modified Rayleigh number (EN ISO 10456:2007):

$$Ra_m = 3 \cdot 10^6 \frac{dk\Delta T}{\lambda} \qquad (4.10)$$

where

ΔT is the temperature difference across the insulation, K;

d is the thickness of the insulation, m;

k is the permeability of the insulation, m^2;

λ is the thermal conductivity of the insulation without convection, W/(mK).

The permeability of insulation is calculated as follows:

$$k = \eta \cdot L \qquad (4.11)$$

where

η is the dynamic viscosity of air, Pa s;

L is the air permeability of the insulation material (Table 4.1), m^2/s Pa.

The dynamic air viscosity is calculated as follows:

$$\eta = \left(17 + \left(0.05 \cdot \delta_{air}\right)\right) \cdot 10^{-6} \qquad (4.12)$$

where

δ_{air} is the mean temperature in the insulation, ^{o}C.

When the Rayleigh number is below the critical value, heat transfer is primarily in form of conduction; when it exceeds the critical value, heat transfer is primarily in form of convection. The critical value of Rayleigh number for horizontal direction of heat flow is 2.5 (EN ISO 10456:2007).

4.5.4 Material costs' calculation

The main assumption in material costs' calculation is that the load bearing structures and connections between walls and roof, ground floor, windows, doors are not taken into account. Considerable materials are: thermal insulation, wind barriers, vapor barriers, gypsum boards.

Material costs, C_i, are calculated for 1 m^2 of the wall. All timber studs and elements are mounted with step 600 mm in horizontal or vertical direction.

Table 4.1 Gyproc materials

Material	t, mm	λ_D, W/mK	L, m^2/Pa s	Price, €/m^2
Gyproc GTS 9	9	0.25	-	3.19
Gyproc GEK-13	13	0.25	-	4.44

Table 4.2 ISOVER insulation

Material	t, mm	λ_D, W/mK	L, m^2/Pa s	Price, €/m^2
ISOVER KL-33	50	0.033	60×10^{-6}	3.15
ISOVER KL-33	100	0.033	60×10^{-6}	5.04
ISOVER KL-33	125	0.033	60×10^{-6}	6.23
ISOVER KL-33	150	0.033	60×10^{-6}	7.49
ISOVER KL-33	175	0.033	60×10^{-6}	8.84
ISOVER KL-33	200	0.033	60×10^{-6}	10.10
ISOVER KL-37	50	0.037	120×10^{-6}	2.39
ISOVER KL-37	100	0.037	120×10^{-6}	3.80
ISOVER KL-37	125	0.037	120×10^{-6}	4.70
ISOVER KL-37	150	0.037	120×10^{-6}	5.64
ISOVER KL-37	175	0.037	120×10^{-6}	6.66
ISOVER KL-37	200	0.037	120×10^{-6}	7.77
ISOVER RKL-31 FACADE	50	0.031	30×10^{-6}	10.34
ISOVER RKL-31 A	75	0.031	30×10^{-6}	12.15
ISOVER REK-31	25	0.031	30×10^{-6}	6.61
ISOVER Vario	0,22	0.340	-	1.85

Prices for all ISOVER and GYPROC materials on Finnish market were taken from official factory pricelists.

4.5.5 Energy losses' costs calculation

To take into account long time period and annual energy price increase in energy losses' costs calculation, the following formula is used:

$$C_e = P\sum_{n=1}^{N}(1+i)^n \tag{4.13}$$

where

C_e	is energy losses costs, €/m^2;
P	is present energy price for energy losses trough 1 m^2 of the wall, €;
N	is time period, years;
i	is percent of energy price increasing, in fraction.

The present price for energy losses trough 1 m^2 of the wall is calculated as follows:

$$P = Q_T \cdot C \tag{4.14}$$

where

P	is present energy price for energy losses trough 1 m^2 of the wall per year, €;
Q_T	is energy losses trough 1 m^2 of the wall per year, kWh;
C	is present energy price, €/kWh.

Energy losses are calculated with DOF-THERM software for each month of the year as fallows:

$$Q = U(t_2 - t_1)h \tag{4.15}$$

where

Q	is energy losses trough 1 m^2 of the wall, kWh;
U	is the thermal transmittance, W/(m^{2}K);

h	is the period of time, hours;
t_1	is the external air temperature, ^{o}C;
t_2	is the internal air temperature, ^{o}C.

The total energy loss through 1 m^2 of the wall per year, Q_T, is a sum of all months' energy losses.

4.6 Final result

Final result can be obtained with Formula 4.2. With this formula all costs for the wall during its life span can be calculated.

Final optimal characteristics of each wall type are determined after comparison of 6 different variants of this structure. The difference of the variants is in the thicknesses of thermal insulation, which are selected in such a way to provide thermal transmittances of the Passive House external wall in the interval from 0.07 W/(m^{2}K) to 0.13 W/(m^{2}K). Thus, cost optimization of walls is reduced to a simple comparison of structures with high level of thermal insulation costs and low level of energy losses' costs, structures with low level of thermal insulation costs and high level of energy losses' costs, and structures with intermediate parameters.

Proposed cost optimization method is quite easy to understand and apply. However, large number of structures and variants of structures, studied in this thesis, enforce to use calculation software. For calculation of technical characteristics of structures, DOF-THERM software and manual calculations are used. For cost calculation and cost optimization, Excel tool is used.

5 COST OPTIMIZATON OF EXTERNAL WALLS

5.1 Timber frame with ISOVER KL-33 insulation (US1)

Structure is introduced in ISOVER Passive House structure library as PAUS 1001.A detailed drawing and LCC calculation of structure is shown in the Appendix 1.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US1F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-33 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 18 - (-1.53) = 19.53$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{19.53}{2}\right)\right) \cdot 10^{-6} = 17.49 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.49 \cdot 10^{-6} \cdot 60 \cdot 10^{-6} = 1049.4 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \frac{0.4 \cdot 1049.4 \cdot 10^{-12} \cdot 19.53}{0.033} = 0.75$$

As the Rayleigh number for the US1F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US1 variants is also primarily in form of conduction.

Charts 5.1, 5.2, and 5.3 show how costs for materials, energy losses and total costs of US1 structure change in different conditions, while thickness of thermal insulation layer increase.

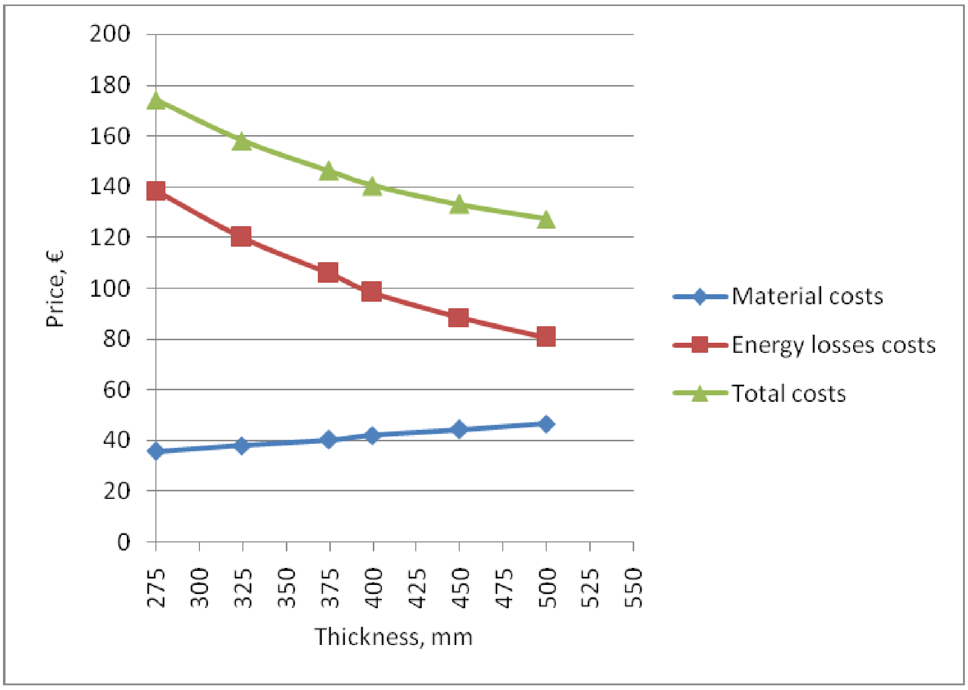

Chart 5.1 LCC analysis results for US1 with 50 years life span and 2% energy price increase.

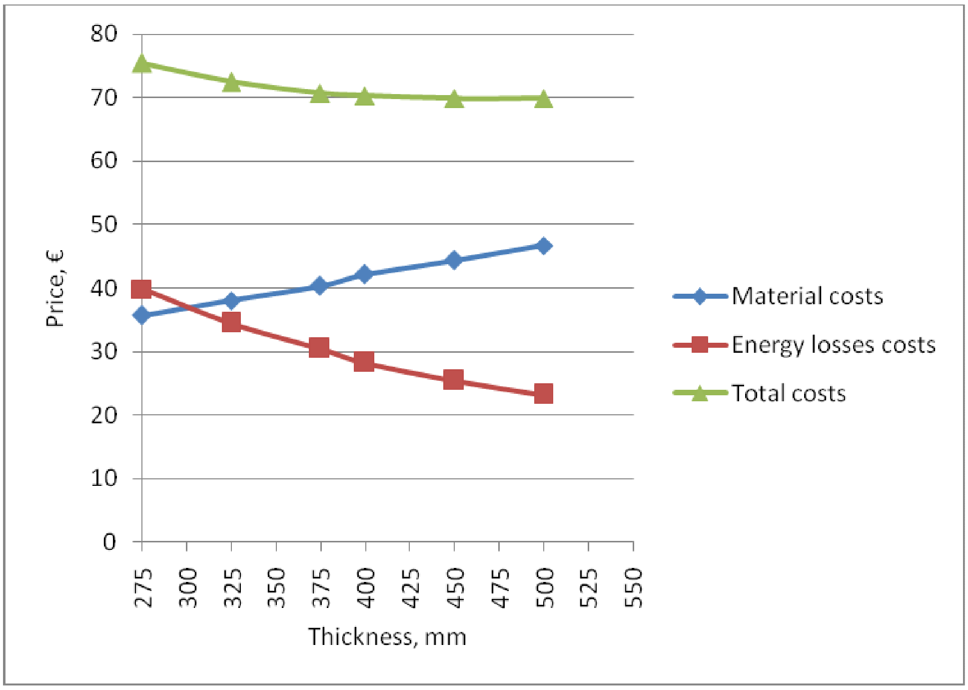

Chart 5.2 LCC analysis results for US1 with 20 years life span and 2% energy price increase.

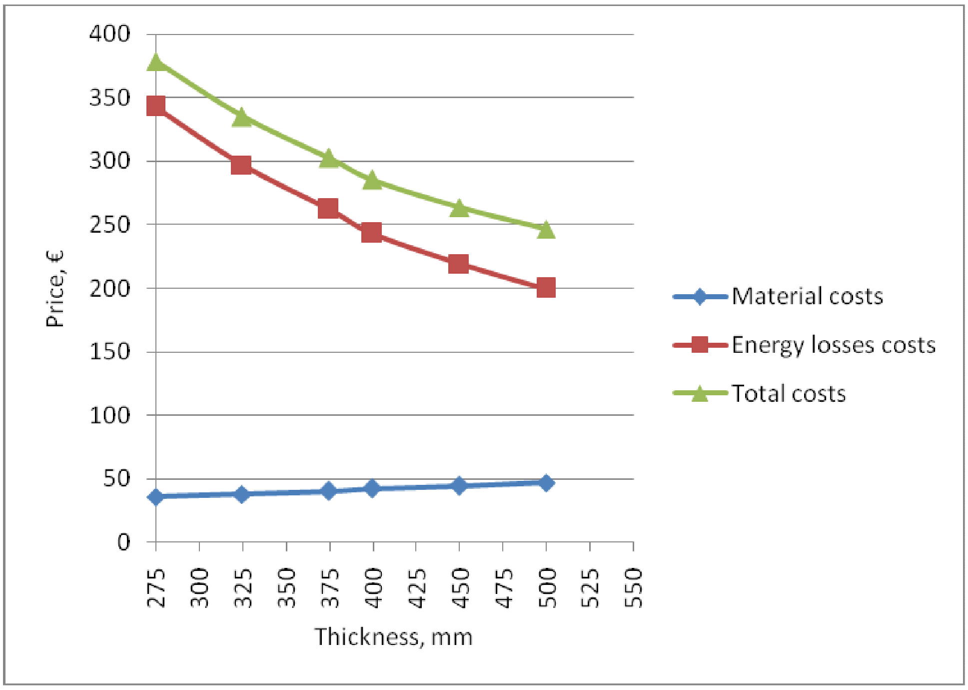

Chart 5.3 LCC analysis results for US1 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US1F (127.41€) and US1E on the life span of 20 years (69.86€). The best structure according to the LCC calculation with 5% annual energy price increasing on life span of 50 years is US1F (246.45€).

5.2 Crossing timber frame with ISOVER KL-33 insulation (US2)

Structure is introduced in ISOVER Passive House structure library as PAUS 1005. A detailed drawing and LCC calculation of structure are shown in the Appendix 2.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US2F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-33 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.34 - (-1.65) = 18.99$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.99}{2}\right)\right) \cdot 10^{-6} = 17.48 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.48 \cdot 10^{-6} \cdot 60 \cdot 10^{-6} = 1048.8 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \, \frac{0.4 \cdot 1048.8 \cdot 10^{-12} \cdot 18.99}{0.033} = 0.72$$

As the Rayleigh number for the US2F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US2 variants is also primarily in form of conduction.

Charts 5.4, 5.5, and 5.6 show how costs for materials, energy losses and total costs of US2 structure change in different conditions, while thickness of thermal insulation layer increases.

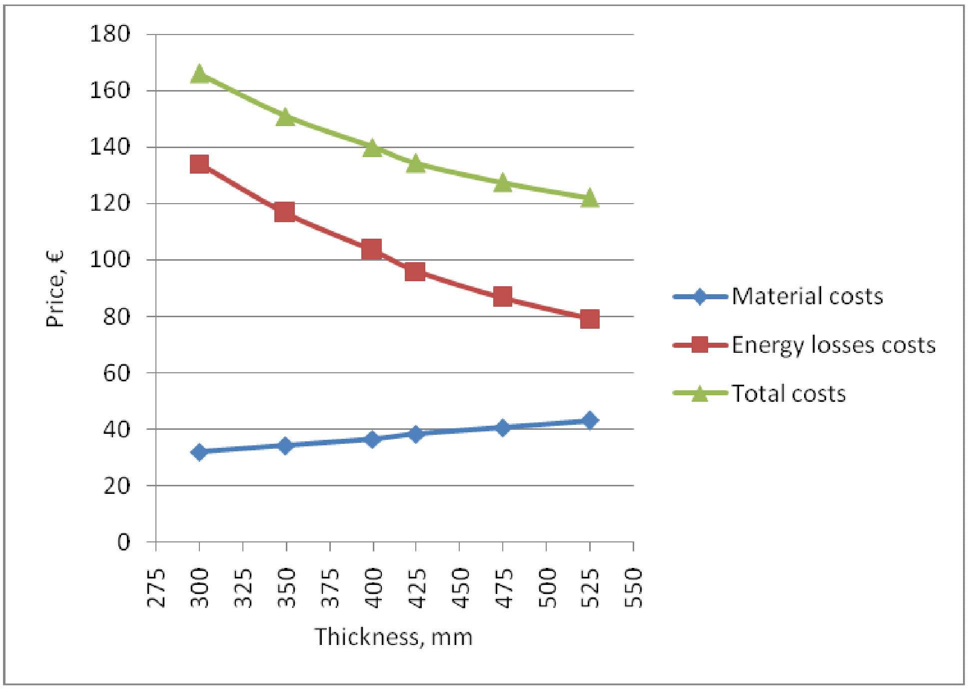

Chart 5.4 LCC analysis results for US2 with 50 years life span and 2% energy price increase.

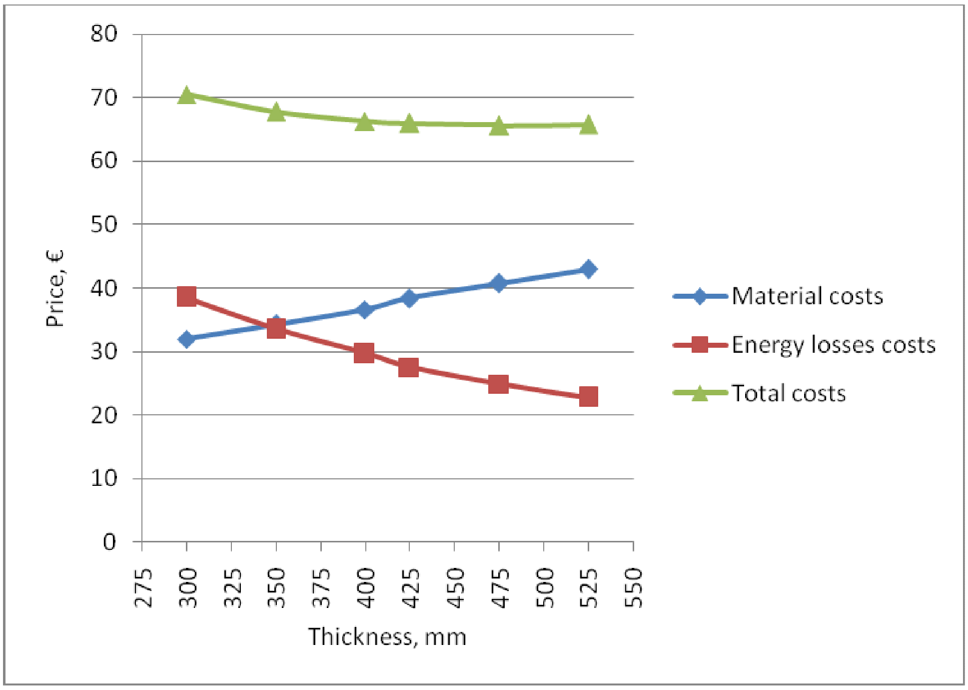

Chart 5.5 LCC analysis results for US2 with 20 years life span and 2% energy price increase.

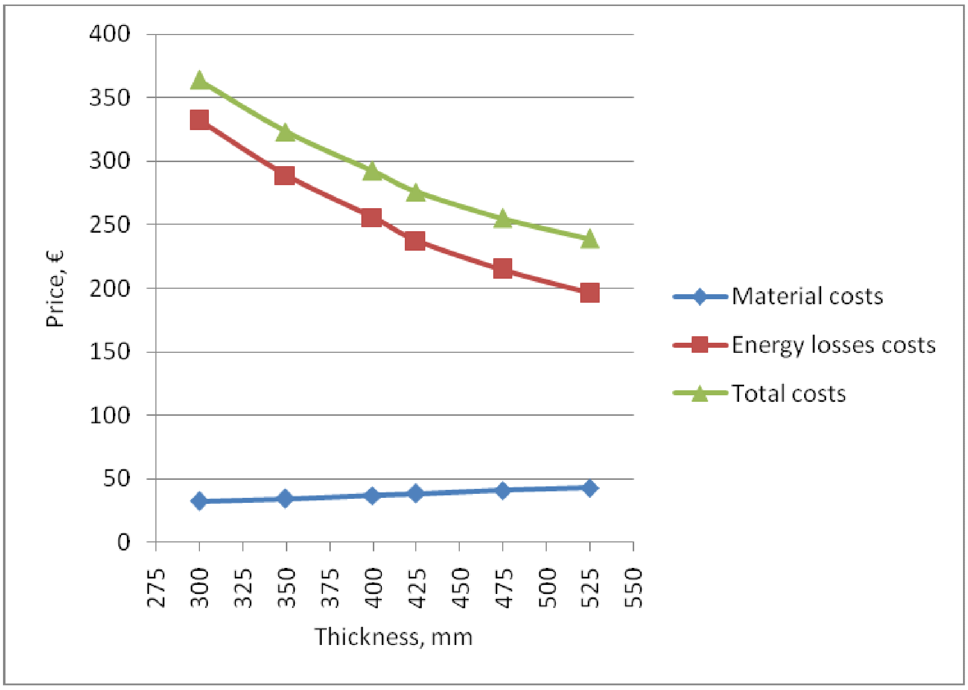

Chart 5.6 LCC analysis results for US2 with 50 years life span and 5% energy price increase

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US2F (122.13€) and US2E on the life span of 20 years (65.61€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US2F (238.87€).

5.3 I-joist timber frame with ISOVER KL-33 insulation (US3)

The main idea of the structure is to reduce influence of thermal bridges by usage of I-joist studs. While calculating DOF-THERM, this fact was taken into account by dividing the layer with studs into 3 different layers: 2 layers with flanges of the stud and 1 layer with the web. A detailed drawing and LCC calculation of structure are shown in the Appendix 3.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US3F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-33 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.34 - (-1.65) = 18.99$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.99}{2}\right)\right) \cdot 10^{-6} = 17.48 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.48 \cdot 10^{-6} \cdot 60 \cdot 10^{-6} = 1048.8 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \frac{0.4 \cdot 1048.8 \cdot 10^{-12} \cdot 18.99}{0.033} = 0.72$$

As the Rayleigh number for the US3F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US3 variants is also primarily in form of conduction.

Charts 5.7, 5.8, and 5.9 show how costs for materials, energy losses and total costs of US3 structure change in different conditions, while thickness of thermal insulation layer increases.

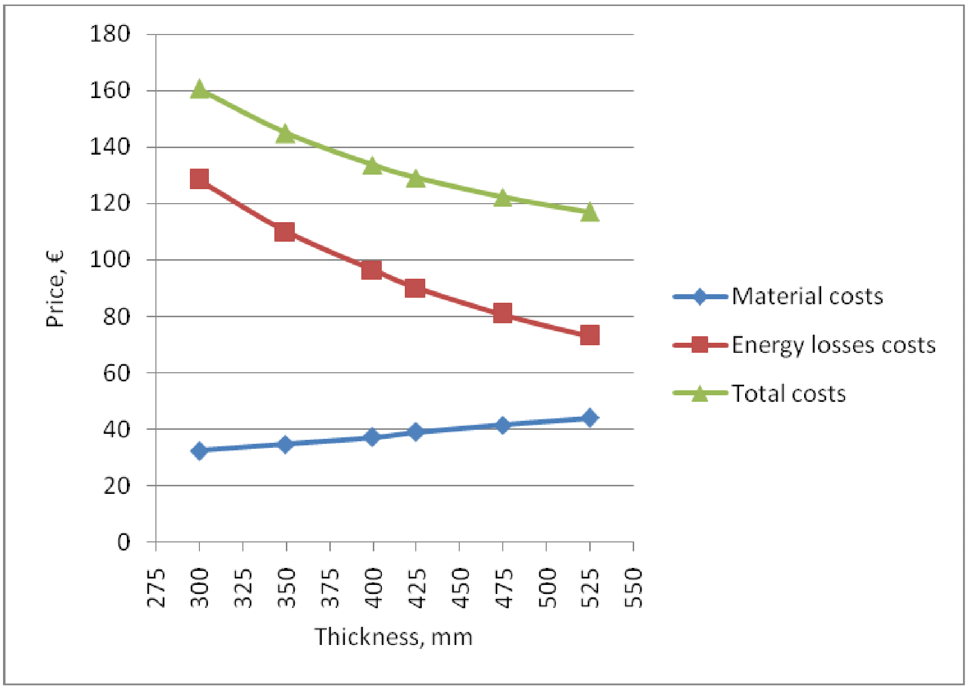

Chart 5.7 LCC analysis results for US3 with 50 years life span and 2% energy price increase.

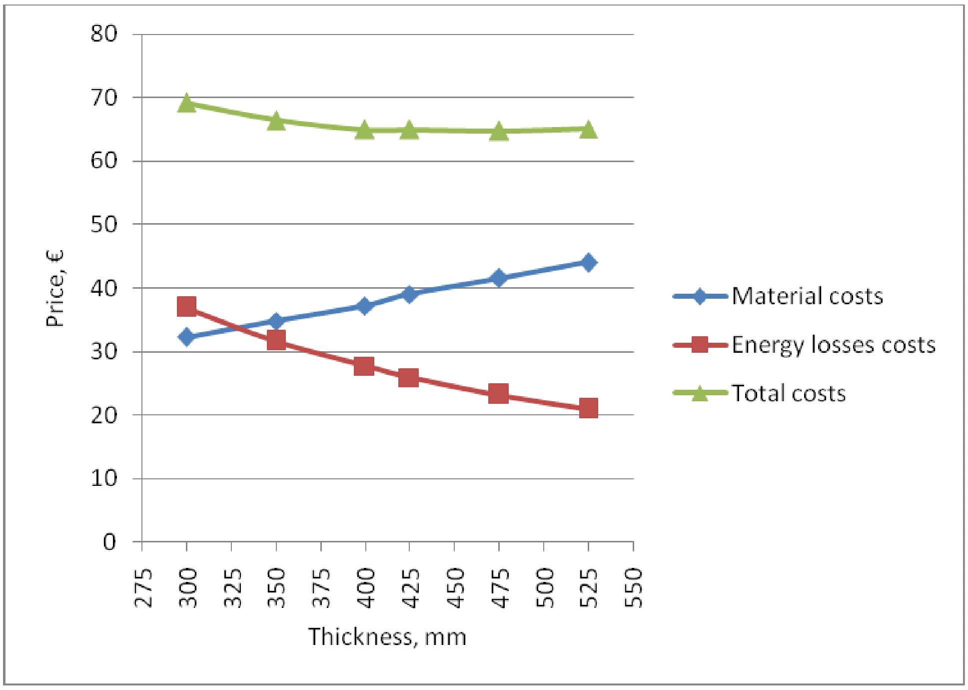

Chart 5.8 LCC analysis results for US3 with 20 years life span and 2% energy price increase.

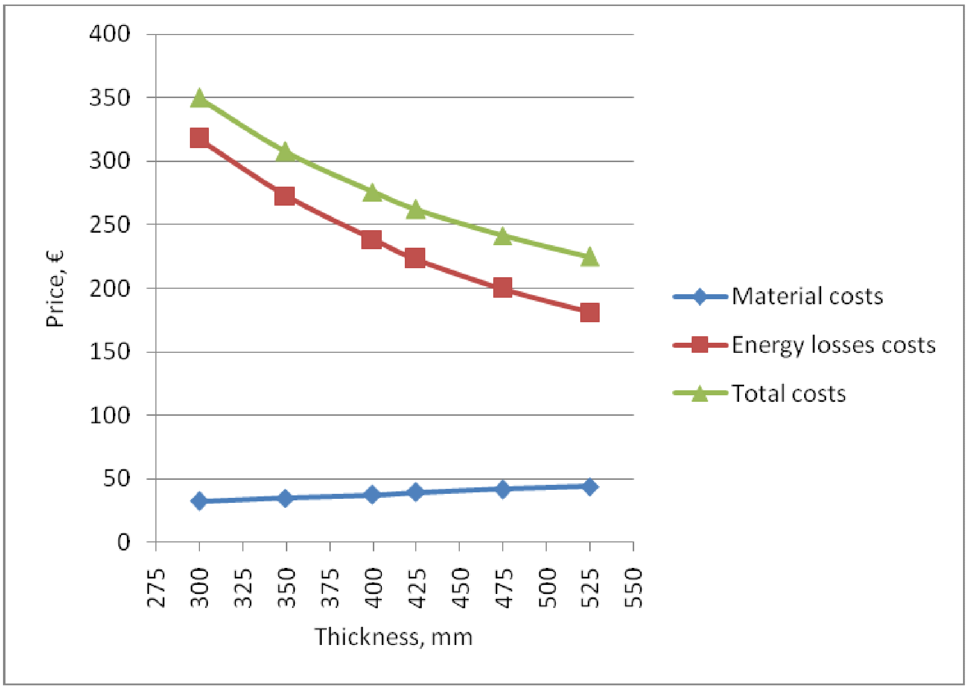

Chart 5.9 LCC analysis results for US3 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US3F (117.13€) and US3E on the life span of 20 years (64.73€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US3F (224.99€).

5.4 Double timber frame with ISOVER KL-33 insulation (US4)

The main idea of the structure is to reduce influence of thermal bridges by usage of insulation layer without timber elements. A detailed drawing and LCC calculation of structure are shown in the Appendix 4.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US4F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-33 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.34 - (-1.65) = 18.99$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.99}{2}\right)\right) \cdot 10^{-6} = 17.48 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.48 \cdot 10^{-6} \cdot 60 \cdot 10^{-6} = 1048.8 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \frac{0.4 \cdot 1048.8 \cdot 10^{-12} \cdot 18.99}{0.033} = 0.72$$

As the Rayleigh number for the US4F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US4 variants is also primarily in form of conduction.

Charts 5.10, 5.11, and 5.12 show how costs for materials, energy losses and total costs of US4 structure change in different conditions, while thickness of thermal insulation layer increases.

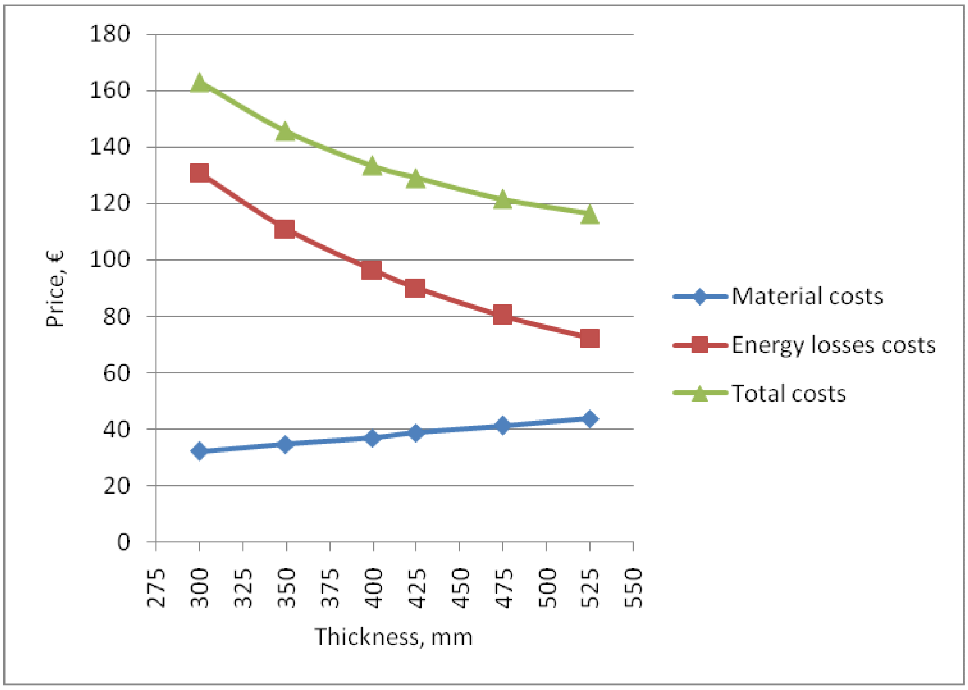

Chart 5.10 LCC analysis results for US4 with 50 years life span and 2% energy price increase.

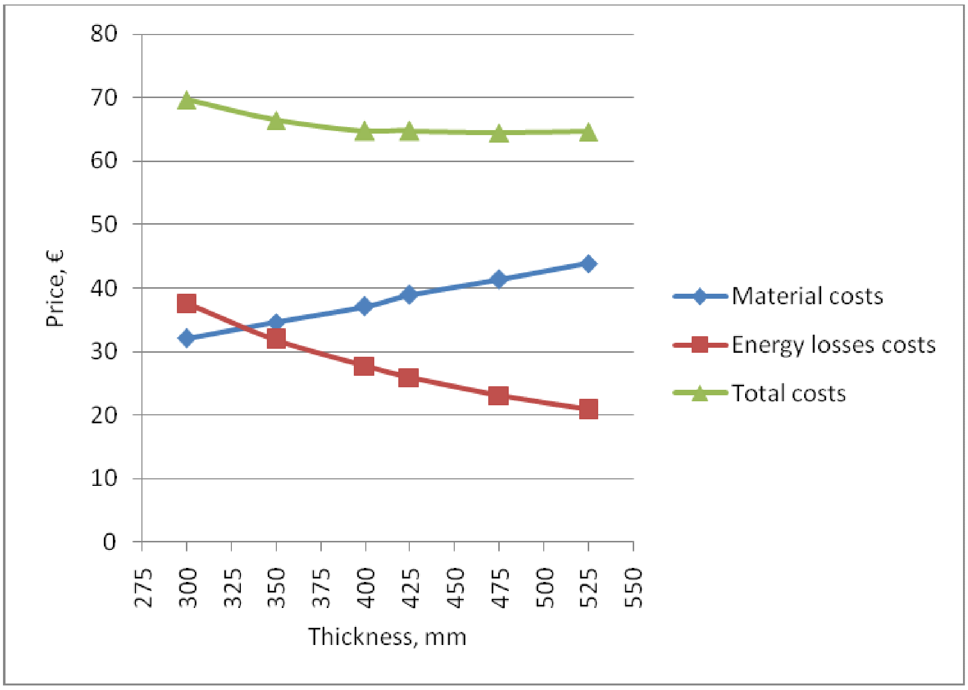

Chart 5.11 LCC analysis results for US4 with 20 years life span and 2% energy price increase.

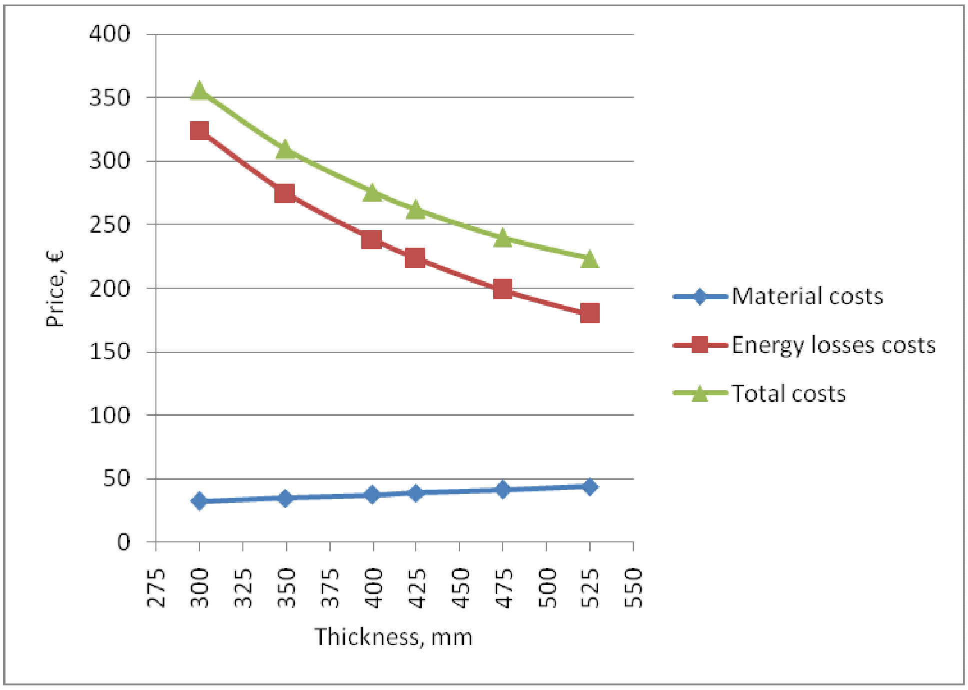

Chart 5.12 LCC analysis results for US4 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US4F (116.31€) and US4E on the life span of 20 years (64.45€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US4F (223.20€).

5.5 No crossing timber frame with ISOVER KL-33 insulation (US5)

The main idea of the structure is to reduce influence of thermal bridges by usage of timber frame without crossing elements. A detailed drawing and LCC calculation of structure are shown in the Appendix 5.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US5F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-33 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.34 - (-1.65) = 18.99$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.99}{2}\right)\right) \cdot 10^{-6} = 17.48 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.48 \cdot 10^{-6} \cdot 60 \cdot 10^{-6} = 1048.8 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \, \frac{0.4 \cdot 1048.8 \cdot 10^{-12} \cdot 18.99}{0.033} = 0.72$$

As the Rayleigh number for the US5F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US5 variants is also primarily in form of conduction.

Charts 5.13, 5.14, and 5.15 show how costs for materials, energy losses and total costs of US5 structure change in different conditions, while thickness of thermal insulation layer increases.

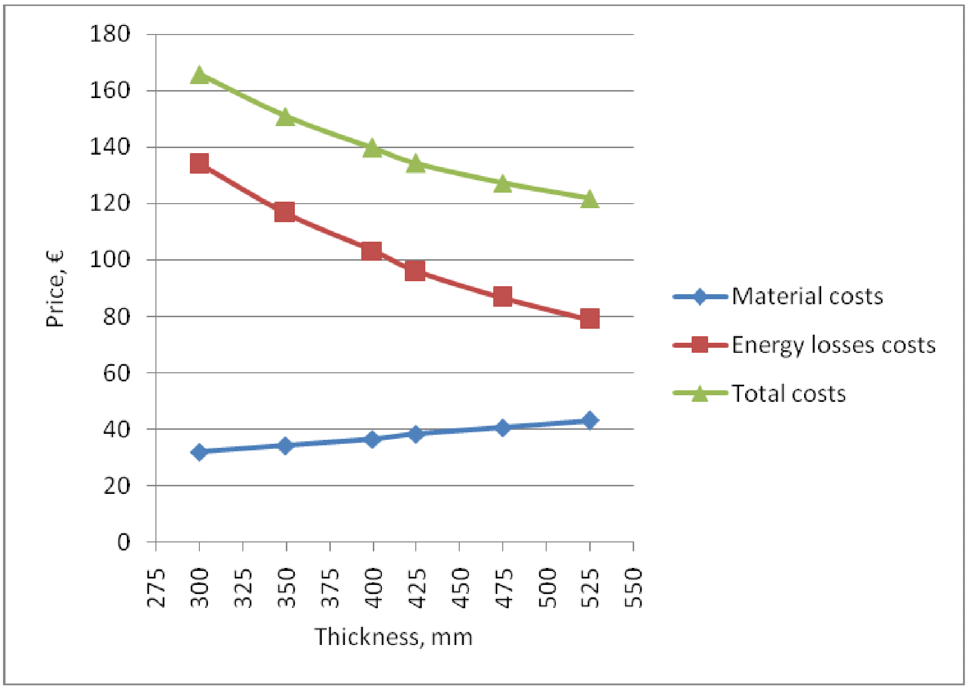

Chart 5.13 LCC analysis results for US5 with 50 years life span and 2% energy price increase.

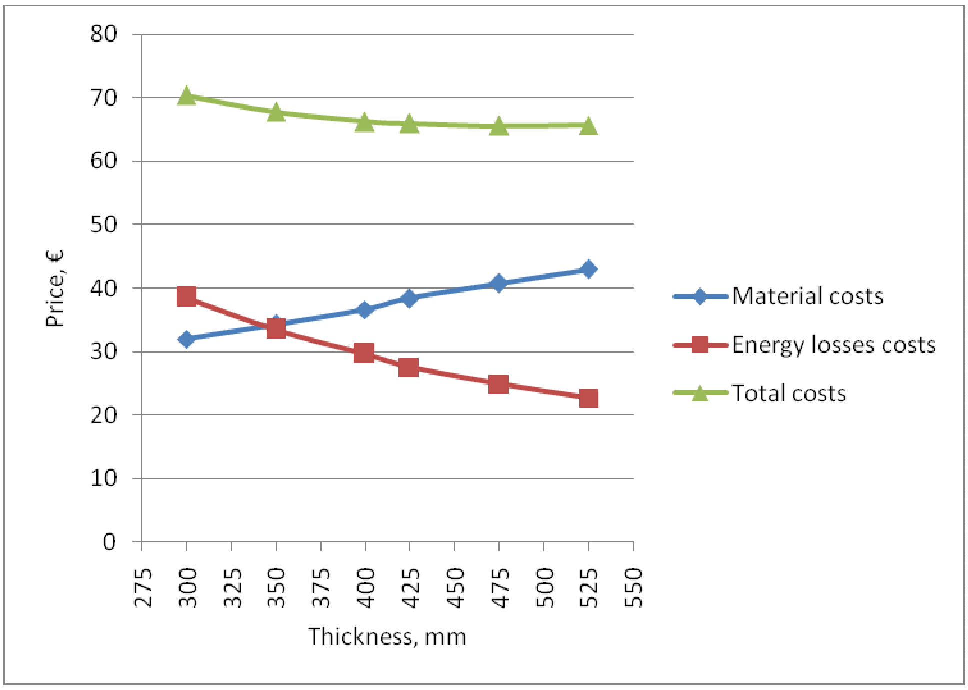

Chart 5.14 LCC analysis results for US5 with 20 years life span and 2% energy price increase.

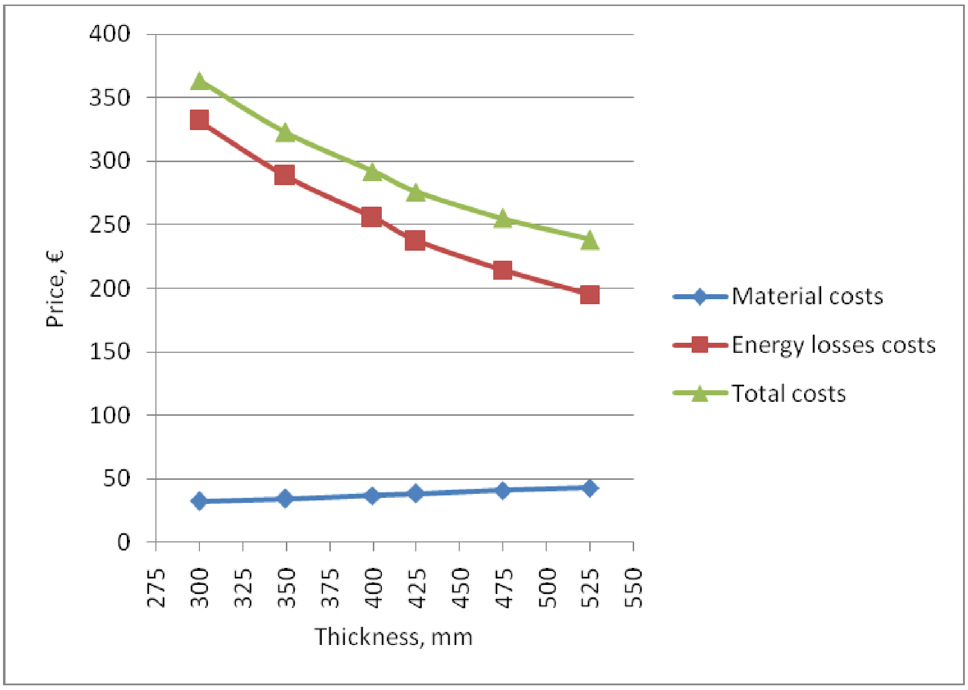

Chart 5.15 LCC analysis results for US5 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US5F (121.88€) and US5E on the life span of 20 years (65.58€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US5F (238.24€).

5.6 Timber frame with ISOVER KL-37 insulation (US6)

The structure is introduced in ISOVER Passive House structure library as PAUS 1001. A detailed drawing and LCC calculation of structure are shown in the Appendix 6.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US6F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-37 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.82 - (-1.16) = 18.98$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.98}{2}\right)\right) \cdot 10^{-6} = 17.48 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.48 \cdot 10^{-6} \cdot 120 \cdot 10^{-6} = 2097.6 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \frac{0.4 \cdot 2097.6 \cdot 10^{-12} \cdot 18.98}{0.037} = 1.29$$

As the Rayleigh number for the US6F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US6 variants is also primarily in form of conduction.

Charts 5.16, 5.17, and 5.18 show how costs for materials, energy losses and total costs of US6 structure change in different conditions, while thickness of thermal insulation layer increases.

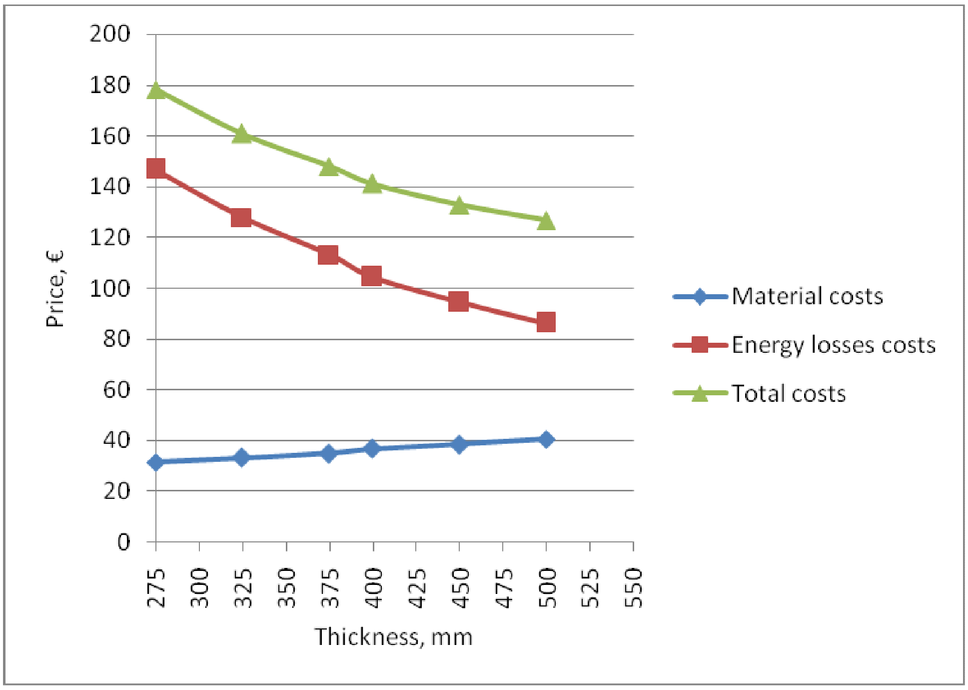

Chart 5.16 LCC analysis results for US6 with 50 years life span and 2% energy price increase.

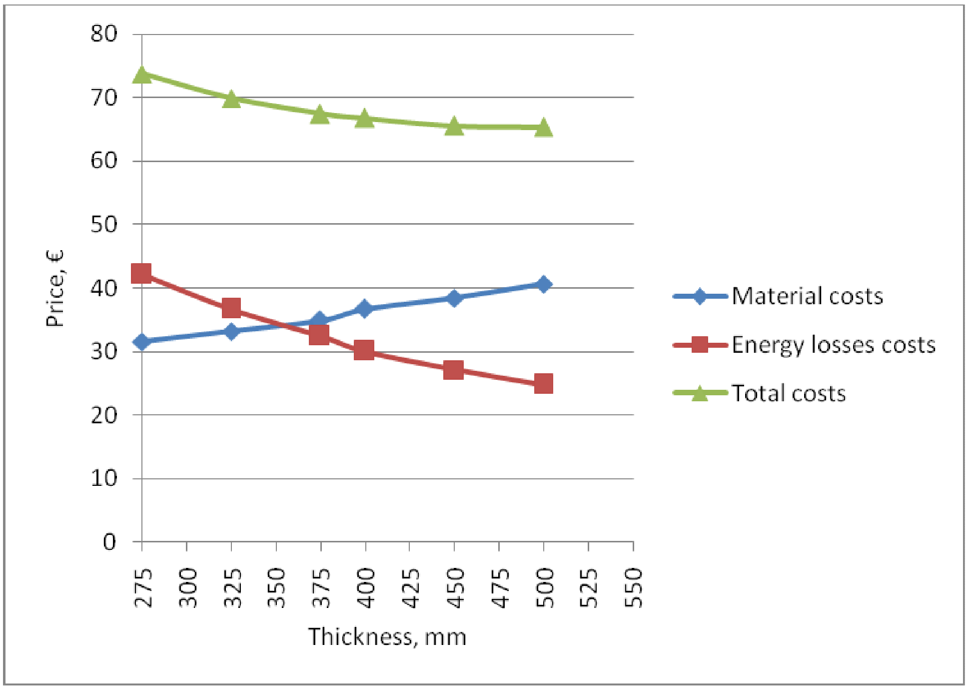

Chart 5.17 LCC analysis results for US6 with 20 years life span and 2% energy price increase.

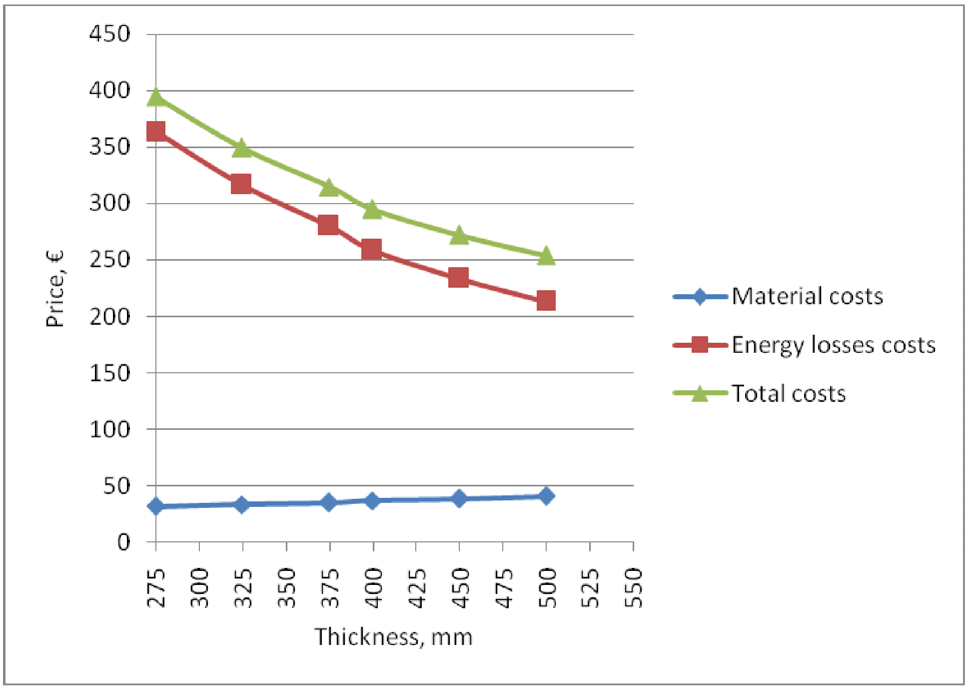

Chart 5.18 LCC analysis results for US6 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US6F (126.84€) and US6F on the life span of 20 years (65.40€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US6F (254.01€).

5.7 Crossing timber frame with ISOVER KL-37 insulation (US7)

The structure is introduced in ISOVER Passive House structure library as PAUS 1005. A detailed drawing and LCC calculation of structure are shown in the Appendix 7.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US7F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-37 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.36 - (-1.25) = 18.61$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.61}{2}\right)\right) \cdot 10^{-6} = 17.47 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.47 \cdot 10^{-6} \cdot 120 \cdot 10^{-6} = 2096.4 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \frac{0.4 \cdot 2096.4 \cdot 10^{-12} \cdot 18.61}{0.037} = 1.27$$

As the Rayleigh number for the US7F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US7 variants is also primarily in form of conduction.

Charts 5.19, 5.20, and 5.21 show how costs for materials, energy losses and total costs of US7 structure change in different conditions, while thickness of thermal insulation layer increases.

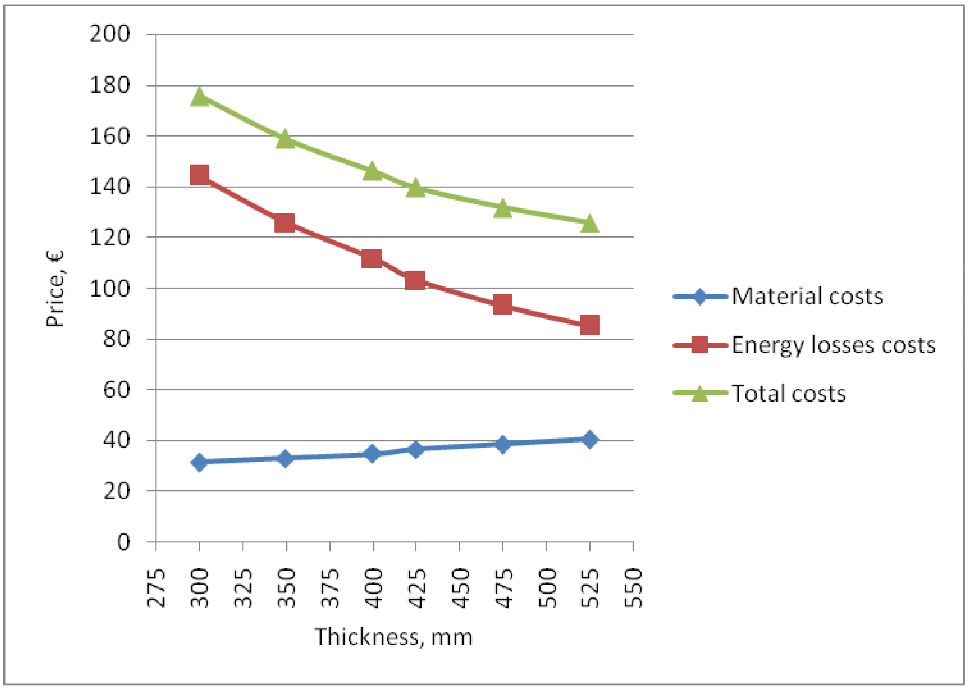

Chart 5.19 LCC analysis results for US7 with 50 years life span and 2% energy price increase.

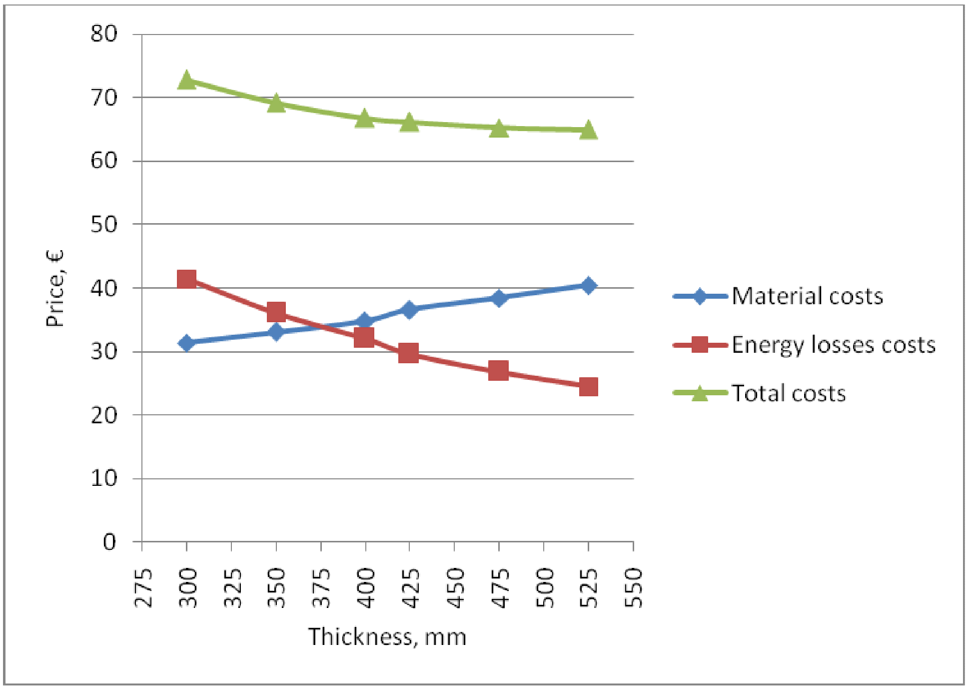

Chart 5.20 LCC analysis results for US7 with 20 years life span and 2% energy price increase.

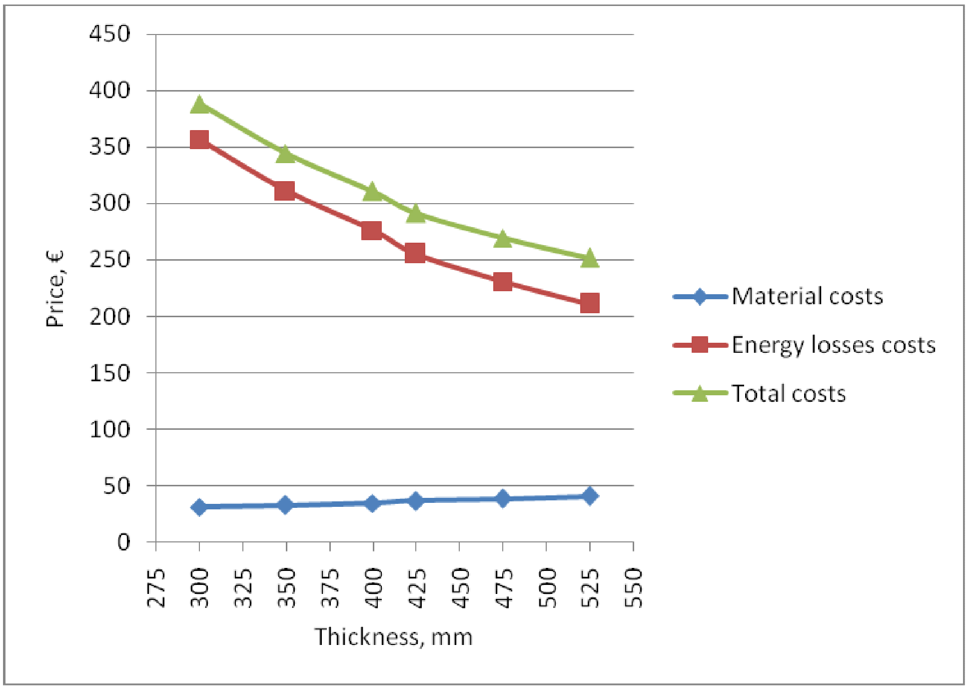

Chart 5.21 LCC analysis results for US7 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US7F (125.75€) and US7F on the life span of 20 years (64.96€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US7F (251.58€).

5.8 I-joist timber frame with ISOVER KL-37 insulation (US8)

The main idea of the structure is to reduce influence of thermal bridges by usage of I-joist studs. While calculating DOF-THERM, this fact was taken into account by dividing the layer with studs into 3 different layers: 2 layers with flanges of the stud and 1 layer with the web. A detailed drawing and LCC calculation of structure are shown in the Appendix 8.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US8F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-37 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.36 - (-1.25) = 18.61$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.61}{2}\right)\right) \cdot 10^{-6} = 17.47 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.47 \cdot 10^{-6} \cdot 120 \cdot 10^{-6} = 2096.4 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \frac{0.4 \cdot 2096.4 \cdot 10^{-12} \cdot 18.61}{0.037} = 1.27$$

As the Rayleigh number for the US8F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US8 variants is also primarily in form of conduction.

Charts 5.22, 5.23, and 5.24 show how costs for materials, energy losses and total costs of US8 structure change in different conditions, while thickness of thermal insulation layer increases.

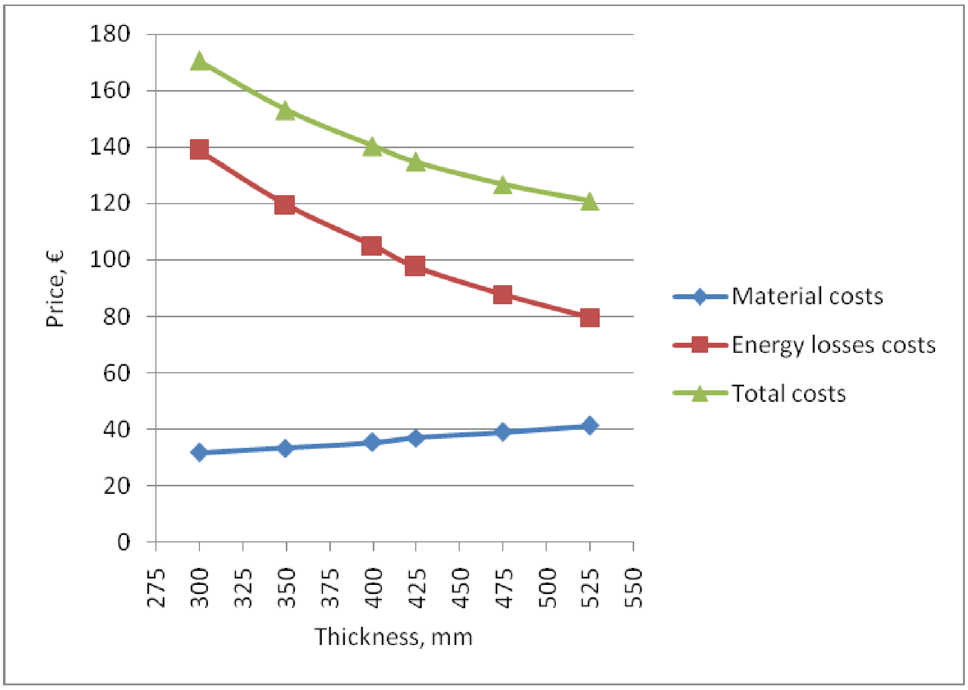

Chart 5.22 LCC analysis results for US8 with 50 years life span and 2% energy price increase.

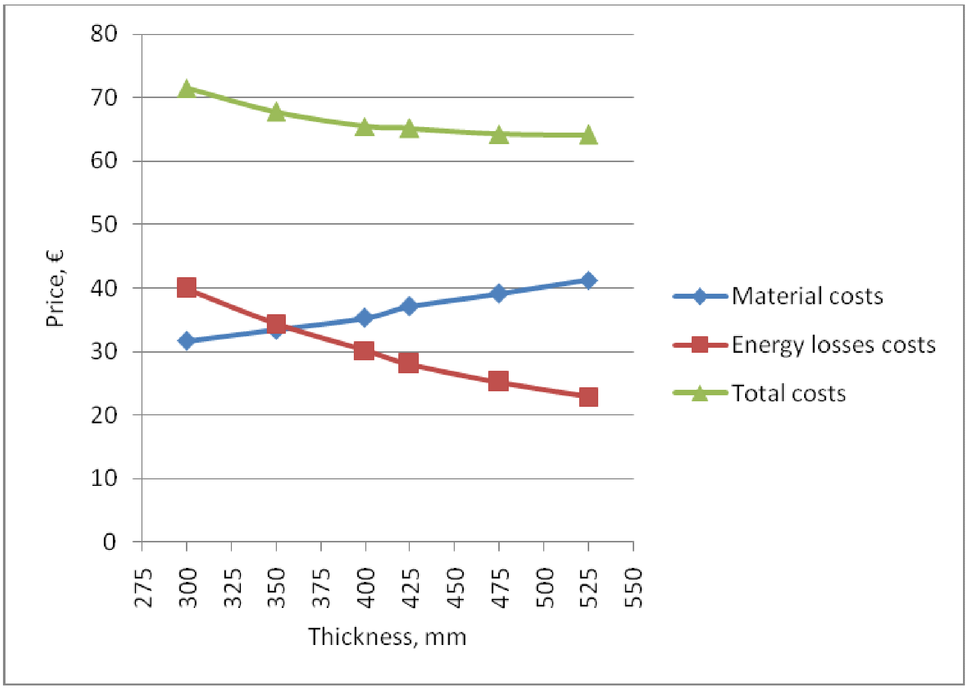

Chart 5.23 LCC analysis results for US8 with 20 years life span and 2% energy price increase.

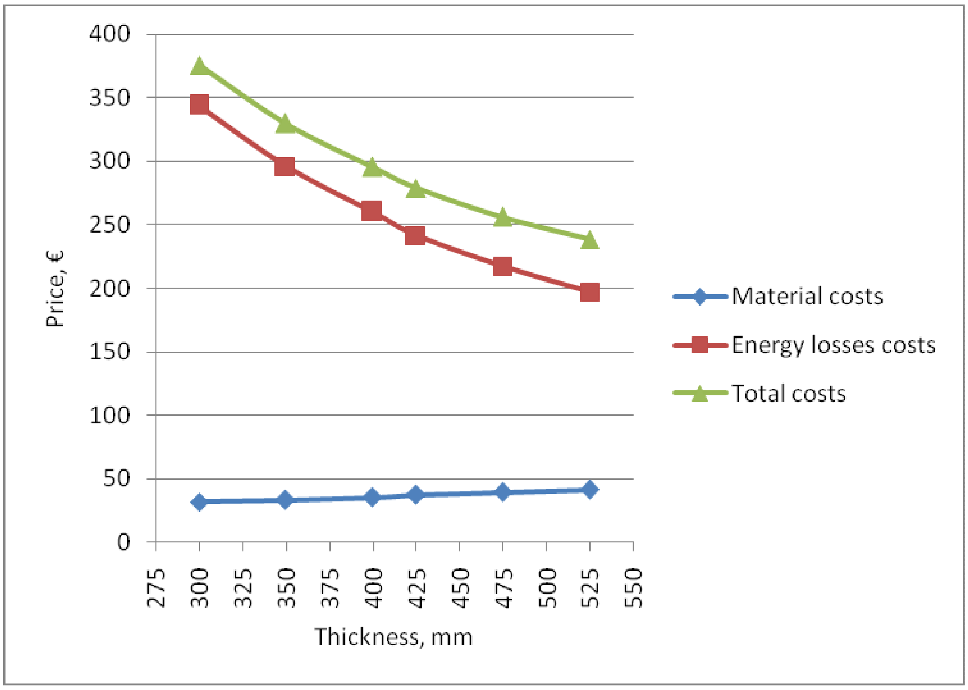

Chart 5.24 LCC analysis results for US8 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US8F (120.90€) and US8F on the life span of 20 years (64.12€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US8F (238.41€).

5.9 Double timber frame with ISOVER KL-37 insulation (US9)

The main idea of the structure is to reduce influence of thermal bridges by usage of insulation layer without timber elements. A detailed drawing and LCC calculation of structure are shown in the Appendix 9.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US9F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-37 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.36 - (-1.25) = 18.61$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.61}{2}\right)\right) \cdot 10^{-6} = 17.47 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.47 \cdot 10^{-6} \cdot 120 \cdot 10^{-6} = 2096.4 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \frac{0.4 \cdot 2096.4 \cdot 10^{-12} \cdot 18.61}{0.037} = 1.27$$

As the Rayleigh number for the US9F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US9 variants is also primarily in form of conduction.

Charts 5.25, 5.26, and 5.27 show how costs for materials, energy losses and total costs of US9 structure change in different conditions, while thickness of thermal insulation layer increases.

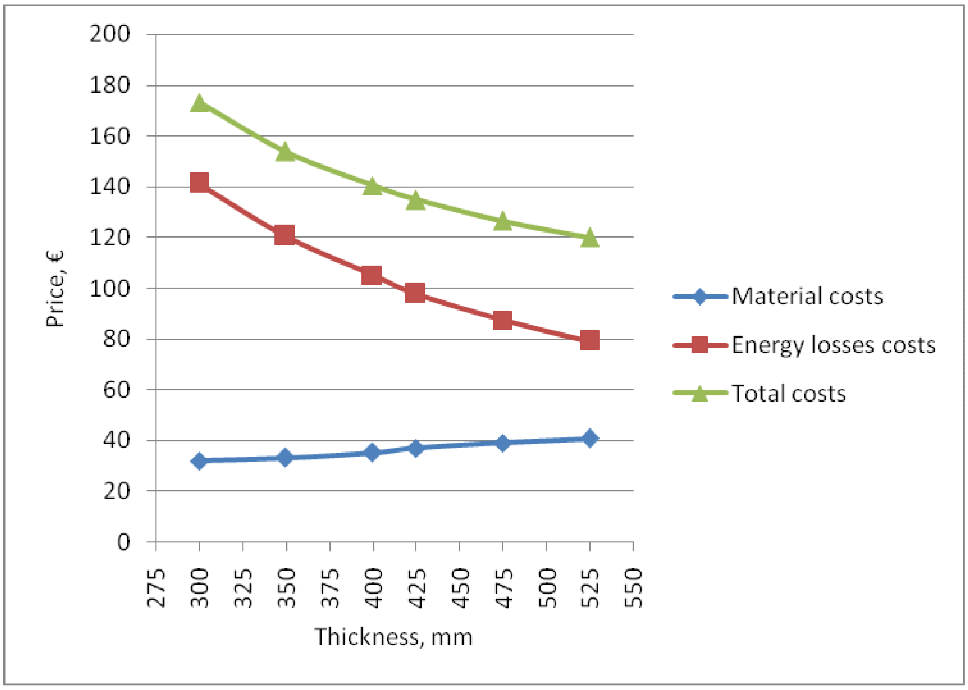

Chart 5.25 LCC analysis results for US9 with 50 years life span and 2% energy price increase.

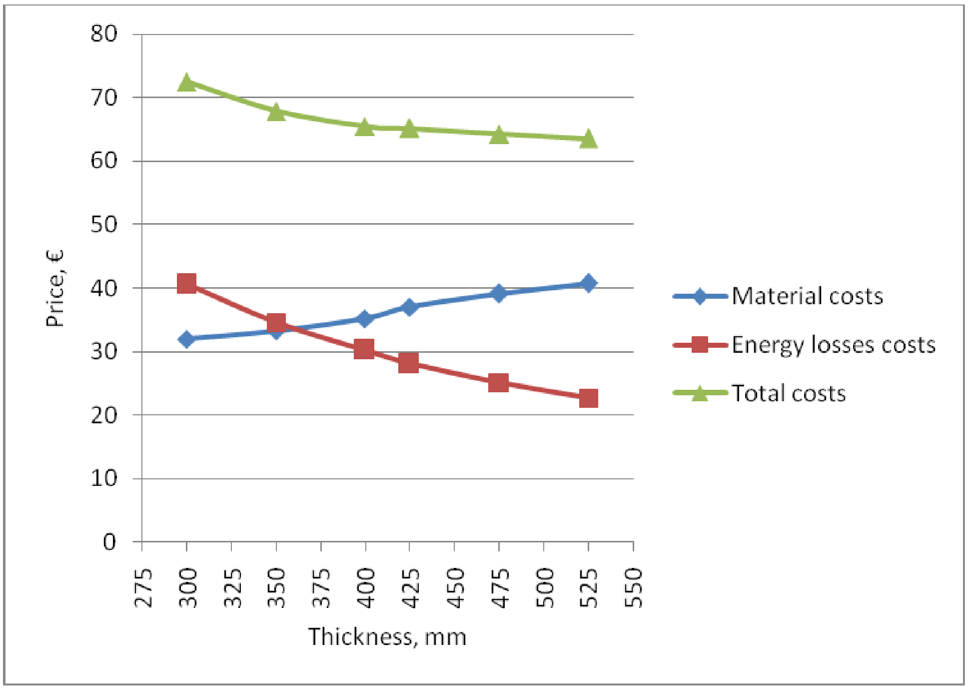

Chart 5.26 LCC analysis results for US9 with 20 years life span and 2% energy price increase.

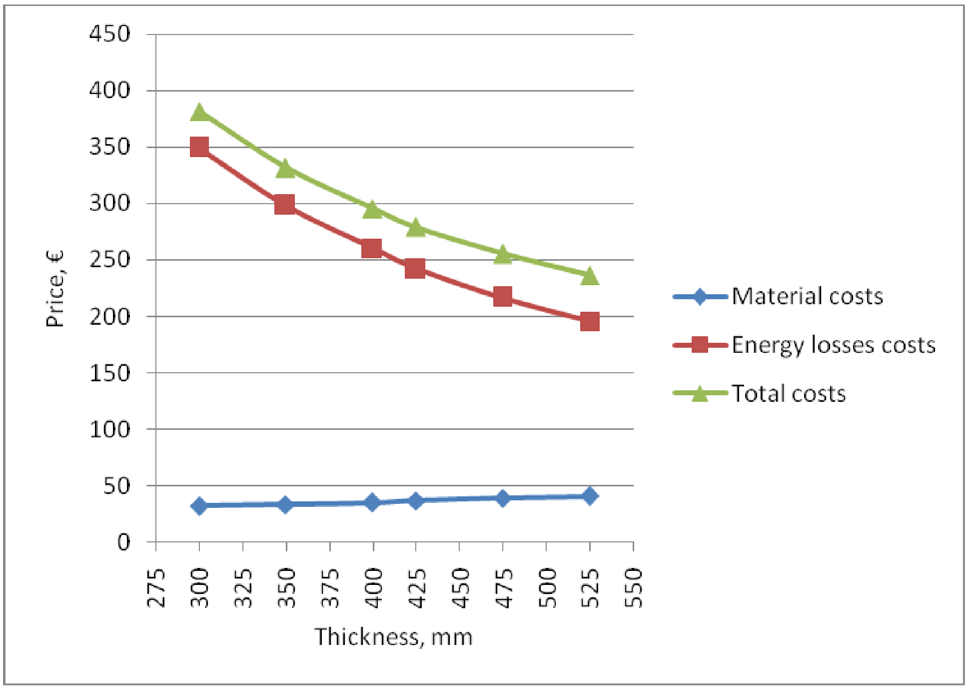

Chart 5.27 LCC analysis results for US9 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US9F (119.89€) and US9F on the life span of 20 years (63.51€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US9F (236.58€).

5.10 No crossing timber frame with ISOVER KL-37 insulation (US10)

The main idea of the structure is to reduce influence of thermal bridges by usage of timber frame without crossing elements. A detailed drawing and LCC calculation of structure are shown in the Appendix 10.

According to the Formula 4.10, the best conditions for natural convection are provided by variant US10F with the thickest insulation, during January. Location is Helsinki. Calculation is done for the ISOVER KL-37 insulation layer (0.4m) between wind barrier and vapor barrier. DOF-THERM calculation showed that the temperature difference across the insulation is $\Delta T = 17.36 - (-1.25) = 18.61$ K.

Natural convection check:

$$\eta = \left(17 + \left(0.05 \cdot \frac{18.61}{2}\right)\right) \cdot 10^{-6} = 17.47 \cdot 10^{-6} \text{ Pa s}$$

$$k = 17.47 \cdot 10^{-6} \cdot 120 \cdot 10^{-6} = 2096.4 \cdot 10^{-12} \text{ m}^2$$

$$Ra_m = 3 \cdot 10^6 \frac{0,4 \cdot 2096.4 \cdot 10^{-12} \cdot 18.61}{0.037} = 1.27$$

As the Rayleigh number for the US10F variant is below the critical value 2.5, heat transfer is primarily in form of conduction. Thus, heat transfer for other US10 variants is also primarily in form of conduction.

Charts 5.28, 5.29, and 5.30 show how costs for materials, energy losses and total costs of US10 structure change in different conditions, while thickness of thermal insulation layer increases.

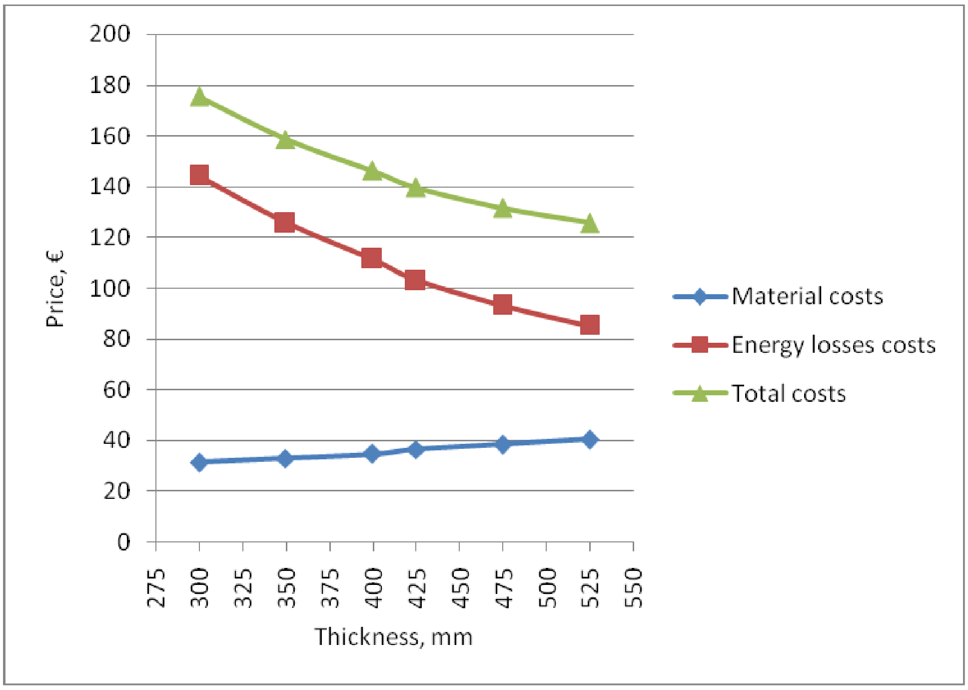

Chart 5.28 LCC analysis results for US10 with 50 years life span and 2% energy price increase.

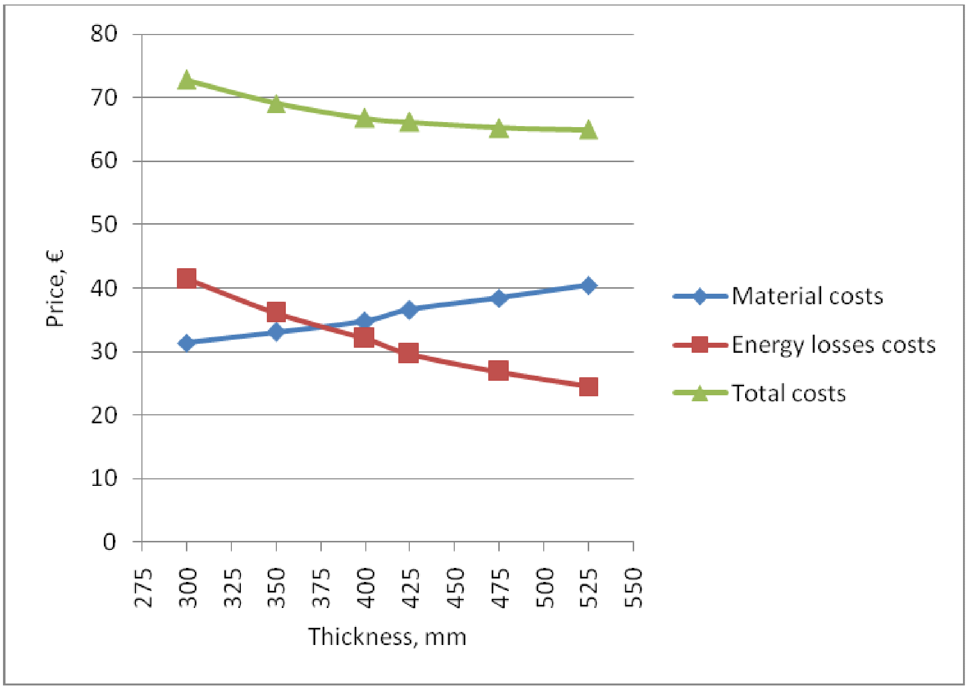

Chart 5.29 LCC analysis results for US10 with 20 years life span and 2% energy price increase.

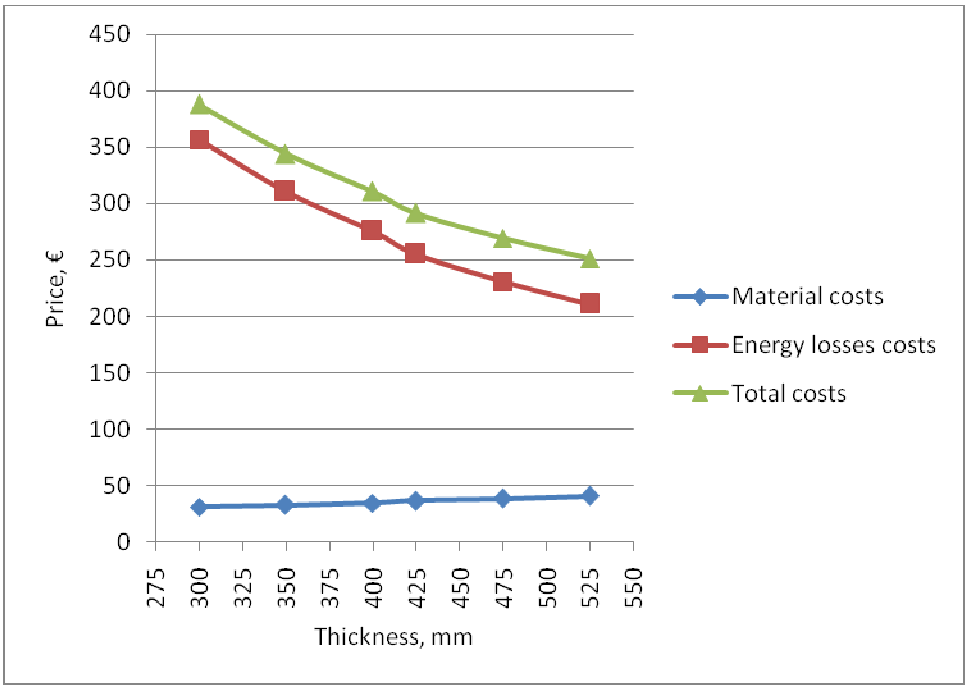

Chart 5.30 LCC analysis results for US10 with 50 years life span and 5% energy price increase.

The best structure according to the LCC calculation with 2% annual energy price increase on the life span of 50 years is US10F (125.68€) and US10F on the life span of 20 years (64.94€). The best structure according to the LCC calculation with 5% annual energy price increase on life span of 50 years is US10F (251.40€).

6 CONCLUSIONS

6.1 Comparison of wall structures

The evaluation is based on calculation results. While making conclusions, it is important to remember the assumptions. This research introduces only cost optimization for insulation usage in external walls. If load bearing structures are taken into account, results may differ.

The most important aspect revealed by the results is that the usage of ISOVER KL-37 is more profitable when the study period is short and energy price increase is small (Chart 6.2). But it should be considered that in this case thicknesses of thermal insulations are different. Structures with ISOVER KL-37 are thicker (F variant) than structures with ISOVER-KL-33 (E variant). This may affect the final decision of architect while designing.

The usage of ISOVER KL-37 insulation in investigated structures allows not to take into account life span (at least from 20 to 50 years), as the best variant is always the same (F variant). The situation with ISOVER KL-33 is different. On life span of 50 years, F variant is the best. On life span of 20 years E variant is the best. However, according to the charts in the 5th chapter, differences between E and F variants on life span of 20 years are very small.

6.1.1 Study period 50 years, annual energy price increasing 2%

Chart 6.1 shows total costs of all studied structures on life span of 50 years with 2% annual energy price increase. Variant F with the thickest insulation has the best results for all structures.

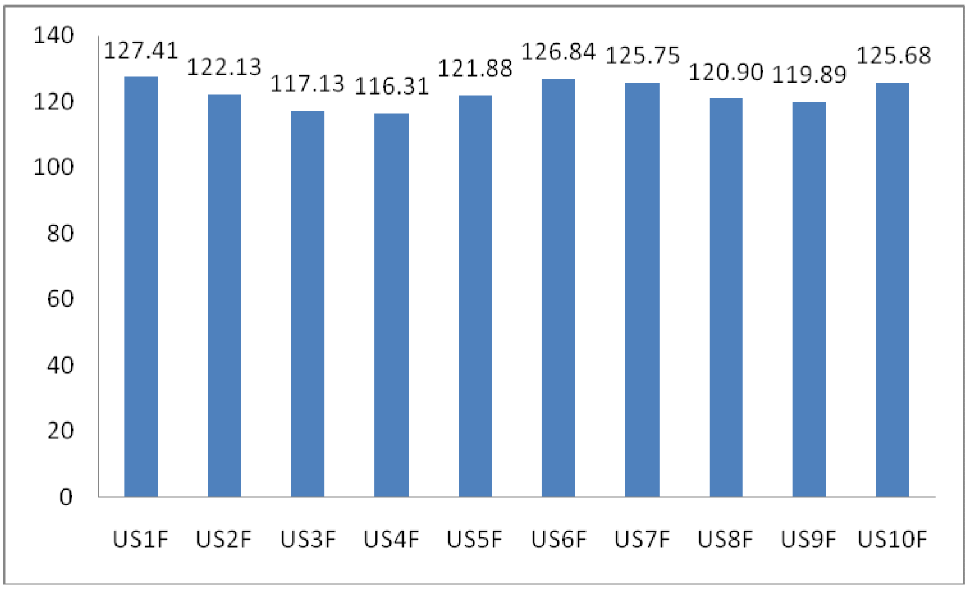

Chart 6.1 Total costs on life span of 50 years with 2% annual energy price increase

Chart 6.1 shows that the usage of ISOVER KL-33 insulation in studied Passive House wall structures is more profitable than usage of ISOVER KL-37, except US1F and US6F (Timber frame). The best structure of all is US4F (Double timber frame with ISOVER KL-33). Almost the same results are shown by US3F (I-joist timber frame). Furthermore, it is worth mentioning that I-joist timber frame is easier to construct than Double timber frame. This may lead to additional final benefits.

6.1.2 Study period 20 years, annual energy price increasing 2%

Chart 6.2 shows total costs of all studied structures on life span of 20 years with 2% annual energy price increase. Variant F with the thickest insulation has the best results for structures with ISOVER KL-37 insulation. For structures with ISOVER KL-33 insulation the best variant is E.

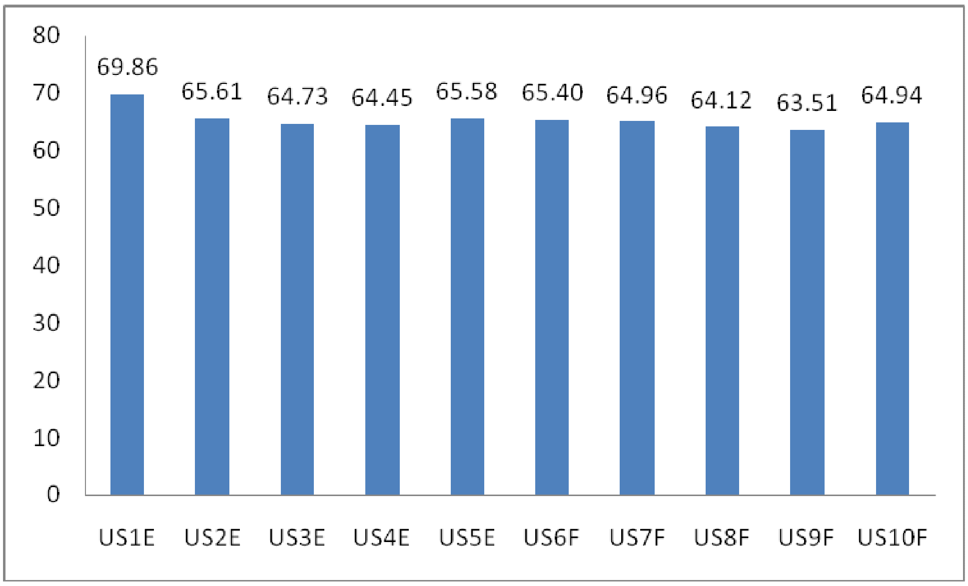

Chart 6.2 Total costs on life span of 20 years with 2% annual energy price increase

Chart 6.2 shows that the usage of ISOVER KL-37 is more profitable on this life span. The best structure of all is US9F (Double timber frame). One more interesting aspect is that the difference between total costs of almost all structures is not so big. So, the final results most likely will differ, if erecting costs and costs of load bearing structures are considered.

6.1.3 Study period 50 years, annual energy price increasing 5%

Chart 6.3 shows total costs of all studied structures on life span of 50 years with 5% annual energy price increase. Variant F with the thickest insulation has the best results for all structures. Results of LCC calculation with this initial data confirm that usage of cheaper insulation with worse thermal performance is profitable when the study period is short and annual energy price increase is not large, i.e. when the influence of energy losses costs is not so big compared with material costs.

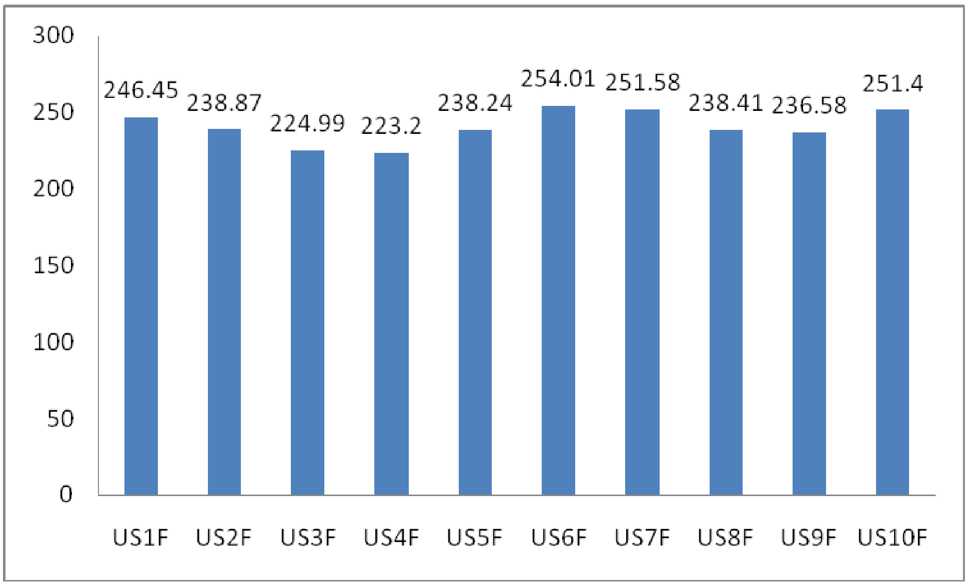

Chart 6.3 Total costs on life span of 50 years with 5% annual energy price increase

Chart 6.3 shows that the usage of ISOVER KL-33 insulation in studied Passive House wall structures is more profitable than usage of ISOVER KL-37. The best structure of all is US4F (Double timber frame with ISOVER KL-33).

6.2 Summary

Unfortunately, there was not enough time to make all investigations that were planned. For instance, it would be good to make a moisture calculation of structures with WUFI software. And, according to Timo Lehtoviita, the tutor from Saimaa University of Applied Sciences, some changes in structures may take place. One more improvement is to make the same study for other insulation manufacturers.

According to Jussi Jokinen, the tutor from ISOVER company, it was a good idea to make a special Excel calculator, as in many cases managers need such a simple tool for preliminary cost estimations.

FIGURES

CHARTS

TABLES

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Timber frame with ISOVER KL-33 insulation (US1)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.123	0.106	0.094	0.087	0.079	0.072	$W/(m^2K)$
Insulation thickness	275	325	375	400	450	500	mm
Annual energy losses	15.809	13.701	12.096	11.208	10.109	9.209	kWh

Material costs (C_i)

	Structure variations						
	A	B	C	D	E	F	
Material costs	35.67	37.98	40.29	42.10	44.41	46.72	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C_e)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	138.53	120.05	105.99	98.21	88.58	80.69	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	174.20	158.03	146.28	140.31	132.99	127.41	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C_e)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	39.79	34.49	30.45	28.21	25.45	23.18	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	75.46	72.47	70.74	70.31	69.86	69.90	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

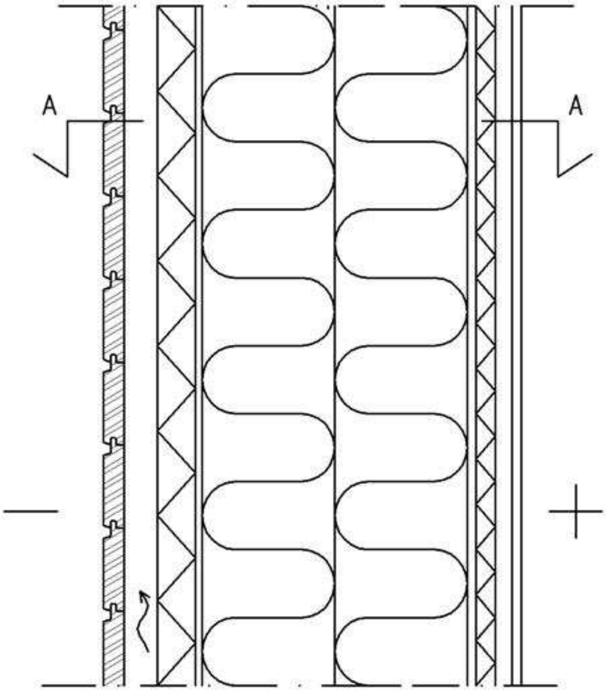
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

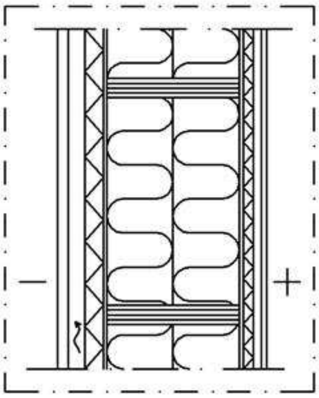
	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	342.87	297.15	262.34	243.08	219.25	199.73	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	378.54	335.13	302.63	285.18	263.66	246.45	€

Project Cost optimization of Passive House external walls	Structure Timber frame with ISOVER KL-33 insulation	
Designer	Work No. Date	US1





Section A-A

	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
50 mm	Wind barier and thermal insulation, ISOVER RKL-31 FACADE
	Gypsum plasterboard Gyproc GTS 9
300 mm	Thermal insulation ISOVER KL-33 2x150mm and timber frame 50x300 step 600
12 mm	Plywood
25 mm	Hard aluminium surface mineral wool insulation plate ISOVER REK-31
22 mm	Timber elements 22x100 step 300, air gap
13 mm	Gypsum plasterboard GEK-13

Thermal transmittance

VERSION	INSULATION	U-value
A	ISOVER RKL-31 Facade 50mm + KL-33 200mm + REK-31 25mm	U=0,123
B	ISOVER RKL-31 Facade 50mm + KL-33 250mm + REK-31 25mm	U=0,106
C	ISOVER RKL-31 Facade 50mm + KL-33 300mm + REK-31 25mm	U=0,094
D	ISOVER RKL-31 A 75mm + KL-33 300mm + REK-31 25mm	U=0,087
E	ISOVER RKL-31 A 75mm + KL-33 350mm + REK-31 25mm	U=0,079
F	ISOVER RKL-31 A 75mm + KL-33 400mm + REK-31 25mm	U=0,072

Crossing timber frame with ISOVER KL-33 insulation (US2)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.119	0.104	0.092	0.085	0.077	0.07	W/(m^{2}K)
Insulation thickness	300	350	400	425	475	525	mm
Annual energy losses	15.313	13.321	11.795	10.952	9.898	9.031	kWh

Material costs (C$_i$)

	Structure variations						
	A	B	C	D	E	F	
Material costs	31.95	34.26	36.57	38.38	40.69	43.00	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	134.18	116.72	103.35	95.97	86.73	79.13	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	166.13	150.98	139.92	134.35	127.42	122.13	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	38.55	33.53	29.69	27.57	24.92	22.73	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	70.50	67.79	66.26	65.95	65.61	65.73	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

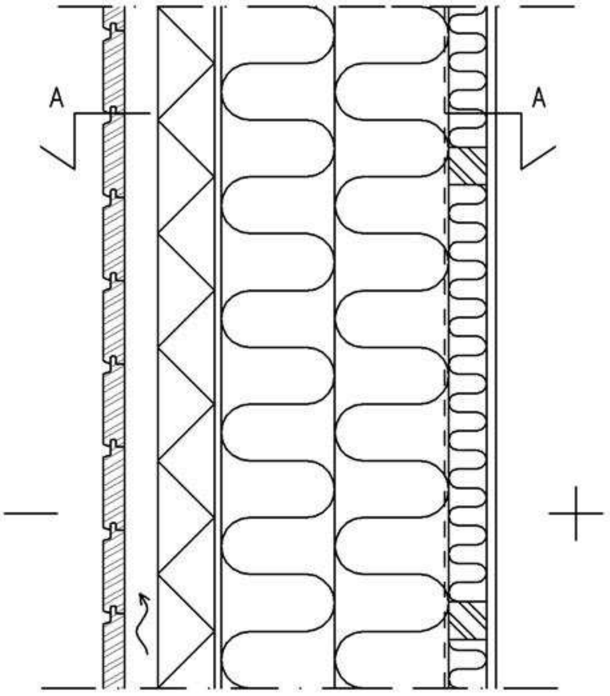
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	332.12	288.91	255.82	237.53	214.67	195.87	€

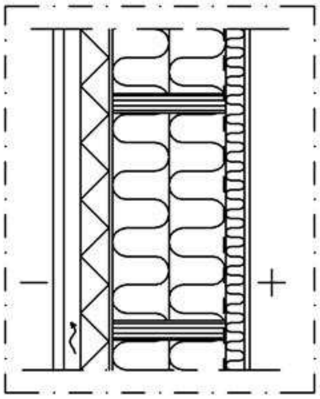
Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	364.07	323.17	292.39	275.91	255.36	238.87	€

Project Cost optimization of Passive House external walls	Structure Crossing timber frame with ISOVER KL−33 insulation
Designer	Work No. Date
	US2



Section A−A



	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
75 mm	Wind barier and thermal insulation, ISOVER RKL−31 FACADE
	Gypsum plasterboard Gyproc GTS 9
300 mm	Thermal insulation ISOVER KL−33 2x150mm and timber frame 50x300 step 600
	Vapor barier ISOVER VARIO
50 mm	Thermal insulation ISOVER KL−33 50mm and timber frame 50x50 step 600
13 mm	Gypsum plasterboard GEK−13

Thermal transmittance

VERSION	INSULATION	U−value
A	ISOVER RKL−31 Facade 50mm + KL−33 200mm + KL−33 50mm	U=0,119
B	ISOVER RKL−31 Facade 50mm + KL−33 250mm + KL−33 50mm	U=0,103
C	ISOVER RKL−31 Facade 50mm + KL−33 300mm + KL−33 50mm	U=0,091
D	ISOVER RKL−31 A 75mm + KL−33 300mm + KL−33 50mm	U=0,085
E	ISOVER RKL−31 A 75mm + KL−33 350mm + KL−33 50mm	U=0,077
F	ISOVER RKL−31 A 75mm + KL−33 400mm + KL−33 50mm	U=0,070

I-joist timber frame with ISOVER KL-33 insulation (US3)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.114	0.098	0.086	0.08	0.072	0.065	$W/(m^2K)$
Insulation thickness	300	350	400	425	475	525	mm
Annual energy losses	14.657	12.570	11.006	10.282	9.212	8.344	kWh

Material costs (C_i)

	Structure variations						
	A	B	C	D	E	F	
Material costs	32.30	34.77	37.25	39.06	41.54	44.02	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C_e)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	128.43	110.14	96.44	90.10	80.72	73.11	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	160.73	144.91	133.69	129.16	122.26	117.13	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C_e)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	36.89	31.64	27.70	25.88	23.19	21.00	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	69.19	66.41	64.95	64.94	64.73	65.02	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

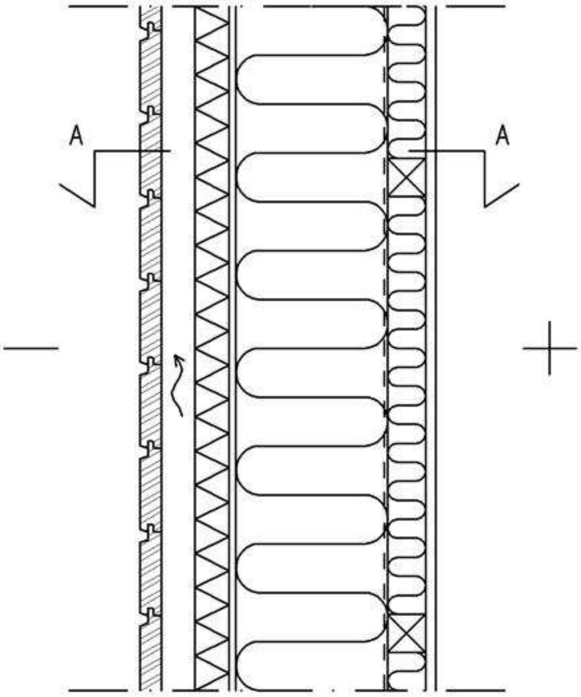
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	317.89	272.62	238.70	223.00	199.79	180.97	€

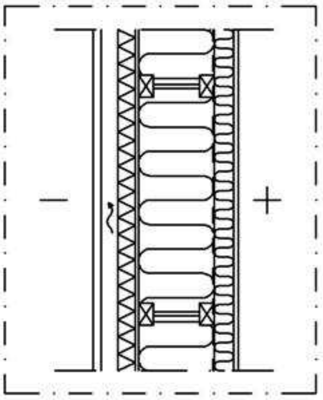
Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	350.19	307.39	275.95	262.06	241.33	224.99	€

Project Cost optimization of Passive House external walls	Structure I-joist timber frame with ISOVER KL-33 insulation	
Designer	Work No.	US3
	Date	



Section A-A



	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
50 mm	Wind barier and thermal insulation, ISOVER RKL-31 FACADE
	Gypsum plasterboard Gyproc GTS 9
200 mm	Thermal insulation ISOVER KL-33 200mm and I-joist timber frame step 600
	Vapor barier ISOVER VARIO
50 mm	Thermal insulation ISOVER KL-33 50mm and timber frame 50x50 step 600
13 mm	Gypsum board GEK-13

Thermal transmittance

VERSION	INSULATION	U-value
A	ISOVER RKL-31 Facade 50mm + KL-33 200mm + KL-33 50mm	U=0,114
B	ISOVER RKL-31 Facade 50mm + KL-33 250mm + KL-33 50mm	U=0,098
C	ISOVER RKL-31 Facade 50mm + KL-33 300mm + KL-33 50mm	U=0,086
D	ISOVER RKL-31 A 75mm + KL-33 300mm + KL-33 50mm	U=0,080
E	ISOVER RKL-31 A 75mm + KL-33 350mm + KL-33 50mm	U=0,072
F	ISOVER RKL-31 A 75mm + KL-33 400mm + KL-33 50mm	U=0,065

Double timber frame with ISOVER KL-33 insulation (US4)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.116	0.098	0.086	0.080	0.071	0.064	W/(m^{2}K)
Insulation thickness	300	350	400	425	475	525	mm
Annual energy losses	14.945	12.669	11.005	10.288	9.168	8.270	kWh

Material costs (C$_i$)

	Structure variations						
	A	B	C	D	E	F	
Material costs	32.09	34.61	37.06	38.87	41.37	43.84	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	130.95	111.01	96.43	90.15	80.33	72.47	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	163.04	145.62	133.49	129.02	121.70	116.31	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	37.62	31.89	27.70	25.90	23.08	20.82	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	69.71	66.50	64.76	64.77	64.45	64.66	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

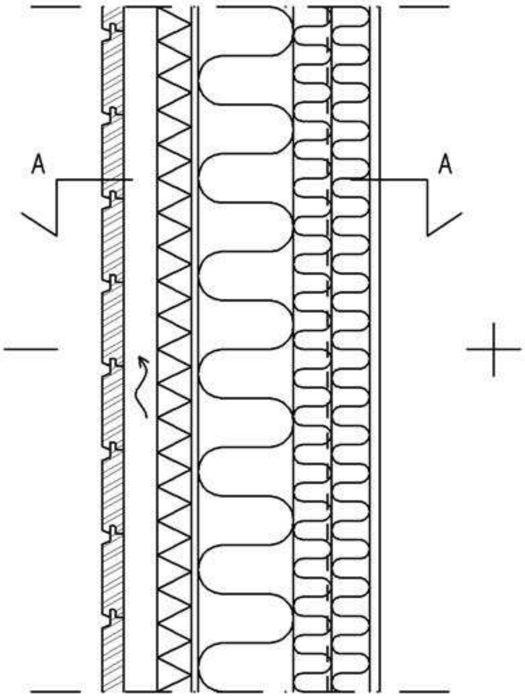
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	324.13	274.77	238.68	223.13	198.84	179.36	€

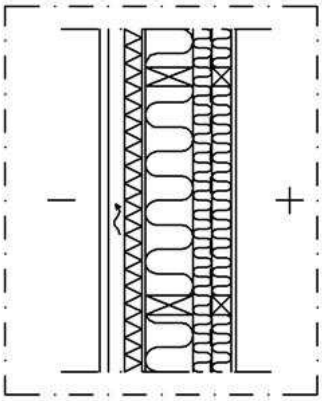
Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	356.22	309.38	275.74	262.00	240.21	223.20	€

Project Cost optimization of Passive House external walls	Structure Double timber frame with ISOVER KL-33 insulation	
Designer	Work No. Date	US4



Section A–A



	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
50 mm	Wind barier and thermal insulation, ISOVER RKL–31 FACADE
	Gypsum plasterboard Gyproc GTS 9
150 mm	Thermal insulation ISOVER KL–33 150mm and timber frame 50x150 step 600
50 mm	Thermal insulation ISOVER KL–33 50mm
	Vapor barier ISOVER VARIO
50 mm	Thermal insulation ISOVER KL–33 50mm and timber frame 50x50 step 600
13 mm	Gypsum board GEK–13

Thermal transmittance

VERSION	INSULATION	U–value
A	ISOVER RKL–31 Facade 50mm + KL–33 150mm + KL–33 50mm + KL–33 50mm	U=0,116
B	ISOVER RKL–31 Facade 50mm + KL–33 150mm + KL–33 100mm + KL–33 50mm	U=0,098
C	ISOVER RKL–31 Facade 50mm + KL–33 150mm + KL–33 150mm + KL–33 50mm	U=0,086
D	ISOVER RKL–31 A 75mm + KL–33 150mm + KL–33 150mm + KL–33 50mm	U=0,080
E	ISOVER RKL–31 A 75mm + KL–33 150mm + KL–33 200mm + KL–33 50mm	U=0,071
F	ISOVER RKL–31 A 75mm + KL–33 150mm + KL–33 250mm + KL–33 50mm	U=0,064

No crossing timber frame with ISOVER KL-33 insulation (US5)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.119	0.103	0.092	0.085	0.077	0.07	$W/(m^2K)$
Insulation thickness	300	350	400	425	475	525	mm
Annual energy losses	15.291	13.303	11.778	10.940	9.887	9.002	kWh

Material costs (C_i)

	Structure variations						
	A	B	C	D	E	F	
Material costs	31.95	34.26	36.57	38.38	40.69	43.00	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C_e)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	133.99	116.57	103.20	95.86	86.63	78.88	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	165.94	150.83	139.77	134.24	127.32	121.88	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C_e)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	38.49	33.49	29.65	27.54	24.89	22.66	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	70.44	67.75	66.22	65.92	65.58	65.66	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

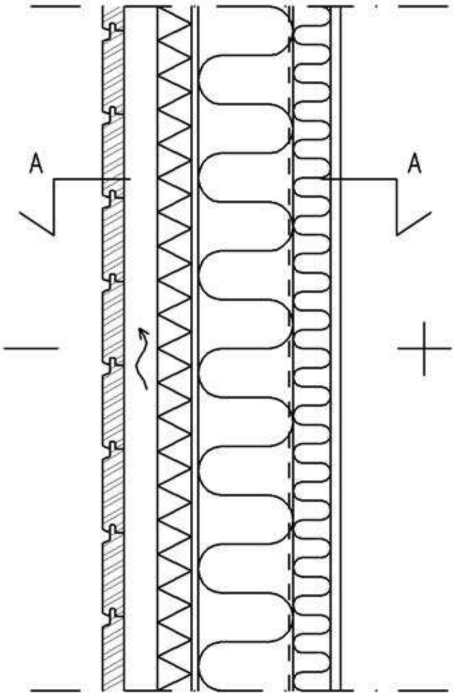
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

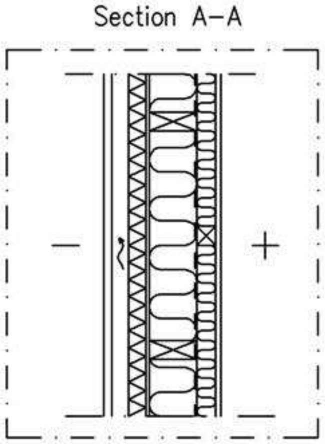
	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	331.64	288.52	255.45	237.27	214.43	195.24	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	363.59	322.78	292.02	275.65	255.12	238.24	€

Project Cost optimization of Passive House external walls	Structure No crossing timber frame with ISOVER KL-33 insulation	
Designer	Work No. Date	US5





	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
50 mm	Wind barier and thermal insulation, ISOVER RKL-31 FACADE
	Gypsum plasterboard Gyproc GTS 9
200 mm	Thermal insulation ISOVER KL-33 200mm and timber frame 50x200 step 600
	Vapor barier ISOVER VARIO
50 mm	Thermal insulation ISOVER KL-33 50mm and timber frame 50x50 step 600
13 mm	Gypsum board GEK-13

Thermal transmittance

VERSION	INSULATION	U-value
A	ISOVER RKL-31 Facade 50mm + KL-33 200mm + KL-33 50mm	U=0,119
B	ISOVER RKL-31 Facade 50mm + KL-33 250mm + KL-33 50mm	U=0,103
C	ISOVER RKL-31 Facade 50mm + KL-33 300mm + KL-33 50mm	U=0,092
D	ISOVER RKL-31 A 75mm + KL-33 300mm + KL-33 50mm	U=0,085
E	ISOVER RKL-31 A 75mm + KL-33 350mm + KL-33 50mm	U=0,077
F	ISOVER RKL-31 A 75mm + KL-33 400mm + KL-33 50mm	U=0,070

Timber frame with ISOVER KL-37 insulation (US6)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.13	0.113	0.100	0.093	0.084	0.076	W/(m^{2}K)
Insulation thickness	275	325	375	400	450	500	mm
Annual energy losses	16.753	14.581	12.912	11.916	10.777	9.838	kWh

Material costs (C$_i$)

	Structure variations						
	A	B	C	D	E	F	
Material costs	31.55	33.20	34.92	36.73	38.45	40.64	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	146.80	127.76	113.14	104.41	94.43	86.20	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	178.35	160.96	148.06	141.14	132.88	126.84	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	42.17	36.70	32.50	30.00	27.13	24.76	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	73.72	69.90	67.42	66.73	65.58	65.40	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

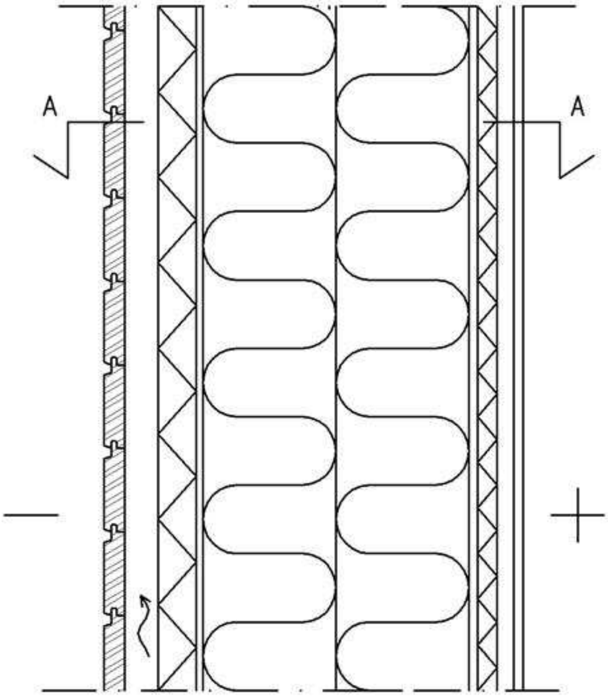
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	363.35	316.24	280.04	258.44	233.74	213.37	€

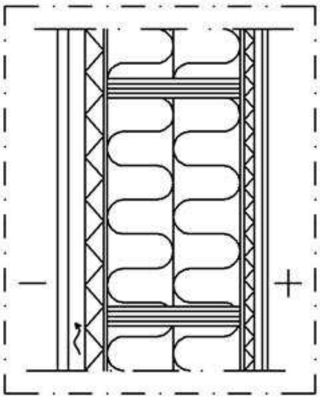
Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	394.90	349.44	314.96	295.17	272.19	254.01	€

Project Cost optimization of Passive House external walls	Structure Timber frame with ISOVER KL-37 insulation	
Designer	Work No. Date	US6



Section A−A



	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
50 mm	Wind barier and thermal insulation, ISOVER RKL−31 FACADE
	Gypsum plasterboard Gyproc GTS 9
300 mm	Thermal insulation ISOVER KL−37 2x150mm and timber frame 50x300 step 600
12 mm	Plywood
25 mm	Hard aluminium surface mineral wool insulation plate ISOVER REK−31
22 mm	Timber elments 22x100 step 300, air gap
13 mm	Gypsum plasterboard GEK−13

Thermal transmittance

VERSION	INSULATION	U−value
A	ISOVER RKL−31 Facade 50mm + KL−37 200mm + REK−31 25mm	U=0,130
B	ISOVER RKL−31 Facade 50mm + KL−37 250mm + REK−31 25mm	U=0,113
C	ISOVER RKL−31 Facade 50mm + KL−37 300mm + REK−31 25mm	U=0,100
D	ISOVER RKL−31 A 75mm + KL−37 300mm + REK−31 25mm	U=0,093
E	ISOVER RKL−31 A 75mm + KL−37 350mm + REK−31 25mm	U=0,084
F	ISOVER RKL−31 A 75mm + KL−37 400mm + REK−31 25mm	U=0,076

Crossing timber frame with ISOVER KL-37 insulation (US7)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.128	0.112	0.099	0.091	0.083	0.076	$W/(m^2K)$
Insulation thickness	300	350	400	425	475	525	mm
Annual energy losses	16.464	14.358	12.735	11.766	10.652	9.734	kWh

Material costs (C_i)

	Structure variations						
	A	B	C	D	E	F	
Material costs	31.37	33.02	34.74	36.55	38.42	40.46	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C_e)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	144.26	125.81	111.59	103.10	93.34	85.29	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	175.63	158.83	146.33	139.65	131.76	125.75	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C_e)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	41.44	36.14	32.06	29.62	26.81	24.50	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	72.81	69.16	66.80	66.17	65.23	64.96	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

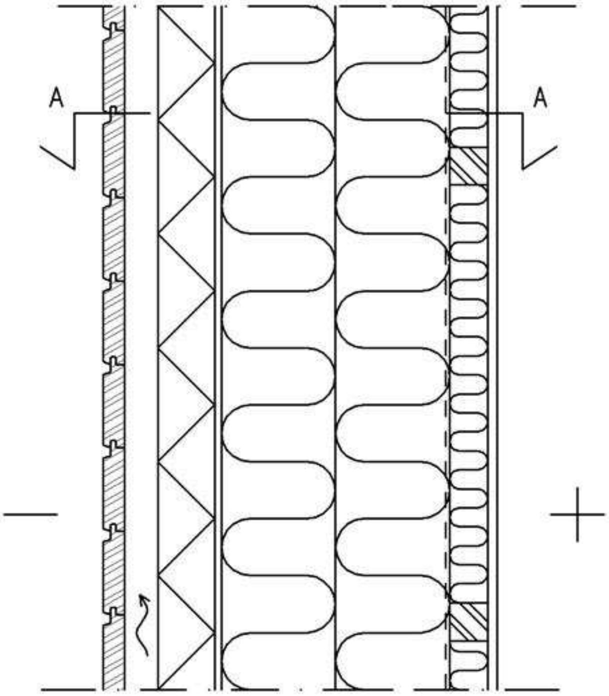
Energy price	0.1036	€/kWh					
Energy price increasing	5	%	- annual increase				
Study period	50	years					

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	357.08	311.40	276.20	255.19	231.03	211.12	€

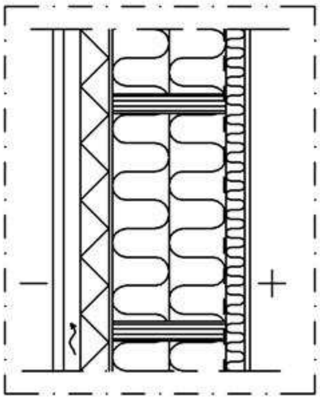
Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	388.45	344.42	310.94	291.74	269.45	251.58	€

Project Cost optimization of Passive House external walls	Structure Crossing timber frame with ISOVER KL-37 insulation	
Designer	Work No.	US7
	Date	



Section A-A



	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
75 mm	Wind barier and thermal insulation, ISOVER RKL-31 FACADE
	Gypsum plasterboard Gyproc GTS 9
300 mm	Thermal insulation ISOVER KL-37 2x150mm and timber frame 50x300 step 600
	Vapor barier ISOVER VARIO
50 mm	Thermal insulation ISOVER KL-37 50mm and timber frame 50x50 step 600
13 mm	Gypsum plasterboard GEK-13

Thermal transmittance

VERSION	INSULATION	U-value
A	ISOVER RKL-31 Facade 50mm + KL-37 200mm + KL-37 50mm	U=0,128
B	ISOVER RKL-31 Facade 50mm + KL-37 250mm + KL-37 50mm	U=0,112
C	ISOVER RKL-31 Facade 50mm + KL-37 300mm + KL-37 50mm	U=0,099
D	ISOVER RKL-31 A 75mm + KL-37 300mm + KL-37 50mm	U=0,091
E	ISOVER RKL-31 A 75mm + KL-37 350mm + KL-37 50mm	U=0,083
F	ISOVER RKL-31 A 75mm + KL-37 400mm + KL-37 50mm	U=0,076

I-joist timber frame with ISOVER KL-37 insulation (US8)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.123	0.106	0.093	0.087	0.078	0.071	W/(m^2K)
Insulation thickness	300	350	400	425	475	525	mm
Annual energy losses	15,855	13,655	11,994	11,144	10,013	9,091	kWh

Material costs (C$_i$)

	Structure variations						
	A	B	C	D	E	F	
Material costs	31.63	33.40	35.25	37.06	39.07	41.24	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	138.93	119.65	105.10	97.65	87.74	79.66	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	170.56	153.05	140.35	134.71	126.81	120.90	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	39.91	34.37	30.19	28.05	25.20	22.88	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	71.54	67.77	65.44	65.11	64.27	64.12	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

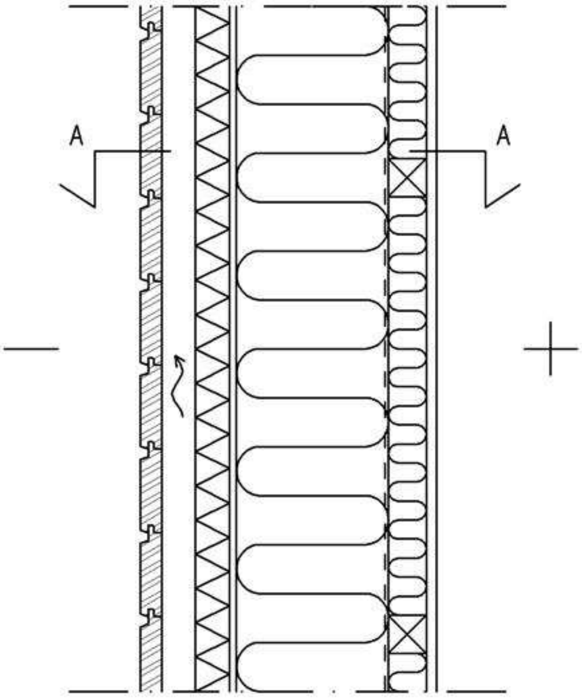
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	343.87	296.16	260.13	241.70	217.17	197.17	€

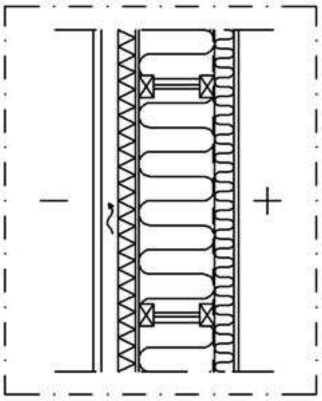
Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	375.50	329.56	295.38	278.76	256.24	238.41	€

Project Cost optimization of Passive House external walls	Structure I–joist timber frame with ISOVER KL–37 insulation	
Designer	Work No. Date	US8



Section A–A



	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
50 mm	Wind barier and thermal insulation, ISOVER RKL–31 FACADE
	Gypsum plasterboard Gyproc GTS 9
200 mm	Thermal insulation ISOVER KL–37 200mm and I–joist timber frame step 600
	Vapor barier ISOVER VARIO
50 mm	Thermal insulation ISOVER KL–37 50mm and timber frame 50x50 step 600
13 mm	Gypsum board GEK–13

Thermal transmittance

VERSION	INSULATION	U–value
A	ISOVER RKL–31 Facade 50mm + KL–37 200mm + KL–37 50mm	U=0,123
B	ISOVER RKL–31 Facade 50mm + KL–37 250mm + KL–37 50mm	U=0,106
C	ISOVER RKL–31 Facade 50mm + KL–37 300mm + KL–37 50mm	U=0,093
D	ISOVER RKL–31 A 75mm + KL–37 300mm + KL–37 50mm	U=0,087
E	ISOVER RKL–31 A 75mm + KL–37 350mm + KL–37 50mm	U=0,078
F	ISOVER RKL–31 A 75mm + KL–37 400mm + KL–37 50mm	U=0,071

Double timber frame with ISOVER KL-37 insulation (US9)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.125	0.107	0.093	0.087	0.078	0.07	W/(m^{2}K)
Insulation thickness	300	350	400	425	475	525	mm
Annual energy losses	16.124	13.755	12.002	11.155	9.978	9.028	kWh

Material costs (C$_i$)

	Structure variations						
	A	B	C	D	E	F	
Material costs	31.96	33.28	35.21	37.02	39.15	40.78	€

Life span 50 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	141.29	120.53	105.17	97.74	87.43	79.11	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	173.25	153.81	140.38	134.76	126.58	119.89	€

Life span 20 years and annual energy price increasing 2%

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	40.59	34.62	30.21	28.08	25.12	22.73	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	72.55	67.90	65.42	65.10	64.27	63.51	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

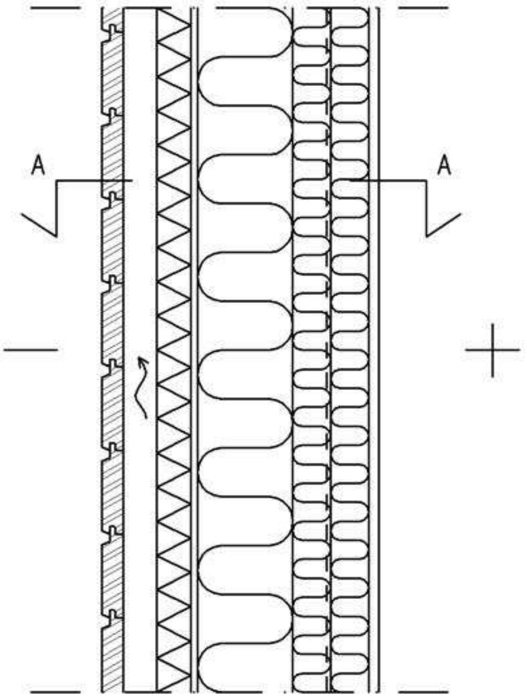
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	349.70	298.32	260.30	241.93	216.41	195.80	€

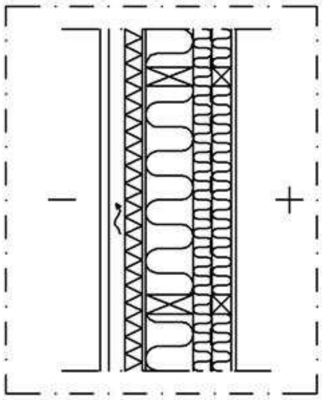
Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	381.66	331.60	295.51	278.95	255.56	236.58	€

Project Cost optimization of Passive House external walls	Structure Double timber frame with ISOVER KL-37 insulation	
Designer	Work No. Date	US9



Section A–A



	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
50 mm	Wind barier and thermal insulation, ISOVER RKL–31 FACADE
	Gypsum plasterboard Gyproc GTS 9
150 mm	Thermal insulation ISOVER KL–37 150mm and timber frame 50x150 step 600
50 mm	Thermal insulation ISOVER KL–37 50mm
	Vapor barier ISOVER VARIO
50 mm	Thermal insulation ISOVER KL–37 50mm and timber frame 50x50 step 600
13 mm	Gypsum board GEK–13

Thermal transmittance

VERSION	INSULATION	U–value
A	ISOVER RKL–31 Facade 50mm + KL–37 150mm + KL–37 50mm + KL–37 50mm	U=0,125
B	ISOVER RKL–31 Facade 50mm + KL–37 150mm + KL–37 100mm + KL–37 50mm	U=0,107
C	ISOVER RKL–31 Facade 50mm + KL–37 150mm + KL–37 150mm + KL–37 50mm	U=0,093
D	ISOVER RKL–31 A 75mm + KL–37 150mm + KL–37 150mm + KL–37 50mm	U=0,087
E	ISOVER RKL–31 A 75mm + KL–37 150mm + KL–37 200mm + KL–37 50mm	U=0,078
F	ISOVER RKL–31 A 75mm + KL–37 150mm + KL–37 250mm + KL–37 50mm	U=0,070

No crossing timber frame with ISOVER KL-37 insulation (US10)

General information

	Structure variations						
	A	B	C	D	E	F	
U-value	0.128	0.111	0.099	0.091	0.083	0.076	W/(m^{2}K)
Insulation thickness	300	350	400	425	475	525	mm
Annual energy losses	16.446	14.342	12.721	11.756	10.644	9.726	kWh

Material costs (C$_i$)

	Structure variations						
	A	B	C	D	E	F	
Material costs	31.37	33.02	34.74	36.55	38.42	40.46	€

Life span 50 years

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	144.11	125.67	111.47	103.01	93.27	85.22	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	175.48	158.69	146.21	139.56	131.69	125.68	€

Life span 20 years

Energy losses costs (C$_e$)

Energy price	0.1036	€/kWh	
Energy price increasing	2	%	- annual increase
Study period	20	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	41.40	36.10	32.02	29.59	26.79	24.48	€

Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	72.77	69.12	66.76	66.14	65.21	64.94	€

Life span 50 years and annual energy price increasing 5%

Energy losses costs (C_e)

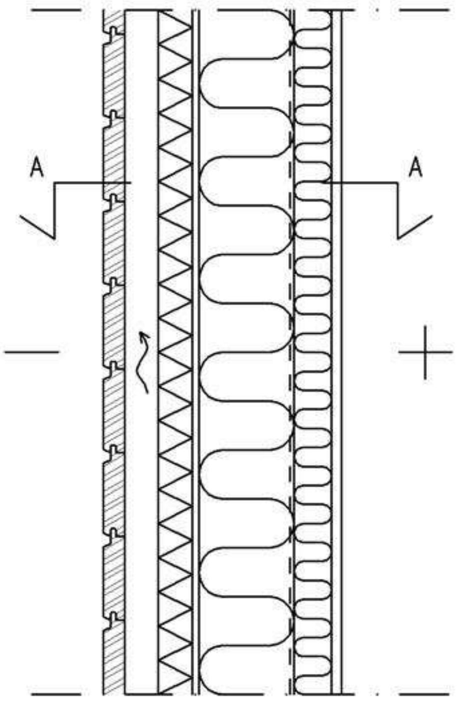
Energy price	0.1036	€/kWh	
Energy price increasing	5	%	- annual increase
Study period	50	years	

	Structure variations						
	A	B	C	D	E	F	
Energy losses costs	356.69	311.06	275.90	254.97	230.85	210.94	€

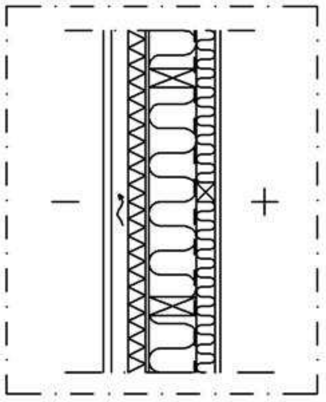
Total costs (LCC)

	Structure variations						
	A	B	C	D	E	F	
Total costs	388.06	344.08	310.64	291.52	269.27	251.40	€

Project Cost optimization of Passive House external walls	Structure No crossing timber frame with ISOVER KL-37 insulation	
Designer	Work No. Date	US10



Section A-A



	Cladding
22+22 mm	Timber elements 22x100 step 600 + 22x100 step 600 (ventilation)
50 mm	Wind barier and thermal insulation, ISOVER RKL-31 FACADE
	Gypsum plasterboard Gyproc GTS 9
200 mm	Thermal insulation ISOVER KL-37 200mm and timber frame 50x200 step 600
	Vapor barier ISOVER VARIO
50 mm	Thermal insulation ISOVER KL-37 50mm and timber frame 50x50 step 600
13 mm	Gypsum board GEK-13

Thermal transmittance

VERSION	INSULATION	U-value
A	ISOVER RKL-31 Facade 50mm + KL-37 200mm + KL-37 50mm	U=0,128
B	ISOVER RKL-31 Facade 50mm + KL-37 250mm + KL-37 50mm	U=0,111
C	ISOVER RKL-31 Facade 50mm + KL-37 300mm + KL-37 50mm	U=0,099
D	ISOVER RKL-31 A 75mm + KL-37 300mm + KL-37 50mm	U=0,091
E	ISOVER RKL-31 A 75mm + KL-37 350mm + KL-37 50mm	U=0,083
F	ISOVER RKL-31 A 75mm + KL-37 400mm + KL-37 50mm	U=0,076