DISSERTATION

Development of Design Approach for the Optimal Model of an Energy-Efficient Timber House

A thesis submitted for the academic degree of Doctor of Technical Sciences

UNDER THE SUPERVISON OF

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

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List of symbols

Q_h	specific annual energy demand for heating
Q_k	specific useful cooling energy demand
$Q_h + Q_k$	sum total of specific annual energy demand for heating and specific useful cooling energy demand
AGAW	glazing-to-wall area ratio
AGAF	glazing-to-floor area ratio
$AGAW_{opt}$	*optimal value for* glazing-to-wall area ratio
N	north
S	south
W	west
E	east
Eq.	Equation
GHG	greenhouse gas emissions
U_{wall}	thermal transmittance coefficient of wall
U_g	thermal transmittance coefficient of window glazing
U_f	thermal transmittance coefficient of frame
EN	European Norm
ISO	International Organization for Standardization

Abstract

The present times, characterized by specific circumstances in the sphere of climate change, witness an intensive focus of the sciences of civil engineering and architecture on searching for ecological solutions and construction methods that would allow for greater energy efficiency and, consequently, for a reduced environmental burden. Being a natural raw material, timber represents one of the best choices for energy efficient construction since it also functions as a material with good thermal transmittance properties if compared to other construction materials, plays an important role in the reduction of CO_2 emissions (Natterer, 2009), has good mechanical properties and ensures a comfortable indoor living climate. The latter statements accord well with the statements of Joseph and Tretsiakova-McNally (2010) who declare that the use of timber in construction gains more and more support, especially in the regions with vast forest resources, because it can reduce both the energy demands of the buildings and the concentration of GHG in the atmosphere. Respecting all these facts the energy-efficient properties of prefabricated timber buildings are, in comparison with other types of buildings, excellent but not only because they use less energy for heating, which is environmentally friendly, but also due to the extremely positive feelings that homeowners have when living in such houses. Additionally the use of glazing surfaces in timber structures is becoming an important issue of energy-efficient construction. Over a number of years of development glazing manufacturers have improved their products' thermal-insulation and strength properties as well as their coefficient of permeability of total solar radiation energy and thus enabled the use of large glazing surfaces not only to illuminate indoor areas but also to ensure passive solar heating. The features listed above make prefabricated timber structures suitable for the construction of energy efficient houses of various classes where an increased proportion and a suitable orientation of the glazing surfaces play an important part due to solar heat gains. It follows that timber construction along with the use of suitable and correctly oriented glazing surfaces represents a great potential in residential and public building construction, which is also the main point of the presented research.

The current research is generally based on a case study of a two-storey prefabricated timber house. In the first part of the thesis a deep parametric analysis of an increased-proportion-of-the-glazing-surfaces impact, taking the climate data for Ljubljana into consideration, is performed. The analysis is carried out on different exterior prefabricated timber wall elements having different thermal properties, i.e. different thermal transmittance coefficients, while the rest of the parameters, such as the ground plan of the model as well as the active systems, roof and floor slab assemblies remain constant. It is important to underline that the presented research is limited to timber construction only, which is also termed as lightweight construction, since the influence of the different thermal capacities of the materials as well as the thermal mass of the building were not taken into consideration. The graphical presentation includes figures showing the annual energy demand for heating and cooling dependant on the proportion of the glazing area in relation to the total surface area of the south-oriented façade. The comparative analysis results can nevertheless serve as a good frame of reference to civil engineers and architects in an approximate estimation of energy demand accompanying the different positioning and proportion of glazing surfaces while using various prefabricated timber wall elements as well as serving some basic practical and very useful principles regarding the energy efficient refurbishment of old timber buildings.

However, the main aim of the presented doctoral dissertation, as well as its main contribution to science, is the development of an innovative theoretical approach applicable for the architectural design of an optimal energy-efficient prefabricated timber house. Since many important and various parameters occur in the design process, such as the location and orientation of the building, as well as the material properties and climate condition, the whole process is very wide and complex. For this purpose several research steps, which are clearly presented and described in Chapter 5.2, have to be simultaneously performed and attentively analyzed. Thus, the main advantage of the presented research is a transformation of this very huge and complex problem, consisting of many various parameters, to only one single independent variable (U_{wall}-value), which becomes the only variable parameter, for all contemporary prefabricated timber construction systems, independent of the type of construction system. In this way, firstly, the computational procedure of a functional dependence of the optimal south-oriented glazing size from the U-value of the exterior wall element is defined and secondly, the energy demand dependence on the U-value of the exterior wall element, as the only independent variable, is defined as well. Many additional test calculations prove the regularity of the given approach.

Finally, it is important to stress that principally the findings of the current thesis are determined only for the selected base-case study model. Our main objective was to demonstrate the general design approach, which can be used to define the optimal glazing surface for each main cardinal direction in order to plan the optimal model of energy-efficient house dependant on one single independent variable (U_{wall}-value) only. The developed approximated expressions for the optimal glazing size and consequently the possible energy savings, given in relatively simple forms at the end of the thesis, serve as a good opportunity to determine the basic, simple and rapid predictions in the modern and energy-efficient planning and renovation of timber buildings.

However, it is possibly difficult to establish what a realistic optimal model is, since most buildings are unique, and trends also vary over time. Nevertheless, with the given application of the presented approach for each individual timber house, the optimal glazing surface is determinable with regard to the lowest energy demand for heating and cooling, and the houses can still keep their uniqueness. Therefore, for further research the influence of additional important parameters, such as different ground plans, different climate conditions, different indoor temperatures, different types of glazing, different house orientations etc. has to be analyzed in order to set up the complex approach for the design of the optimal model of an energy-efficient prefabricated timber house.

Keywords: Timber Construction; Glazing Surfaces; Prefabricated Buildings; Energy Efficiency; Energy Demand, Optimal Glazing Size, Building Simulation, Mathematical Modelling.

List of Publications

1. Premrov M., Žegarac Leskovar V., (2010), *Timber in modern architecture and construction with a focus on energy efficiency of the buildings*, **Invited keynote lecture**, Published international congress proceedings, Slovenian World Congress, IV. Conference of Slovenian architects and civil engineers from World and Slovenia, 42-47**.**

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4. Žegarac Leskovar V., Premrov M., (2010), *Impact of the proportion of glazing surface on energy efficiency of prefabricated timber-frame houses*, Published international congress proceedings, E-nova 2010 International Congress – Sustainable Buildings, Forschungs- und Studienzentrum Pinkafeld, Pinkafeld, 121-128**.**

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6. Žegarac Leskovar V., Premrov M., (2010), Vpliv deleža steklenih površin na energijsko učinkovitost montažnih lesenih okvirnih zgradb – *Influence of glazing share on energy efficiency of prefabricated timber-frame houses*, **Invited lecture,** Published proceedings New technologies in building with wood, University of Ljubljana, Biotechnical Faculty, Department of Wood Technology, 91-102.

7. Premrov M., Žegarac Leskovar V., (2010), *Timber-framed residential buildings with enlarged impact of glass panels.* V: LUČIĆ, Duško (ur.). Treći Internacionalni naučno-stručni skup Građevinarstvo - nauka i praksa Žabljak, 15-19. februara 2010. *Zbornik radova*. Podgorica: Univerzitet Crne Gore, Građevinski fakultet, 2010, knj. 1, 383-388.

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12. Žegarac Leskovar V., Premrov M., (2010), *Energy Efficiency of Prefabricated Timber-Frame Buildings with Enlarged Glazing Surfaces in South Façade*, submitted for publication in Journal of Mechanical Engineering.

13. Sitar M., Žegarac Leskovar V., Krmelj V., (2009), *Stimulating integral refurbishment principles in social housing as a challenge for sustainable development: case study: energy*

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List of publicly presented parts of the thesis

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and

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CONTENTS

1 INTRODUCTION

The dissertation is based on the parametric study of a base-case model and deals with the influence of the size and orientation of the glazing surfaces, installed in different construction types of timber wall elements, on the energy balance of a building. Based on the analysis and findings of the parametric study the aim of the dissertation is to develop a design approach for the optimal model of an energy efficient timber house.

1.1 Problem description

The present times, characterized by specific circumstances in the sphere of climate change, witness an intensive focus of the sciences of civil engineering and architecture on searching for ecological solutions and construction methods that would allow for greater energy efficiency and, consequently, for a reduced environmental burden. In order to present the seriousness of this specific environmental issue only a selection of the existing facts, taken from an unlimited list of accessible data, is given. Buildings are known as the largest energy consumers and greenhouse gas emitters. Joseph and Tretsiakova-McNally (2010) declare that in continental Europe, the energy use in buildings alone is responsible for up to 50% of carbon dioxide emission. Therefore, the energy saving stategies related to buildings, such as the use of eco-friendly building materials, reduction of energy demand for heating, cooling and lighting, GHG emissions control etc, are strongly recommended. Regarding building materials Calkins (2009) estimates that cement and concrete industry generates up to 7% of global anthropogenic CO2 emissions. Moreover, the production of steel causes a relatively high amount of greenhouse gas emissions. Furthermore, the brick production process causes high energy use and high GHG emissions. In contrast, the use of timber in construction has been gaining ever more support, especially in the regions with vast forest resources, because it can reduce both the energy demands of the buildings and the concentration of GHG in the atmosphere (Joseph and Tretsiakova-McNally, 2010). Being a natural raw material, timber represents one of the best choices for energy efficient construction since it also functions as a material with good thermal properties if compared to other construction materials. In addition, it plays an important role in reduction of the CO_2 emissions (Natterer, 2009), has good mechanical properties and ensures a comfortable indoor living climate. Respecting all these facts, the energy-efficient properties of timber-frame buildings are, in comparison with other types of building, constructed with concrete, brick or steel, excellent but not only because well-insulated buildings use less energy for heating, which is environmentally friendly, but also due to the extremely positive feelings that homeowners have when living in such houses.

Additionally the use of glazing surfaces in timber structures is becoming an important issue of energy-efficient construction. Over a number of years of development, glazing manufacturers have namely improved their products' thermal-insulation and strength properties as well as their coefficient of permeability of total solar radiation energy and thus enabled the use of large glazing surfaces, primarily south-oriented, not only to illuminate indoor areas but also to ensure solar heating. The features listed above make prefabricated timber structures suitable for the construction of energy efficient houses of various standards where an increased proportion and a suitable orientation of the glazing surfaces play an important part due to solar heat gains. It follows that timber construction along with the use of suitable and correctly oriented glazing surfaces represents a great potential in residential and public building construction.

State of the art of the existing research

The research focused on energy efficiency of buildings is not a matter of the last decade only. Since the motives for the research of specific themes usually arise from existing reality-based problems, the first intensive studies related to energy and buildings were already carried out in the seventies and eighties, as a consequence of the oil crisis which started in 1973 due to an Arab oil embargo. Many studies have been performed since then focusing on the research of specific parameters influencing the energy performance of buildings.

In the study of Johnson et al. (1984), the influence of glazing systems on component loads and annual energy use in prototypical office buildings were systematically explored for different climates and orientations. Although in the study the influence of glazing focuses on electric lighting energy reductions due to daylighting, the relationship between glazing size and heating or cooling load is studied as well for different orientations and different climates (cold and warm climate). The results for a cold climate were similar in some aspects to the findings of our research, although the input parameters regarding the U-values of the wall elements and glazing were selected differently from our base-case study. According to Johnson the heating demand is reduced with increased glazing, due to solar loads. He claims that even for the north orientation, heating demand is reduced by approximately 30 per cent with an effective glazing size compared to a wall with no glazing. The results showed also that increasing the size of the glazing surfaces always increases the cooling demand, where south, west and east orientations show approximately the same increases, which is evident in the numerical part of our study as well. One of conclusions of the Johnson study, that increasing the window area frequently reaches a point, depending on the climate and orientation, beyond which total energy consumption increases due to greater cooling loads, is comparable to our findings for an optimal glazing size regarding the energy demand for heating and cooling.

Next, the research of general means for estimating the total area of the exposed surface of domestic buildings by authors Steadman and Brown (1987) was performed on the basis of an empirical study of a house plan from the City of Cambridge. Among a range of researched parameters, such as the relationship between the wall area and floor area, built form etc., the glazing areas are examined from the viewpoint of heat loss. The interest was focused principally on south-oriented glazing. The glazing-to-wall area ratio was analysed for six selected houses, although no specific conclusions were set for the relationship between glazing size and heat loss, which was at least shown to be important and necessary for further work.

Research of the glazing area regarding three different types of Indian climate was performed by Bansal et al. (1994). The study was based on a model with a constant U-value of construction elements. The results showed the recommended glazing-to-floor area ratio, which was 10% for a composite climate, 20% for a cold, cloudy climate and

30% for a cold, sunny climate. According to the presented results, the study shows that a larger glazing area has a similar influence on the energy performance of a building as shown by the higher thermal transmittance of the building elements.

A simple model for assessing the energy performance of windows presented by Karlsson et al. (2000) renders a very simple way to compare different advanced windows in different geographical locations, orientations and types of building. Although the work is focused mainly on the comparison of glazing types, the conclusion, that in a practical case, a change in the type of window may also lead to lower energy needs and thus simplified heating and cooling systems, which serves as a basis for our work.

A Turkish study performed by Inanici and Demirbilek (2000) analysed variations of the window-to-wall ratio from 25 to 90% for different types of climate. The results for the apartment units showed that for a north-facing glazing area the total energy load decreases with an increased window area. When increasing the south-facing window area the total energy load decreased for cool climates and increased for the warm climates. The optimum size in hot climates was 25% of the facade area.

Among comparable newer studies a parametric study of heating and cooling demand was performed by Bülow-Hübe (2001) in order to determine the optimal design for office windows for the Swedish climate. The study was based on a single-person office model with windows in the south facade. It included many variable parameters, such as glazing size, type and orientation, daylight utilisation, internal load, ventilation rate, wall insulation and climate. It was estimated that the effect of changing the window size is relatively large for the cooling demand, while the heating demand is less affected. Rotating the single-person office model, the results for different orientations were carried out. For the north orientation the highest heating demand and lowest cooling demand was shown. East and west orientations showed similar behaviour. The cooling demand was similar for south, west and east orientations, while the heating demand was significantly higher for the south orientation. As already stated in the Johnson study, the importance of limiting the window size was emphasized, since the cooling demand depends strongly on the size of window.

Another Swedish study was performed by Persson et al. (2005) for the 20 low-energy terraced houses built in 2001 outside Gothenburg. The purpose of the work was to investigate how decreasing the south-oriented window size and increasing the north-oriented window size would influence energy consumption. The analysed houses are oriented with the large window area facing south, the building construction is more air tight and more insulated than traditional houses in Sweden. The variable parameters of this research were the orientation, U-values of the construction elements and different triple-glazed window combinations. It was shown that less energy is needed for heating if the houses are placed with the large window area facing south. Orienting the windows to the west or east did not influence the energy balance noticeably, which is similar to our findings. Also re-orienting the houses to the north has no significant influential change in their energy balance. Therefore the authors conclude that it is possible to orient the houses differently without losing too much energy. It should also be possible to distribute the window area more evenly, i.e. decrease the window area facing south and increase the area facing north. By comparing the case of no windows facing south with the original one with energy-efficient glass, it was shown that using energy-efficient windows can be even better than having a highly insulated wall without windows. The simulations of the case study indicated that a window area to the south could be found, which is optimal from an energy point of view. The authors assume the probability that besides the south orientation there is an optimum area for all of the orientations of the windows, which is contradictory to our findings for north, west and east orientations.

Next, many findings were found in the dissertation of Persson (2006) which are in some aspects comparative to our research. Apart from the findings relating to the glazing size, which are compared to ours in Chapter 4, the explanation regarding the influence of climate and location is found to be very important. According to the data from a table presenting data for different locations with different climates and altitudes. If considering the altitude of the house it is also important to take into account the latitude and longitude data, while at the same height above sea level, solar radiation is lower for northern locations in comparison to those in the south. Therefore the analysis of the location and climate influence on energy performance is very important.

According to Ford et al. (2007), the optimum glazing surface for mild winters is equal to 30% of the total surface of the building. In locations with more severe winters this optimum does not exist but a glazing surface of between 15% and 30% of the total surface is recommended. In the framework of a European project different simulations and analyses were performed for different low-energy buildings for five European countries (UK, France, Italy, Portugal, Spain) with a relatively warm climate. Many variations have been studied in further detail, such as variations in the glazing area, orientation, the summer night ventilation strategy, in surface area versus volume ratio etc. The software used for calculations was PHPP software. Some of the statements based on an Italian case-study analysis of variations in the glazing size from 20% to 40% for total southern façades for three different Italian climates shows that a larger glazing area can reduce the net useful demand for heating in proportion to the incident solar radiation. The results presented were similar to ours when the climate for Milan was considered (Pagliano et al. 2007). It is also stated that an increase in the area of glazing facing south, if the glazing is well shaded, has a lower influence on cooling demand, which increased in the same way for three climates. Regarding the latter statement we have to call attention to the data that the analysis was carried out for glazing sizes up to 40%, so the denotation »large« for glazing surface in this study is presumably related to this maximum value. Variations of the orientation showed the best results by orienting the building with the façade having a large glazed area facing south.

Among the existing studies many of them are provided for non-European climates. Bouden (2007) investigated whether glass curtain walls are appropriate for the Tunisian local climate. The investigation only concerned the influence of different sizes and types of glazing oriented in different directions on a building's heating and cooling load. Simulations were performed on the main façade of an administrative four-storey building. The yearly energy consumption was the lowest when the building's main façade was directed towards the south, followed by north and west directions. This resulted from the fact that the north orientation was the best in summer. The east orientation was the most energy-consuming orientation. Next the influence of different sizes of glazing area showed that especially regarding single-glazing the energy consumption increased on account of an increase in the glazing size. The simulation results showed that walls with approximately 90% of a glazed surface perform better than normal masonry walls with small windows covering 20% of the total wall area, if an appropriate kind of glazing was selected.

Yet another study considering non-European climate conditions investigated the influence of windows on the energy balance of apartment buildings in Amman, Jordan, performed by Hassouneh et al. (2010). The study was performed firstly for one room of a three-storey apartment building by making variations on the type of glazing, area of glazing and orientation (N, S, E and W). Secondly, the energy saved due to proper fenestration of the whole apartment was calculated. Regarding the type of glass used it was found that some types of glazing are more efficient in a specific cardinal direction than others. Next it has been found that increasing the area of glazing in the south direction can save more energy in winter depending on the type of glazing and the best way to save energy in the north direction is to reduce the glazing area as much as possible. Some types of glazing are more efficient than others and most types of glazing installed in the north direction cause energy losses, except type B – an insulating glass unit composed of double-pane clear glass, one air gap and a low emissive coating on the inner pane, which was proved to save energy. Glass type A – an insulating glass unit of double-pane clear glass with one air gap proved to be the most adequate for south, west and east orientations. It has been found also that increasing the glazing area for each type of glazing in the east and west directions can provide a good opportunity to save energy, which is contradictory to our case-study findings. The best type of window from an energy point of view was defined as a window that can save energy, save money, reduces heat loss, the cost of which is low, meaning that the payback period for the cost of glazing was considered as another guide for selecting the best window type and size.

In a study which was focused on the role of active systems and thermal protection for passive and plus energy residential buildings, Praznik and Kovič (2010) explain that for south-oriented windows the solar gains are 2/3 higher than the heat losses. The relationship between solar gains and heat losses is almost equal for south and west-oriented windows, while for north-oriented windows the heat losses are about 3 times higher than the solar gains.

In general all of the presented studies deal mainly with the influence of variable parameters on the energy performance of buildings of different types (residential, offices, public) and mainly of massive construction systems. Many of the introduced statements accord well with some of the findings of our study.

From the existing research we can summarize that the process of defining the optimal residential building is very complex, which is influenced by specific basic parameters listed below:

- location of the building and climate data for the specific location,
- orientation of the building,
- properties of installed materials, such as timber, glass, insulation, boards etc. in our case,
- building design (form, ground plan, composition of the building envelope, window size and arrangement in the façade)
- selection of active systems.

One of the general critical remarks of the authors regarding existing studies on the impact of windows on heating and cooling demand was that most of them are just calculations for a single building. In our research an attempt for a more systematic analysis has been made, with the model of a building of our base-case study being performed in many variations of timber construction systems.

1.2 Aims and objectives

Despite the knowledge developed in the last number of decades regarding energy-efficient construction, a great amount of energy used in numerous timber buildings is still lost due to several parameters, such as insufficient insulation of the thermal envelope, inadequate ventilation, thermal bridges, inappropriate glazing disposition, quality and size etc. Although some general directions for an energy-efficient design are available, there haven't been any accurate definitions developed yet regarding the optimal glazing size for differently oriented external wall elements of specific timber construction systems.

The main aim and scientific contribution of the presented doctoral dissertation is in developing an innovative theoretical approach applicable for the architectural design of an optimal energy-efficient prefabricated timber house.

While in a design process many important and various parameters occur, such as the location and orientation of the building, as well as its material properties and climate conditions, the whole process is very wide and complex. For this purpose several research steps, which are clearly presented and described in further text, have to be simultaneously performed and attentively analyzed.

I. The first step includes the analyses of different timber construction systems with different thermal properties of wall elements in order to define the influence of the construction system on the energy efficiency of the building.

II. Parallel to the first step, the influence of an enlarged glazing surface for the main cardinal directions (south, north, west and east) has to be analysed, where special attention should be focused on the south cardinal direction of the building, which is the only cardinal direction with a positive impact of enlarged glazing surfaces on energy efficiency. In this research the south orientation presents the equator-facing orientation, due to location of the base-case model on the northern hemisphere. It is important to stress that this research considers only the mid-European climate conditions for a specific location at an altitude of 298 metres above sea level, latitude of 46.03° and longitude of 14.3° east.

III. Next, the optimal glazing size in south-oriented external walls has to be determined for each individual construction system in order to define the functional dependence of the optimal south-oriented glazing size from the type of construction system. With the purpose of widening and generalizing the latter relation, this complex problem has to be transformed to only one single independent variable (U-value), which becomes the only variable parameter, for all contemporary prefabricated timber construction systems, independent of the type of construction system. Firstly the functional dependence of the optimal south-oriented glazing size on the U-value of the exterior wall element has to be defined and secondly the energy demand dependence on the U-value of the exterior wall element has to be determined. The transformation of the problem to only one variable parameter is important due to the generalization of the theory which becomes valid for all contemporary prefabricated timber construction systems, independent of the type of construction system. At the same time this represents the main theoretical advantage of the presented research.

IV. If feasible, the final aim of the dissertation has to be attained, which is to develop the approximate mathematical expressions, based on the base-case study results, for the definition of the energy demand (gains and losses) dependant on the glazing size or the U-value of a south-oriented exterior wall element.

With the attainment of the aims and objectives of the current dissertation the important step towards the development of a design approach of an optimal model of energy-efficient building is made, which has to be systematically completed in further research.

The main aim of the presented doctoral dissertation is the development of an innovative theoretical approach applicable for the design of an optimal energy-efficient prefabricated timber house considering the share of the glazing surfaces and their orientation, which can have an influence on the reduction of the energy demand for heating, cooling and consequently on $C0_2$ emissions. The basic theoretical contribution of the presented dissertation is the transformation of a complex energy-related problem to only one single independent variable (U_{wall}-value) where the influence of active systems in not taken into account. It is important to be aware that the current study was carried out for a specific location, which is Ljubljana, with specific climate data that can be generalized as mid-European for lower altitudes, therefore the corresponding climate data have to be considered when using this approach for the detailed calculations of other objects.

1.3 Principal presumptions and limitations

The dissertation is based on the parametric study performed on the base-case model, although the generalization of the problem on one single variable, which is the U_{wall}-value, opens the bounds of possibility to the performance of new wider research of additional variable parameters that influence the energy balance of the building and which have not been analysed in this research.

The criteria for the determination of the building's energy efficiency in this dissertation are the specific annual space heating demand (Q_h), in further text termed as the energy demand for heating, and the specific useful cooling energy demand (Q_k), in further text termed as the energy demand for cooling, as well as the sum of both (Q_h+Q_k).

The analysis was carried out only for the base-case model of a specific ground plan. The relationship between the external wall area and floor area is fixed, no variations for this relationship are performed.

The influence of glazing size is analysed only for the main cardinal directions, north, south, east and west. The influence of glazing installed in wall elements of intermediate cardinal directions such as south-west, south-east, north-west and north-east have to be analysed additionally in further research.

No variations of glazing quality are performed, while only high quality coated triple-glazing, which is most suitable for the design of an optimal model, is analysed. For further research an analysis of the influence of glazing of varying qualities is suggested in the conclusions chapter. Some of the results of existing studies could be adopted from Bülow-Hübe (2001), Hassouneh et al. (2010) and Pagliano et al. (2007), with a consideration of different climate conditions. In Bülow-Hübe (2001) it is shown that the total window U-value has little or no influence on the energy demand for heating.

For large glazing surfaces attention should be focused on the risk of overheating, although the PHPP software is not suitable for providing reliable data for the frequency of overheating. For that reason, this data was not presented graphically, however it is only listed in tables in the annex section.

For the parametric study the climate for Ljubljana, which is a mid-European climate, is taken into consideration.

No variations or analyses are made for the internal gains from the occupants, ventilation systems and heating systems. No photovoltaic system was analysed, nor taken into consideration either.

The research is limited to timber construction only, which is also termed as lightweight construction, since the influence of different thermal capacities of the materials as well as the thermal mass of the building were not taken into consideration.

The analysed wall elements are considered to be vertical with an inclination angle of 90°.

No analysis of the primary energy demand, which also includes DHW and electrical energy demand, was performed.

Although the performing of daylighting simulations could influence the findings relating to the optimal glazing size of energy-efficient buildings, in this study no daylighting calculations were performed. Due to its importance for the accurate definition of the optimal glazing size, it is necessary to perform daylighting calculations in further research.

A study of how economical such a method of construction would be is not the object of this research, although it should be performed in further research.

1.4 Outline of the dissertation

The dissertation consists of five chapters.

In Chapter 1, the base concept of the thesis with the up-to-date data of existing research is introduced. The main aims, objectives and limitations of the thesis are introduced as well.

The basic principles of timber construction are described in Chapter 2. Firstly the general properties of timber construction are listed and secondly the main preferences regarding the energy efficiency of timber buildings are presented. Two specific timber construction systems and their modifications, which are analyzed in our case study are described in detail.

In Chapter 3 the basic principles of energy-efficient design are presented, with the focus being on parameters that influence the energy performance of a building. The short presentation of legislation framework relating to the energy efficiency of buildings is presented in this chapter as well.

The numerical parametric study of the base-case study model and analyses of the calculated results are presented in Chapter 4. Analyses were carried out for different glazing-to-wall area ratios (0%-80%), for different orientations (N, S, W, E) and for different prefabricated timber construction systems (TF, TFCL, KLH).

The general conclusions of the thesis are listed In Chapter 5, together with a list of suggestions for further research.

2 BASIC PRINCIPLES OF PREFABRICATED TIMBER CONSTRUCTION

Timber is commonly associated with lightweight construction although it is ubiquitous as a building material. Timber construction is an important part of the infrastructure in a number of areas around the world. Brand new and improved features, having been introduced in the early 80's, brought about the expansion of timber-frame buildings all over the world. Over the past thirty years, timber construction has undergone major changes. The most important (Premrov, 2008) are the following introduced changes: transition from on-site construction to prefabrication in a factory, transition from elementary measures to modular building and development from a single-panel to a macro-panel wall prefabricated panel system. All of these greatly improve the speed of building.

The brick and concrete industry are responsible for about 10% of global CO_2 emissions into the environment, whereas wood, which is a natural raw material produced partly by the energy from the sun, helps the environment by absorbing and storing CO_2 while it grows. Respecting all these facts the energy-efficient properties of timber-frame buildings are, in comparison with other types of building, (brick, concrete, steel) excellent but not only because well-insulated buildings use less energy for heating, which is environmentally friendly, but also due to the extremely positive feelings of homeowners when living in such houses. Especially for regions rich in forests, building with timber represents an environmentally friendly construction approach, owing to a recommendation that building materials should not be transported over great distances and that regionally available materials should be used.

It becomes clear that timber construction is capable of offering significant solutions for the future of the built environment (Kaufman 2009), whereas working with timber demands expertise and the well-founded knowledge of experts. Allowing for the latter statement, our research work in the field of energy-efficient timber construction represents an important issue for the future development of timber buildings.

Regarding construction we can distinguish between the following basic timber construction systems:

- frame system
- balloon system
- massive system
- composite system.

Each system is additionally divided into different sub-systems, which is presented in Table 2-1. Additionally some systems are graphically presented in Figure 2-1. However, there are two main and competitive prefabricated structural systems, mostly used in residential timber buildings; the timber-frame system and the massive panel system.

In our study we accurately examine the influence of glazing on the energy performance of a single-family timber house, where the parameters such as glazing size, glazing type and the construction system vary. We make simulations on different wall elements, which are constructed in different timber frame or massive construction systems. Therefore both basic systems are presented in detail in the following sub-chapters.

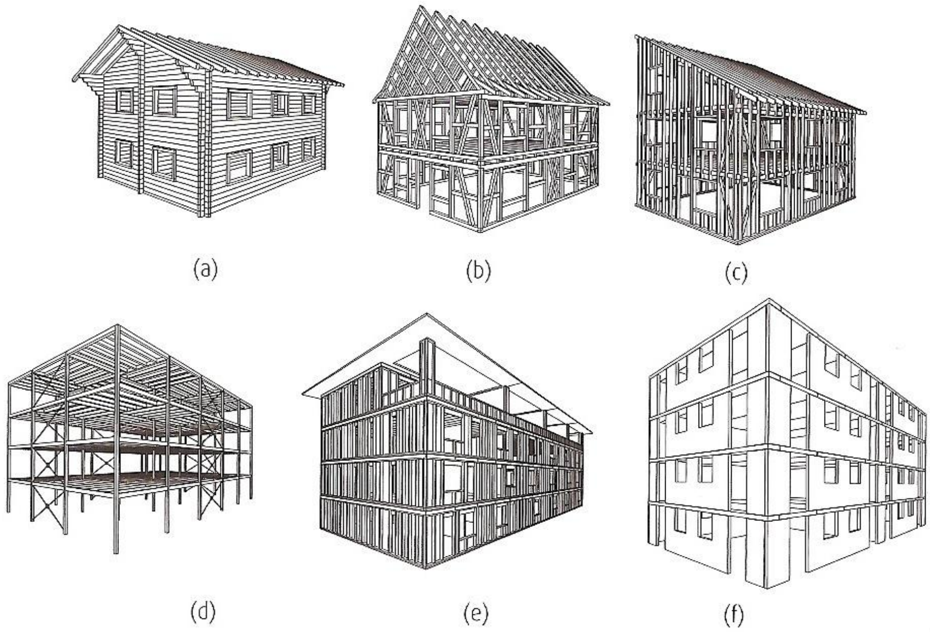
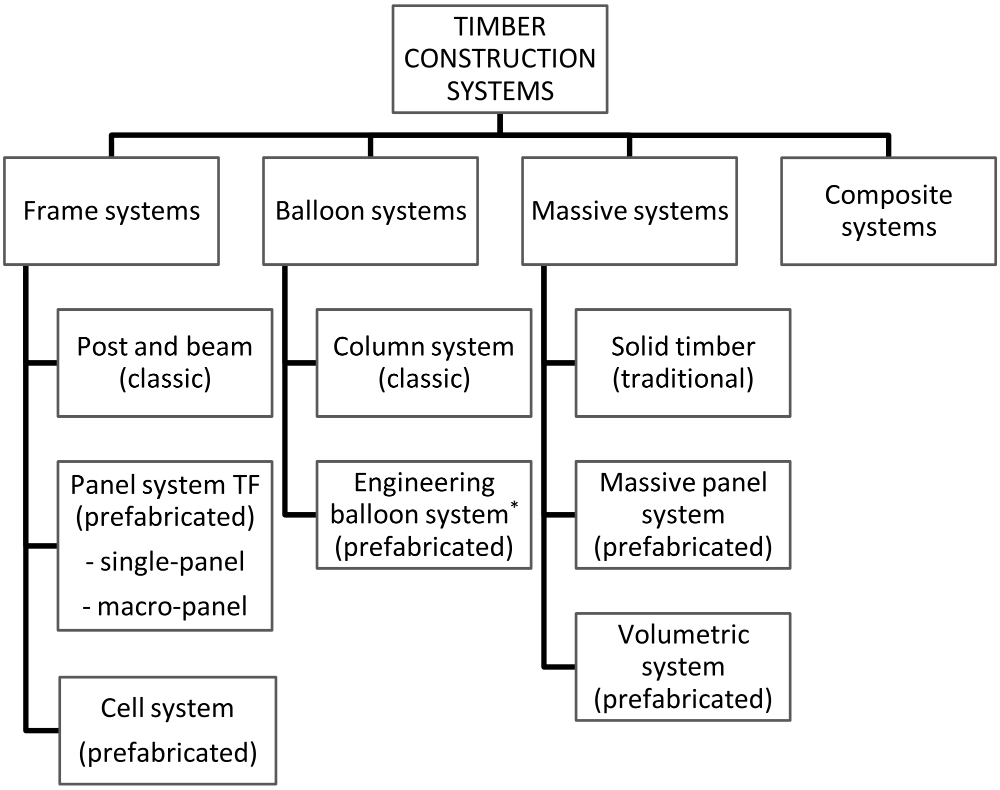


Figure 2-1: Timber construction systems: a.) Massive system –Solid timber, b.) Frame system – Post and beam, c.) Balloon system – Column system, d.) Frame system - Panel system (TF), e.) Frame system – Cell system, f.) Massive system – Massive panel system (KLH).

Table 2-1: Classification of timber structural systems.



* for engineering timber objects only, not for residential buildings

2.1 Timber-frame construction system

In timber-frame buildings the basic vertical load bearing elements are panel walls consisting of load bearing timber frames and sheathing boards. Because all elements are prefabricated (Figure 2-4a), the erection of such a building is very fast. Development from an old single-panel (Figure 2-3a) to a new macro-panel wall system (Figure 2-3b) in the middle of the 90’s additionally increases the speed of building dramatically. The wall elements with a total length of up to 12.5 metres, containing openings for doors and windows, are now completely produced in a factory (Kozem Šilih and Premrov, 2010). The construction systematically creates a floor-by-floor building; after the walls are constructed the floor platform for the next level is built, as it is schematically presented in Figure 2-2. Therefore, this system is very useful and popular for multi-storey buildings and interest in this system is growing around the world.

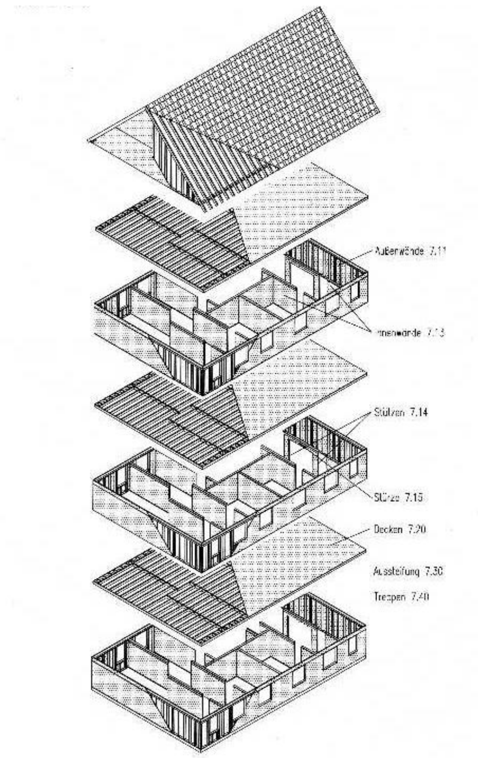


Figure 2-2: Scheme presenting a platform building of timber- frame panel construction

Dependent on the dimensions of the walls, one can distinguish between single-panel and macro-panel wall systems. In single-panel, which can also be called a classical single-panel system, a wall element usually consists of three timber studs with an overall wall width of 100 – 130 cm (Figure 2-3a). The macro-panel system was developed from the single-panel system in the last two decades and represents an important milestone in panel timber frame building. The aim of the system is that whole wall assemblies, including windows and doors, are totally constructed in a horizontal plane in a factory (Figure 2-4a) from where they are transported to the building-site (Figure 2-4b). Consequently, because there is practically no need for horizontal connections between wall elements, the houses are built in a substantially shorter period of time compared with the single-panel system.

a. b.

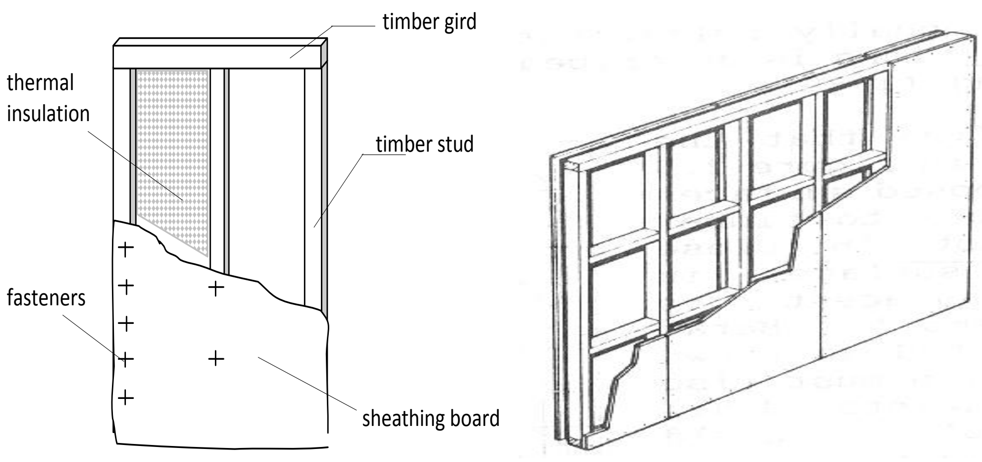


Figure 2-3: Composition of the wall element; a.) classical single-panel system, b.) macro-panel system.

Figure 2-3 shows how prefabricated timber-frame walls as main vertical bearing capacity elements, of usually typical dimensions with a width *b=1250* mm and a height *h=2500–2600 mm*, are composed of a timber frame and sheets of board-material fixed by mechanical fasteners to both sides of the timber frame. There are many types of panel sheet products available which may have some structural capacity such as wood-based materials (plywood, oriented strand board, hardboard, particleboard, etc., or fibre-plaster boards), originally started in Germany and recently the most frequently used type of board in Central Europe. Between the timber studs and girders a thermo-insulation material is inserted the thickness of which depends on the type of external wall. The sheathing boards on both sides of the wall can be covered with a 12.5 mm gypsum-cardboard.

a. b.

Figure 2-4: a. Factory manufacturing of prefabricated timber-frame walls. b. Assembly of macro-panel walls on a building-site

Producers usually offer a variety of construction composite elements of different types relating to energy efficiency. In this study we will treat three main typical wall elements, Timber-frame 1 (TF 1), Timber-frame 2 (TF 2) and Timber-frame 3 (TF 3), according to different thicknesses of the timber frame and thermal insulation. The main geometrical and material properties of the TF 1, TF 2 and TF 3 wall elements are listed in Table 2-2, moreover they are presented graphically in Figure 2-5.

Table 2-2: Composition of three typical macro-panel wall elements.

TF 1		TF 2		TF 3	
material	**thickness** [mm]	**Material**	**thickness** [mm]	**material**	**thickness** [mm]
rough coating	6	rough coating	6	rough coating	9
thermal insulation: EPS foam**	100	thermal insulation: MW*	100	thermal insulation: wood fibreboard	60
gypsum fibreboard	15	gypsum fibreboard	15	/	
thermal insulation: MW* between timber frame	160	thermal insulation: MW* between timber frame	160	thermal insulation: CF* between timber frame	360
vapour barrier	0.2	vapour retarder	0.2	OSB	15
/	/	thermal insulation: MW* between timber sub-structure	60	/	/
gypsum fibreboard	15	gypsum fibreboard	15	/	/
gypsum fibreboard	10	gypsum fibreboard	10	gypsum plasterboard	12.5
total thickness [mm]	306.2	total thickness [mm]	366.2	total thickness [mm]	456.5
U_{wall}–value [W/m^{2}K]	0.164	U_{wall}–value [W/m^{2}K]	0.137	U_{wall}–value [W/m^{2}K]	0.102

MW* - mineral wool, EPS foam** - expanded polystyrene foam, CF*** - cellulose fibre

Figure 2-5: Composition of three typical timber-frame macro-panel wall elements.

From the data presented in Table 2-1, as well as in Figure 2-5, we can notice a difference in insulation properties of the wall elements, such as the insulation thickness, number of insulating layers or insulation type. Consequently, the thermal transmittance of the three wall elements differs as well. The TF 3 system, which is also called a passive wall element, has a slightly different form of vertical stud (I-profile), so the section of this stud is slimmer in comparison to the TF 1 and TF 2 systems.

Additionally, three old prefabricated single-panel wall elements (Figure 2-3a) Timber-frame classical 1 (TFCL 1), Timber-frame classical 2 (TFCL 2) and Timber-frame classical 3 (TFCL 3), are analysed to prove some basic statements. The basic TFCL 2 system was produced in Slovenia in the late 70s and early 80s and was mainly used in the construction of residential buildings (Figures 2-6a,b). The other two selected systems, TFCL 1 and TFCL 3, are fictive systems obtained by adding or removing the insulation from the TFCL 2 construction system. The main geometrical and material properties of the TFCL 1, TFCL 2 and TFCL 3 wall elements are listed in Table 2-3, moreover the composition of the TFCL 2 wall element is presented graphically in Figure 2-6b.

Table 2-3: Composition of selected single-panel wall elements.

TFCL 1 – fictive system			**TFCL 2**			**TFCL 3 – fictive system**		
Material		**thick-ness** [mm]	**material**		**thick-ness** [mm]	**material**		**thick-ness** [mm]
wooden planks		22	wooden planks		22	wooden planks		22
timber sub-structure with open air gaps	bitumen sheet cardboard	0.5	timber sub-structure with open air gaps	bitumen sheet cardboard	0.5	thermal insulation MW*	timber sub-structure	40
timber sub-structure with open air gaps	timber frame	50	timber sub-structure with open air gaps	timber frame	20	bitumen sheet cardboard		0.5
bitumen sheet cardboard	timber frame	0.5	bitumen sheet cardboard	timber frame	0.5	/	/	/
thermal insulation MW*	timber frame	50	thermal insulation MW*	timber frame	80	thermal insulation MW*	timber frame	100
aluminium foil		/	aluminium foil		/	aluminium foil		/
Particleboard		13	particleboard		13	particleboard		13
gypsum plasterboard		10	gypsum plasterboard		10	gypsum plasterboard		10
total thickness [mm]		146	**total thickness** [mm]		146	**total thickness** [mm]		185.5
$\mathbf{U_{wall}}$**–value** [W/m^{2}K]		0.7	$\mathbf{U_{wall}}$**–value** [W/m^{2}K]		0.48	$\mathbf{U_{wall}}$**–value** [W/m^{2}K]		0.3

MW* - mineral wool, EPS foam** - expanded polystyren foam

a.

b.

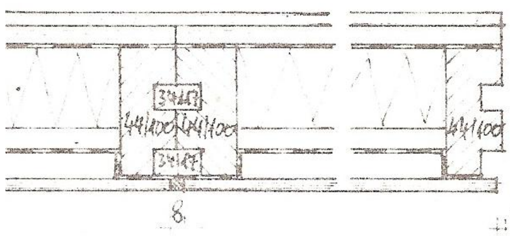


Figure 2-6: a.) On-site erection of single-panel wall elements in Varlovo housing estate in Maribor (1979), b.) Composition of TFCL 2 single-panel wall element.

On Figure 2-6a we can see Varlovo housing estate under construction. It was designed under the influence of Scandinavian architectural patterns and built with single-panel classical timber system.

2.2 Massive panel system

In the case of massive panel timber buildings the wall elements consist of cross-laminated timber boards, also commonly known as “cross-laminated timber - CLT” or “kreuzlagenholz – KLH” or X-lam (Figure 2-7a). As a result of the crossing of board layers its load distribution properties in both directions are very good. The width of a wall element depends on the number of layers, which is usually 3, 5 or even 7. The typical wall width of a three-layered wall element is 90 or 95 mm. Due to the gluing of longitudinal and transverse layers, the “working” of the wood is reduced to a negligible degree. Cross-laminated timber is a contemporary building material which has more uniform and better mechanical properties than solid timber and therefore presents an architectural challenge and an important trend in such a way as to ensure modern, energy efficient and seismic-resistant single family prefabricated houses and multi-storey prefabricated residential timber buildings. It is also suitable for office, industrial, and commercial buildings. Wall elements are completely prefabricated. Similarly the assembly of the building (Figure 2-7b) is done in a very similar way to that of timber-frame buildings and usually demands an almost equal amount of time to finish the building.

a. b.

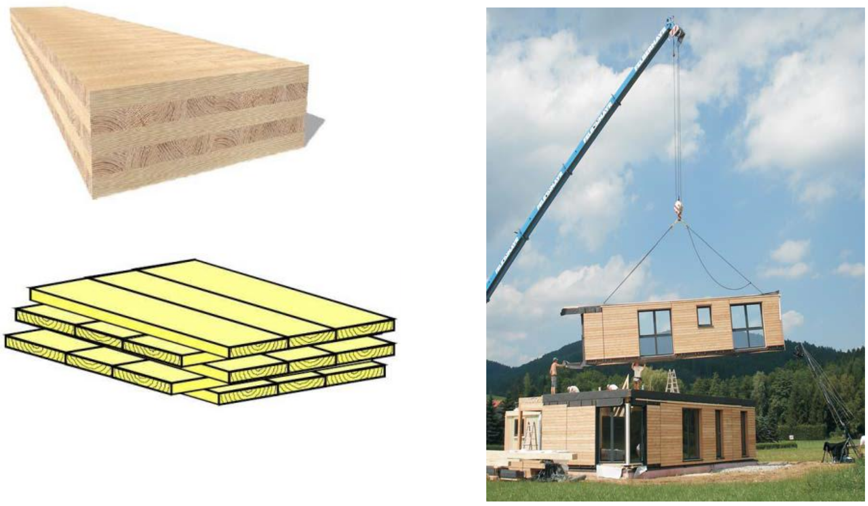


Figure 2-7: a.) Composition of cross-laminated panels b.) On-site erection of a house built using the massive panel system.

Producers usually offer a variety of massive panel elements of different thicknesses, which can form, in composition with different thicknesses of insulating materials, wall composite elements of different thermal properties. In this study we will treat three main typical wall elements according to different thicknesses of the timber panel and thermal insulation. The main geometrical and material properties of the KLH 1, KLH 2 and KLH 3 wall elements are listed in Table 2-4.

Table 2-4: Composition of selected massive panel wall elements

KLH 1		**KLH 2**		**KLH 3**	
material	**thickness** [mm]	**Material**	**thickness** [mm]	**Material**	**thickness** [mm]
rough coating	6	rough coating	6	rough coating	6
thermal insulation: MW*	180	thermal insulation: MW*	180	thermal insulation: MW*	220
cross laminated timber	95	cross laminated timber	95	cross laminated timber	142
/	/	timber sub-structure with thermal insulation: MW*	60	timber sub-structure with thermal insulation: MW*	60
gypsum fibreboard	15	gypsum fibreboard	15	gypsum fibreboard	15
gypsum fibreboard	10	gypsum fibreboard	10	gypsum fibreboard	10
total thickness [mm]	306	**total thickness** [mm]	366	**total thickness** [mm]	453
U_{wall}–value [W/m^{2}K]	0.181	**U_{wall}–value** [W/m^{2}K]	0.148	**U_{wall}–value** [W/m^{2}K]	0.124

MW* - mineral wool, EPS foam** - expanded polystyrene foam

According to the data presented in Table 2-4, the selected compositions of wall elements differ in the construction thickness of a massive panel and in the insulation thickness. Due to these differences, the thermal transmittance of each individual wall element differs as well. KLH 1 with a U-value=0.181 W/m^{2}K, KLH 2 with a U-value=0.148 W/m^{2}K and KLH 3 with a U-value=0.124 W/m^{2}K are analysed in our study and compared to timber-frame wall elements.

3 ENERGY-EFFICIENT BUILDING DESIGN

The definition of an energy efficient architectural design is related to the specific design approach comprising exactly defined parameters which influence the energy balance of buildings. The basis of energy-efficient house design is to take advantage of as many renewable energy sources and of climatic conditions in combination with low energy technology as possible in order to reduce the need for conventional building technology which is inefficient or consumes a lot of fossil fuel energy. Parallel to a reduced demand for a fossil fuel to heat the building, the CO_2 emissions are reduced as well. Therefore commonly used terms, such as climate-conscious architecture, bio-climatic architecture or energy-efficient architecture, present specific approaches in contemporary architectural building design, which have to be applied in conjunction with the structural and aesthetic aspects of architecture.

There exist few classifications of energy-efficient houses that differ from each other minimally regarding energy demand. As an example a low-energy house is a house with an annual requirement for a space heating energy demand of less than 50 kWh/m^{2}a, however the requirements differ from one country to another, while for a passive house this requirement is strictly defined with the value being lower than 15 kWh/m^{2}a in all countries. Besides the space heating energy demand, additional parameters, such as the U-value of external building elements, the air tightness of the building's envelope, window quality, building form etc., have to meet specific demands.

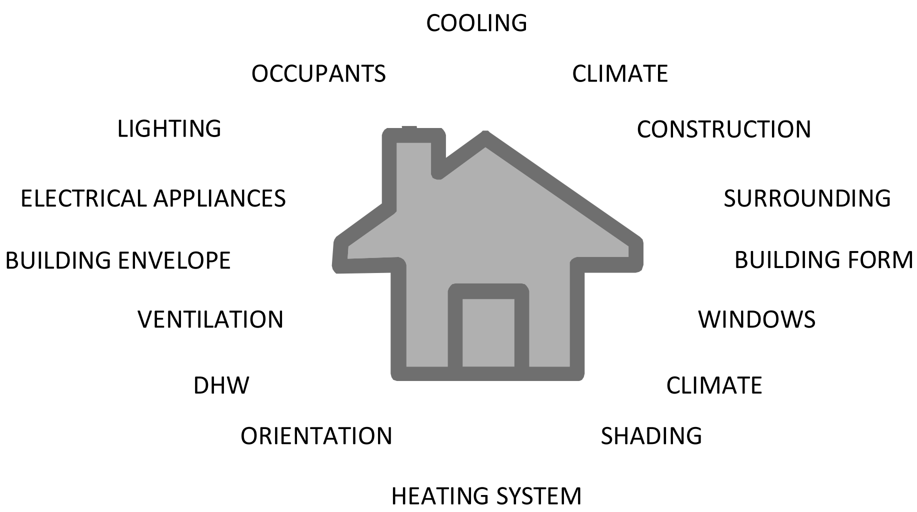


Figure 3-1: Different parameters that influence the design of an energy-efficient house (according to Persson 2006).

In an energy-efficient house the specified low energy consumption can be achieved by well-considered design that includes a proper selection of building materials, excellent envelope insulation, air tightness, thermally efficient glazing, a compact form of the building, construction without thermal bridges and passive solar design which is preconditioned by appropriate southern orientation with well-designed shading. On the other hand active house design systems include heat recovery ventilation, ground source heat pumps, lightning with low energy lamps and more.

3.1 Legislative framework

Burdening of the environment and its impact on climate change have launched new document preparation, in compliance with the European Union (EU) guidelines whose implementation is nevertheless becoming ever more dispersed among different sectors (Sitar et al. 2009). The European Union adopted a wide-ranging package on climate change, which focuses on three areas: emissions cuts, renewables and energy efficiency. Although changes have been made to the original package from 2008, the overall 20-20-20 targets have been kept: a 20% reduction in emissions of greenhouse gases by 2020, compared with 1990 levels; a 20% increase in the share of renewables in the energy mix; and a 20% reduction in energy consumption. Due to the fact that buildings are responsible for approximately 40 % of end energy use in the EU as well as for 35% of total CO_2 emissions., the targets are binding for buildings. Therefore the energy performance of existing buildings has to be improved through a complex process of energy efficient renovation and the sustainable construction of energy-efficient buildings with the use of renewables has to be performed.

The Directive on the energy performance of buildings (EPBD 2002/91/ES) which was adopted in 2002 was inspired by the Kyoto Protocol which committed the ratifying states to reduce CO2 and five other greenhouse gas (GHG) emissions. The EPBD (2002/91/ES) required all EU countries to enhance their building regulations and to introduce energy certification schemes for buildings. All countries were also required to have inspections of boilers and air-conditioners. As a result of the slow transfer of EPBD (2002/91/ES) requirements into legislation and practice, the new updated EPBD (2010/31/EU) was published in 2010. According to the Brittain's (2010) interpretation the key provisions of the recast EPBD 2010 include requirements listed in further text, relating to: the setting of minimum energy performance requirements for new buildings and existing buildings that are undergoing major renovation, the taking into account of the feasibility of using high energy-efficient systems before the construction of a new building begins, buildings owned or occupied by the public sector which need to be "nearly zero-energy" by 31 December 2018, financial incentives to support the implementation of the EPBD 2010, investments in the efficient use of energy (households, public and service sectors, industry), investments in environmentally friendly energy production and the use of Energy performance certificates, which must be displayed in buildings over 500m2 (instead of 1000m2 under the EPBD 2002) that are occupied by public authorities and frequently visited by the public.

The Ministry of the Environment and Spatial Planning of the Republic of Slovenia (MOP) is responsible for the transfer of the EBPD into Slovenian legislation. Due to its complexity the transfer was accomplished through three legal acts which are the Construction Act (ZGO–1), the Energy Act (EZ) and the Environmental Protection Act (ZVO-1) and additionally through legal rules, especially through Rules on the efficient use of energy in buildings (PURES). According to the updated EPBD 2010 requirements, the update of the Rules on the efficient use of energy in buildings is to be adopted in 2010. According to the explanation in Šijanec Zavrl (2010), PURES 2010 prescribes the planning of a building considering the principles of bio-climatic design, which reduces the energy demand for heating and cooling, as well as the total final energy demand. By the end of 2014, the annual energy demand for the heating of new buildings has to be in a range between 30 - 50 kWh/m^{2}a, while from 2015 this range will be between 20 - 40 kWh/m^{2}a, which. The cooling demand for new buildings is limited as well to a maximum of 50 kWh/m^{2}a. The maximal total energy demand for operating of all systems has to range between 170 and 200 kWh/m^{2}a. It is essential to use renewable energy sources to ensure a minimum end-energy use of 25%. There are also many technical obligations which have to be implemented, such as limiting U-values for external construction elements ($U_{wall-max}$ =0.28W/m^{2}K). The three-pane glazing is not prescribed, although it will be necessary to achieve a class A or B rating regarding the Classification of energy-efficient houses (see Table 3-1). Other requirements are related to the specific performance of ventilation, hot water generation and lighting.

According to the Slovene legislative framework, particularly to the Energy Act, the system of energy performance certification is defined in Rules on the methodology of construction and issuance of building energy certificates. On the basis of these rules, the classification of energy-efficient houses was carried, which is listed in Table 3-1. For the certification of the buildings two methods are defined. As a first option a calculation procedure is suggested for the determination of energy use parameters, which is based on the SIST EN ISO 13790 standard. And secondly it is expected to use the method of measuring actual average energy use over a three year period, based on SIST EN 15206.

Table 3-1: Classification of energy-efficient houses on the basis of "Rules on the methodology of construction and issuance of building energy certificates".

Degree / Classification in accordance with the rules	Generally used classification in practice	Q_h* [kWh/m^{2}a]	Variation of execution (according to Praznik and Kovič, 2010)
Class C	minimal requirements for low-energy house	35 – 50 (60)	classical prefabricated construction, conventional heating system, contemporary windows (doors), no central ventilation system
Class B2	low-energy house	25 – 35	thermally improved building envelope
Class B1	better low-energy house	15 – 25	thermally improved building envelope + HRV** + HP***
Class A2	passive house	10 – 15	additionally thermally improved building envelope + HRV + HP
Class A1	1-litre house	≤ 10	additionally thermally improved building envelope + HRV +HP + improved U-value of windows (doors)

* specific annual heating demand, **heat recovery ventilation, ***heat pump

The Ministry of the Environment and Spatial Planning of the Republic of Slovenia encourages – directly or through the Eco Fund – certain activities, incentives for investments in the efficient use of energy (households, public and service sectors, industry) and investments in environmentally friendly energy production (renewable energy sources, cogeneration systems). In principle, the Ministry also supports energy counselling and the raising of awareness, informing and energy user training or other target group training (Sitar et al., 2009a).

3.2 Energy-efficient building design principles

Energy efficient design requires a careful balance between energy consumption, energy conservation and energy gain. If the conservation is principally related to compactness and the homogeneous insulation of the building skin, the energy gain depends on passive use of solar energy (Gonzalo and Haberman, 2006). From a planning perspective the building proportion and orientation, which depend to a certain degree on building typology, are of great importance. Furthermore, the location and its belonging climate play a vital role in energy-efficient building design, since the building with its properties has to adapt completely to the existing climate conditions.

3.2.1 Climate and location

Climate and location data are important due to different temperatures and different values of solar radiation. For the calculation of the heating and cooling demand of a building, the climatic data for a specific location is necessary. According to Szokolay (2008), the main climatic elements regularly measured by meteorological organisations are temperature, humidity, air movement i.e. wind, precipitation, cloud cover, sunshine duration and solar radiation. As the four environmental variables directly affecting thermal comfort are temperature, humidity, radiation and air movement, these are most important for the purposes of building design.

Regarding the design principles in relation to the sun, there are two essential aspects to understand: the apparent movement of the sun and the energy flows from the sun, which have to be handled in a way of making use of it or excluding it. The position of the sun can be determined by two angles, altitude and azimuth. The solar altitude angle or solar elevation angle is the angle between the direction of the geometric center of the sun's apparent disk and the idealized horizon, while the solar azimuth angle is defined as the angle from due north in a clockwise direction (see Figure 3-2).

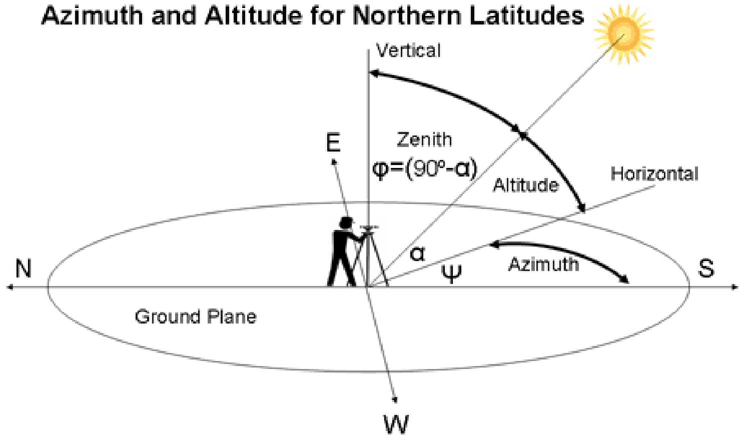


Figure 3-2: Azimuth and Altitude angles for northern latitudes.

The relatively simple and practical tools for depicting the sun's apparent movement is called Sun-path diagram.

Solar radiation is a quantity that can be measured with an irradiance value in W/m^2 or with an irradiation value in J/m^2 or Wh/m^2, which is described as an energy quantity integrated over a specified period of time. In our human perception we can distinguish:

- UV radiation (20-380 nm), which is mostly absorbed by the atmosphere if UV is below 200 nm,
- light, or visible radiation (from 380 to 700 nm),
- shortwave infrared radiation (700-2300 nm), or thermal radiation.

Large variations in irradiation appear in relation to different locations on the Earth, which is dependant on the angle of incidence, atmospheric depletion and on the duration of sunshine, i.e. the length of the daylight period and to a lesser extent also on the local topography. For any selected point in time the solar radiation can be calculated. The global irradiance (G in W/m^2) incident on a particular surface consists of two main components, which are the direct component (Gb) and the diffuse component (Gd). The direct component reaches the Earth's surface along a straight line from the sun, while the diffuse component represents the radiation scattered by the atmosphere. An additional component is the reflected component (Gr), which is relevant for non-horizontal surfaces that may be reached by radiation reflected from the ground or nearby surfaces.

3.2.2 Orientation

Orientation is a parameter which is defined for each of the external walls of the building. The orientation is defined as the angle between the normal to the wall and the north cardinal direction. For example the south orientation is defined by the angle of 180°, north by the angle of 0°, east by the angle of 90° and west by the angle of 270°. According to general directions for an energy-efficient house design, buildings should be oriented mainly to the south. At this point we have to give an additional explanation regarding the term "south". In literature the term "facing the equator" or "equatorial" orientation is used frequently, to describe the orientation in respect to the north and south of the Earth's hemisphere. For the northern hemisphere the equatorial orientation is the south orientation. While in our base-case study the house is placed in Ljubljana, we are going to use the terms south (S), north (N), west (W) and east (E) to describe the selected orientation in further text. The south orientation of external walls with a large glazing area causes an increase in heat gains due to a large amount of solar radiation. To prevent overheating in the summer period a well-designed system of solar control is desired. According to Pagliano et al. (2007) the percentage of glazing surface in relation to the floor area (glazing-to-floor area, AGAF) should be around 20% for the south orientation and 5% for the north orientation for a passive design.

3.2.3 Building form

The general building form is defined by all the external elements, such as the walls, floor slab and roof which separate indoor spaces from outdoor spaces. Regarding quantity one can distinguish between different typologies using the parameter of compactness (Ford et al. 2007). Compactness is defined as the ratio between the total treated volume of a building and its total heat loss surface area, also called the building's envelope.

$$F_c = V / A \ [m] \qquad \text{(Eq. 3-1)}$$

- F_c – factor of of compactness
- V - total treated volume of a building
- A - total heat loss surface area

The variable parameter related to the form of the building is in some cases called the shape factor expressed by the opposite relation (F_s=*A/V).* From Eq. 3-1 we can see that if we carry out a comparison of two buildings with an equal volume, the one with a higher compactness factor has less external surface area, which means that this building's form is more compact. According to the general directions for an energy-efficient house design, the correct form should be a house with a high level of compactness, due to the reduction of transmission heat losses through the existing envelope. As the form of a building becomes more compact, the heating demand becomes lower. As an example we can mention that the suggested maximal compactness for a passive house is 2.2 m. At this point we have to add that the parameter of compactness should be further dissected with regard to the composition of the building's envelope, as the building envelope is composed of a different share of transparent and opaque surfaces, which definitively influences the quantity of transmission heat losses as well as solar heat gains.

3.2.4 Thermal behaviour of buildings

In order to understand the energy efficient design principles, some basic knowledge on thermal behaviour of buildings is required. According to Szokolay's (2008) Introduction to Architectural Science the building can be considered as a thermal system, with a series of heat inputs and outputs, such as internal heat gain (Qi), conduction heat gain or loss (Qc), solar heat gain (Qs), ventilation heat gain or loss (Qv) and evaporative heat loss (Qe). The thermal balance of the building is preconditioned by the relationship between heat inputs and outputs, where the sum of all heat flow terms (Qi+Qc+Qs+Qv+Qe) is zero.

The most significant energy input into a building is solar radiation, therefore apart from solar radiation, a special attention has to be focused to this specific energy input and its control.

Solar heat gain

Solar heat gain refers to the increase in temperature in a space, object or structure that results from solar radiation. The amount of solar gain increases with the strength of the sun, and with the ability of any intervening material to transmit or resist the radiation. According to Szokolay's (2008) explanation the solar heat gain is considered differently for transparent and opaque surfaces. In both cases the global irradiance incident on the surface must be known. For transparent elements i.e. glazing surfaces, the solar gain is the product of the global irradiance incident on the surface, the size of the glazing area and the solar gain factor (sgf or g-value) of the glazing. Some part of the incident radiation is reflected, some transmitted and some absorbed within the glass element. The solar gain factor indicates what part of the incident radiation reaches the interior. For the opaque elements the solar heat gain is treated through the sol-air temperature concept (Szokolay 2008).

Solar control

The main task of solar control is to determine the situation when solar radiation is desired, for instance solar heating for the unheated period, or when it should be excluded due to overheating. Therefore shading devices have to be designed in a selective way - they should allow radiation to reach the building in winter, while in the summer period they should block radiation. Regarding the shading design of a building, of which a task is to control the sun's penetration, the most effective tools are external shading devices that can be divided into three basic categories:

- vertical devices
- horizontal devices
- egg-crate devices.

Vertical devices, e.g. vertical louvres or projecting pins are characterized by horizontal shadow angles (HSA). They are most effective when the sun shines towards one side of the direction the window is facing. The next category is that of horizontal devices, e.g. projecting eaves or horizontal louvres, which are characterized by a vertical shadow angle (VSA). They are most effective when the sun shines from almost the opposite side to the shaded window. Finally the egg-crate devices, e.g. concrete grille blocks or metal grilles produce a complex shading mask in a combination of the horizontal and vertical elements, therefore they can´t be characterized by a single angle. A stereographic projection can be used for the simulation of solar access and consequently the shadow angle.

Natural ventilation

The term 'ventilation' refers to three totally different processes in a building. Firstly it can be explained as the supply of fresh air, due to smell and CO_2 removal. Next it is used to remove some internal heat when the interior temperature rises above the exterior temperature. Ventilation also serves the purpose of promoting heat dissipation from the skin.

The air exchange rate (N) is the number of times the total building volume of air is replaced (number of air changes per hour).

The ventilation rate can be found as:

$$vr = N \times V / 3600 \ [m^3/s] \qquad \text{(Eq. 3-2)}$$

In order to maintain the internal air quality, a minimum of 8-10 litres of fresh air per second per person is required, which is the basis for a winter period. In the summer period ventilation can also be required to remove internal heat gains, therefore higher ventilation rates are necessary.

Natural ventilation which is driven by either wind or thermal forces is the process of an air-exchange through window openings or ventilation vents and should be controlled manually or automatically. Uncontrolled ventilation through openings as well as an uncontrolled infiltration through the building's envelope should be minimized to avoid unwanted heat loss in winter and heat gains in summer. The most effective are cross and stack ventilation, while single-sided natural ventilation is usually less effective (Figure 3-3).

a. b. c.

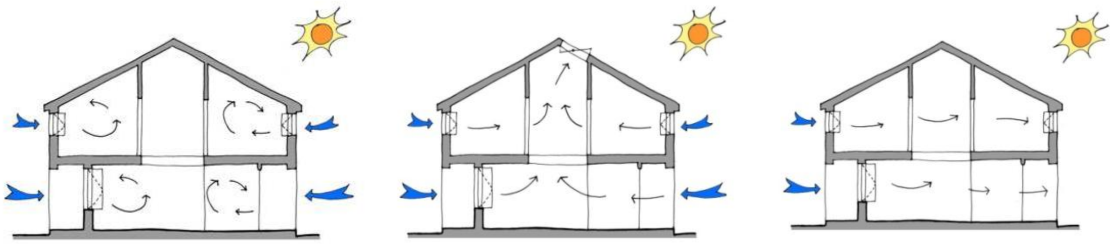


Figure 3-3: Natural ventilation: a.) single-sided, b.) stack-ventilation, c.) cross-ventilation.

Night ventilation is used in an energy efficient design concept where in the night-time cool air is drawn into the house to flush out any residual heat from the day and to pre-cool the internal surfaces for the following day.

Mechanical ventilation is a process of ventilation which requires electrical energy for its operation. A heat recovery ventilator (HRV) can help make mechanical ventilation more cost-effective by reclaiming energy from exhaust airflows (recovering). HRVs use heat exchangers to heat or cool incoming fresh air, recapturing 60-80 % of the conditioned temperatures that would otherwise be lost.

In Design guidelines for low-energy homes Ford et al. (2007) explain that the choice between mechanical and natural ventilation for housing depends on the climate characteristics, the air tightness, the value of heat recovery and of the occupants' preferences as well.

Internal gains

Internal heat gains (Qi) are the sum of heat generated inside the building from occupants, lighting and household appliances.

3.2.5 Energy-efficient design of building components

Technical components and construction should be harmonized in every detail with the requirements determined by use and climate. The heating requirement of a building is largely determined by the heat losses through the building skin, which is usually composed of transparent and non-transparent building components. As a result of their U-value, glazing areas have much higher heat transmission losses than non-transparent building components (Gonzalo and Habermann, 2006). On the other hand the glazing areas provide a basis for the passive solar heat gains.

Thermal mass

Thermal mass is a building design concept of providing inertia against temperature fluctuations. This effect is provided by materials within a building that can absorb and store large quantities of heat, i.e. materials with a high thermal capacitance. Timber is not a suitable material to provide such an effect due to its low thermal storage capacity.

Timber construction is treated as a lightweight construction system, while materials that can store more heat, like brick and concrete, are composites of a heavyweight construction system.

In the energy efficient design concept the proper use of thermal mass can be a considerable advantage for the energy balance of a house in the winter and summer periods. Heat gains absorbed during the day can be released into space at night during the winter period, while in summer stored heat is released into the external atmosphere through night time convection, therefore the overheating does not occur. In our base-case study the thermal mass effect is not the subject of this research.

Insulation

The selection of the type and quantity of insulation depends on the climate, the composition of the construction element that has to be insulated and of the general building properties. For ground insulation the depth of the floor slab is important as well. However ground insulation is usually thinner than that of the building elements adjacent to the ambient air, especially if the floor slab is constructed at a depth of more than one meter, where the temperature of the ground is almost constant, slightly above the annual average air temperature. The materials used for ground insulation have to be pressure and humidity resistant. The wall insulation reduces the average heat flow through the external wall element. The effect is characterised by the heat transmission coefficient (U-value or in further text U_{wall}-value [W/m^2K]), which signifies the heat flow through 1 square meter of wall area at a constant temperature difference of 1 K (=1°). Sufficient wall insulation helps to reduce the heat gains into a building in the summer period and limits the transmission heat losses when the external temperature is lower than the desired temperature of the interior space. The latter explanation regarding heat transfer reduction is valid for the roof insulation as well. Especially in the summer period the roofs are even more exposed to solar radiation than walls, due to their inclination angle and to no shading elements being present in their surroundings.

For a lightweight construction system, which is the object of our research, the typical U-value of building elements that compose a thermal envelope has to be below 0.20 W/m^2K.

Thermal bridge-free construction

For the energy efficient house design it is necessary to reduce the thermal bridges to a minimum, which can generally be achieved by making sure that there is no interruption of the insulating layer. Windows present an exception, while a thermal envelope is interrupted at the point of the window's placement, although the thermal bridge can be maximally reduced if a highly insulated window is installed in the insulating layer. The thermal bridge-free construction helps to reduce transmission losses or transmission heat loads.

Construction system

The most appropriate construction systems for energy-efficient house construction are the massive brick and lightweight timber construction systems. Although if constructed with brick and other high thermal capacity materials, the advantages of a thermal mass effect can effectively be used to improve a building's thermal balance, there are many advantages if constructing with timber, which have already been described in Chapter 2.

Infiltration and air tightness

The leaking of a building envelope results in a number of problems which can occur especially during the winter period, when cold air infiltration increases the energy demand for heating. In older buildings this leaking was accepted to a lesser extent with the explanation that it contributes to fresh air exchange, although the truth is that it cannot provide a sufficient quantity of fresh air and in that manner cannot replace the necessary ventilation.

With regard to the requirements for energy-efficient house design, the level of air tightness differs from one class to another. In the case of a passive house standard, where mechanical heat recovery ventilation is required, the air tightness of a building has to be excellent. The air leakage must not exceed 0.6 h^{-1} (volume per hour) at a pressure differential of 50 Pa, which is measured by the so-called Blower-door test. In houses with no mechanical ventilation system, the air tightness should be accordingly smaller. The air tightness is achieved using an airtight layer running inside the thermal envelope of a building. The appropriate material to use for an airtight layer are internal plaster, plywood board, particle board, OSB, durability-stabilized plastic foils, bituminous felt and finally a frequently used tear-proof building paper. Special attention has to be paid to the building element junctions, where a certain degree of air tightness has to be assured as well.

Windows

Windows are very important for the energy-efficient construction of residential and commercial buildings. They are responsible for heat transfer, provision of daylight, ventilation, weather protection and acoustic insulation. Due to the high heat conductivity of the glass, an unwanted heat gain or loss takes place between the building and the surroundings. There are several ways to improve energy conservation and windows sustainability: use of low-emissivity (low-e) coatings; replacement of air with inert gases; adjustment of the gap between glass panes in double or triple glazing. (Joseph and Tretsiakowa-McNally, 2010).

A window consists of a window glazing and a window frame. The window performance may be described by its characteristics such as the U-value and the g-value. The U-value is the thermal transmittance, separately defined for a glazing and for a window frame while the g-value is the coefficient of the permeability of total solar radiation energy denoted with a number between 0 and 1. In addition the air leakage has an influence on the energy performance of the window when it is installed in a building. Heat losses through windows are proportional to their U-value so, in general, it is convenient to diminish the U-value for windows in all orientations. However, on the other hand, when the U-value is decreased the radiation passing through the window is lower too and consequently solar gains are reduced (Ford et al. 2007).

According to Gustavsen et al. (2007) there are two different ways of calculating the thermal transmittance (U-value) of glass panes and window frames, in particular (ASHRAE or ISO procedures). The two approaches are different in the way they treat the effect of the glazing spacer on the heat transfer through the frame and the glazing unit near the frame, and the two calculation approaches result in different frame and glass U-values.

Regarding the window glazing properties the following parameters are important:

- glass (single, double, triple, etc.)
- spacer (al, swisspacer, thermix, etc.)
- cavity gas (air, argon, krypton, xenon)
- glass coating (low-emissivity coatings, solar control coatings, etc.)

The window glazing U-value (U_g) depends on the number of panes, the cavity thickness, the choice of cavity gas and the number of low-emissivity coatings which is, according to Gustavsen et al. (2007), presented in Table 3-2.

Table 3-2: Typical Ug-values for window glazing depending on the number of glass panes, selection of cavity gas and number of low-emissivity coatings.

Glazing U-value [W/m²K]				
Glazing Configuration [mm]		Cavity Gas		
		Air	Argon	Krypton
No low-emissivity coating	4	5.8	-	-
	4-12-4	2.9	2.7	2.6
	4-12-4-12-4	2.0	1.9	1.7
Low-emissivity coating	4-12-E4	1.6	1.3	1.1
	4-12-4-12-E4	1.3	1.0	0.8
	4E-12-4-12-E4	1.0	0.7	**0.5**

(E = low-emissivity coating, each cavity 12 mm, 4 mm thick glasses)

In our base-case study we have selected the glazing with the lowest U_g- value of 0.51 W/m^{2}K, which is glazing with three layers of glass, two low-emissivity coatings and krypton in the cavities for a normal 4E-12-4-12-E4 configuration. The g-value of such glazing is 0.52.

Regarding the window farme properties the following parameters are important:

- various frame or casing structures, fixed or opening windows, etc.
- structural frame materials
- highly thermal insulating materials

According to Menzies et al. (2005) the material of a window frame, which normally has a higher U-value than the glazing component, must be considered carefully. Generally, wooden frames provide better thermal insulation compared to aluminium or plastic ones. Moreover, lower values of embodied energy make timber frames more sustainable than aluminium, PVC, steel and aluminium-clad timber types of frames.

Various window frame types which include the insulating materials in addition to the structural materials are listed below:

- wood frame
- wood frame with insulation-filled Al cladding
- PVC frame
- PVC frame with insulation-filled Al cladding

- Al frame
- fixed wood and Al frame
- glass facade system

This division is based on the actual frames found on the market (Gustavsen et al. 2007)

In our base-case study the frame type is a wooden window frame (INTERNORM - ed[it]ion passiv - with a 'Thermix' spacer) with insulation-filled aluminium cladding and a 'Thermix' spacer. The window frame U-value (U_f) is 0.73 W/m^{2}K, while the frame width is 0.114 m.

There exist several certification schemes for the definition of the energy-efficiency requirements of a window. As an example the requirement regarding window properties that fulfil the demands for a passive house is shown:

- $U_g \leq$ 0.80 W/m^{2}K (window glazing)
- $U_w \leq$ 0.80 W/m^{2}K (window as a whole - installed)
- U_f so that $U_w \leq$ 0.80 W W/m^{2}K (window frame).

3.2.6 Active controls

Heating and ventilation

For the heating of the internal space condensing boilers, ground source heat pumps and radiant panels for surface heating (walls, slabs, ceilings) are highly efficient solutions. In low-energy houses the ventilation system is necessary to ensure suitable indoor air quality, therefore heat recovery from the outgoing exhaust air is convenient. A heat recovery ventilator (HRV) can help make mechanical ventilation more effective by reclaiming energy from exhaust airflows (recovering). HRVs use heat exchangers to heat or cool incoming fresh air, recapturing 60-80 % of the conditioned temperatures that would otherwise be lost. In a typical system configuration air is supplied to the living room and bedrooms and removed from the kitchen and bathroom. Heat recovery ventilation in combination with a ground source heat pump unit can ensure adequate heating during cold periods as well as cooling during the summer period. The installation of a subsoil heat exchanger under or close to a building uses the active temperature difference between the ground temperature and the local air temperature, which provides potential for heating and cooling a building. Hot water generation is provided by a heat pump and by solar collectors in combination with a boiler and an electric heater. For the converting of solar radiation into direct electricity, i.e. generating electrical power, the solar photovoltaic (PV) method can be used.

Lighting

In order to ensure an adequate daylighting scenario and to reduce the need for artificial lighting, which consumes electrical energy, the windows should be designed in such a manner so as to give evenly distributed lighting conditions in the interior spaces. Therefore apart from the window size the window displacement is of great importance as well. Regarding artificial lighting it is important to use energy-saving light bulbs and luminaires.

Appliances

As the heating and cooling demand of buildings is limited for an optimal low-energy house design, the relative importance of energy demand by the household grows. The use of energy-efficient appliances contributes to the reduction of the total primary energy demand. Apart from the proper selection of appliances, the method and frequency of their can use also influence energy demand.

Respecting all the parameters listed above, the energy efficient building design is understood as an extremely complex process which demands an accurate approach in planning and selecting of each individual parameter.

4 NUMERICAL CASE STUDY

In this chapter the numerical case study of a two-storey house and its parametric analysis of an increased-proportion-of-the-glazing-surfaces impact on energy demand for heating and cooling is presented.

4.1 Description of the base-case study model

4.1.1 Plan

A model of a two-storey single-family house was selected out of sixteen projects created in the workshop called Timber low-energy house. The selected model was modified minimally in order to make more comparable starting point conditions for all of the main cardinal directions of the house. The house was designed with a low-energy standard. The external horizontal dimensions are 11.66 m x 8.54 m for the ground floor and 11.66 m x 9.79 m for the upper floor (Figure 4.1). The total heated floor area is 168.36 m^2, the total heated volume is 437.84 m^3. The shape factor (*Fs=A/V*) of the model is 0.38 m^{-1}.

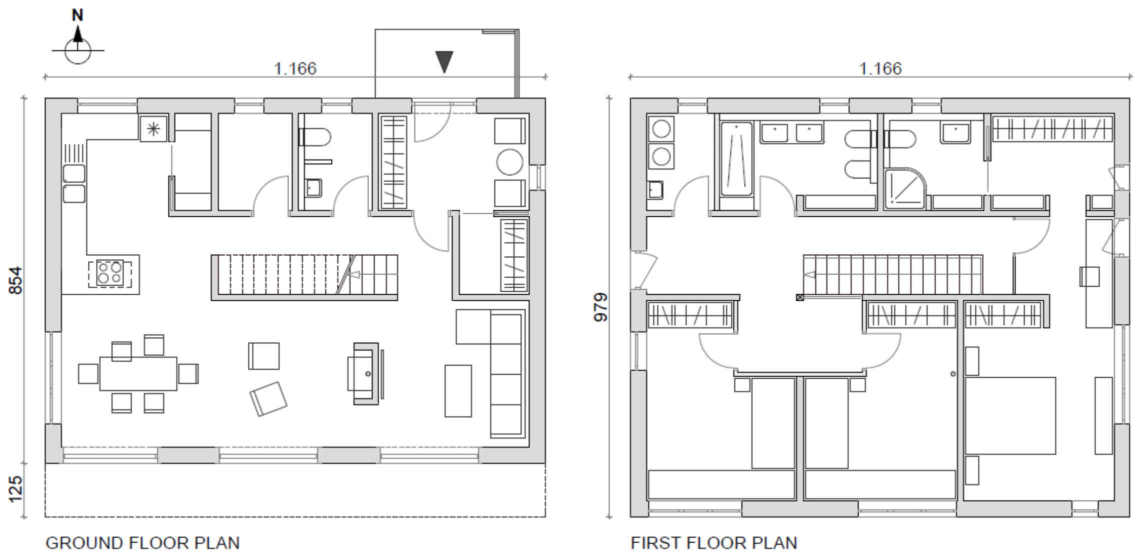


Figure 4-1: Ground plan of base-case study model

4.1.2 Construction

The exterior walls are constructed using a timber-frame macro-panel system. The exterior wall U-value is 0.137 W/m^{2}K. Owing to the characteristics of the exterior wall the base-case model was labelled as TF 2. The U-values of the other external construction elements are 0.135 W/m^{2}K for the floor slab, 0.135 W/m^{2}K for the flat roof and 0.13 W/m^{2}K for the south-oriented overhang construction above the ground floor area. It is important to underline that the presented research is limited to timber construction only, which is also termed as lightweight construction, since the influence of the different thermal capacities of the materials as well as the thermal mass of the building were not taken into consideration

4.1.3 Windows

A window glazing (Unitop 0.51 – 52 – UNIGLAS) with three layers of glass, two low-emissive coatings and krypton in the cavities for a normal configuration of 4E-12-4-12-E4, each cavity being 12 mm thick, with 4 mm thick glass panes, was installed. The glazing configuration with a g-value of 52% and a U-value (U_g) of 0.51 W/m^{2}K assures a high level of heat insulation and light transmission (http://www.uniglas.net). The frame type is a wooden window frame (INTERNORM - ed[it]ion passiv - with a 'Thermix' spacer) with insulation-filled aluminium cladding and a 'Thermix' spacer. The window frame U-value (U_f) is 0.73 W/m^{2}K, while the frame width is 0.114 m. The 'Thermix' spacer which is constructed from PVC and high grade steel reduces the thermal transmittance value (Ψ) by about 50% in comparison to aluminium spacers (Gustavsen et al. 2007).

The glazing-to-wall area ratio (AGAW) of the south-oriented façade is 27.6%, while the AGAW values of the rest of the cardinal directions are 8.9% in north, 10.5% in east and 8.5% in west façades. The glazing-to-floor area ratio (AGAF) for the base case is described in Table 4.1.

Table 4-1: Glazing-to-wall area ratio and glazing-to-floor area ratio

	SOUTH	NORTH	EAST	WEST
AGAW (%)	27.6	8.9	10.5	8.4
AGAF (%)	12.1	3.9	3.7	2.9

From the data presented in Table 4-1 the sum total AGAF of our base-case model is 22.6% which is sufficient according to Pagliano (2007).

4.1.4 Location, orientation and climate data

The house is located in Ljubljana and oriented with the longer side with the large glazed area facing south. The south, east, north and west elevations are presented in Figures 4.2 and 4-3.

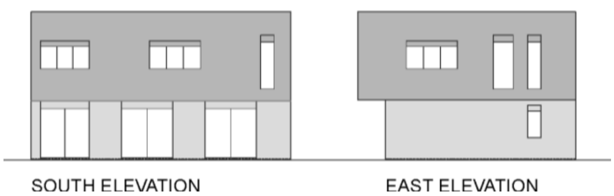


Figure 4-2: Elevation plan of base-case study model (south and east elevations).

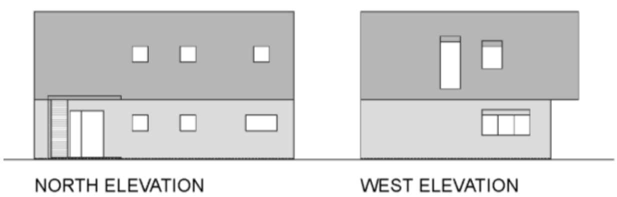


Figure 4-3: Elevation plan of base-case study model (north and west elevations).

The city of Ljubljana is located at an altitude of 298 metres, latitude of 46.03° and longitude of 14°31′ east. According to (Köppen climate classification "Cfb"), Ljubljana's climate is Oceanic, bordering on a Humid subtropical climate zone (Köppen climate classification Cfa), with continental characteristics such as warm summers and moderately cold winters. July and August are the warmest months with daily highs generally between 25 and 30 °C, and January is the coldest month with temperatures mostly hovering around 0 °C. The city experiences 90 days of frost per year, and 11 days with temperatures above 30 °C (86 °F). The city is known for its fog, which is recorded on average on 121 days a year, mostly in autumn and winter, and can be particularly persistent in conditions of temperature inversion. The average annual temperature, based on the 30-year period (1961-1990) is 9.8 °C. The average duration of solar radiation is 1712 hours annually.

4.1.5 Shading

The house is constructed with a south-oriented extended overhang above the ground floor, which blocks the direct solar radiation from entering the ground floor windows to the south during the summer, while it lets it enter in winter when the angle of incidence of the sun is lower. The rest of the windows on the upper floor and those of the east, west and north-oriented walls are shaded with external shading devices.

A common recommendation for low-energy residential houses is to place large glazing areas on the south of the building, while north-oriented glazing areas should be reduced to a minimal size and can be left without shading. If the north-oriented glazing areas of our base-case model remained unshaved, the cooling demand would increase dramatically by the enlargement of the AGAW. Solar radiation entering large glazing areas in the south in addition to solar radiation entering large north-oriented glazing areas during the morning and evening would cause a risk of overheating and consequently increase the cooling demand. To avoid results that would not be objective, we decided to shade the north-facing glazing areas as well. As one of the requested data in the PHPP software we have selected the temporary shading reduction factor z=50% for glazing areas in all four façades.

4.1.6 Internal gains

A value of 2.1 W/m^2 for internal heat gains from electrical appliances and body heat was used in the PHPP software internal heat sources calculation.

4.1.7 Active technical systems

The calculated length of the heating period is 205 days, although it varies minimally from year to year. The house is equipped with a central heat recovery unit. The efficiency of the selected unit which is placed within the thermal envelope is specified with values of 82% for heat recovery efficiency and 0.41 Wh/m^3 for electrical efficiency. The average air change rate is set to a minimum recommended value of 0.30 h^{-1}. To prevent overheating in the summer period the summer ventilation for cooling through manual window night ventilation was planned. Furthermore additional summer operation of the heat recovery ventilation system was planned as well. No other cooling devices were installed. The interior temperatures were designed to a T_{min} of 20°C and T_{max} of 25°C. No solar collectors were installed. Domestic hot water generation (DHW) and an additional requirement for a space heating are covered by a heat pump with a sub-soil heat exchanger and just minimally (5%) with electric heating.

4.1.8 Parameters varied

The influence on energy demand of the following factors was studied: different glazing-to-wall area ratio (AGAW) in four main cardinal directions; north, south, east and west. Modifications were made separately for each cardinal direction for six timber systems; TF 1, TF 2, TF 3, KLH 1, KLH 2, KLH 3 and only for south-oriented glazing areas for three additional systems, TFCL 1, TFCL 2 and TFCL 3 with higher U-values ($U_{TFCL\ 1}$=0.70 W/m^{2}K, $U_{TFCL\ 2}$=0.48 W/m^{2}K and $U_{TFCL\ 3}$=0.30 W/m^{2}K) which are constructed using an old classic single-panel system. Additionally calculations for both new and classic construction systems with three different U_{wall}-values (U_a=0.1 W/m^{2}K, U_b=0.20 W/m^{2}K and U_c=0.25 W/m^{2}K) were carried out as well. The modifications of the size of glazing areas were in the range of AGAW of 0% to nearly 80%, which is graphically presented in Figures 4-4a, 4-4b, 4-5a and 4-5b.

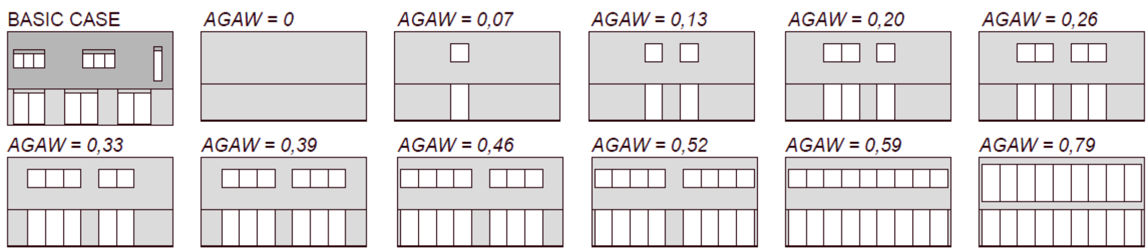


Figure 4-4a: South-oriented façade of the base-case study model with schemes of the glazing area size modification.

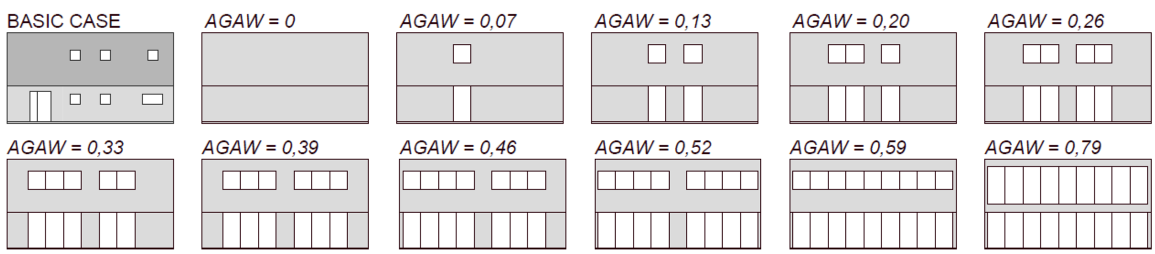


Figure 4-4b: North-oriented façade of the base-case study model with schemes of the glazing area size modification.

The glazing size modifications are performed step-by-step. Each step performs increase of the glazing size, where two windows that consist of glazing and a frame are added to the previous model. Such approach is more realistic from the one, where only glazing without frame is being modified, due to the influence of frame U-value on total window U-value. The glazing size is expressed by AGAW values.

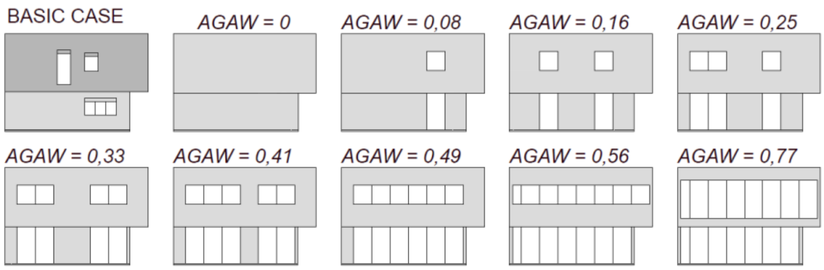


Figure 4-5a: West-oriented façade of the base-case study model with schemes of the glazing area size modification.

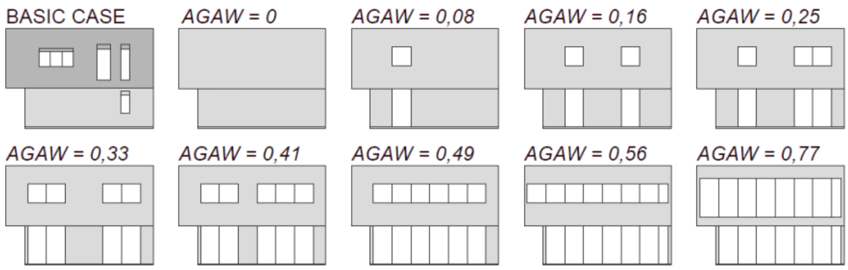


Figure 4-5b: East-oriented façade of the base-case study model with schemes of the glazing area size modification.

From the modification process, which is graphically presented in Figures 4-4a, 4-4b, 4-5a and 4-5b, the AGAW values of each individual modification are shown.

Basic data for nine treated systems and six additional modifications are presented in Table 4-2. The thermal transmittance of the roof, floor slab and the south-oriented overhang construction above the ground floor area remain constant in all of the studied cases.

Table 4-2: Basic data representing treated construction systems

System	U_{wall}-value (W/m^2K)	Wall thickness (mm)	Bearing constr. thickness (mm)	Insulation thickness (mm)	Groud plan area (m^2)	External wall area (m^2)
TF 1	0.164	306.2	160	160+100	168.36	262.16
TF 2	0.137	366.2	160	60+160+100	168.36	264.84
TF 3	0,102	456.5	360	360+60	168.36	269.52
KLH 1	0.181	306	95	180	168.36	262.16
KLH 2	0.148	366	95	60+180	168.36	264.84
KLH 3	0.124	453	142	60+220	168.36	269.52
TFCL 1	0.3	185.5	100	100+40	168.36	255.51
TFCL 2	0.48	146	100	80	168.36	253.56
TFCL 3	0.7	146	100	50	168.36	253.56
TF 1a=TF 3	0.102	456.5	360	360+60	168.36	269.52
TF 1b	0.2	266	160	160+60	168.36	260.34
TF 1c	0.25	226	160	160+20	168.36	258.32
TFCL 2a	0.102	405	100	100+270	168.36	267.43
TFCL 2b	0.2	235	100	100+100	168.36	258.82
TFCL 2c	0.25	205	100	80+70	168.36	257.31

4.1.9 Object of the research

The object of this research is the relationship between the glazing area size, the glazing area orientation (north, south, west and east) and the type of external wall construction system. The aim of the research is to define the optimal glazing-to-wall area ratio for each main cardinal direction for the selected timber construction systems. In this research we are not observing the orientations between the main cardinal points such as southwest, northeast and northwest, as these orientations are going to be examined in one of our future research projects. The calculated results observed in the calculations provided by the PHPP software are the **specific annual energy demand for heating** and the **specific useful cooling energy demand** and the **sum total** of both. The overheating risk is taken into account only in cases with extreme glazing areas, although it cannot be considered as authoritative data, due to a PHPP software characteristic, that the calculation of overheating frequency is not reliable when large daily temperature swing is present.

4.1.10 Description of the software and calculation method

The Passive House Planning Package 2007 (PHPP 2007) is used to perform calculations of the energy demand of the base-case study model as well as of all the treated modified models. The PHPP is a design-tool, which can be basically used by the architects and the engineers to design and optimize their Passive House projects. The calculation method used is the annual method in accordance with EN ISO 13790 (2004). Apart from the ISO 13790, The PHPP 07 is based also on other European standards and on algorithms, corrections and extensions of the authors of the software from the Passivhaus Institut Dr. Volfgang Feist. In 2008 the updated standard ISO 13790 has been adopted. However, the main differences between the 2004 and 2008 versions of ISO 13790 are that the simple hourly method has been included and that the cooling algorithms have been included. The latter (taken from a draft version of the 2008 standard and verified by dynamic simulations) actually served as a template for the cooling worksheet in the PHPP 2007.

The software is certified as a planning tool for passive houses and was presented to be able to describe the thermal building characteristics of passive houses surprisingly accurately, although it can be used also for low-energy house design. The PHPP software includes worksheets with tools for the U-value calculation of building components, an energy balance calculation, a comfort ventilation design facility, a heating and cooling load calculation, heat distribution and supply, electricity demand and primary energy demand, a window parameter calculation, a shading calculation as well as a calculation of the summer comfort performance of the building. PHPP was presented for the first time in 1998 and has since been continuously developed further. (http://www.passiv.de/index.html?/07_eng/phpp/PHPP2007_F.htm)

4.2 Results and analyses

The results are presented separately for each typical timber construction system. The values for the specific annual space heat demand, in further text the energy demand for heating (Q_h) and specific useful cooling energy demand, in further text the energy demand for cooling (Q_k) and the sum total of both (Q_h+Q_k) dependant on the glazing-to-wall area ratio (A gl. / A wall) in further text termed as the AGAW are presented graphically in the text, likewise in the tables at the end of the text. Values are presented separately for south (S), north (N), west (W) and east (E) cardinal directions. For comparison purposes some of the results are associated in figures at the end of individual sub-chapters.

4.2.1 Timber-frame 1 construction system

The results for the energy demand behaviour dependant on the south-oriented glazing area size for the TF 1 construction system are presented in Figure 4-6.

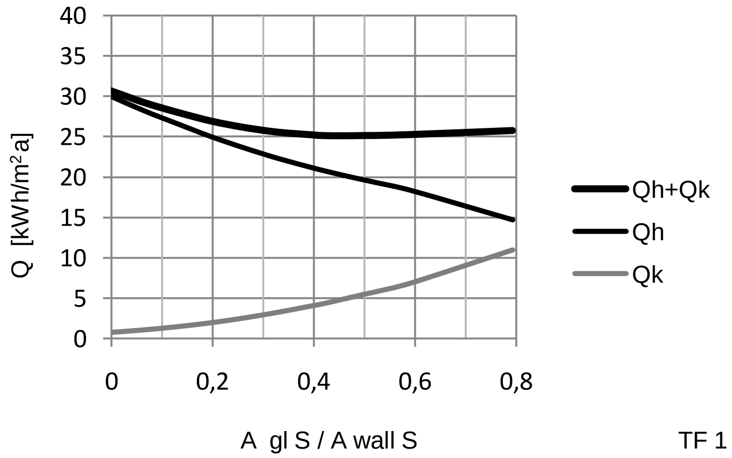


Figure 4-6: Annual energy demand in TF 1 construction system as a function of AGAW for south orientation.

According to the presented data in Figure 4-6 the influence of changing the glazing area in the south-oriented external wall on annual energy demand for heating and cooling is relatively large. By increasing the glazing area the energy demand for heating as a function of the AGAW shows an almost linear dependence, heat gains at *AGAW=0.79* are almost 15 kWh/m^{2}a which represents 51% of the Q_h value at *AGAW=0*, in further text termed as the starting-point. Meanwhile the energy demand for cooling increases slightly faster than linearly. The sum total of the energy demand for heating and cooling decreases almost linearly from the starting-point to AGAW ≈ 0.20, furthermore it shows the lowest value, which is defined as the functional optimum or the optimal point, at *AGAW≈0.46*, by further increasing the glazing area the energy demand increases minimally, therefore the function curve practically converges. The definition of the optimal point is described as the optimal glazing-to-wall area ratio (AGAW) in the south-oriented external wall element at which the sum total of heating and cooling demand reaches the lowest value. The optimal AGAW for Q_h+Q_k in the TF 1 construction system is not clearly evident. The convergence of the function curve is relatively favourable from the practical viewpoint of energy efficiency with a conclusion that the maximal size of the glazing area in the TF 1 construction system is not limited to specific AGAW values. While the solar heat gains cause an increase in the cooling demand and decrease in the heating demand at the same time, the sum total of heating and cooling energy demands remains almost constant by the glazing share of the south-oriented façade which is larger than 47%.

The results for the energy behaviour dependant on the north-oriented glazing area size for the TF 1 construction system is presented in Figure 4-7.

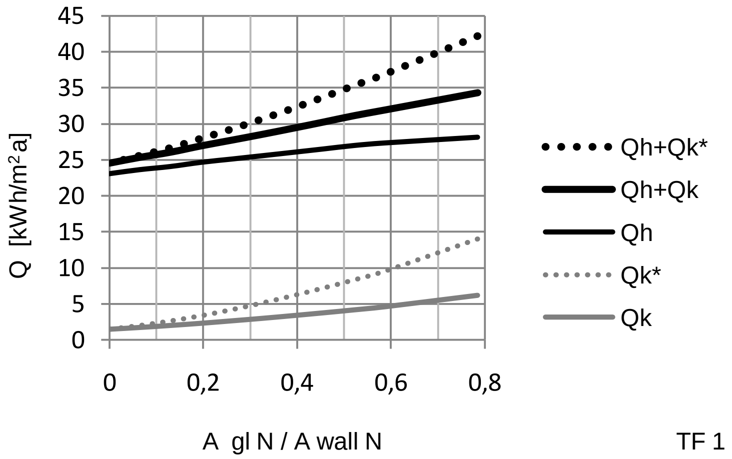


Figure 4-7: Annual energy demand in TF 1 construction system as a function of AGAW for north orientation.

In Figure 4-7 two functional curves appear representing the energy demand for cooling as well as the sum total of energy demand for heating and cooling. The Q_k and Q_h+Q_k represent results obtained from calculations for modifications of north-oriented glazing areas where no external shading devices were installed. By designing our base-case model we have followed the common recommendation for low-energy residential houses which is to place large glazing areas on the south wall, while north-oriented glazing areas should be reduced to a minimal size so that they could remain unshaved. As the first modifications of north-oriented glazing areas for the TF 1 construction system were performed, the annual cooling demand increased dramatically using higher values of AGAW. The solar radiation entering through existing large glazing areas in the south in addition to solar radiation entering through large north-oriented glazing areas during the morning and evening periods caused a risk of overheating and a consequently expressive increase in energy demand for cooling. With the intention of avoiding results that would not be objective, we decided to shade the north-facing glazing areas of the base-case model as well as the north-facing glazing areas of all treated models built with different construction systems treated in our further simulations.

The results for Q_h, Q_k and Q_h+Q_k are analysed in the further text. The behaviour of the energy demand for heating as well as for cooling increases in almost linear dependence with increases in the AGAW, consequently the sum total of the heating and cooling demand increases linearly, too. The Q_h+Q_k losses at *AGAW = 0.79* reach almost 10 kWh/m^{2}a which is about 40% of the Q_h+Q_k value at *AGAW = 0*. The behaviour of the sum total of the energy demand function curve, which shows higher energy demand by larger glazing areas, justifies the commonly presented directions for low-energy house design related to the size of north-oriented glazing areas which are supposed to be minimal.

According to Johnson et al. (1984) the heating demand is reduced with increased glazing, due to solar loads. He claims that even for the north orientation, heating demand is reduced by approximately 30 per cent with an effective glazing size compared to a wall with no glazing, which is due to a cold climate. This does not accord with the presented results of our case study.

The Influence of the west-oriented glazing area size on the energy balance in the TF 1 construction system is presented in the Figure 4-8.

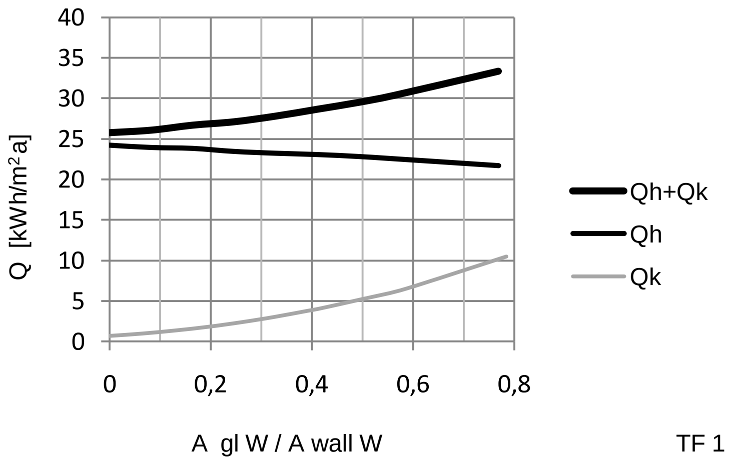


Figure 4-8: Annual energy demand in TF 1 construction system as a function of AGAW for west orientation.

The influence of changing the glazing area size facing west on energy demand for heating presented in the Figure 4-8 is relatively small, the heat gain of only 2.5 kWh/m^{2}a or 10% of the starting-point value is obtained through modification of the glazing size from *AGAW=0* to *AGAW=0.77.* On the other hand the form of the cooling demand function curve, which is slightly exponential, shows greater functional dependence of cooling demand from the glazing area increase. Consequently the sum total of the heating and cooling demand is growing with the increase of the AGAW value of the west oriented external wall.

The Influence of the east oriented glazing area size on energy balance in the TF 1 construction system is presented in Figure 4-9.

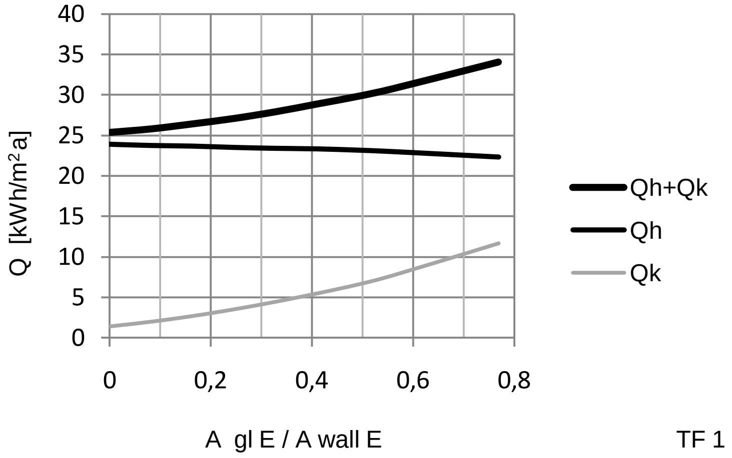


Figure 4-9: Annual energy demand in TF 1 construction system as a function of AGAW for east orientation.

According to the data presented in Figure 4-9 the behaviour of the heating and the cooling demands is very similar to those of west-oriented surfaces. The sensitivity to modification of the glazing area is relatively large for the energy demand for cooling, while the energy demand for heating remains almost constant, with just a minimal decrease. Due to the resembling behaviour of Q_h and Q_k as a function of AGAW for west and east orientations, the further analyses are presented together for both cardinal directions.

The comparison of energy demand for heating as a function of the glazing area size for different cardinal directions of the TF 1 construction system is presented in Figure 4-10.

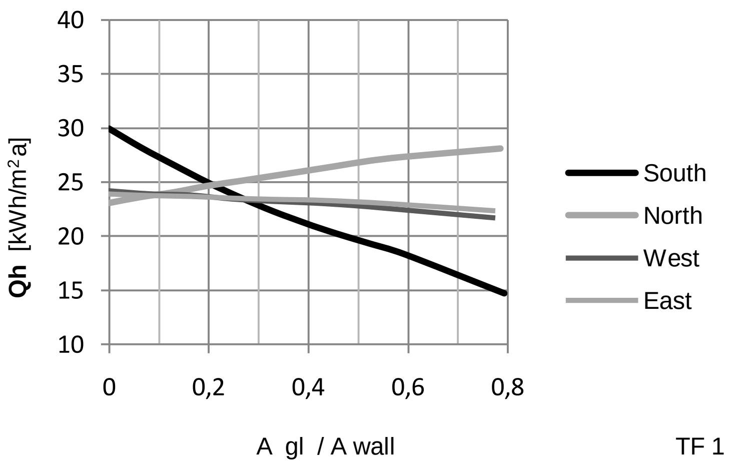


Figure 4-10: Annual energy demand for heating in TF 1 construction system as a function of AGAW for different cardinal directions.

According to the data presented in Figure 4-10 the influence of changing the glazing area on energy demand for heating is the largest in the south, where Q_h decreases almost linearly with a growing AGAW. The heat gains at *AGAW = 0.79* add up to almost 15 kWh/m^{2}a or 51% with regard to an external wall without any glazing. On the contrary in the north the energy demand for heating increases with a growing AGAW, although the influence is smaller compared to the south orientation, a heat loss of 5 kWh/m^{2}a or 22% of the starting-point value is evident as the result of the total AGAW increase. The west and east orientations show practically similar behaviour of Q_h which is almost independent of the size of the glazing area, although the heating demand is slightly higher in the east. The stated analyses accord well with the results of parametric study research of the effect of glazing type and size on the annual heating and cooling demand for Swedish offices (Bülow-Hübe H, 2001) as well as with some statements from design guidelines for comfortable low-energy homes (Ford B. et al., 2007) considering the climate in Milano, Italy. Also the results for Q_h and Q_k for different glazing orientations of terraced houses built outside Gothenburg, Sweden presented in case study research (Person M.L. et al., 2006) show similarities to our case, with some minimal deviations caused by different climate conditions, but only for a limited range of AGAW≈0.30, since the Swedish case study model with a constant glazing area size was oriented in different cardinal directions for the research purposes of the mentioned study. Figure 4-10 also shows an interesting situation at low AGAW values where the Q_h is much higher for south orientations, while other orientations result in an almost equivalent Q_h value, which is noticeably lower from the Q_h for the south orientation. The explanation is relatively simple while it corresponds to the glazing area design of the base-case study model which is arranged with large glazing areas in the south and smaller glazing areas in the other orientations. At a starting-point situation of *AGAW=0* in the south, the rest of the glazing areas in the three other cardinal directions receive less solar gains due to relatively small glazing surfaces. The opposite is the starting-point situation for north, west and east orientations, where solar gains through large south-oriented glazing areas are significant, on account of which the Q_h for the other orientations at *AGAW=0* is relatively higher. The latter explanation shows the weakness of the case study model research, which indicates the probability that the model of a simple box with glazing only in one orientation could be considered as an appropriate option to obtain more realistic results.

The comparison of energy demand for cooling as a function of the glazing area size for different cardinal directions for the TF 1 construction system is presented in Figure 4-11.

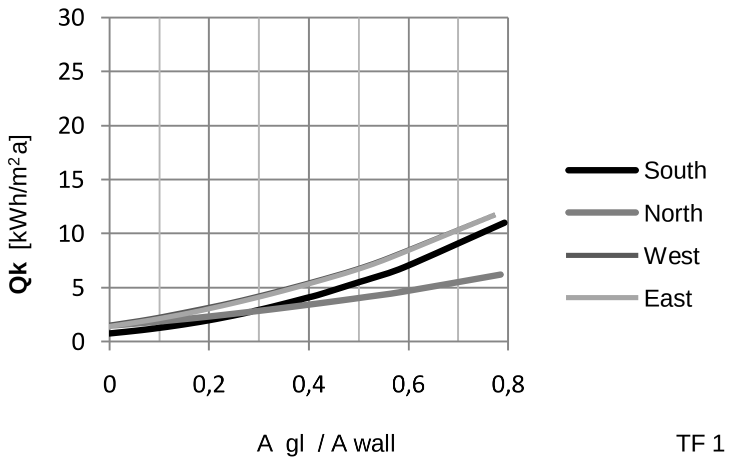


Figure 4-11: Annual energy demand for cooling in TF 1 construction system as a function of AGAW for different cardinal directions.

The comparison of the Q_k behaviour patterns for south, north, west and east is presented in Figure 4-11. The lowest cooling demand is seen for the north orientation, while west and east orientations show almost equivalent behaviour which is just slightly higher than the Q_k for the south orientation. The latter can once again be ascribed to the high quantity of heat gains through the existing large south-oriented glazing area of the base-case study model during the proceeding of the west and east-oriented glazing area modifications.

The comparison of energy demand for heating and cooling as a function of the glazing area size for different cardinal directions for the TF 1 construction system is presented in Figure 4-12.

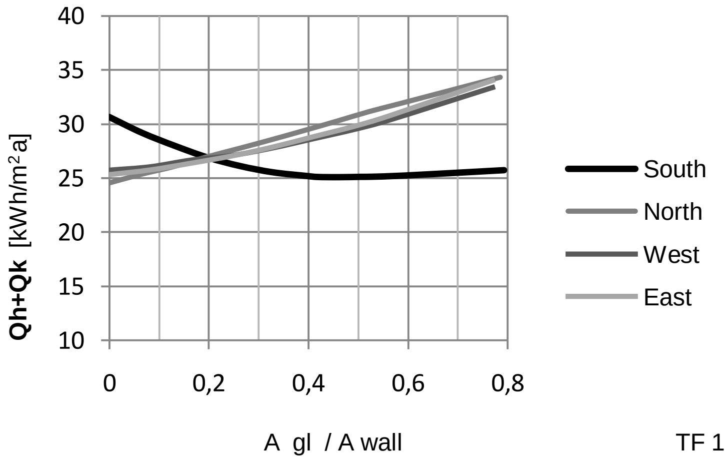


Figure 4-12: Annual sum total of energy demand for heating and cooling in TF 1 construction system as a function of AGAW for different cardinal directions.

The comparison of the results for Q_h+Q_k for different orientations is presented in Figure 4-12. The function curves for west and east orientations show similar behaviour, although the energy demand is slightly higher for the east orientation, which is comparable to findings in parametric study research of the effects of glazing type and size on the annual heating and cooling demand for Swedish offices (Bülow-Hübe H, 2001). The Q_h+$Q_{k,}$as a function of the north-oriented glazing area increases linearly with an increase in the size of the glazed area. Most interesting is the analysis for the south orientation which shows the slightly inexpressive functional optimum at *AGAW≈0.46,* by further increasing the glazing area the energy demand increase is minimal as demonstrated by the convergence of the function curve. The analysed results resemble those in design guidelines for comfortable low-energy homes (Pagliano et al., 2007) considering the climate in Milano, Italy as well as findings from Swedish case study research (Person M.L. et al., 2006). At the same time the results are comparable to commonly presented directions for low-energy house design, related to the size and orientation of the glazing areas. In present research we pay special attention to the definition of the optimal AGAW value related to an optimal Q_h+Q_k value for different construction systems, which has not yet been researched in the studied literature.

4.2.2 Timber-frame 2 construction system

The influence of changing the glazing area in the south-oriented external wall of the TF 2 construction system on the energy demand for heating and cooling is presented in Figure 4-13.

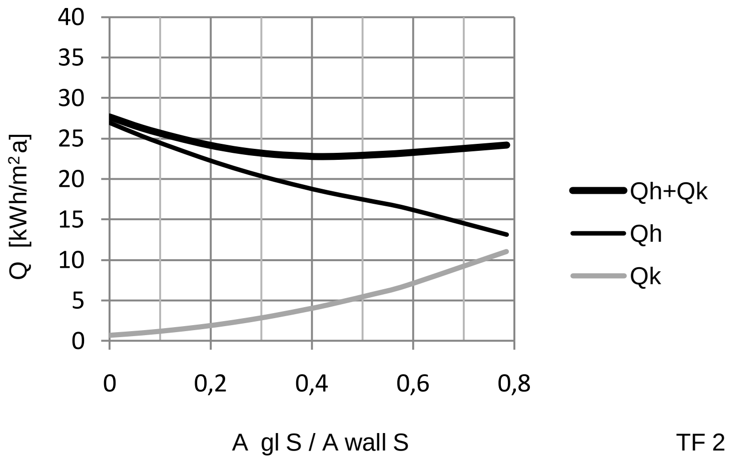


Figure 4-13: Annual energy demand in TF 2 construction system as a function of AGAW for south orientation.

The data presented in Figure 4-13 show that the Q_h decreases almost linearly with an increase in glazing area, heat gains at *AGAW = 0.79* are almost 14 kWh/m^{2}a which is approximately 51% of the *Qh* value at the starting-point, while the Q_k increases slightly exponentially. The sum total of the energy demand for heating and cooling decreases almost linearly at lower AGAW values, while it reaches the functional optimum at *AGAW=0.41*, a further increase in the glazing area results in a minimal increase in energy demand and no convergence of the function curve like that of the TF 1 system is evident anymore.

The results for the energy demand behaviour dependant on the north-oriented glazing area size for the TF 2 construction system are presented in Figure 4-14.

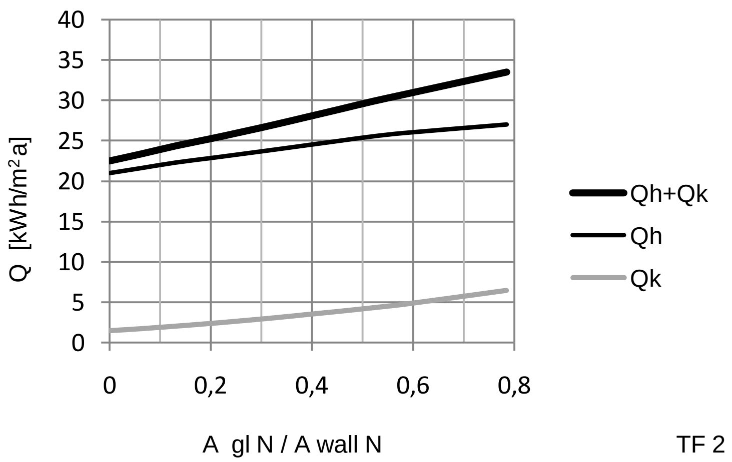


Figure 4-14: Annual energy demand in TF 2 construction system as a function of AGAW for north orientation.

According to the data presented in Figure 4-14 increasing the north-oriented glazing in a range from *AGAW=0* to *AGAW=0.79* causes an almost linear increase in the energy demand for heating as well as in the energy demand for cooling. Consequently the sum total of the heating and cooling demands increases linearly, too. The Q_h+Q_k increase at *AGAW = 0.79* is 11 kWh/m^{2}a which is about 49 % related to the energy demand at the starting-point. From a practical viewpoint this means that north-oriented glazing areas should remain as small as possible, if only the heating and cooling energy demand is considered.

The influence of the size of the west and east-oriented glazing area on the energy balance in the TF 2 construction system is presented in Figure 4-15.

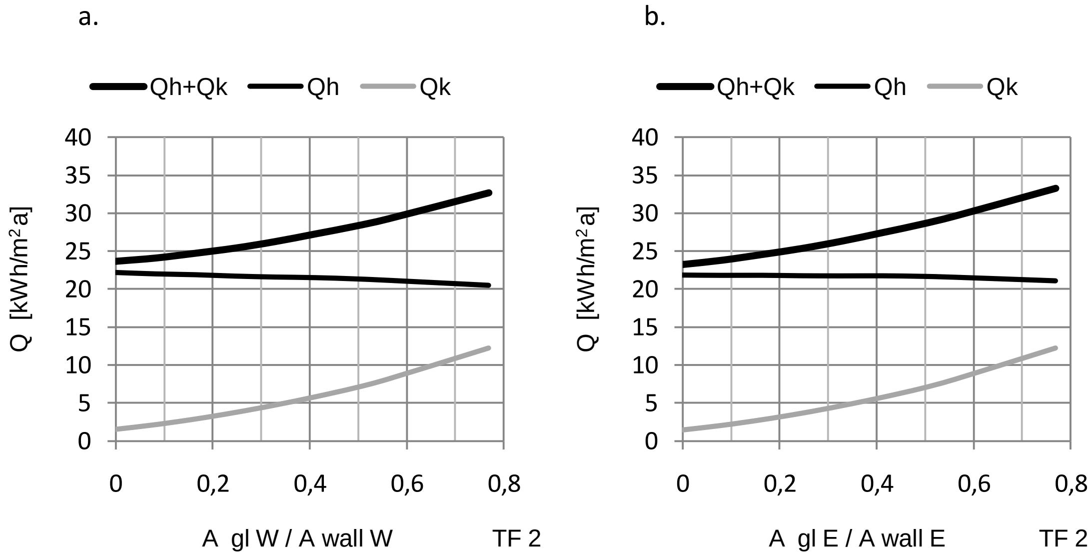


Figure 4-15 a, b: Annual energy demand in TF 2 construction system as a function of AGAW for west and east orientation.

In Figure 4-15a it is evident that by a total modification of the west-oriented glazing area from a starting-point at *AGAW=0* to a maximum glazing share of AGAW = 0.77, the energy demand for heating remains almost constant with just a minimal decrease which results in a heat gain of only 1.67 kWh/m^{2}a or 8% of the starting-point value. The influence of increasing the glazing area is relatively large on the energy demand for cooling, which increases slightly exponentially. The sum total of the heating and cooling demand grows almost linearly with an increase in the AGAW values of the west-oriented external walls. The behaviour of the annual energy demand for heating and cooling as a function of the east-oriented glazing area, which is presented in Figure 4-15b is almost identical to the energy demand patterns in the west orientation. The Q_h function curve shows a slightly higher demand at *AGAW=0.77* than that for the west orientation. The decrease in the heat demand of only 0.76 kWh/m^{2}a or 3% of the starting-point value caused by a maximal increase in glazing area demonstrates even more constant behaviour of the Q_h function curve compared to that in the west orientation. Both energy demand patterns for west and east show that the heating energy demand sensitivity on the size of the glazing area is minimal, which is not significant for the energy demand for cooling. The sensitivity of the energy demand for cooling is larger for both west and east orientations. It increases slightly exponentially in relation to an increase in the glazing area. The above presented data show that the size of the west and east-oriented glazing area has no specific influence on the energy demand for heating, while it causes a risk of overheating if the glazing area exceeds 40% of the total west or east-oriented external wall. The latter is evident only from the data presented in Tables Ap-7 and Ap-8 in Appendix, where overheating frequencies are also presented. The overheating limit is set to a maximum of 25°C. If the "frequency over 25°C" exceeds 10%, additional measures to protect against summer heat waves are necessary.

The comparison of energy demand for heating as a function of the glazing area size for different cardinal directions of the TF 2 construction system is presented in Figure 4-16.

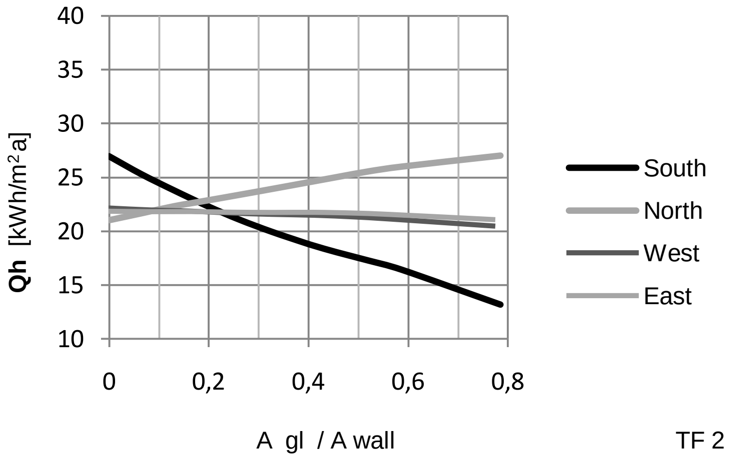


Figure 4-16: Annual energy demand for heating in TF 2 construction system as a function of AGAW for different cardinal directions.

According to the data presented in Figure 4-16 the influence of increasing the glazing area size is the largest for the south orientation, where Q_h decreases almost linearly with a growing AGAW and the heat gains at *AGAW = 0.79* add up to almost 14 kWh/m^{2}a or 51% of the Q_h value at AGAW 0. The heat loss of 6 kWh/m^{2}a or 29% related to the energy demand at the starting-point shows that the influence of changing the glazing area facing north is less expressive than that of its southern counterpart, but important due to the confirmation of the theoretical and practical experience in low-energy house design, that smaller glazing surfaces on the north side are favourable for the energy demand for heating. East and west orientations show similar behaviour, although the heating demand is slightly higher in the east but only at higher AGAW values. The minimal difference could be due to a minimal difference in the size of the east and west-oriented windows of the base-case model. Once again we discover that the base-case study model might have some weaknesses and that the model of a simple box might be more appropriate from some points of view. However, the above stated explanations are only presumptions which should be examined in our further research. At this point we have to stress that the energy demand for heating is observed on an annual basis. It would be interesting for one of our next research projects to observe the energy demand behaviour on a monthly or even on a daily basis, where the influence of east and west-oriented glazing surfaces would be especially interesting on account of the effect that morning and afternoon solar gains would have on the energy balance.

The comparison of energy demand for cooling as a function of the glazing area size for different cardinal directions of the TF 2 construction system is presented in Figure 4-17.

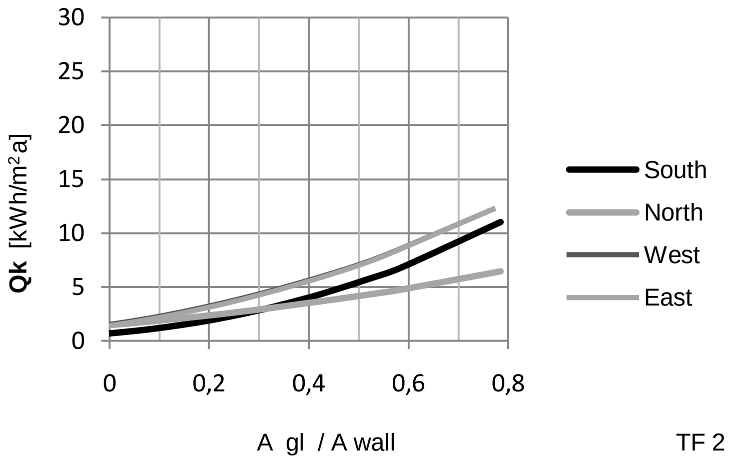


Figure 4-17: Annual energy demand for cooling in TF 2 construction system as a function of AGAW for different cardinal directions.

The comparison of the cooling demand behaviour patterns presented in Figure 4-17 shows the lowest cooling demand for the north orientation, while west and east orientations show almost equivalent behaviour which is just slightly higher than the cooling demand for the south orientation. Once again we can see the exceptional situation at AGAW values lower than 0.32, where the Q_k is slightly higher for the north than for the south orientation. We suppose that by the modification process of the size of the north-oriented windows, the south-oriented window size remains large as it was designed in the base-case study model, which causes relatively higher solar gains. For our further research it would be appropriate to compare the existing results with the results obtained by the modification of the glazing areas of the simple box model, with glazing installed only in one façade at a time. However we can state that increasing the size of the glazing surfaces in all the main cardinal directions causes an increase in the energy demand for cooling.

The comparison of the sum total of energy demand for heating and cooling as a function of the glazing area size for different cardinal directions of the TF 2 construction system is presented in Figure 4-18.

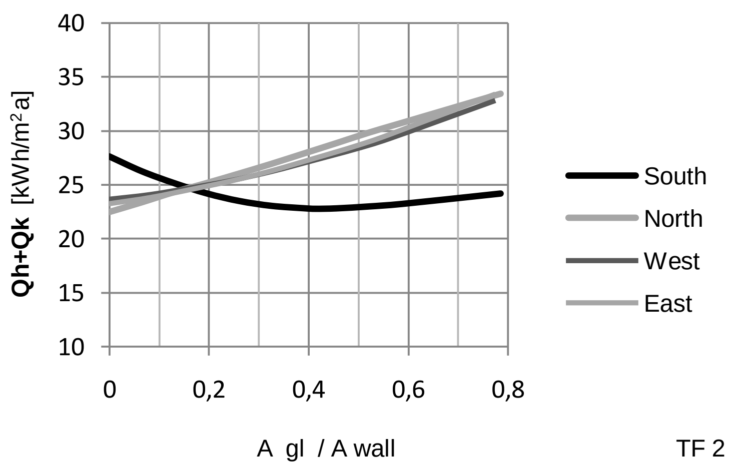


Figure 4-18: Annual sum total of energy demand for heating and cooling in TF 2 construction system as a function of AGAW for different cardinal directions.

According to the data presented in Figure 4-18 the sum total of the cooling and heating demand increases linearly with the glazing areas in the north. East and west orientations show similar behaviour with a slightly higher energy demand in the east, although the difference is more or less negligible. The analysis for the south orientation shows the appearance of the functional optimum at *AGAW=0.41,* a further increase in the glazing area results in a minimal energy demand increase. The results show that Q_h+Q_k is the most interesting for the southern orientation, where the optimal glazing size is predictable with a value of 41% of the total external wall area.

4.2.3 Timber-frame 3 construction system

The influence of changing the glazing area in the south-oriented external wall of the TF 3 construction system on the energy demand for heating and cooling is presented in figure 4-19.

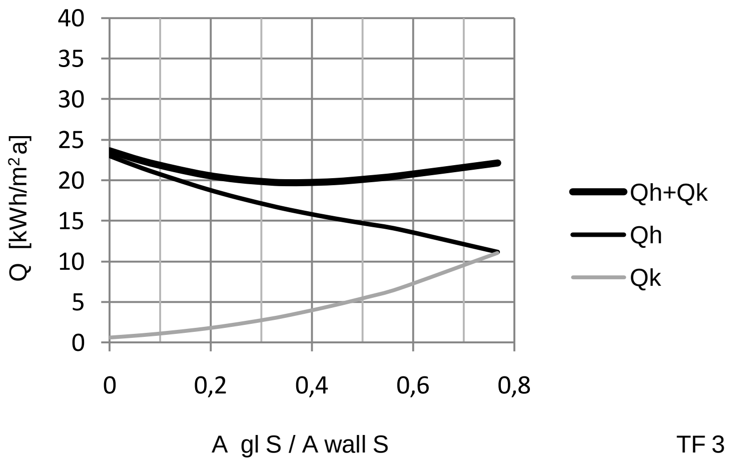


Figure 4-19: Annual energy demand in TF 3 construction system as a function of AGAW for south orientation.

The influence of changing the glazing area in the south-oriented external wall of the TF 3 construction system on the annual energy demand for heating and cooling presented in Figure 4-19 shows that by increasing the glazing area the heating demand decreases almost linearly, heat gains at *AGAW=0.79* reach almost 12 kWh/m^{2}a which is approximately 52% of the Q_h value at *AGAW=0*. The function curve which represents the energy demand for cooling increases slightly exponentially. The sum total of the annual heating and cooling demand decreases almost linearly from the starting point to AGAW≈*0.20*, while it reaches the lowest value, the functional optimum, in the range of *AGAW≈0.34–0.38*, a further increase in the glazing area results in the evident energy demand increase.

The results for the energy demand behaviour dependant on the north-oriented glazing area size for the TF 3 construction system are presented in Figure 4-20.

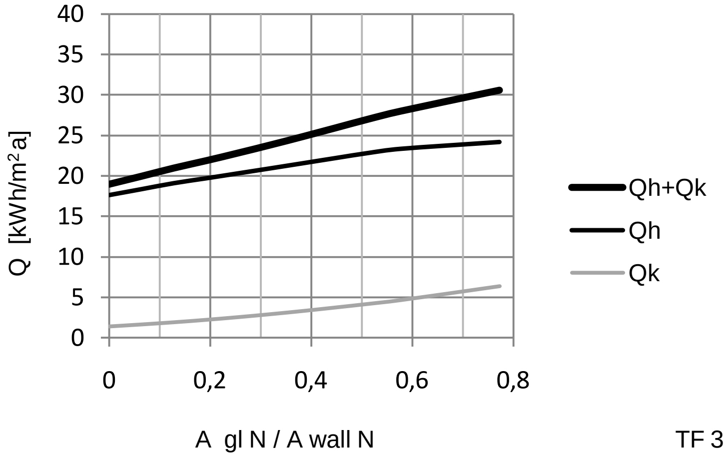


Figure 4-20: Annual energy demand in TF 3 construction system as a function of AGAW for north orientation.

According to the data presented in Figure 4-20 an increase in the glazing area in the range from *AGAW=0* to *AGAW = 0.79* causes the heating and the cooling demand to increase almost linearly, consequently the sum total of the heating and cooling demands increases linearly, too. The sum total of the energy demand for heating and cooling loss at *AGAW=0.79* is almost 12 kWh/m^{2}a which is about 61% of the energy demand at the starting-point.

The influence of the size of the west and east-oriented glazing area on the energy balance in the TF 3 construction system is presented in Figure 4-21.

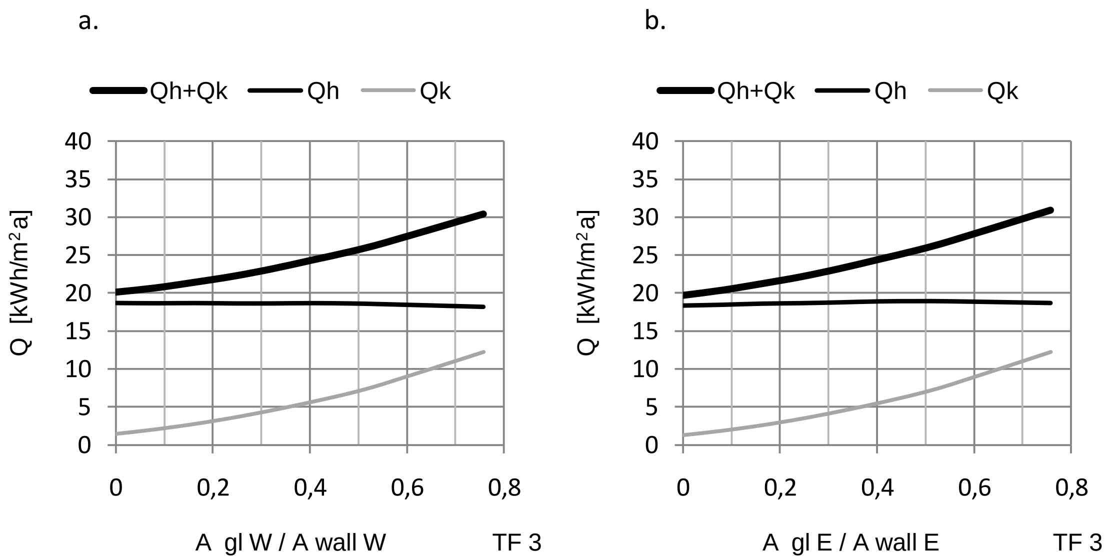


Figure 4-21 a, b: Annual energy demand in TF 3 construction system as a function of AGAW for west and east orientation.

The results presented in Figure 4-21a show that by total modification of the west-oriented glazing area from the starting-point at *AGAW=0* to a maximal glazing size at *AGAW=0.77*, the energy demand for heating remains almost constant with a negligible decrease of only 0.55 kWh/m^{2}a which is no more than 3% of the Q_h starting-point value. The influence of increasing the west-oriented glazing area is relatively large for the Q_k, which increases slightly exponentially. The Q_h+Q_k is growing almost linearly with an increase in the AGAW values of the west-oriented external walls. The behaviour of the energy demand patterns for heating and cooling as a function of the east-oriented glazing area presented in Figure 4-21b is almost identical to the energy demand patterns in the west. The Q_h function curve shows a slightly higher demand at *AGAW=0.77* than that of the west orientation. The decrease in the heat demand by only 0.32 kWh/m^{2}a or less than 2% of the Q_h starting-point value as a result of a maximal increase in the glazing area demonstrates the constant behaviour of the heating demand function curve. The above presented data show that the size of the west and east-oriented glazing areas have no specific influence on the energy demand for heating, while it causes a risk of overheating if the glazing area exceeds 40% of the total west or east-oriented external wall. The latter is evident only from the data presented in Tables Ap-11 and Ap-12 in Appendix, where overheating frequencies are also presented. The overheating limit is set to a maximum of 25°C. If the "frequency over 25°C" exceeds 10%, additional measures to protect against summer heat waves are necessary.

The comparison of energy demand for heating as a function of the glazing area size for different cardinal directions of the TF 3 construction system is presented in Figure 4-22.

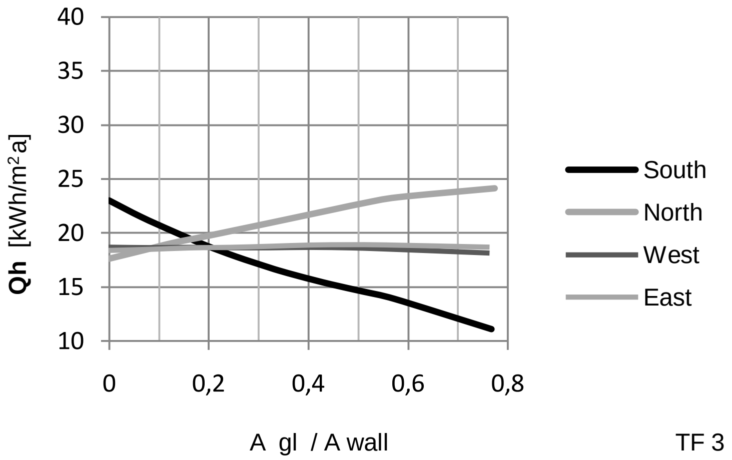


Figure 4-22: Annual energy demand for heating in TF 2 construction system as a function of AGAW for different cardinal directions.

In Figure 4-22 it is presented that the largest influence of increasing the glazing area size is evident for the south orientation, where Q_h decreases almost linearly with a growing AGAW and the heat gains at *AGAW=0.79* add up to almost 12 kWh/m^{2}a or 52% of the Q_h value at *AGAW=0*. The heat loss of almost 7 kWh/m^{2}a or 37% related to the energy demand at the starting-point shows that the influence of changing the glazing area facing north is less expressive than that of its southern counterpart. East and west orientations show similar behaviour, although the heating demand is slightly higher in the east but only at values of AGAW>0.30. According to the analysed results the size of the west and east-oriented glazing area has almost no affect on the energy demand for heating.

The comparison of energy demand for cooling as a function of the glazing area size for different cardinal directions of the TF 3 construction system is presented in Figure 4-23.

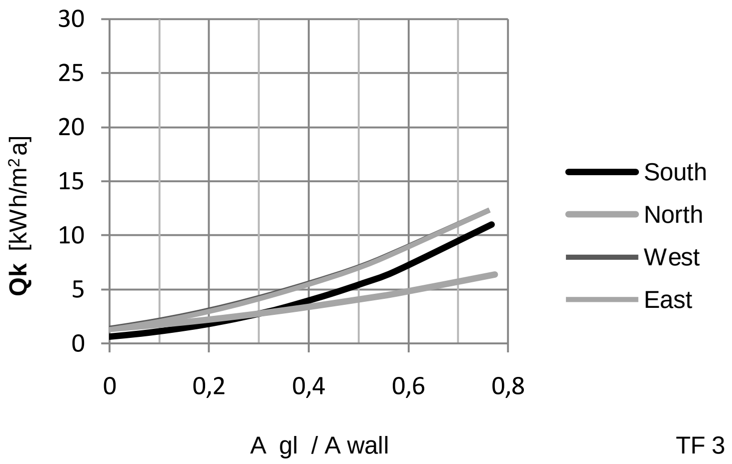


Figure 4-23: Annual energy demand for cooling in TF 3 construction system as a function of AGAW for different cardinal directions.

The comparison of the cooling demand behaviour patterns presented in Figure 4-23 show the lowest Q_k for the north orientation, while west and east orientations show almost equivalent behaviour which is similar to the behaviour for the south orientation. From the presented data it is evident that an increase in the size of the glazing surfaces in all of the main cardinal directions has a relatively negative influence on the energy demand for cooling. At the specific AGAW value the risk of overheating appears (see Tables Ap-9 to Ap-12 in Appendix), where overheating frequencies are presented. If the "frequency over 25°C" exceeds 10%, additional measures to protect against summer heat waves are necessary. For the south orientation the risk of overheating appears at AGAW≥0.51, for north at AGAW>0.58, for west and east at AGAW≥0.40.

The comparison of the sum total of energy demand for heating and cooling as a function of the glazing area size for different cardinal directions of the TF 3 construction system is presented in Figure 4-24.

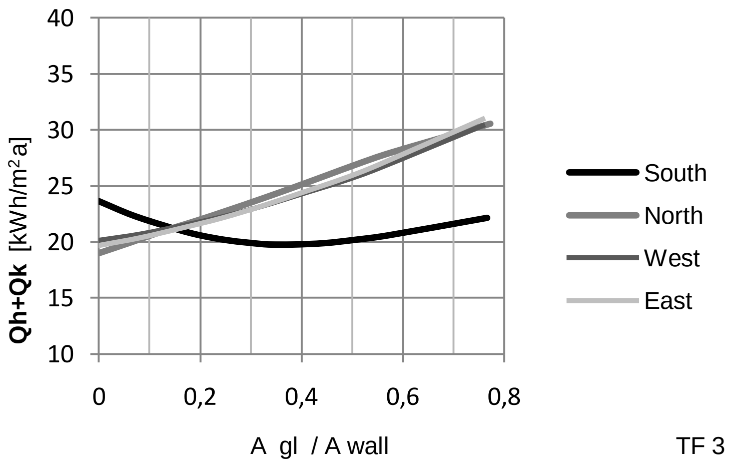


Figure 4-24: Annual sum total of energy demand for heating and cooling in TF 2 construction system as a function of AGAW for different cardinal directions.

The comparison of the results for the sum total of energy demand for heating and cooling for different orientations of the TF 3 construction system is presented in figure 4-24 show similar behaviour for north, east and west orientations; the Q_h+Q_k function curve increases linearly with the north-oriented glazing areas, while it increases almost linearly with the increase of east and west-oriented glazing surfaces. The east orientation shows a slightly higher energy demand, although the difference is more or less negligible. On the contrary, the total demand for the south-oriented glazing area decreases almost linearly from the starting point to AGAW≈*0.20*, while it reaches the lowest value, the functional optimum, in the range of *AGAW≈0.34–0.38*, a further increase in the glazing area results in the evident energy demand increase. The results show that the optimal glazing size for the southern orientation is predictable with a value of 34% to 38% of the total external wall area.

4.2.4 Comparison of energy demand in timber-frame (TF 1 – TF 3) construction systems

The behaviour of the TF 1, TF2 and TF3 systems for north, west and east directions is very similar because no Q_h gains appear for these orientations, therefore only the south direction, which is the main point of our special interest, will be additionally analysed and compared for all construction systems (Figure 4-25 to 4-27).

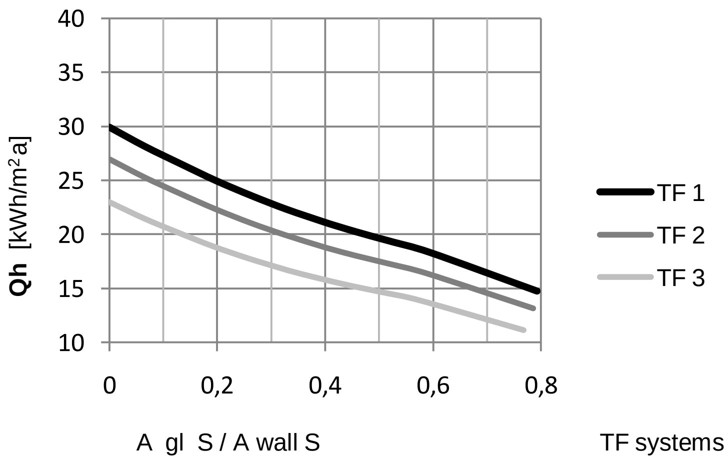


Figure 4-25: Comparison of energy demand for heating as a function of AGAW for southern orientation of selected TF construction systems (TF 1 – TF 3).

The results presented in Figure 4-25 show an almost linear functional dependence of Q_h on the size of the glazing area. Observation of the results shows also that the energy demand for heating is the highest in the TF 1 and lowest in the TF 3 construction system, which we suppose is related to the different U-values of external wall elements of specific construction systems.

In the following Figure 4-26 the comparison of energy demand for cooling dependant on the size of the glazing area for different construction systems (TF 1 – TF 3) is presented.

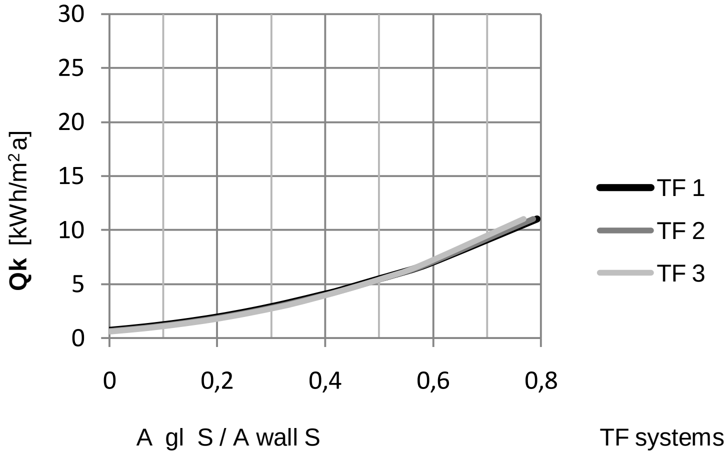


Figure 4-26: Comparison of energy demand for cooling as a function of AGAW for southern orientation of selected TF construction systems (TF 1 – TF 3).

According to the results presented in Figure 4-26, the behaviour of the energy demand for cooling is similar in all TF construction systems. The cooling demand varies almost linearly by increasing the glazing area, which is similar to the results in Persson (2006). Upon more detailed examination some crossing of function curves of different construction systems is evident, but only in a very limited range of AGAW values. More interesting is the finding which distinguishes them from the results for Q_h; the increase in the south-oriented glazing area in wall elements of higher thermal transmittance as well as in wall elements of lower thermal transmittance is similar. On the basis of this research, we can see that the U-value of the external wall has no distinctive impact on the behaviour of the energy demand for cooling, it depends more on the size of the glazing area as well as on the orientation and of course on other parameters which are not analysed in this research.

The most interesting point is the comparison of the Q_h+Q_k demand for different construction systems (TF 1 – TF 3), which is presented in Figure 4-27.

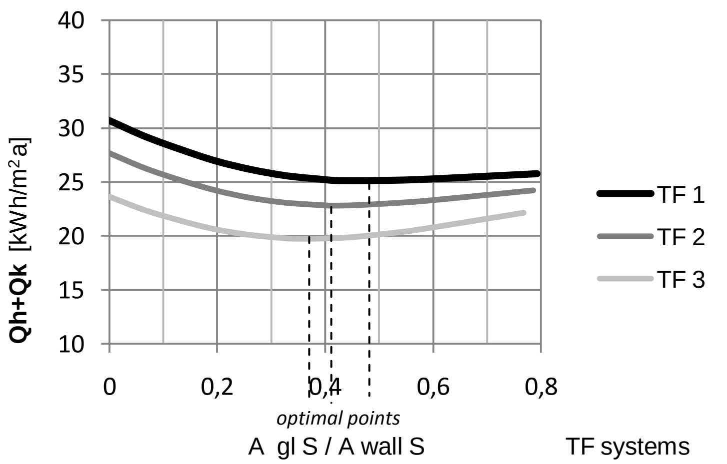


Figure 4-27: Comparison of energy demand for heating and cooling as a function of AGAW for southern orientation of selected TF construction systems (TF 1 – TF 3).

The results for sum total energy demand show an interesting appearance related to the optimal point with the lowest Q_h+Q_k demand, which is clearly evident in the TF 3 construction system appearing at the range of *AGAW≈0.34-0.38* and less evident in the TF 2 system at *AGAW=0.41* as well as in the TF 1 system at *AGAW≈0.46*. We assume that the optimal share of glazing surface in south-oriented exterior walls depends on the thermal transmittance of the exterior wall. The optimal share of glazing area in walls with extremely low U-values is smaller than that of walls with higher U-values. If we pay attention to the behavior of the Q_h+Q_k function curve after reaching the optimal point, we notice that the sum total energy demand for heating and cooling increases more in the TF 3 construction system, which has the lowest thermal transmittance, while in the TF 1 system, with a higher U_{wall}-value the function converges. If applied to the praxis this means that in extremely isolative south-oriented exterior wall elements, the optimal glazing share concerning the sum total of energy demand for heating and cooling is approximately 34 - 38% of the total external wall area, while in wall elements with a U-value reaching 0.164 W/m^{2}K the optimal share is larger - approximately 46% of the total wall area should be glazed. Even if the share of the glazing area in the TF 1 construction system is larger, we can notice only a minimal increase in Q_h+Q_k. The functional optimum moves to lower AGAW values as the U_{wall}-value of a specific system is higher.

4.2.5 Comparison of energy demand in classic single-panel timber-frame (TFCL 1 – TFCL 3) and new timber-frame (TF 1 – TF 3) construction systems

For comparison purposes as well as for support in setting up the basic principle of the glazing surface's impact on energy behaviour patterns, an analysis of the classic single-panel prefabricated wall elements was carried out., but only for the south orientation where the influence of the size of the glazing area on energy demand in previously analyzed TF systems was the greatest. Firstly the TFCL 2 with U_{wall}*=0.48 W/m^{2}K*, as well as the two additional fictive wall elements TFCL 1 with U_{wall}*=0.70 W/m^{2}K* and TFCL 3 with U_{wall}*=0.30 W/m^{2}K* were analyzed. The thermal properties of the selected wall elements do not satisfy even the basic requirements for the thermal transmittance of an exterior wall (U_{wall}-value) for energy-efficient house design. It is important to point out that only the wall elements of higher U-values are applied as parameters in this part of our case-study, while the rest of the parameters such as the roof and floor slab assemblies as well as the active systems and the air-tightness of the building remain constant. The latter should be taken into consideration when analyzing the energy demand results of TFCL systems with the intention of avoiding an incorrect inference, that an increase in the glazing area in older houses built with prefabricated classical single-panel system causes energy savings for heating of the same values as those presented in our research.

The results for TFCL 1 – TFCL 3 compared with the results for new macro-panel systems, are presented in Figure 4-28 to 4-30.

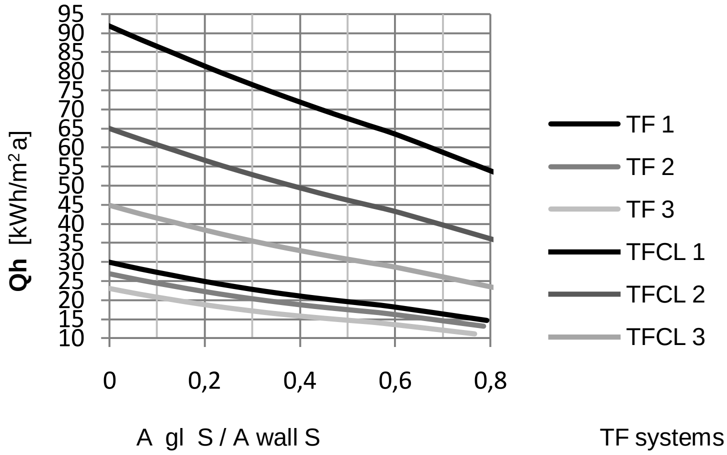


Figure 4-28: Comparison of energy demand for heating as a function of AGAW for southern orientation of selected TF (TF 1 – TF 3) and TFCL (TFCL 1 – TFCL 3) construction systems.

According to the data presented in Figure 4-28 an expressive linear functional dependence of Q_h from AGAW for TFCL systems is evident, while the inclination of the function lines presenting TF systems is smaller. It is evident that the thermal transmittance of the exterior wall element plays an important role; the higher the U-value (TFCL 1, TFCL 2) the greater and more favourable is the influence of the glazing area increase on the energy demand for heating. In the case of an increase in the total glazing area in TFCL 1 fictive system the energy saving for heating represents almost 39 kWh/m^{2}a. In further analyses we notice that the decrease in energy demand for heating is smaller in systems with a lower U-value; in the TFCL 2 system the Q_h saving represents almost 30 kWh/m^{2}a and only approximately 22 kWh/m^{2}a in the TFCL 3 system. The comparison of energy savings for heating for two extreme systems with regard to the U_{wall}-value, shows significant differences; a saving of 39 kWh/m^{2}a for TFCL 1 and only 12 kWh/m^{2}a for TF 3, which has the best insulating features. From the results presented above we infer that an increase in the south-oriented glazing areas in external wall elements of lower insulation features (higher U-value) has a greater influence on Q_h compared to the glazing modifications in wall elements of better insulation features (lower U-value). This confirms the statement mentioned in the text above, that the influence of an increase in the glazing area on the energy demand for heating is more favourable in external wall elements with a higher U-value. This accords well with the findings from Bansal et al. (1994) where it is presented that a larger glass area could compensate for the higher U-value of the buildings external elements. In regard to the presented results which show that for the construction systems with a relatively high U_{wall}-value there is almost no limit in the increasing of glazing size. At this point we have to stress that the overheating risk must be taken into consideration when glazing area is extremely large (AGAW > 0.54 for TFCL 3 and AGAW > 0.60 for TFCL 2). The frequency of temperatures above the comfort limit, defined by a maximal summer interior temperature of 25°C, should not exceed 10% of the year, therefore in the cases of extremely large glazing area the data for the overheating frequency has to be controlled. The regularity of the data presenting the overheating frequency with the PHPP software is only approximate.

Next we compare the results for the energy demand for cooling (Figure 4-29).

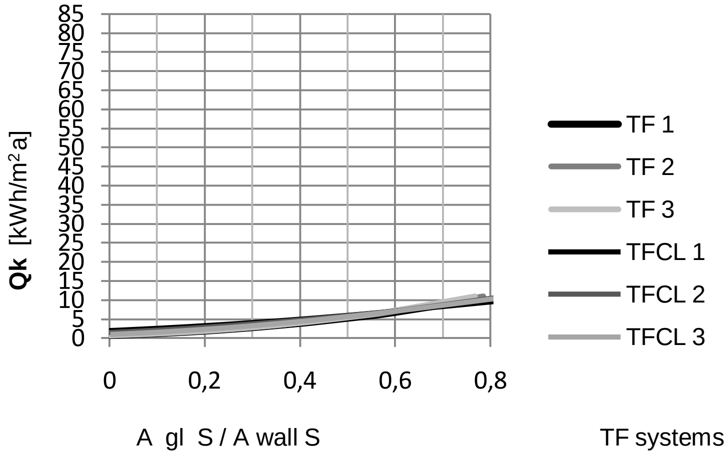


Figure 4-29: Comparison of energy demand for cooling as a function of AGAW for southern orientation of selected TF (TF 1 – TF 3) and TFCL (TFCL 1 – TFCL 3) construction systems.

According to the results presented in Figure 4-29, the behaviour of the energy demand for cooling is similar in all treated construction systems. We can notice an interesting finding which is opposite to the results for Q_h, an increase in the south-oriented glazing areas in wall elements of lower insulation features has a similar influence on the energy demand for cooling compared to the glazing modifications in highly isolative (insulated?) wall elements, so we can see that the U-value of the external wall has no distinctive impact on the behaviour of the energy demand for cooling.

Next we compare the results for the sum total of energy demand for heating and cooling (Figure 4-30).

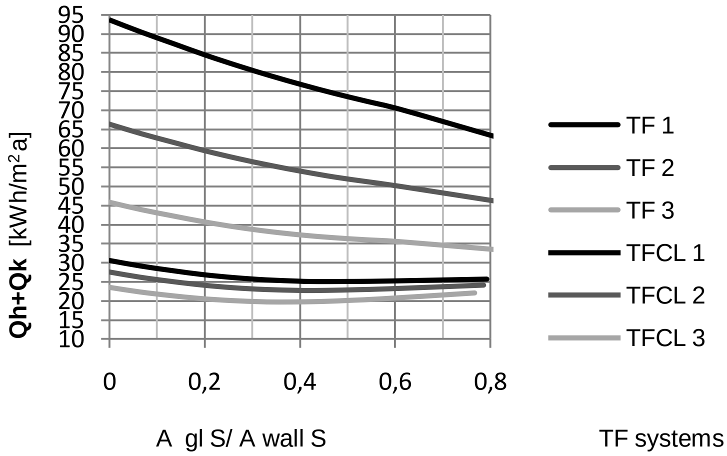


Figure 4-30: Comparison of sum total of energy demand for heating and cooling as a function of AGAW for southern orientation of selected TF (TF 1 – TF 3) and TFCL (TFCL 1 – TFCL 3) construction systems.

The analyses of the sum total of heating and cooling demand presented in Figure 4-30 seem to be the most interesting; at higher U-values of exterior wall elements, the functional optimum (lowest Q_h+Q_k value) disappears, the Q_h+Q_k function curve passes from parabolic dependence in construction systems with extremely low U_{wall}-values (TF 2 and TF 3) to linear dependence in construction systems with high U_{wall}-values (TFCL 1 – TFCL 3). The inclination of a function line presenting TFCL systems depends on the U_{wall}-value, which is similar to the analysis of the Q_h demand. Energy savings caused by an increase in the total glazing area (from *AGAW=0* to *AGAW≈0.79*) represent approximately 31 kWh/m^{2}a or 33% of the starting point value for the TFCL 1 system to only 12 kWh/m^{2}a or 27% for the TFCL 3 system. In comparison to the TF 3 system with the highest insulation features, the difference is even greater, the Q_h+Q_k savings at an optimal value of *AGAW≈0.34–0.38* represent only about 4 kWh/m^{2}a. It is evident from the results for Q_h+Q_k for TFCL construction systems, that an increase in the south-oriented glazing areas in exterior walls with higher thermal transmittance adds up to a sum total of energy savings. This is especially important for the renovation principles of the existing timber-framed housing stock built with the classic prefabricated single-panel system, since the installation of large glazing areas in south-oriented external walls improves the energy efficiency of the building. This might not be the optimal solution from an economic point of view, however it represents an alternative solution to the renovation principle of adding insulation to the existing external walls of old prefabricated timber-framed houses. Finally the renovation of old timber-frame buildings can be optimally performed with a combination of improving the insulation of the external walls and the optimal installation of the glazing in the south-oriented façade.

4.2.6 Massive panel construction system 1 - KLH 1

The results for the energy demand behaviour dependant on the south-oriented glazing area size for the KLH 1 construction system are presented in Figure 4-31.

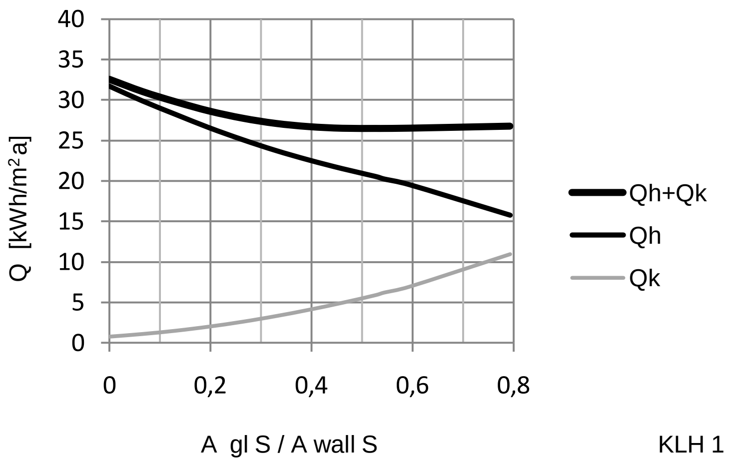


Figure 4-31: Annual energy demand in KLH 1 construction system as a function of AGAW for south orientation.

According to the data presented in Figure 4-31 an almost linear dependence of the Q_h function is evident by increasing the glazing area, heat gains at *AGAW=0.79* reach 16 kWh/m^{2}a which is about 50% of the starting-point value. On the other hand the energy demand for cooling increases slightly faster than linearly, which is similar to the Q_k behaviour pattern of timber-framed systems and is presented by an energy loss of slightly over 9 kWh/m^{2}a. The sum total of the annual heating and cooling demand shows the functional optimum at *AGAW≈0.52–0.54;* with a further increase in the glazing area the energy demand increase is minimal, therefore the function practically converges, which is comparable to the behaviour of the Q_h+Q_k function of the south-oriented wall in the TF 1 system. The convergence of the function curve is relatively favourable from the viewpoint of energy-efficiency as well as from the viewpoint of contemporary house-design with large glazing areas, since the largest size of the south-oriented glazing area in the KLH 1 construction system is not limited.

The results for the energy demand behaviour dependant on the north-oriented glazing area size for the KLH 1 construction system are presented in Figure 4-32.

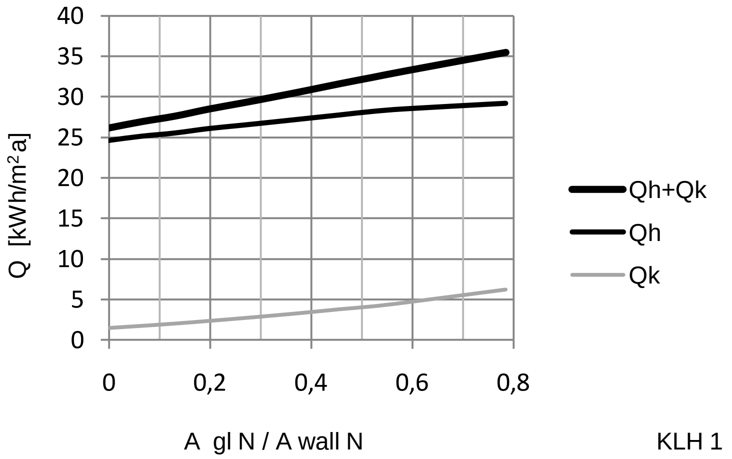


Figure 4-32: Annual energy demand in KLH 1 construction system as a function of AGAW for north orientation.

Figure 4-32 shows that the behaviour of the energy demand for heating and cooling increases in linear dependence with an increase in AGAW. By increasing the glazing area from *AGAW=0 to AGAW=0.79* the energy demand for heating rises by more than 4 kWh/m^{2}a , the energy demand for cooling by almost 5 kWh/m^{2}a , so the sum total energy demand loss at *AGAW=0.79 i*s slightly over 9 kWh/m^{2}a which is about 26 % of the starting-point value. From the presented results we can infer that increasing north-oriented glazing areas causes an increased energy demand for heating and cooling.

The influence of the of the size of the west and east-oriented glazing area on the energy balance in the KLH 1 construction system is presented in Figure 4-33.

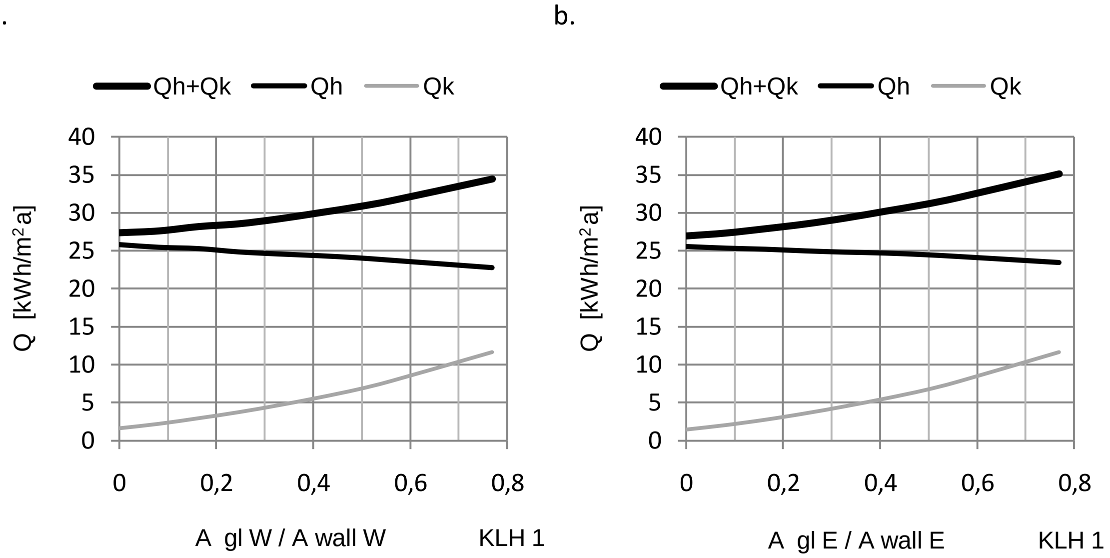


Figure 4-33 a, b: Annual energy demand in KLH 1 construction system as a function of AGAW for west and east orientation.

The influence of changing the glazing area size facing west on the energy demand for heating presented in Figure 4-33a is relatively small, the heat loss of only 3 kWh/m^{2}a or 12% of the starting point value is proved by modification of the glazing size from *AGAW=0* to *AGAW=0.77*. On the other hand the form of the cooling demand function, which is slightly exponential, shows a greater functional dependence from the size of the glazing area. Consequently the sum total of the heating and cooling demand grows slightly more than linearly with an increase in the west-oriented glazing areas, too. The east orientation shows very similar behaviour of Q_h, Q_k and Q_h+Q_k functions to the west (see Figure 4-33b).

The comparison of energy demand for heating as a function of the glazing area size for different cardinal directions of the KLH 1 construction system is presented in Figure 4-34.

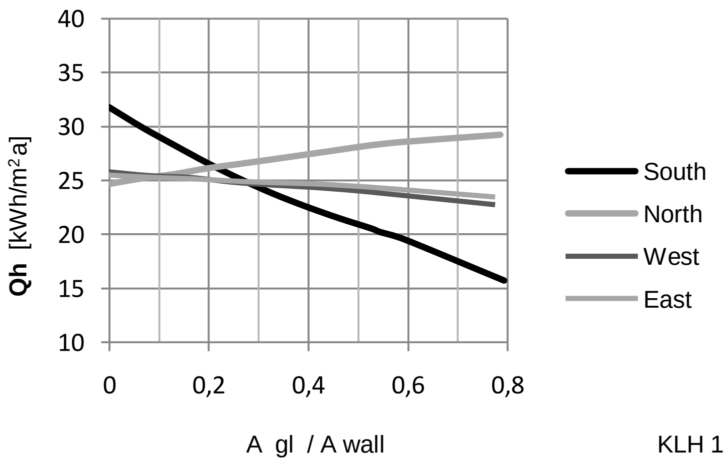


Figure 4-34: Annual energy demand for heating in KLH 1 construction system as a function of AGAW for different cardinal directions.

According to the data presented in Figure 4-34 the influence of changing the glazing area on energy demand for heating is the largest in the south orientation, where Q_h decreases almost linearly with a growing AGAW. The heat gains at *AGAW=0.79* add up to almost 16 kWh/m^{2}a or 50% with regard to walls without any glazing. On the contrary in the north the energy demand for heating increases with a growing AGAW, although the influence is smaller compared to the south orientation, the heat loss of almost 5 kWh/m^{2}a or 16% is evident as a result of the total AGAW increase. The west and east orientations show practically similar behaviour of Q_h which is almost independent from the size of the glazing area.

The comparison of energy demand for cooling as a function of the glazing area size for different cardinal directions of the KLH 1 construction system is presented in Figure 4-35.

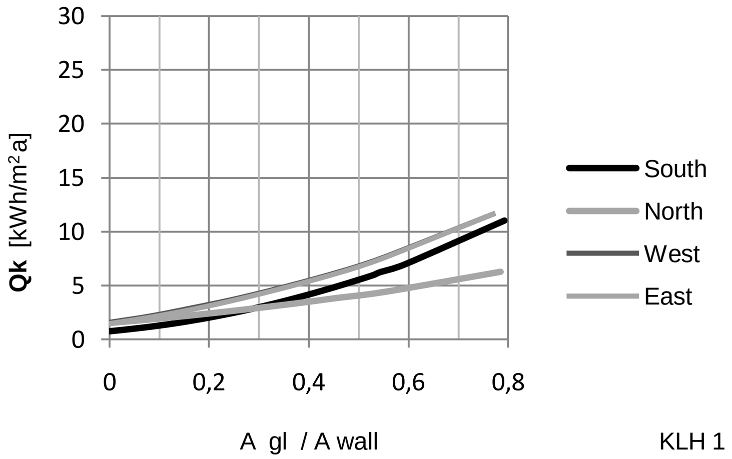


Figure 4-35: Annual energy demand for cooling in KLH 1 construction system as a function of AGAW for different cardinal directions.

From the data presented in Figure 4-35 it is evident that the sensitivity of the energy demand for cooling to the glazing size is the weakest for the north orientation. West, east and south orientations show similar behaviour, although the Q_k is slightly lower for the south orientation, which can be ascribed to the large south-oriented glazing area of the basic model.

The comparison of the sum total of energy demand for heating and cooling as a function of the glazing area size for different cardinal directions of the KLH 1 construction system is presented in Figure 4-36.

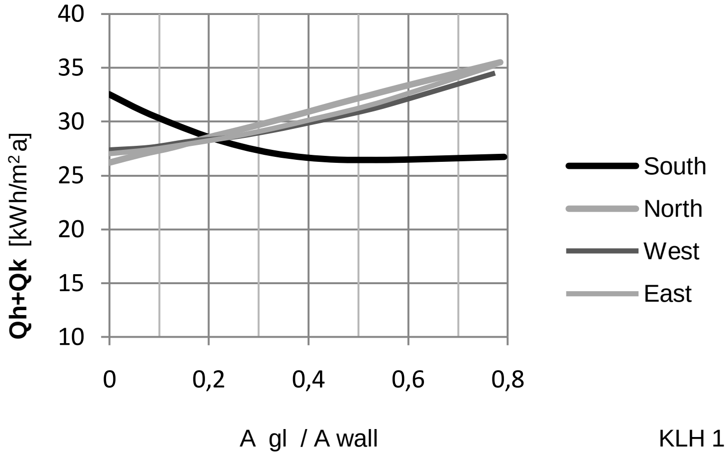


Figure 4-36: Annual sum total of energy demand for heating and cooling in KLH 1 construction system as a function of AGAW for different cardinal directions.

As already seen in the former analyses for timber-frame systems the most interesting are the results for the sum total of heating and cooling energy demand. The functions for west and east orientation present similar behaviour, although the sum total of energy demand is slightly higher for the east orientation, which is comparable to the findings of parametric study research of the effects of glazing type and size on annual heating and cooling demand for Swedish offices (Bülow-Hübe H, 2001). The Q_h+Q_k function is totally linear for the north orientation. The analysis for the south orientation proves a significant functional optimum at *AGAW≈0.52-0.54,* by further increasing the glazing area the energy demand increase is minimal, the function practically converges, which is comparable to the behaviour of the Q_h+Q_k function of the south-oriented wall in the TF 1 system. The latter is important from a practical viewpoint, while the maximum size of the south-oriented glazing area is not limited if only the energy demand is concerned.

4.2.7 Massive panel construction system 2 - KLH 2

The results for the energy demand behaviour dependant on the south-oriented glazing area size for the KLH 2 construction system are presented in Figure 4-37.

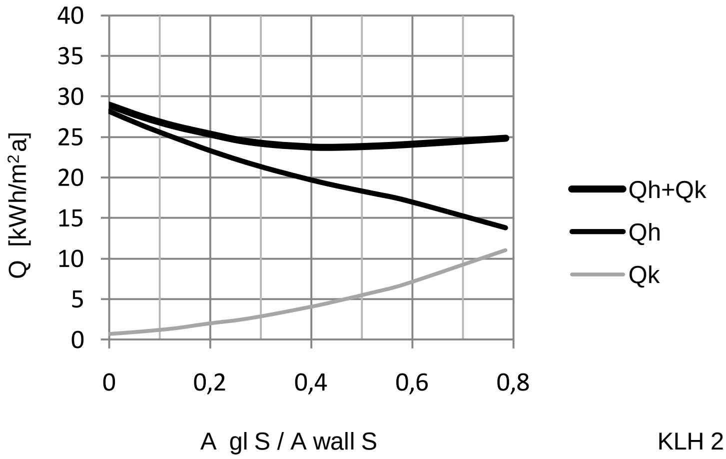


Figure 4-37: Annual energy demand in KLH 2 construction system as a function of AGAW for south orientation.

The analysis of the results presented in Figure 4-37 shows that the Q_h and Q_k patterns are similar to those of the TF 2 system. The functional dependence of Q_h from a growing AGAW is almost linear with a heat gain of almost 15 kWh/m^{2}a or 51% at a glazing increase from *AGAW=0 to AGAW=0.79*. The Q_k function shows nearly exponential behaviour, which indicates a rather large effect of an increase in the glazing area on the cooling energy demand. More interesting is the observation of the sum total of heating and cooling energy demand where energy savings of approximately 5 kWh/m^{2}a or 18% appear at *AGAW≈0.41-0.46.* By further increasing the glazing area the energy demand increases at a minimal pace.

The results for the energy demand behaviour dependant on the north-oriented glazing area size for the KLH 2 construction system is presented in Figure 4-38.

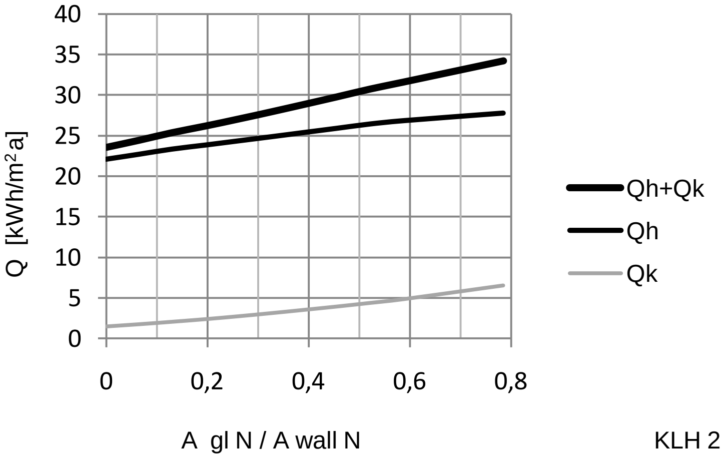


Figure 4-38: Annual energy demand in KLH 2 construction system as a function of AGAW for north orientation.

The influence of changing the glazing area facing north in the KLH 2 construction system on annual energy demand for heating and cooling is presented in Figure 4-38. By increasing the glazing area in the range of *AGAW=0* to *AGAW=0.79* both the heating and cooling demand increase almost linearly, consequently the sum total of the heating and cooling demand increases linearly, too. The sum total of the increase in heating and cooling demand at *AGAW=0.79* reaches almost 11 kWh/m^{2}a which is about 46 % related to the energy demand at the starting-point.

The influence of the size of the west and east-oriented glazing area on the energy balance in the KLH 2 construction system is presented in Figure 4-39.

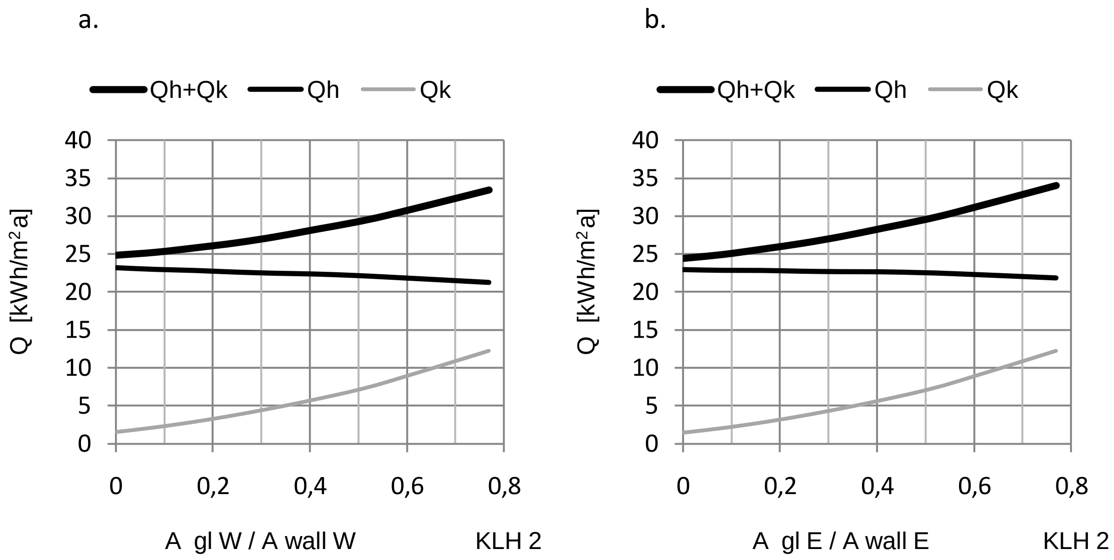


Figure 4-39 a, b: Annual energy demand in KLH 2 construction system as a function of AGAW for west and east orientation.

The presented data in Figure 4-39a show that by total modification of the glazing area from the starting-point at *AGAW=0* to a maximum glazing size at *AGAW=0.77*, the energy demand for heating remains almost constant with just a minimal decrease which results in a heat gain of only 2 kWh/m^{2}a or almost 9% of the starting-point value. The influence of increasing the glazing area is relatively large for the energy demand for cooling, which increases slightly exponentially. The sum total of the heating and cooling demand grows almost linearly with an increase in the AGAW values of the west-oriented external walls. The behaviour of the annual energy demand for heating and cooling as a function of the east-oriented glazing area presented in Figure 4-39b is almost identical to the energy demand patterns in the west. The Q_k function curve shows a slightly higher demand at *AGAW=0.77* than that in the west orientation. The decrease in the heat demand by only 1 kWh/m^{2}a or about 5% of the starting-point value caused by a maximal increase in the glazing area demonstrates even more constant behaviour of the Q_k function curve compared to that in the west orientation.

The comparison of energy demand for heating as a function of the glazing area size for different cardinal directions of the KLH 2 construction system is presented in Figure 4-40.

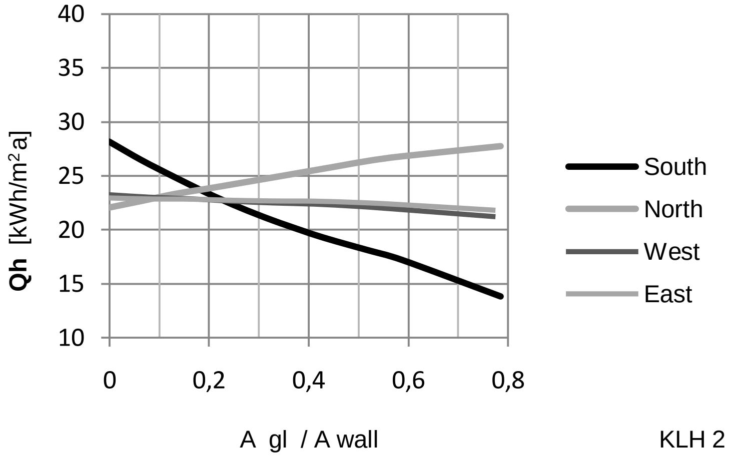


Figure 4-40: Annual energy demand for heating in KLH 2 construction system as a function of AGAW for different cardinal directions.

According to the data presented in Figure 4-40 the influence of changing the glazing area on energy demand for heating is the largest in the south orientation, where Q_h decreases almost linearly with a growing AGAW. The heat gains at *AGAW=0.79* add up to slightly over 14 kWh/m^{2}a or 51% with regard to walls without any glazing. On the contrary in the north orientation the energy demand for heating increases with a growing AGAW, although the influence is smaller compared to the south orientation, a heat loss of about 6 kWh/m^{2}a or 26% with regard to the starting-point value is evident as a result of a total AGAW increase. The west and east orientations show practically similar behaviour of Q_h which is almost independent from the size of the glazing area.

The comparison of energy demand for cooling as a function of the glazing area size for different cardinal directions of the KLH 2 construction system is presented in Figure 4-41.

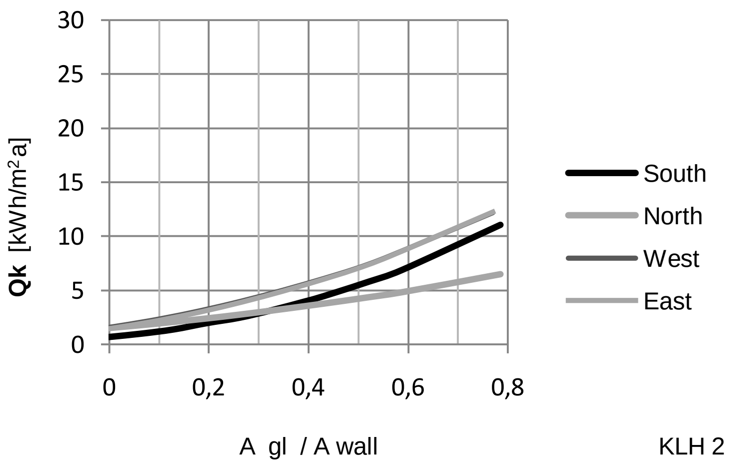


Figure 4-41: Annual energy demand for cooling in KLH 2 construction system as a function of AGAW for different cardinal directions.

The comparison of the cooling demand behaviour patterns in relation to the glazing area size for different cardinal directions in the KLH 2 construction system presented in Figure

4-41 shows the lowest cooling demand for the north orientation, while west and east orientations show almost equivalent behaviour which is similar to the behaviour for the south orientation. The presented results show that an increase in the glazing surfaces in all the main cardinal directions has a relatively negative influence on the energy demand for cooling.

The comparison of the sum total of energy demand for heating and cooling as a function of the glazing area size for different cardinal directions of the KLH 2 construction system is presented in Figure 4-42.

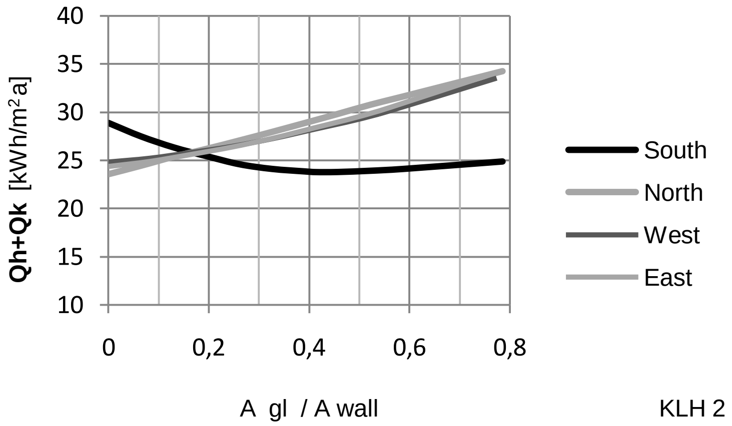


Figure 4-42: Annual sum total of energy demand for heating and cooling in KLH 1 construction system as a function of AGAW for different cardinal directions.

According to the data presented in Figure 4-42 the sum total of the cooling and heating demand increases linearly with the glazing areas in the north orientation. East and west orientations show similar behaviour with a slightly higher energy demand in the east, although the difference is more or less negligible. The analysis for the south orientation shows the functional optimum at *AGAW≈0.41-0.46,* a further increase in the glazing area results in a minimal energy demand increase. The optimal AGAW value is more evident in the KLH 2 system than in the KLH 1 system.

4.2.8 Massive panel structural system 3 - KLH 3

The results for the energy demand behaviour dependant on the south-oriented glazing area size for the KLH 2 construction system are presented in Figure 4-43.

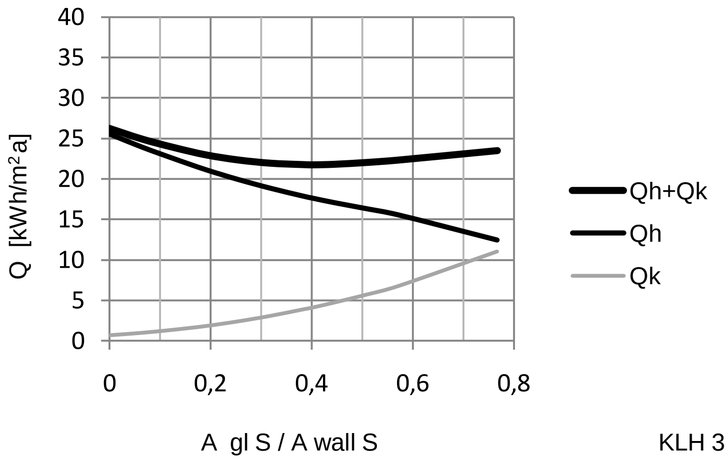


Figure 4-43: Annual energy demand in KLH 2 construction system as a function of AGAW for south orientation.

From the results presented in Figure 4-43 it is evident that by increasing the glazing area the functional dependence of Q_h is almost linear, heat gains at *AGAW=0.79* are slightly over 13 kWh/m^{2}a or 51% of the starting-point value. The Q_k function curve shows nearly exponential behaviour, similar to those of previously analysed timber-frame and KLH systems. The Q_h+Q_k function curve shows the functional optimum at *AGAW≈0.38-0.40,* where the energy savings reach more than 4 kWh/m^{2}a. By further increasing the glazing area the Q_h+Q_k increases by almost 2 kWh/m^{2}a, which is more than in the KLH 1 or KLH 2 construction systems.

The results for the energy demand behaviour dependant on the north-oriented glazing area size for the KLH 3 construction system is presented in Figure 4-44.

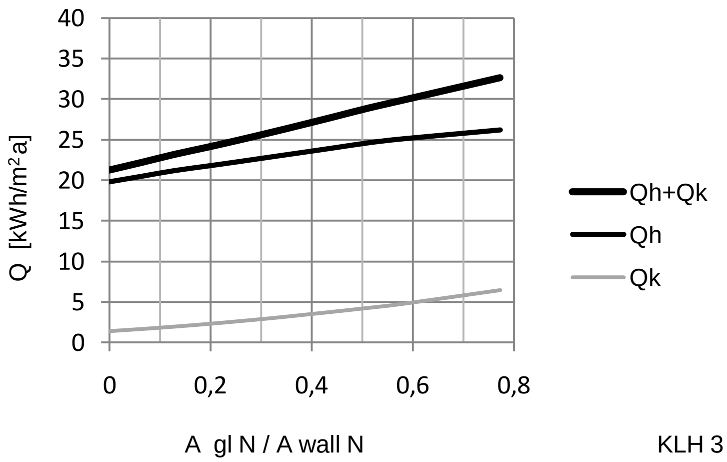


Figure 4-44: Annual energy demand in KLH 3 construction system as a function of AGAW for north orientation.

Similar to previously presented analyses for the TF and KLH construction systems the energy demand increases almost linearly with an increase in the glazing size. The Q_h loss as a consequence of the total glazing modification from AGAW=0 to AGAW=0.78 exceeds 6 kWh/m^{2}a or 32% of the starting-point value. The Q_k increases by about 5 kWh/m^{2}a and consequently the Q_h+Q_k by more than 11 kWh/m^{2}a.

The influence of the size of the west and east-oriented glazing area on the energy balance in the KLH 2 construction system is presented in Figure 4-39.

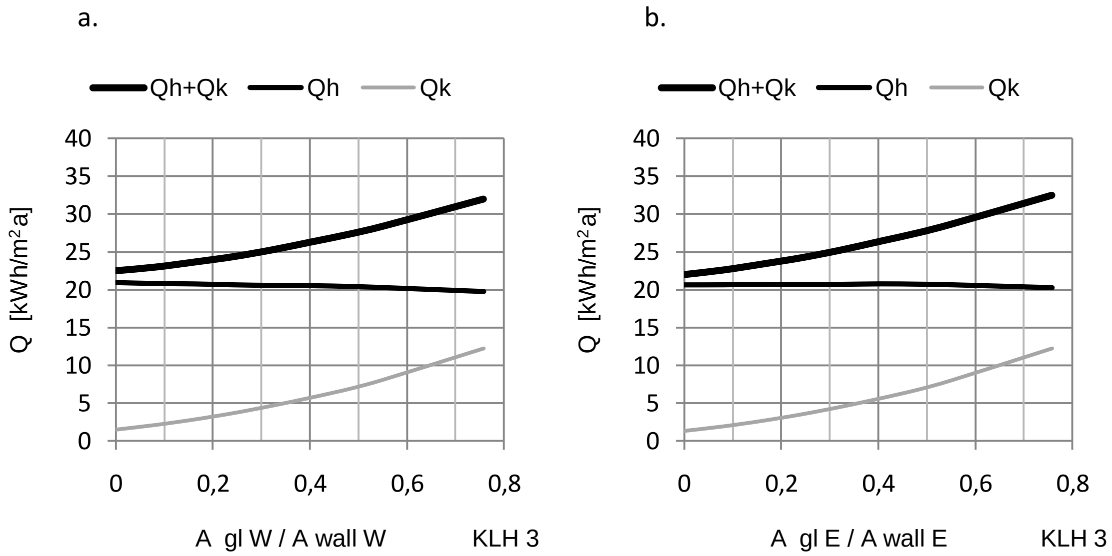


Figure 4-45 a, b: Annual energy demand in KLH 3 construction system as a function of AGAW for west and east orientation.

The influence of changing the size of the glazing area facing west is rather weak concerning the energy demand for heating, which remains almost constant. The Q_h energy demand pattern is similar for west and east orientations. On the other hand, an increase in the glazing size affects the energy demand for cooling more strongly, which increases slightly exponentially. The sum total of the heating and cooling demand grows almost linearly with an increase in the AGAW values of the west as well as the east-oriented external walls (see Figure 4-45a and 4-45b).

The comparison of energy demand for heating as a function of the glazing area size for different cardinal directions of the KLH 3 construction system is presented in Figure 4-46.

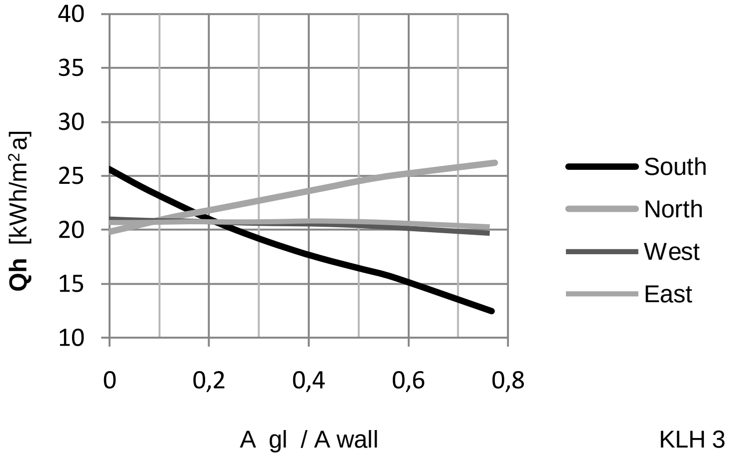


Figure 4-46: Annual energy demand for heating in KLH 3 construction system as a function of AGAW for different cardinal directions.

According to the data presented in Figure 4-46 the influence of changing the glazing area on energy demand for heating is the largest in the south orientation, where Q_h decreases almost linearly with a growing AGAW. The heat gains at *AGAW=0.79* add up to slightly over 13 kWh/m^{2}a or 51% with regard to walls without any glazing. On the contrary in the north orientation the energy demand for heating increases with a growing AGAW, although the influence is smaller compared to the south orientation, a heat loss of slightly over 6 kWh/m^{2}a or 32% of the starting-point value is evident as a result of a total AGAW increase. The west and east orientations show practically similar behaviour that is almost independent of the size of the glazing area.

The comparison of energy demand for cooling as a function of the glazing area size for different cardinal directions of the KLH 3 construction system is presented in Figure 4-47.

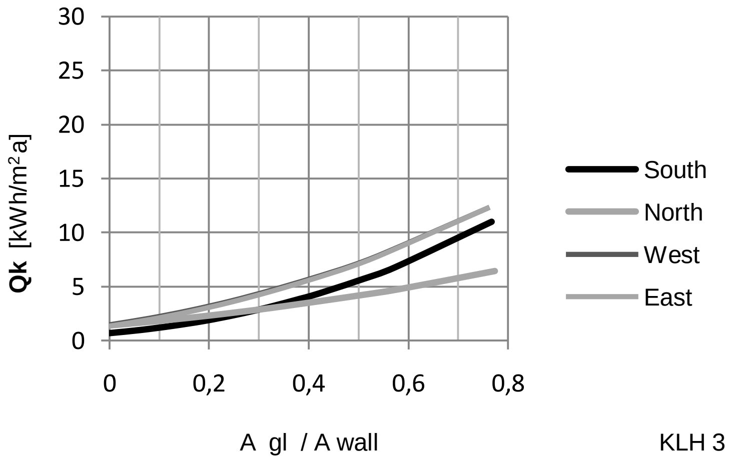


Figure 4-47: Annual energy demand for cooling in KLH 3 construction system as a function of AGAW for different cardinal directions.

Energy demand patterns presented in Figure 4-47 show that the sensitivity of the energy demand for cooling to the glazing size increase is the weakest for the north orientation.

West, east and south orientations show similar behaviour, although the Q_k is slightly lower for the south orientation, which can be ascribed to the large south-oriented glazing area of the basic model (see explanation of Figures 4-10 and 4-11).

The comparison of the sum total of energy demand for heating and cooling as a function of the glazing area size for different cardinal directions of the KLH 3 construction system is presented in Figure 4-48.

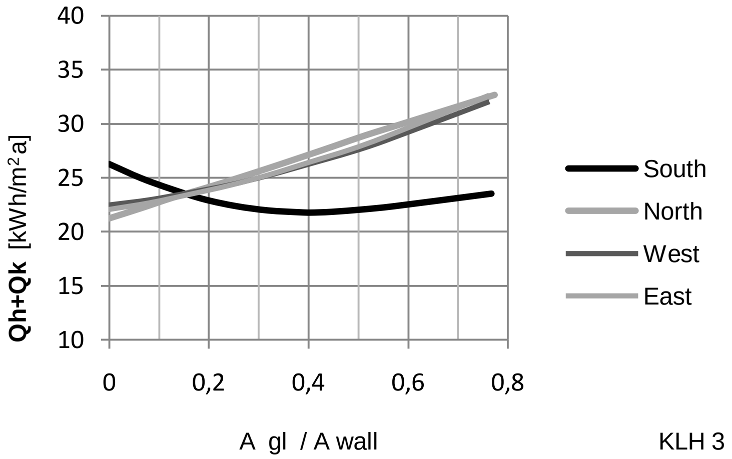


Figure 4-48: Annual sum total of energy demand for heating and cooling in KLH 3 construction system as a function of AGAW for different cardinal directions.

The comparison of the results for the sum total of energy demand for heating and cooling for different orientations in the KLH 3 construction system are presented in Figure 4-47. The sum total of the cooling and heating demands increases linearly with an increase in the glazing area in the north orientation. East and west orientations show similar behaviour with a slightly higher energy demand in the east, although the difference is more or less negligible. The analysis for the south orientation shows the functional optimum at *AGAW≈0.38-0.40,* with a further increase in the glazing area the energy demand for heating starts to increase at a minimal pace.

4.2.9 Comparison of energy demand in massive panel (KLH 1 – KLH 3) construction systems

The comparison of energy demand for heating for different massive panel construction systems (KLH 1 – KLH 3) is presented in Figure 4-49.

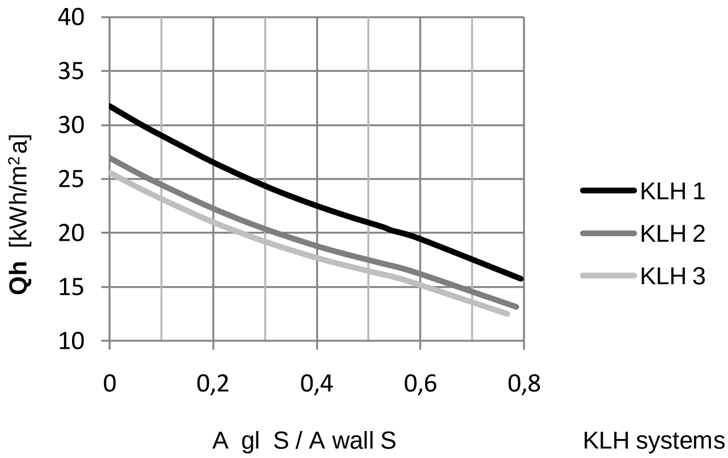


Figure 4-49: Comparison of energy demand for heating as a function of AGAW for southern orientation of selected KLH construction systems (KLH 1 – KLH 3).

The results in Figure 4-49 show an almost linear functional dependence of Q_h on the size of the glazing area. If energy demand patterns of the selected KLH systems are compared, we can see that the energy demand for heating is the highest in the KLH 1 and lowest in the KLH 3 construction system, which we suppose is related to the U-value of external wall elements.

The comparison of energy demand for cooling for different massive panel construction systems (KLH 1 – KLH 3) is presented in Figure 4-50.

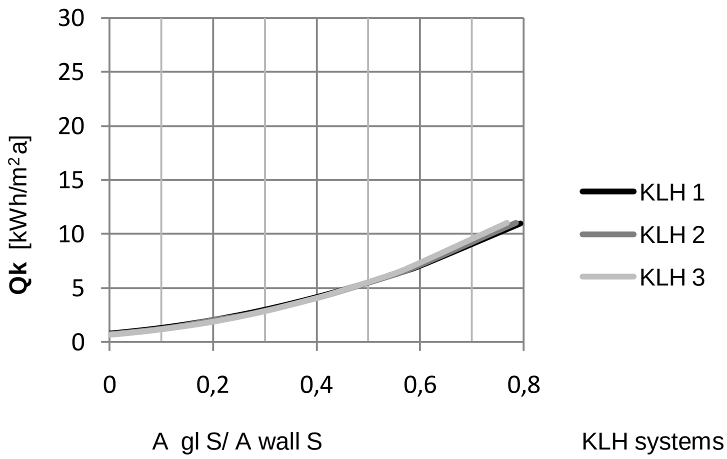


Figure 4-50: Comparison of energy demand for cooling as a function of AGAW for southern orientation of selected KLH construction systems (KLH 1 – KLH 3).

According to the results presented in Figure 4-50 the behaviour of energy demand for cooling is similar for all KLH construction systems. Upon a more detailed examination some crossing of function curves of different construction systems is evident, but only in a very limited range of Q_k values. More interesting is the finding which distinguishes from the results for Q_h; an increase in the south-oriented glazing area in wall elements of higher thermal transmittance as well as in wall elements of lower thermal transmittance is similar. On the basis of this research, we can see that the U-value of the external wall has no distinctive impact on the behaviour of the energy demand for cooling, it depends only on the size of the glazing area as well as on its orientation and of course on other parameters which are not analysed in this research.

The comparison of the sum total of energy demand for heating and cooling for different massive panel construction systems (KLH 1 – KLH 3) is presented in Figure 4-51.

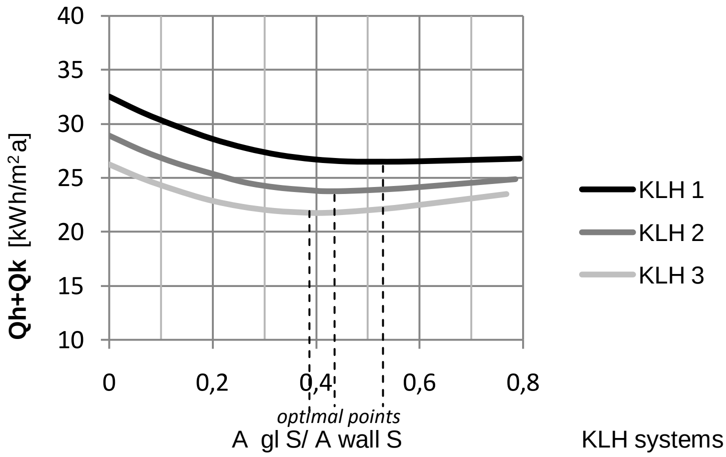


Figure 4-51: Comparison of sum total of energy demand for heating and cooling as a function of AGAW for southern orientation of selected KLH construction systems (KLH 1 – KLH 3).

The results for the sum total energy demand presented in Figure 4-51 show an interesting appearing of the functional optimum, which is clearly evident in the KLH 3 construction system appearing in the range of *AGAW≈0.38-0.40* and less expressive in KLH 1, appearing in the range of *AGAW≈0.52-0.54*. On the basis of the analysed results we expect that the optimal size of the glazing area in south-oriented external walls depends on the thermal transmittance of selected wall elements. For comparison purposes as well as for support in setting up the basic principle of the glazing surface‘s impact on energy behaviour patterns, a comparison of the TF and KLH construction systems was carried out as well.

4.2.10 Comparison of energy demand in timber-frame (TF 1 – TF 3) and massive panel (KLH 1 – KLH 3) construction systems

The comparison of energy demand for heating for different construction systems (TF1 – TF 3 and KLH 1 – KLH 3) is presented in Figure 4-52.

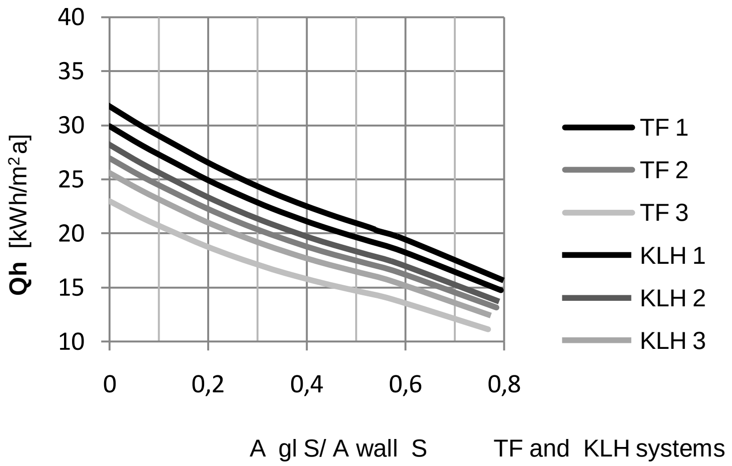


Figure 4-52: Comparison of energy demand for heating as a function of AGAW for southern orientation of selected TF (TF 1 – TF 3) and KLH (KLH 1 – KLH 3) construction systems.

The results in Figure 4-52 show an almost linear functional dependence of Q_h on the size of the glazing area in all treated construction systems. Observation of the results shows also that the energy demand for heating is the highest for the KLH 1 system, where the U-value of the external wall element is the highest, and lowest in the TF 3 construction system, with the lowest U_{wall}-value. If we compare Q_h energy savings, caused by the glazing increase from AGAW=0 to AGAW≈0.78, we notice that despite minimal differences in the values expressed in units [kWh/m^{2}a], for instance the Q_h saving of about *12 kWh/m^{2}a* for TF3 or *16 kWh/m^{2}a* for KLH1, the Q_h savings represent just the same share of the starting point value of each selected construction system which is about 51% for all TF and KLH construction systems.

The comparison of energy demand for cooling for different construction systems (TF1 – TF 3 and KLH 1 – KLH 3) is presented in Figure 4-53.

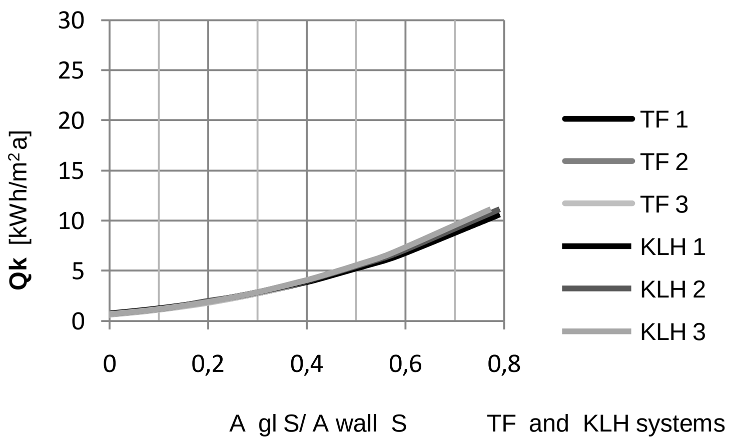


Figure 4-53: Comparison of energy demand for cooling as a function of AGAW for southern orientation of selected TF (TF 1 – TF 3) and KLH (KLH 1 – KLH 3) construction systems.

According to the results presented in Figure 4-53, the behaviour of the energy demand for cooling is similar for the TF and KLH construction systems. As already seen in the previously analysed comparison of selected TF (TF 1 – TF 3) and KLH (KLH 1 – KLH 3) construction systems, an increase in the south-oriented glazing area in wall elements with a higher thermal transmittance as well as in wall elements with a lower thermal transmittance is similar. On the basis of this research, we anticipate that the U-value of the external wall has no distinctive impact on the behaviour of the energy demand for cooling, it depends more on the size of the glazing area as well as on its orientation and of course on other parameters which are not analysed in this research.

The comparison of the sum total of energy demand for heating and cooling for different construction systems (TF1 – TF 3 and KLH 1 – KLH 3) is presented in Figure 4-54.

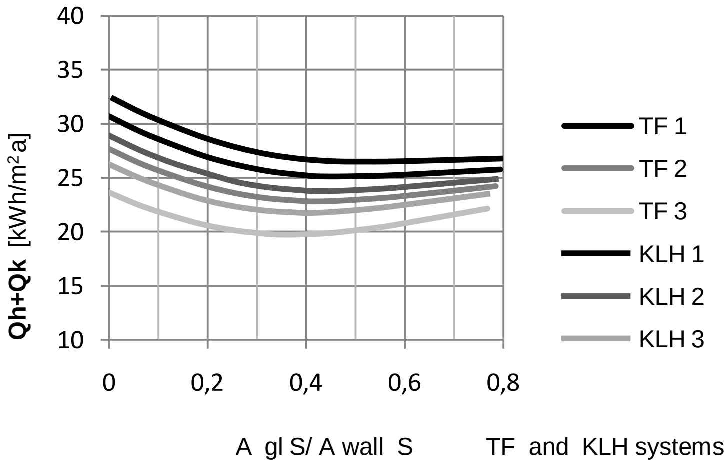


Figure 4-54: Comparison of sum total of energy demand for heating and cooling as a function of AGAW for southern orientation of selected TF (TF 1 – TF 3) and KLH (KLH 1 – KLH 3) construction systems.

According to the results presented in Figure 4-54 the energy savings in the KLH 1 construction system reach about 6 kWh/m^{2}a or 19% of the starting point value, while in the TF 3 construction system, which possesses the best thermal properties among analysed systems, savings of only about 4 kWh/m^{2}a or slightly over 16% are evident. Further observation of the results for compared construction systems shows that the optimal point appears at different values for AGAW in each individual system. So in KLH 3 the optimum appears at *AGAW≈0.38-0.40*, in KLH 2 at *AGAW≈0.41-0.46*, in KLH 1 at *AGAW≈0.52-0.54*, in TF 3 at *AGAW≈0.34-0.38*, in TF 2 at *AGAW≈0.41* and finally in TF 1 at *AGAW≈0.42-0.50*. The analyses of formerly presented results shows that the optimal glazing share is larger for exterior wall elements with a higher U-value reaching a maximal optimal share of 54% of the total south-oriented external wall surface in KLH 1, while it is somewhat lower for exterior wall elements with a lower U-value, reaching a minimal share of 34% in the TF 3 construction system. Next, the form of the Q_h+Q_k function curve in different systems was analysed as well, the optimal point is clearly evident in systems with a lower U_{wall}-value, where the sum of total energy demand increases noticeably after reaching the optimum, while the optimum is less expressive in systems with a higher U_{wall}-value, where the function curve converges after reaching the optimum. If applied to praxis this means that for exterior wall elements with excellent thermal properties (*U_{wall}-value≈0.1-0.124 W/m^{2}K*) the optimal share of glazing is strictly defined, while for wall elements of higher U-values (*U_{wall}-value≈0.164-0.181 W/m^{2}K*), the glazing share can exceed the optimal value without any noticeable consequences regarding an increase in the sum total of energy demand for heating and cooling. In regard to the presented results which show that for the construction systems with a higher U_{wall}-value convergence appears, we have to stress that the overheating risk must be taken into consideration when glazing area is extremely large (*AGAW>0.53* for TF 1 and KLH 1). The frequency of temperatures above the comfort limit, defined by a maximal summer interior temperature of 25°C, should not exceed 10% of the year, therefore in the cases of extremely large glazing area the data for the overheating frequency has to be controlled. The regularity of the data presenting the overheating frequency with the PHPP software is only approximate.

Within the selection of the literature quoted in the State-of-the art sub-chapter, it is most reasonable to compare the results of the current study, from the point of view of the construction system, to the numerical parametric study performed by Bülow-Hübe (2001). In our research an attempt for a more systematic analysis has been made, with the model of a building of our base-case study being performed in many variations of timber construction systems. Although the Swedish climate data differ from those for Ljubljana, some of the general conclusions regarding the influence of the window size and orientation on energy demand for heating and cooling are common in some points to our conclusions. The Swedish study, which was carried out on the office building in Lund, built with a timber-frame construction system with a U_{wall}*-value=0.18 W/m²K.* The properties of the glazing surfaces were the following: U_g*-value=0.67 W/m²K and* U_f*-value=1.7 W/m²K,* with the modification of AGAW for south oriented glazing surfaces carried out only in the range of *AGAW=0* to *AGAW=0.50*, which caused a decrease of energy demand for heating $\Delta Q_h=14$ *KWh/m²a,* the latter meaning approximately 19% of the Q_h value at *AGAW=0.* In our study the results for the TF 1 construction system show a difference of $\Delta Q_h \approx 11$ *KWh/m²a* or almost 35% of the starting point value in the same range of AGAW modification. Certainly, the different climate conditions that influence the results obtained for Ljubljana and those for the Swedish city Lund (lat. 55.72° N) with the average annual temperature of 8.2°C have to be considered. Not only due to the climate conditions, but also due to different window qualities, the differences in the absolute values for the heating demand for both buildings, the Slovenian and the Swedish, appear already in the basic model. The energy demand for heating for the two-storey prefabricated model of timber house from our case-study with *AGAW=0.28* for south orientation is approximately $Q_h \approx 23$ kWh/m2a, while the similar building in Sweden with *AGAW=0.30,* points to a much higher energy demand, that of $Q_h \approx 68$ kWh/m2a. This is even not so important, since both parametrical studies have very similar findings considering the influence of east and west oriented glazing surfaces, which in both cases show almost no influence on energy demand for heating.

4.2.11 Comparison of energy demand in new timber-frame (TF 3, TF 1b, TF 1c) and fictive classic single-panel (TFCL 2a, TFCL 2b, TFCL 2c) construction systems with an equivalent U_{wall}-value

In the formerly presented results concerning a comparison of the energy balance in selected construction systems, specific patterns for energy demand appear for each individual construction system. The presumptions were set, that the energy demand patterns for Q_h as well as for $Q_h + Q_k$ depend upon the thermal transmittance of the external wall element. The energy demand patterns for Q_k in different systems were similar to each other, so we anticipated that the U-value of the external wall has no distinctive impact on the behaviour of the energy demand for cooling. For setting up the basic theory of the research, which shall be based on the U_{wall}-value, we need to observe and compare the energy demand behaviour for both, for the new macro-panel wall elements as well as for the classic wall elements with single-panel construction, where the thermal transmittance of the selected wall elements is fictively set at an equal value. In the following Figures (4-55 to 4-57) we present the comparison of the energy demand for construction systems, where wall elements with an equal U_{wall}-value are analysed. The analyses are carried out for three different U_{wall}-values, firstly for a *U_{wall}-value=0.102 W/m^{2}K*, secondly for a *U_{wall}-value=0.20 W/m^{2}K* and finally for a *U_{wall}-value=0.25 W/m^{2}K*.

The first comparison was carried out for the new macro-panel TF 3 system and for the fictive classic single-panel TFCL 2a system, both with a *U_{wall}-value=0.102 W/m^{2}K*. The TFCL 2a system was obtained by adding insulation with a thermal conductivity value *λ=0.035 W/mK* to the classic single-panel TFCL 2 construction system. The comparison of energy demand for both systems is presented in Figure 4-55.

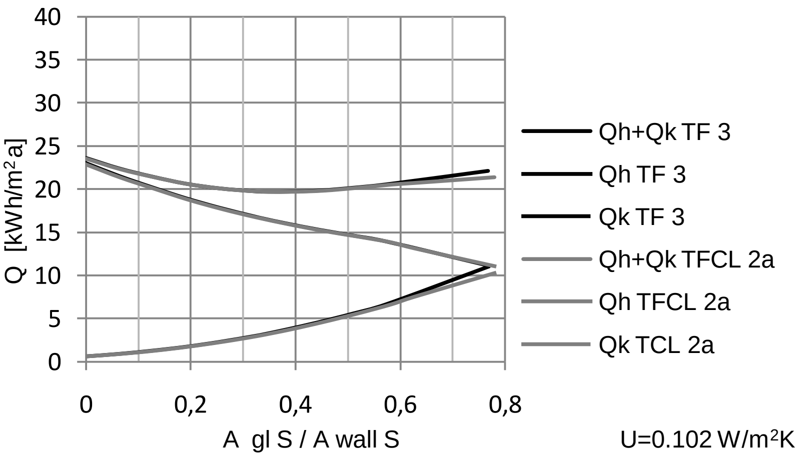


Figure 4-55: Comparison of energy demand for heating and cooling and for sum total of both as a function of AGAW for southern orientation of selected TF 3 and TFCL 2a construction systems with a unique U_{wall}-value=0.102 W/m^{2}K.

The results presented in Figure 4-55 show that the energy demand behaviour is almost equal for the new macro-panel TF 3 system and for the fictive classic single panel construction system TFCL 2a. There are some negligible differences evident for Q_k and consequently for Q_h+Q_k at higher AGAW values, which are caused by a different thickness of wall elements which affects the fact that both systems have different total sizes of external wall area. Consequently the *AGAW=0.80* for the TF 3 system represents a larger glazing area than the same AGAW in the TFCL 2a system. Finally the energy demand for cooling is a bit higher due to minimally larger amounts of solar gain.

The second comparison was carried out for the fictive new macro-panel construction system TF 1b and for the fictive classic single-panel construction system TFCL 2b, both with a *U_{wall}-value=0.20 W/m^{2}K.* The TF 1b system was obtained by removing insulation from the basic TF 1 construction system, as the TF 2b system was obtained by adding insulation with a thermal conductivity value *λ=0.035 W/mK* to the classic single-panel TFCL 2 construction system. The comparison of energy demand for both systems is presented in Figure 4-56.

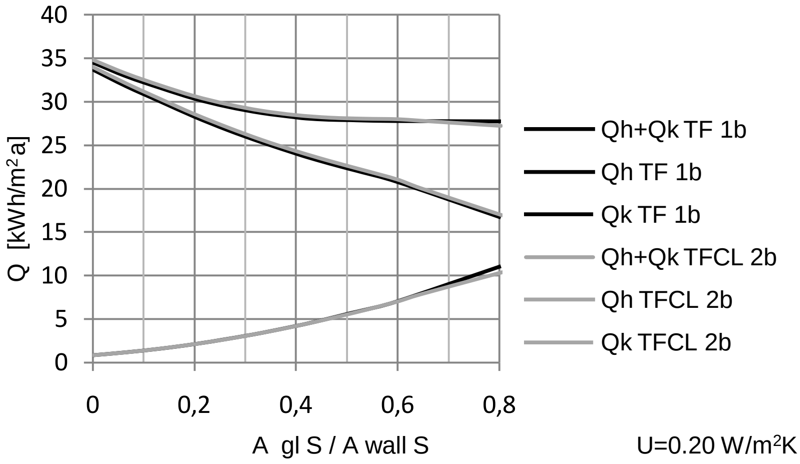


Figure 4-56: Comparison of energy demand for heating and cooling and for sum total of both as a function of AGAW for southern orientation of selected TF 1b and TFCL 2b construction systems with a unique U_{wall}*-value=0.20 W/m²K.*

The results presented in Figure 4-56 show that the energy demand behaviour is almost equal for the fictive macro-panel TF 1b construction system and for the fictive classic single-panel TFCL 2b construction system.

The third comparison was carried out for the fictive new macro-panel construction system TF 1c and for the fictive classic single-panel construction system TFCL 2c, both with an U_{wall}*-value=0.25 W/m²K.* The TF 1c system was obtained by removing insulation from the basic TF 1 construction system, as the TF 2c system was obtained by adding insulation with a thermal conductivity value *λ=0.035 W/mK* to the classic single-panel TFCL 2 construction system. The comparison of energy demand for both systems is presented in Figure 4-57.

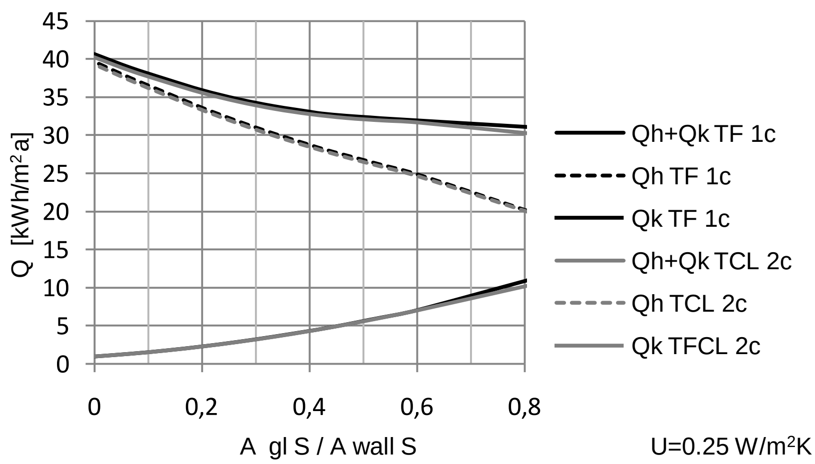


Figure 4-57: Comparison of energy demand for heating and cooling and for sum total of both as a function of AGAW for southern orientation of selected TF 1c and TFCL 2c construction systems with a unique U_{wall}*-value=0.25 W/m²K.*

The results presented in Figure 4-57 show that the energy demand behaviour is almost equal for the fictive macro-panel TF 1c construction system and for the fictive classic single-panel TFCL 2c construction system.

From the previous Figures (4-55 to 4-57) it is evident that the energy demand behaviour is almost equal for fictive timber-frame systems, new and classic, if the U_{wall}-value is equal. Although there are some negligible differences of energy demand patterns evident, the results coincide in a very high range.

Findings based on the latter analyses are very important for support in setting up the basic principle of the functional dependence of annual energy demand, considering the specific share of the south-oriented glazing area, from the U-value of the external wall element. In a further sub-chapter we are going to present the principle of energy demand dependence as well as the optimal glazing area size dependence on the U_{wall} –value, which becomes the only variable parameter, for all contemporary prefabricated timber construction systems, independently of the type of construction system. Therefore we will present the generalisation of the problem on one single independent variable.

4.3 Generalisation of the problem on one single independent variable (U_{wall}-value)

Based on the previously presented analyses where the comparison of new macro-panel (TF), massive panel (KLH) and classic single-panel (TFCL) as well as all fictive construction systems showed very similar results, which were independent of the kind of construction system, we can generalize the problem of the optimization of glazing area size and energy demand behaviour on one single variable which is the U_{wall}-value.

4.3.1 Functional dependence of the optimal share of south-oriented glazing area and parallel of the lowest sum total of energy demand for heating and cooling from the U_{wall}-value

Based on the previous research we are can analyse the relationship between the optimal glazing size in south-oriented external wall elements and the thermal transmittance of the wall element. The data presented in Figure 4-58a show the values of AGAW, at which the sum total of heating and cooling demand reaches the lowest value, dependant on the U-value of the selected external wall element.

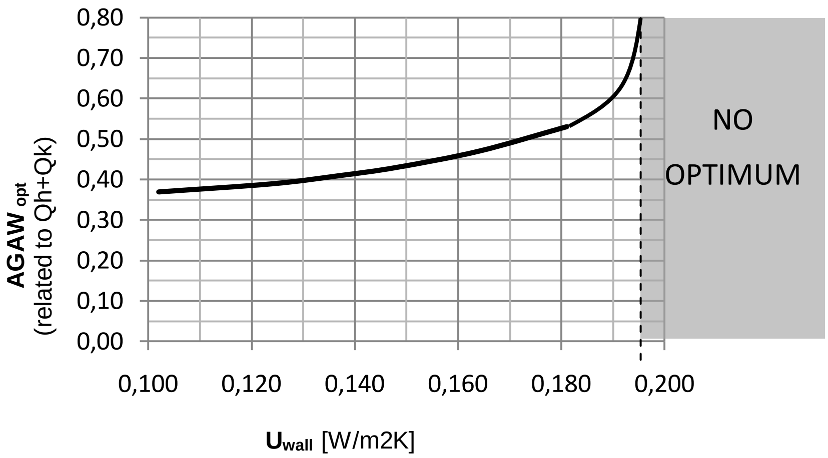


Figure 4-58a: Optimal values of AGAW in south oriented external wall element as a function of U_{wall}–value for timber construction systems

The graphical presentation in Figure 4-58a is supported with the data presented in Figure 4-58b, which show that no optimum or convergence of the function curve is evident for systems with an approximate U_{wall}*-value*$\geq 0.20\ W/m^2K$.

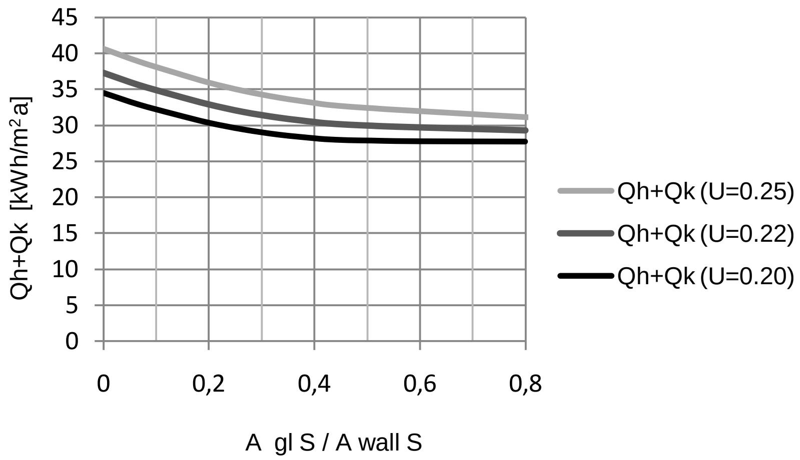


Figure 4-58b: Comparison of sum total of energy demand for heating and cooling as a function of AGAW for southern orientation for three selected construction systems with an U_{wall}*-value=0.20 W/m²K*, U_{wall}*-value=0.22 W/m²K* and U_{wall}*-value=0.25 W/m²K*.

As already explained in analyses presenting individual timber construction systems, the lowest Q_h+Q_k appears at a lower AGAW value in systems with a lower U_{vall}-value, while it passes on to a higher AGAW in systems with a higher U_{vall}-value, which is presented in Figure 4-58. Next the convergence of the function curve appears for analysed wall elements with a U_{wall}*-value=0.164 W/m²K* and U_{wall}*-value=0.181 W/m²K*. In Figure 4-58b we can see that the optimum or the convergence of the function curves appears only in systems with a U_{wall}*-value≤0.20 W/m²K (approximately)*, while in systems with a U_{wall}*-value>0.20 W/m²K* the sum total of energy demand for heating and cooling decreases with a growing AGAW, no optimum or convergence of the function curve is evident anymore.

Regarding the functional optimum, we should once again explain that the definition of the optimal point is described as the optimal glazing-to-wall area ratio (AGAW) in south-oriented external wall elements at which the sum total of the heating and cooling demand reaches the lowest value. The optimal point in systems with excellent thermal properties (U_{vall}*-value=0.102 W/m²K*) appears at *AGAW=0.34-0.38,* while in systems with a higher U-value of wall elements (U_{vall}*-value=0.181 W/m²K*) the optimum in the range of AGAW*=0.52-0.54*. Next, the optimal point is well-defined for systems with a low U_{wall}-value, while in systems with a U_{wall}*-value≈0.164-0.181 W/m²K*, the optimum is less evident and the function curve starts to converge at higher AGAW values. The calculation for wall elements with a U_{wall}*-value≈0.20-0.25* W/m²K showed that no optimum or convergence of the function curve appears anymore, instead of these a straight line with a minimal inclination appears for higher AGAW values (AGAW>0.4). The inclination of the straight line increases with higher U_{wall}-values. Furthermore in systems with a U_{wall}-value≈0.30 the form of the function curve slowly skips to a linear form (not only for higher AGAW values). The presented analysis demonstrates that the appearing of the optimal AGAW in south-oriented exterior walls depends on the thermal transmittance of the exterior wall. For analysed systems with a U_{wall}-value≤0.181 W/m²K the optimal AGAW value is defined, while for analysed systems with lower insulation features, no optimum or convergence appears, the function form starts changing from a parabolic form to a straight line, which means that the lowest Q_h+Q_k is reached with the maximal glazing share.

Additional to a graphical presentation of the optimal AGAW values as a function of U_{wall}-value numerical data are also presented in Table 4-3.

Construction System	U_{wall} [W/m^{2}K]	AGAW $_{optimal}$	*AGAW$_{optimal}$ adjusted*
TF 3	0.102	0,34-0.38*	0,37
KLH 3	0.124	0,38 - 0,40	0,39
TF 2	0.137	0,41	0,41
KLH 2	0.148	0,41 - 0,46	0,43
TF 1	0.164	0,42 - 0,50	0,47
KLH 1	0.181	0,52 - 0,54	0,53
SYSTEMS**	≥0.20	≈0.80	0.80

**at AGAW=0.38 overheating is lower than at AGAW=0.34, **for the construction systems with a U_{wall}-value*≥0.20 W/m^{2}K the optimum is at AGAW≈0.80 (see Figure 4-58)

Table 4-3: Optimal values of AGAW in south oriented external wall element for selected timber construction systems

According to the data presented in Table 4-1 some minimal adjustments of the numerical data have been performed, but only in the range of existing optimal AGAW values.

4.3.2 Functional dependence of energy demand for heating from U_{wall}-value

In further research we observe the relationship between the energy demand for heating and the U-value of the exterior wall element. Firstly the savings of the Q_h, which arise from the total modification of the external south-oriented wall element (from *AGAW=0* to *AGAW≈0.80*) are presented in Figure 4-58a in absolute values as well as in the form of a percentage of the Q_h starting-point value at AGAW=0 in Figure 4-58b.

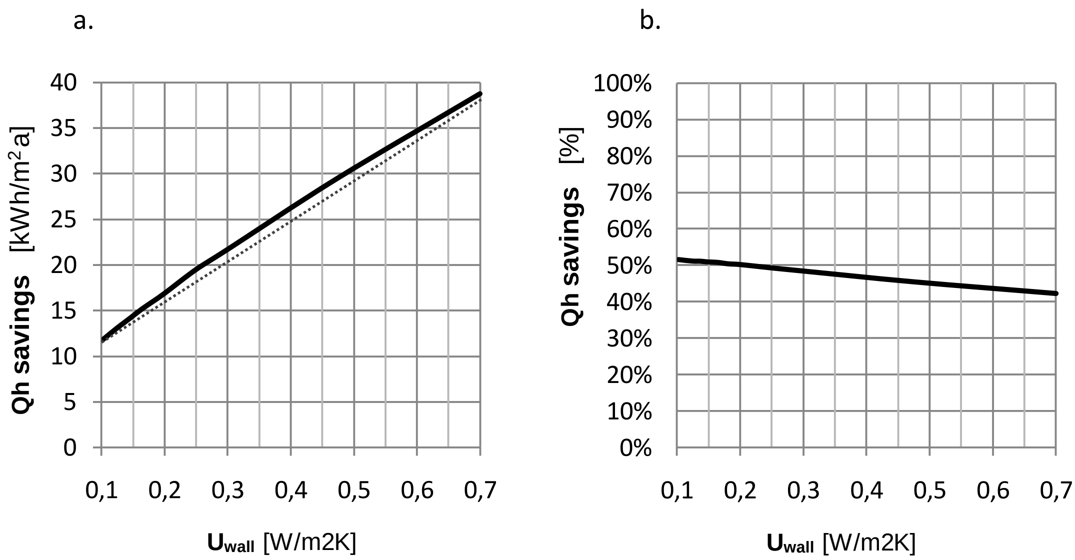


Figure 4-59: $Q_{h\ savings}$ as a function of U_{wall}-value caused by AGAW modification from AGAW=0 to AGAW≈0.80 with a linear approximation.

From the graphical presentation in Figure 4-59a, the Q_h savings presented in units increase linearly with an increase in the U_{wall}-value, which is preconditioned by the fact that the energy demand for heating is expressively higher in construction systems with a higher U_{wall}-value, at *AGAW=0* as well as at all AGAW values (see Figure 4-60). In the systems with a U_{wall}-*value=0.102* W/m^2K the savings exceed 11 kWh/m^2 while in systems with a U_{wall}-*value=0.7* W/m^2K the savings reach almost 40 kWh/m^2 a. In parallel we present the Q_h savings as a share of the starting point value at AGAW=0 (Figure 4-59b), which shows that the Q_h savings decrease linearly with an increase in the U_{wall}-value. For new macro-panel construction systems with a U_{wall}-*value=0.102-0.20* W/m^2K, the Q_h savings are about 50% in relation to a Q_h starting point value at *AGAW=0*. For classic single-panel systems with a U_{wall}-*value=0.3-0.7* W/m^2K the savings presented as a percentage are a bit lower, approximately 45% of the Q_h starting point value at *AGAW=0* on average. Therefore we can see that absolute values of Q_h savings are higher for systems with lower insulation features, although they are lower from a percentage viewpoint at the same time.

According to the results presented in Figure 4-59 we present the equation for the function line representing Q_h savings as a function of the U_{wall}-value caused by an AGAW modification from *AGAW=0* to *AGAW≈0.80*. If we consider a linear approximation (grey dotted line in Figure 4-59) an approximated linear equation can be developed for Q_h in the form of:

$$\Delta Q_h \approx 44.8 \times U_{wall} + 7.38 \quad (4\text{-}1)$$

According to the presented data we can establish that the energy-saving potential is much higher for the construction systems with a higher U_{wall}-value. The latter is very important for the renovation of old prefabricated timber-framed houses built with a single-panel construction system, where apart from the commonly applied renovation where external walls are additionally insulated, the enlargement of existing glazing surfaces if installed in a proper share of the south-oriented façade also contribute to a reduction in the energy demand for heating. The installation of new glazing areas can contribute to better energy performance of the building only if the glazing quality is high-performance triple glazing (described in sub-chapter 4.1.3). For further research it would be necessary to analyse the influence of glazing surfaces, with different performances regarding U_g-value and g-value, on the energy demand of the building.

The general fact that the energy demand for heating is related to the U-value of the exterior wall elements is presented graphically in Figure 4-60.

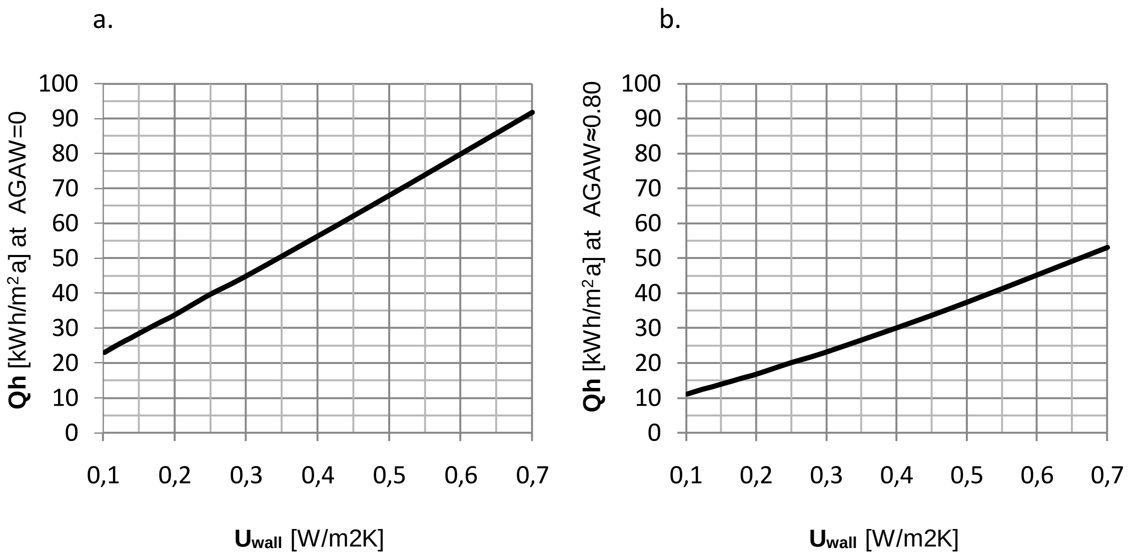


Figure 4-60: Q_h demand as a function of U_{wall}-value at AGAW=0 and at AGAW≈0.80.

In Figure 4-60 it is presented that the energy demand for heating is expressively higher in construction systems with a higher U_{wall}-value at *AGAW=0* (Figure 4-60a) as well as at all *AGAW≈0.80* (Figure 4-60b).

4.3.3 Functional dependence of energy demand for cooling from U_{wall}-value

In further research we observe the relationship between energy demand for cooling and the U-value of the exterior wall element. Firstly the Q_k losses, which arise from the total modification of the external south-oriented wall element (from *AGAW=0* to *AGAW≈0.80*) are presented in Figure 4-61 in absolute values.

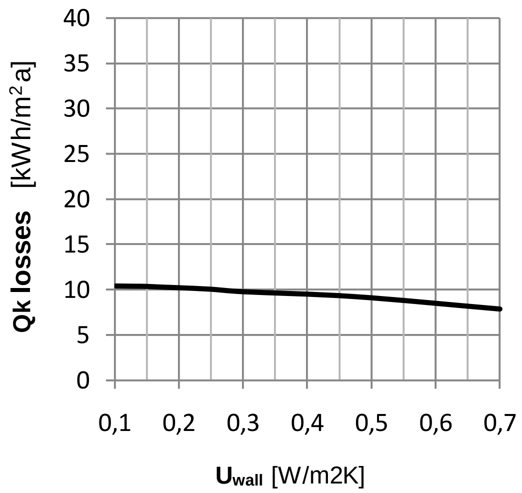


Figure 4-61: Q_k losses as a function of U_{wall}-value caused by AGAW modification from AGAW=0 to AGAW≈0.80.

The Q_k losses caused by a total glazing modification are more or less constant with just a minimal decrease in systems with wall elements of worse thermal properties. From the results presented in Figure 4-61 we can infer that the U_{wall}-value has no distinctive impact on the energy demand for cooling. The latter can be further supported by additional data presented in Figures 4-62a and 4-62b.

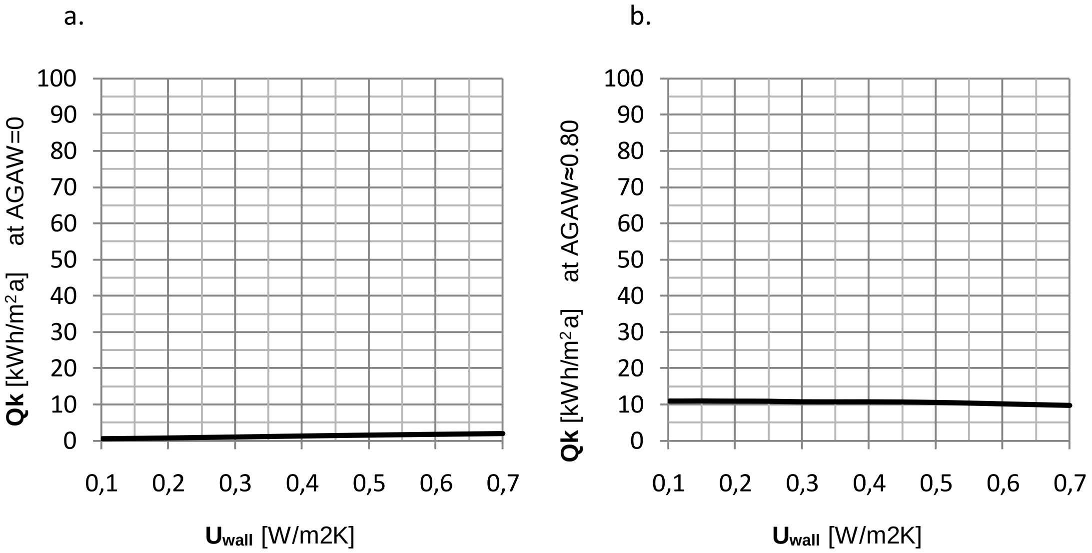


Figure 4-62 a, b: Q_k demand as a function of U_{wall}-value at AGAW=0 and at AGAW≈0.80.

According to the results presented in Figure 4-62a the energy demand for cooling increases at a minimal pace with the increasing of the U_{wall}-value, when wall elements with no glazing are analysed (AGAW=0). The results show that there exists an almost negligible influence of the U_{wall}-value on the energy demand for cooling. Observing the results presented in Figure 4-62b, there is a barely noticeable decrease in Q_k value in systems with a higher U_{wall}-value, when wall elements with a high proportion of glazing (AGAW≈0.80) are analysed. The U_{wall}-value has an even smaller influence at AGAW≈0.80 than at AGAW=0.

The energy demand patterns for cooling in general are more or less constant with a minimal movement if compared to the energy demand patterns for heating. We can once again infer that the U_{wall}-value has no distinctive impact on energy demand for cooling.

4.3.4 Functional dependence of sum total of energy demand for heating and cooling from U_{wall}-value

Finally the sum total of energy demand for heating and cooling dependant on U_{wall}-value is analysed in Figures 4-63 and 4-64 in order to develop mathematical equations which can be applied to all analysed timber framed systems. Firstly we present the Q_h+Q_k savings which arise from modification of the south-oriented glazing size from AGAW=0 to AGAW=optimal, where we have to emphasize that the optimal AGAW values differ from one construction system to another (see Table 4-1), so different AGAW values are taken into consideration in the next Figure 4-63.

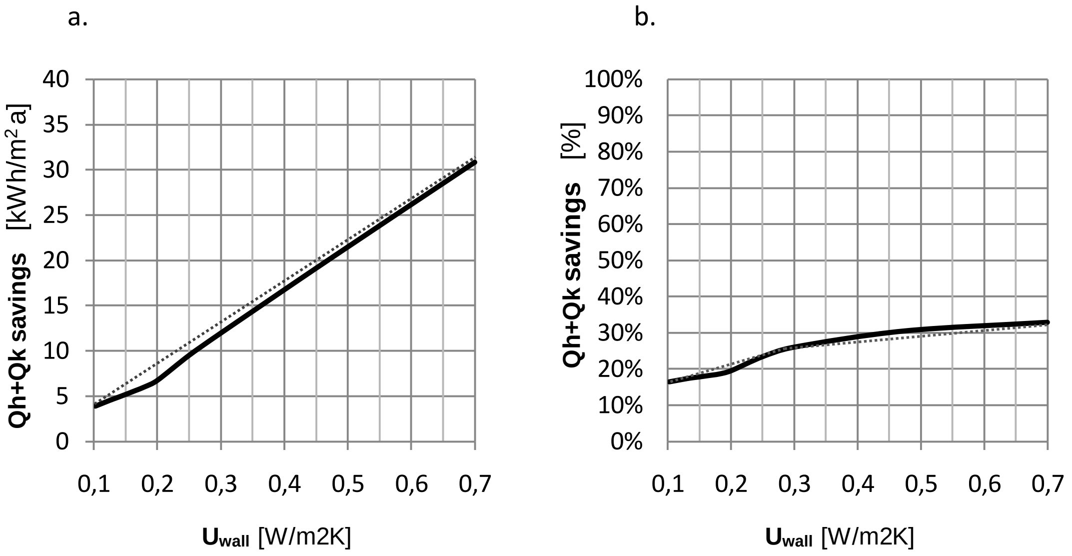


Figure 4-63: Q_h+Q_k savings as a function of U_{wall}-value caused by AGAW modification from AGAW=0 to AGAW=optimal and with an approximated linearization.

Based on the data presented in Figure 4-63a, the equation for the function line representing Q_h+Q_k savings (ΔQ_h) is presented in Eq. (4-1), for which an approximate linearization approach (see grey dotted line in Figure 4-63a) is used. Using this approach we actually neglect the influence of the functional formation of $AGAW_{opt}$ for values of $U_{wall} \leq 0.20$ W/m^{2}K. However the so defined approximate equation is very convenient for the determination of approximate energy savings at optimal size of glazing area with regard to the thermal transmittance of the exterior wall (U_{wall}-value).

$$(Q_h+Q_k)\ savings = \Delta(Q_h+Q_k) \approx 44.95 \times U_{wall} - 0.605 \quad (4\text{-}2)$$

According to the results presented in Figure 4-63a the sum total of energy demand for heating and cooling savings, caused by the total modification of the glazing area in south-oriented exterior walls from *AGAW=0* to *AGAW=optimal*, increases almost linearly with an increase in U_{wall}-values. From the results presented in Figure 4-63a where the Q_h+Q_k savings presented in units, it can be seen that for the systems with a high U_{wall}-value the saving potential by enlargement of the glazing area is bigger than for the systems with a lower U_{wall}-value. The inclination of the function is smaller in Figure 4-63b, where the Q_h+Q_k savings are presented as a percentage of the starting point value for different U_{wall}-values. In the figure on the right where we can detect three different inclinations of the function line which is related to the findings, that in the construction systems with a *U_{wall}-value≤0.20 W/m^{2}K* the optimal AGAW-value appears, parallel to the parabolic dependence of the function curve representing Q_h+Q_k as a function of AGAW, this is evident, while in construction systems with a *U_{wall}-value≥0.20 W/m^{2}K* no optimum appears, the dependence of the function curve representing, Q_h+Q_k as a function of AGAW is only linear.

For setting the next general principle Figure 4-64 with a graphical presentation of the sum total of energy demand for heating and cooling as a function of the U_{wall}-value for three different AGAW values (*AGAW=0, AGAW≈0.40, AGAW≈0.80*) is of great importance.

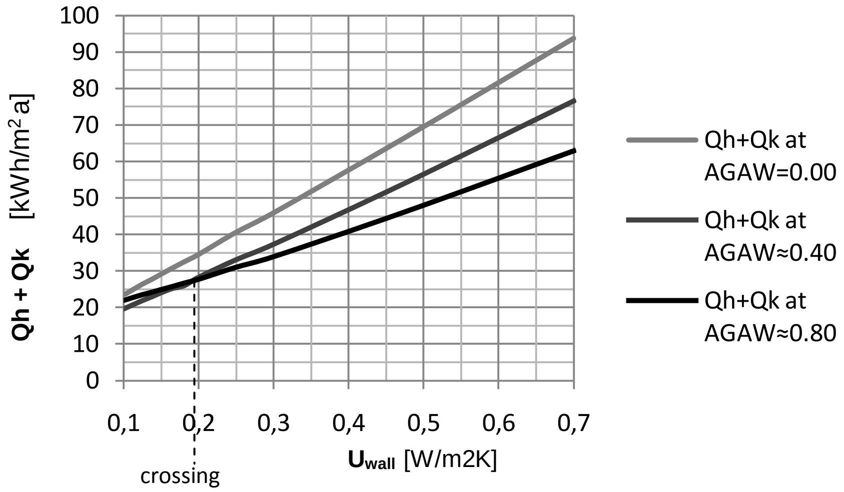


Figure 4-64: Q_h+Q_k demand as a function of U_{wall}-value for AGAW=0, AGAW≈0.40 an AGAW≈0.80.

Results presented in Figure 4-64 show that the Q_h+Q_k demand increases linearly with an increase in the U_{wall}-value. The results for Q_h+Q_k are presented for the three glazing-to-wall ratios, for *AGAW=0*, *AGAW≈0.40* and for *AGAW≈0.80*. Upon more detailed observation of the presented results we can detect a crossing of the function lines representing energy demand at *AGAW≈0.80* and at *AGAW≈0.40* in the range of the x-axis $U≈0.20\ W/m^2K$, (the exact value is going to be calculated and presented in further text) which indicates approximately the U_{wall}-value at which the optimal point disappears. Due to the appearing of the optimum for the wall elements of which the U_{wall}-value is lower than 0.20 W/m^2K, the Q_h+Q_k demand for such elements is lower at *AGAW≈0.40* than at *AGAW≈0.80.* In the case of the wall elements with the U_{wall}*-value*$≥0.20\ W/m^2K$, the Q_h+Q_k demand is lower at the highest possible AGAW value, which is approximately presented by *AGAW≈0.80*. The differences for Q_h+Q_k demand between selected AGAW values are bigger for wall elements with extremely high U_{wall}-values. Values for sum total of energy demand are presented for all three AGAW values with straight lines with an inclination angle depending on the AGAW value**.**The function line equations are defined as:

1. *for AGAW = 0;* $Q_h+Q_k \approx 116{,}80 \times U_{wall} + 11.95$ (4-3)

2. *for AGAW ≈ 0.40;* $Q_h+Q_k \approx 94{,}98 \times U_{wall} + 10.10$ (4-4)

3. *for AGAW ≈ 0.80;* $Q_h+Q_k \approx 67.85 \times U_{wall} + 15.36$ (4-5)

On the basis of the function line equations (4-4) and (4-5) we can mathematically determine the exact x-axis value (U_{wall}-value), at which the crossing of the function line appears. For this purpose we set the next relation:

$$94{,}98 \times U_{wall} + 10.1 = 67.85 \times U_{wall} + 15.36 \rightarrow U_{wall,\ lim} = 0{,}193\ W/m2K \quad (4\text{-}6)$$

of which the derivative gives us the exact x-axis (U_{wall}-value). We calculate that the crossing of the function lines appears approximately at $U_{wall}=0.193\ W/m^2K$. The crossing point represents the limit regarding the U_{wall}-value ($U_{wall,\ lim}$) for the appearing of the functional optimum. Furthermore based on mathematical approximate calculation we establish that for the wall elements with a U_{wall}*-value≥0.193* the functional optimum disappears.

For the results derived using Eq. (4-3) to (4-5) it is very important to be adequate with the total energy savings from Figure 4-63a, which confirms the regularity of the theory related to energy savings at optimal size of the glazing area ($AGAW_{opt}$) in dependence of one single variable U_{wall}-value. If we take Equation (4-2) and consider a case with a U_{wall}*-value=0.70* W/m^2K, which is a value that is higher than a value of $U_{wall}=0.20\ W/m^2K$ (see Figure 4-58), for which the optimal size of the glazing area appears at *AGAW≈0.80,* the following occurs:

$$\Delta(Q_h+Q_k) \approx 44.95 \times U_{wall} - 0.605 \approx 44.95 \times 0.7 - 0.605 \approx 30.86 \text{ kWh/m}^2\text{a} \quad (4\text{-}7)$$

For the first extreme value of AGAW=0, thus a wall with no glazing, according to Eq. (4-3), the following occurs for a case with a U_{wall}*-value=0.70* W/m^2K:

$$Q_h+Q_k \approx 116{,}80 \times U_{wall} + 11.95 \approx 116{,}80 \times 0.7 + 11.95 \approx 93.71\ kWh/m^2a \quad (4\text{-}8)$$

For the next extreme value of *AGAW≈0.80,* thus a wall with a maximal size of glazing area, according to the Eq. (4-5), the following occurs for a case with a U_{wall}*-value=0.70* W/m^2K:

$$Q_h+Q_k \approx 67.85 \times U_{wall} + 15.355 \approx 67.85 \times 0.7 + 15.355 \approx 62.85\ kWh/m^2a \quad (4\text{-}9)$$

If we subtract the value calculated using Eq. (4-8) from the value calculated using Eq. (4-7), we get the result $\Delta(Q_h+Q_k)= 30.86\ kWh/m^2a$, which is equal to the result calculated using Eq. (4-6). Both values are identical, which confirms the regularity of the results.

The graphical presentation in Figure 4-64 as well as the functional record written by Eq. (4-3) to (4-5) respectively enable a relatively simple determination of the Q_h+Q_k value for all arbitrary values of AGAW with regard to a U_{wall}-value. In this we can use the linear interpolation between function lines defined by expressions (4-3) to (4-5) for values of *AGAW=0, AGAW=0.40* and *AGAW≈0.80.* The Q_h+Q_k value for AGAW*=0.60* could in this manner be obtained by a linear interpolation between expressions (4-4) and (4-5):

4. for $AGAW = 0.60$; $Q_h+Q_k \approx 81.42 \times U_{wall} + 12.73$ (4-9)

which means that the Q_h+Q_k value (as for a U_{wall}*-value=0.70* W/m^2K) would reach approximately $69.72\ kWh/m^2a$.

If we are interested in a Q_h+Q_k value for example at AGAW=0.20, we should use an interpolation between Eq. (4-3) and (4-4) which would result in:

5. for $AGAW = 0.20$; $Q_h+Q_k = 105{,}89 \times U_{wall} + 11.025$ (4-10)

which means that the Q_h+Q_k value (as for a U_{wall}*-value=0.70* W/m^2K) would be estimated approximately to $85.15\ kWh/m^2a$.

Both function lines representing Q_h+Q for *AGAW=0.60* and *AGAW=0.20* as a result of linear approximation are evident in Figure 4-65.

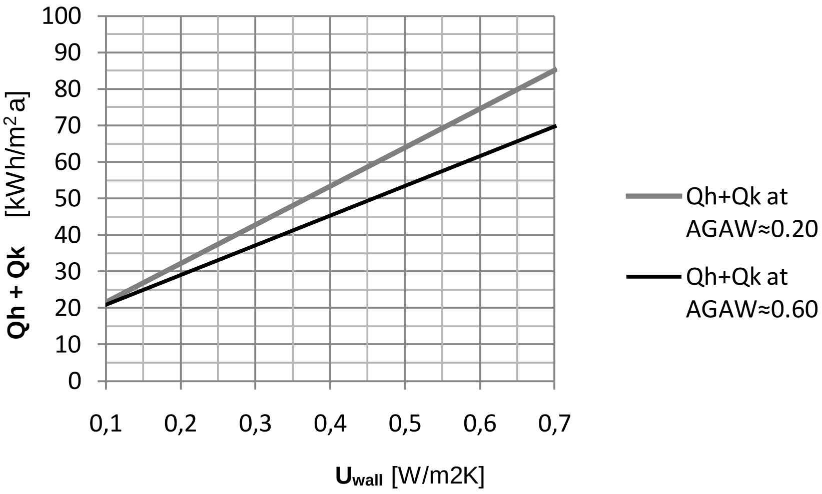


Figure 4-65: Q_h+Q_k demand as a function of U_{wall}-value for AGAW≈0.20 and AGAW≈0.60.

The graphical presentation of the Q_h+Q_k value for AGAW=*0.60* which could in this manner be obtained by a linear interpolation between expressions (4-4) and (4-5) is shown in Figure 4-65. Certainly the linear interpolation is suitable for the calculation of the Q_h+Q_k values for a selected AGAW value as well as for the other U_{wall}-values. The procedure is very simple and applicable owing to the fact that it includes the influence of both of the most important functional variables at the same time (U_{wall}-value and AGAW). In that manner it can be used by designers to obtain a very fast and simple estimation of the expected energy losses or savings at a precisely defined thermal transmittance value of a treated exterior wall element (U_{wall}-value) and of a selected share of the glazing area in the south-oriented façade (AGAW).

5 CONCLUSIONS

5.1 Summary of principal findings based on analyses of the results

In the previous chapter (Ch. 4) analyses of the results of a parametric case study were presented. From among the existing results, obtained by a combination of variable parameters, we have selected and further analysed those of the optimal values related to the energy performance of the case study model. The aim of the calculations performed was to develop an optimal model of a timber prefabricated house regarding the optimal glazing size for each main cardinal direction.

We are presenting the findings based on analyses of the calculated results firstly with regard to the main cardinal directions, secondly with regard to different timber construction systems and finally with regard to one single independent variable which is the U_{wall}-value.

5.1.1 Principal findings for energy demand behaviour with regard to main cardinal directions

The influence of the glazing-to-wall area ratio on the energy demand for heating is the largest and even very favourable, when increasing the glazing surfaces in south-oriented exterior walls. The energy demand for heating decreases almost linearly with an increase in the glazing area. On the other hand the increasing of the glazing surface in north-oriented external walls has a relatively negative influence on the energy demand for heating, moreover it is somewhat smaller in comparison to the influence of increasing the south-oriented glazing surfaces. The influence of the west and east-oriented glazing area is relatively insignificant, with just smaller differences in energy demand for heating being caused by a total glazing modification.

The influence of the glazing-to-wall area ratio on the energy demand for cooling is similar for south, west and east-oriented glazing surfaces, while somewhat weaker for north-oriented glazing surfaces. It is also interesting that the energy demand for cooling does not exceed the limiting value for classification as a passive house, which is 15 kWh/m^2a, in any of the calculated modifications. Notwithstanding a relatively moderate cooling demand, attention has to be paid to the frequency of overheating, especially in cases with an exceedingly high AGAW value, where the frequency of overheating caused by solar gains through large glazing areas can exceed the recommended limit of 10%. Due to a PHPP software warning that the calculation of the frequency of overheating with the PHPP software is not reliable when a large daily temperature swing is present, this data was not included in the analysis in equal measure to the data for the energy demand for heating and cooling. For a more detailed determination of the overheating risk, the application of other software, which supports this kind of information, is necessary.

The influence of increasing the glazing-to-wall area ratio on the sum total of energy demand for heating and cooling is favourable only for the south orientation, while for north, west and east orientations the impact of an increased proportion of glazing area is negative, regardless of the type of construction system. Due to this fact, and considering that the main objective of our research was to define an optimal model of an energy-efficient prefabricated timber house, the north, west and east glazing surfaces were not analysed in detail for additionally selected classic single-panel construction systems, fictive construction systems, nor for the comparison of different construction systems. Also in the second part of the research, where the generalisation of the problem on one single independent variable was carried out, only the south-oriented external wall elements were considered.

For the south orientation the optimum or at least the convergence of the Q_h+Q_k function curve is present, when installing glazing surfaces in contemporary timber wall elements, while for the single-panel wall elements with higher U_{wall}-values an increase in the south-oriented glazing surfaces acts positively on the sum total of energy demand for heating and cooling, which is evident in the linear dependence of the Q_h+Q_k function line. The lowest Q_h+Q_k appears at maximum AGAW values, for which the consideration of data for the overheating risk is required, in order to limit the maximum acceptable glazing size in south-oriented external walls.

5.1.2 Principal findings for energy demand behaviour with regard to different timber construction systems

The comparison of the TF 1-3 and KLH 1-3 contemporary construction systems shows some difference regarding the influence of the south-oriented glazing area size on the energy demand for heating, which is basically related to the U-value of the selected external wall element. On account of the sensitivity on the U_{wall}-value, the comparison of contemporary macro-panel and classic single-panel construction systems shows an explicit difference for the heating energy demand behaviour. On the other hand, the energy demand for cooling is similar for all analysed construction systems, therefore we conclude that the U-value of south-oriented external wall elements have no major impact on the energy demand for cooling. Among the variable parameters of the current base-case study, the glazing size shows a major influence on the energy demand for cooling, as well as the orientation to some extent, which are both related to the amount of solar gains received through glazing surfaces.

For contemporary timber construction systems the optimal south-oriented glazing size which is most favourable for the sum total of energy demand for heating and cooling is determinable. For contemporary timber construction systems with a lower U_{wall}-value (TF 3 and KLH 3) the optimum of the function curve is distinctive and yet the optimal AGAW value is lower than for the systems with a somewhat higher U_{wall}-value (TF 2 and KLH 2). For contemporary construction systems with the highest U_{wall}-value (TF1 and KLH 1) the optimal glazing size (AGAW) is the largest which is shown with the convergence of the Q_h+Q_k function curve. If designing large glazing surfaces in south-oriented external walls, additional attention has to be paid to the frequency of overheating, which should not exceed a value of 10%.

The increasing of glazing surfaces in south-oriented classic single-panel construction systems has a rather positive influence on energy demand. The sum total energy gains show a positive almost linear dependence on an increase in the size of the glazing area. The latter is very favourable for the energy-efficient renovation of old prefabricated timber houses, while not only the additionally insulated thermal envelope but also an increased glazing surface of an adequate quality contribute to a better thermal performance of a renovated building.

5.1.3 Problem transformation: Principal findings for energy demand behaviour with regard to one single independent variable U_{wall}-value

With the transformation of the problem on one single independent variable which is the U_{wall}-value, we generalize the theoretical findings, based on the analysis of our base-case study, to be valid for the whole timber construction, regardless of the construction system. Firstly the energy demand for heating and cooling is proven to be dependent on the glazing-to-wall area ratio, furthermore it is established that the energy demand for heating is also influenced by the U_{wall}-value, and finally the relationship between the optimal glazing size and the U_{wall}-value is determined. The generalisation is valid only for south-oriented external wall elements. The latter presented relationships are going to be theoretically applicable when defining the optimal model of an energy-efficient timber house.

The generalisation of the problem on the U_{wall}-value is going to be applicable from a practical point of view also in cases of renovation of old timber houses, where firstly the average U_{wall}-value is reduced with the installation of an additional layer of insulation, and consequently according to the findings from 5.1.2, the optimal AGAW value is determined according to the new reduced U_{wall}-value. Finally the proper size of glazing surfaces can be installed into south-oriented external walls, which contributes to the better energy performance of the building.

With regard to the optimal sum total of energy demand for heating and cooling it is established that the optimal AGAW in south-oriented external walls depends on the U_{wall}-value. For analysed construction systems with a U_{vall}*-value*$\leq 0.193\ W/m^2K$ the optimal AGAW value is defined as a function of the U_{wall}-value. As the U_{wall}-value rises, the optimal share of south-oriented glazing size rises. Reaching a limiting U_{wall}*-value*$>0.193\ W/m^2K$, the values for an optimal AGAW converge towards the maximal glazing surface. For analysed construction systems with a U_{wall}*-value*$>0.193\ W/m^2K$, no optimum or convergence for AGAW appears. The lowest Q_h+Q_k is reached at the maximum AGAW value, although we have to pay attention to the data for the overheating frequency. The overheating risk is not precisely taken into consideration in the current research, due to a software characteristic, that the PHPP software calculation of the overheating frequency is not reliable when a large daily temperature swing is present.

Next we define the functional dependence of Q_h, Q_k and Q_h+Q_k from the U_{wall}-value, where energy savings and losses were also observed.

The savings of energy demand for heating, which arise from a total glazing modification from $AGAW=0$ to $AGAW\approx0.80$, are in linear correlation with the U_{wall}-value, as the U_{wall}-value rises, more energy is being saved.

The energy demand for cooling, as well as the losses of energy demand for cooling caused by a total glazing modification are not very sensitive to the U_{wall}-value, only minor differences appear for different U_{wall}-values. The energy demand for cooling depends mostly on the size of the glazing area and to some extent on the orientation, which are both related to the solar gains received through glazing surfaces.

The sum total of energy demand for heating and cooling as well as the Q_h+Q_k energy savings caused by a total glazing modification from *AGAW=0* to $AGAW_{opt}$, are in almost linear correlation with the U_{wall}-value, similar to Q_h, the amount of saved energy increases with an increase in the U_{wall}-value.

Finally we define the approximated linear expressions for the Q_h+Q_k savings, which arise from a glazing modification from *AGAW=0* to $AGAW_{opt}$ and the U_{wall}-value (Eq. 4-2). Additionally we define the mathematical relationship between the Q_h+Q_k value and the U_{wall}-value, for specific AGAW values (Eqs. 4-3 to 4-5), on the basis of which we perform a linear interpolation of individual equations in order to calculate the exact energy demand (Q_h+Q_k) for wall elements of different U_{wall}-values for a specific AGAW value (Eqs. 4-9 to 4-10). On the basis of the linear equations (4-4) and (4-5) we mathematically determine the exact limiting U_{wall}-value (Eq. 4-6) at which the crossing of the function lines representing Q_h+Q_k for *AGAW=0.40* and *AGAW≈0.80* appears. At this point the optimum or convergence of the Qh+Qk function curve disappears and skips into a linear dependence on the U_{wall}-value.

Principally the findings of current research are determined only for the selected base-case study model. Our main objective was to demonstrate the approach, which can be used to define the optimal glazing surface for each main cardinal direction in order to obtain the optimal model of an energy-efficient house dependant on one single independent variable (U_{wall}-value). It is difficult to establish what a realistic optimal model is, since most of buildings are unique, and trends also vary over time. However, with the application of the presented approach for each individual timber house, the optimal glazing surface is determinable regarding the lowest energy demand for heating and cooling, and such houses can still keep their uniqueness. For further research the influence of additional parameters has to analysed in order to set up the complex approach for the design of the optimal model of an energy-efficient prefabricated timber house.

5.2 Guidelines for further research

The guidelines for further research are divided into several steps.

5.2.1 Application of current findings on different models

As the first step the findings of the current research have to be tested also for different models of timber house design, for example with different ground plans, as well as for different climate conditions, indoor temperatures, etc.

5.2.2 Simple box model

As already noticed in the analyses part, the research based on the simple model of a square box (all façades are of the same size), with the glazing surfaces only in the cardinal direction, that is going to be analysed at that moment, could provide us with some interesting results, which could be more reliable when the comparison of different orientations is concerned. There is a risk for such a mathematical approach to provide us the results, which might not be applicable to the model of a realistically designed house.

5.2.3 New variable parameter: Glazing quality

For further research purposes additional analysis of the influence of glazing area size on the energy balance should be carried out for glazing of varying qualities as well. The results could provide us with information on where to install the glazing of a specific quality. At the current stage we still cannot answer the question of whether it is necessary to install high quality glazing in all external walls or whether it would be acceptable to use lower quality glazing in some external wall elements in individual cardinal directions.

There are some existing predictions that could be adopted from the findings in Hassouneh (2010) where analyses are carried out for different glazing types in massive stone wall elements considering the climate in Amman, which differs greatly from the central European climate, so these predictions have to be modified properly. Due to the expenses of installing high quality glazing, an accurate study of how economical this would be as a justification of such an installation with a defined pay-back period should be performed. The latter is very important for the renovation of old timber-frame houses, which could be performed through a combination of the improvement of external wall thermal properties and the installation of the optimal size of glazing surface of a specific quality. (see conclusions in 5.1.3.) As a starting point some findings and equations from the numerical model for residential objects considering a mid-Swedish climate from Karlsson et al. (2000) could be taken into consideration.

5.2.4 Optimal natural lighting

In relation to the glazing quality the optimal natural lighting of internal spaces should be analysed as well, where not only the glazing quality but also the optimal disposition of and the inclination of glazing surfaces play an important role. The optimal insulation of interior spaces can positively influence the reduction of electric energy demand for artificial lightning.

5.2.5 Other new variable parameters

There are many additional variable parameters which have to be further analysed in order to develop the optimal model of an energy-efficient prefabricated timber house with appropriate glazing.

New variable parameter 1: Glazing-to-wall area ratio for additional orientations: SE, SW, NE, NW

The influence of the glazing-to-wall area ratio on the energy balance of a prefabricated timber house should be researched also for additional orientations. The analysis for different orientations would provide us with even more usable results, than those of current research, due to the fact that building plots are rarely oriented only in main cardinal directions.

New variable parameter 2: Rotation of the building

An additional analysis of the influence of the buildings declination angle from the main cardinal directions with the definition of the functional dependence of the optimal energy demand with regard to orientation should be carried out as well.

New variable parameter 3: Inclination angle (φ) of external glazed construction elements

For further research purposes an additional analysis for the influence of glazing area on the energy balance should be carried out for glazed wall and roof elements of different inclination angles. This analysis could help the designers to decide at an early design stage, which form of the building, with regard to the inclination angle of the glazed wall or roof, is most favourable on account of its energy balance.

New variable parameter 4: Technical systems - HVAC

Different combinations of heating and ventilation systems, (heat pumps, heat recovery ventilation, solar heating systems) as well as photovoltaic systems have to be presented and applied to the base-case study model.

5.2.6 Definition of the theoretical findings applicable to every construction system (lightweight and massive)

The analyses of the influence of variable parameters have to be carried out as well for other types of construction system, such as massive brick and concrete construction systems, to develop the theoretical findings related to the definition of an optimal model design of a house for different construction systems. For this purpose the thermal storage capacity of the materials has to be considered precisely.

5.2.7 Observation of the energy balance using the monthly or hourly method with the use of different software

The results provided in our research demonstrate the energy performance in approximation for the whole year. It would be necessary to observe the energy demand for heating and cooling also using the monthly method, which is an option in PHPP software. For more realistic simulation the more accurate hourly observation of energy performance is suggested. This kind of dynamic simulation could show us the influence of the sun's radiation on the energy demand at different periods during the day. The interior daily temperature swing dependant on the external thermal conditions and thermal storage capacities of construction composite materials should be taken into consideration. The PHPP software is not suitable for this kind of calculation, therefore the selection of the appropriate dynamic simulation software would be recommended in order to carry out the required analyses.

5.2.8 Economical aspect

Parallel to the development of an optimal model, a study of how economical such a model would be has to be performed in order to determine the optimal costs with the amortization period for which the disposable subsidies have to be taken into consideration as well.

The economical study is especially important in terms of the renovation of old timber houses. Although we have defined the optimal glazing size for old timber systems as maximal, the recommended renovation approach is to first lower the U-value of external wall elements. Consequently the value for optimal glazing size can be calculated as a function of the new U_{wall}-value. From an economical viewpoint the glazing size could also be somewhat lower than the optimal value, if the input costs and amortization period are calculated as being more acceptable. However the economical justification for such a combination of renovation approaches has to be performed.

5.2.9 Optimisation of all researched parameters

Finally the optimal combination of research parameters has to be performed in order to develop and define the approach which is applicable for different models of energy-efficient houses. Using this approach the optimal design for each specific energy-efficient house regarding the optimal energy demand can be accurately defined.

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Appendix