TÉCNICO LISBOA

Building refurbishment work in Karlsruhe, Germany

How to develop a sustainable building process

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Abstract

The objective of this thesis is to propose an overall sustainable solution to reduce heating and cooling consumption, in the scope of the renovation works for a listed building in Karlsruhe (Germany), by developing and assessing different design proposals regarding their energy saving potential for heating and cooling, costs and overall environmental impact.

The current condition of the building was analyzed and served as the basis to develop a model in *EnergyPlus* to assess various insulation proposals for the renovation work. In a subsequent step, a life cycle analysis with the help of the *eLCA* database evaluated the ecological impact of the proposed solutions. Furthermore, the costs of the proposals were estimated. In a final step, a gas and wood-based heating system were compared, striving to propose an overall sustainable heating concept.

Moreover, it was proven that additional measures, challenging the common understanding of thermal comfort, can significantly reduce energy consumption. Lowering indoor temperature by 3 Kelvin, from 21°C to 18°C saves more than 25% of heating demand.

The work revealed the great complexity of ensuring a sustainable solution, while taking all impacts into consideration. Thus, this thesis can also serve as an example, exemplifying an approach on how to evaluate and develop sustainable building processes in general.

Keywords: *thermal comfort, EnergyPlus, heating and cooling demand, LCA, sustainable retrofit*

Resumo

Esta tese tem como objetivo propor uma solução sustentável para reduzir os consumos de aquecimento e arrefecimento de um edifício. Desenvolvida no âmbito de um projeto de renovação de um edifício em Karlsruhe na Alemanha, o trabalho propõe e avalia diferentes soluções de reabilitação relativamente ao potencial de eficiência energética para os serviços de aquecimento e arrefecimento, aos custos e ao impacto ambiental.

A condição atual do edifício foi analisada e serviu de base para desenvolver um modelo em *EnergyPlus* que permitiu a avaliação de diversas propostas de reabilitação centradas no isolamento. Seguidamente, foi realizada uma análise de ciclo de vida recorrendo à base de dados *eLCA* para avaliar o impacto ambiental das soluções propostas. Finalmente, foi feita uma análise de custos. No final, é proposto um novo conceito de climatização sustentável considerando todos os impactos na envolvente do edifício, nas unidades de aquecimento e no conforto térmico. Demontra-se que soluções menos convencionais podem reduzir significativamente o consumo de energia, como por exemplo, reduzir em 3º a temperatura de conforto interior na época de aquecimento (de 21°C para 18ºC), induz poupanças de 25% do consumo de energia.

Este trabalho demonstrou ainda que atingir a sustentabilidade é um processo muito complexo, pois é necessário ter em consideração múltiplos impactos. Desta forma, esta tese serve como exemplo de aplicação de uma abordagem para avaliar o desenvolvimento de uma solução sustentável para reabilitação de edifícios.

Keywords: *Conforto Térmico, EnergyPlus, Aquecimento e Arrefecimento, LCA, reabilitação sustentável*

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Nomenclature

I. Abbreviations

HVAC	heating, ventilation and air conditioning
UV	ultraviolet
IR	infrared
EnEV	Energieeinsparverordnung *(eng. energy saving regulation)*
EPBD	energy performance of buildings directive
IWU	institute for housing and environment
DOE	department of energy
NREL	national renewable energy laboratory
ASHRAE	American society of heating, refrigeration and air-conditioning engineers
ac/h	air changes per hour
DWD	Deutscher Wetterdienst *(eng. German Meteorological Service)*
TRY	Test Reference Year
MBE	mean biased error
cvRMSE	coefficient of variation of root mean square error
BKI	Baukosteninformationszentrum *(eng. Building Costs Information Center)*
BMBU	Bundeministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit *(eng. Federal Ministry for environment, nature protection, construction and nuclear safety)*
LCA	Life Cycle Assessment
PE	Primary Energy Consumption
GWP	Global Warming Potential
EPD	Environmental Product Declaration
PCS	Personal Comfort System
PtG	Power to Gas
CO	carbon monoxide
CO_2	carbon dioxide
CH_4	methane
NO_x	nitrogen oxides

II. Symbols

Symbol	*unit*	*meaning*
λ	W/mK	thermal conductivity
d	m	thickness of material layer
R	m^2K/W	thermal resistance
U	W/m^2K	heat transfer coefficient
U_f	W/m^2K	heat transfer coefficient window frame
U_g	W/m^2K	heat transfer coefficient glazing
U_w	W/m^2K	heat transfer coefficient window
n_{50}	1/h	infiltration air change at a pressure of 50 Pa
n_{nat}	1/h	natural air change per hour due to infiltration
Pa	N/m^2	pressure

1 Introduction

In the beginning of the past century, the average room temperature might have reached 15°C during the heating period. Only the kitchen and perhaps the living room was heated. Rising wealth changed our behavior and expectations of comfort and combined with the access to cheap energy sources, today's standard of full indoor heating has increased significantly. In addition to that, an increase of living space from 8 – 12 m^2 up to 45 m^2 per person was recorded throughout the past 60 years [1, p. 14].
Even though large improvements were made, especially in the use of energy efficient technologies, our overall consumption increased enormously, making up 32% of the final energy consumption in Germany for heating and hot water supply in buildings in 2017 [2]. Including cooling and lighting, the building sector is estimated to represent in average 40% of the final energy consumption. That includes 19 million residential- and 2 million non-residential buildings in Germany.
Legal frameworks, among them the energy saving regulation (EnEV), helped to reduce specific energy consumption throughout the past decades. Compared to an annual energy consumption of 300 kWh/m^2 in 1970, in 2012 only 140 kWh/m^2 have been recorded. New buildings, under the EnEV 2009 regulation, require consumptions below 70 kWh/m^2, but lower values are achieved, combining smart design and state of the art technologies. One of the most famous design standards is the passive house, introduced in the 1990, obtaining values around 15 kWh/m^2.
In terms of resources, the building sector is one of the most energy intensive industries. 517 million tons of resources are put into civil construction each year. However, the sector also accounts for 222.8 million tons of waste per year, which represents about 54 % of the overall German waste production [3]. On the one hand, it represents a large portion of our energy demand, on the other this also offers great energy saving potential. Adding energy efficient measures in existing building structures through renovation can be very effective. Moreover, it only consumes a fraction of the resources compared to building a new house.
According to the institute of housing and environment (IWU), 5% of old buildings are partly or entirely under monument preservation. They include façades and other building parts worth preserving and are referred as listed buildings. In such case, conflicting objectives between energy efficient modernization and preservation of the old structure induce great complexity in retrofit of old buildings and need to be negotiated with the local authority, which is concerned with heritage preservation [4] [5, p. 25].

1.1 Motivation and Scope of work

This thesis work aims to develop a suitable solution for heating for a listed building complex in Karlsruhe, Germany. Targeting an overall sustainable concept for the renovation and subsequent use of the building, various refurbishment proposals need to be considered under the aspect of their energy saving potential as well as their environmental and economical impacts.
Aiming to convert the German building stock nearly climate-neutral by 2050 involves great effort. Nevertheless, to meet our goal to cut non-renewable primary energy consumption by 80% until then, the building stock offers massive saving potentials [6].

Currently lacking incentives to mitigate CO_2 emissions prevent the majority to actively cut todays excessive energy demand. Supported by the “Fridays for Future” movement many started to raise their voice to finally call for action in the course of the past months. In case we really want to comply with the 2015 Paris agreement, change needs to happen right now and from every one of us.
This work is one part of the puzzle, as its objective is to contribute to a holistic, sustainable building design. Various design proposals are compared and evaluated under different aspects. The results can support the decision process of the architect throughout the planning phase. Moreover, the overall approach could serve as an example on how to establish and guarantee sustainable building development.

1.2 Methodology

A great part of this work is the development of a model in *EnergyPlus*, to evaluate different refurbishment designs, in regard to their energy saving potential. An inventory analysis of the building will be carried out to define the initial geometry and material properties in the software. Other relevant parameters within the *EnergyPlus* environment, such as internal gains from people and electric equipment, as well as the infiltration and ventilation ratios are set according to typical values found in literature. Using current weather data, the base model will be calibrated with respect to temperature data of the building, acquired throughout a period of six months, from January until June 2019.

Different refurbishment proposals, improving the energy efficiency of the building envelope are developed. Next to the simulation with *EnergyPlus*, aiming to determine the energy saving potential, a life cycle assessment and cost analysis of each proposals is carried out. This approach is necessary, to ensure a holistic, sustainable solution. The environmental analysis is carried out, using the online tool *eLCA*, relying on the LCA-data base *Ökobaudat*. A simplified economical analysis will be performed with the help of the BKI [7], which summarizes the expenses for typical constructions works in the building sector.

Possibilities to further reduce overall CO_2 emissions are discussed, modifying indoor temperature and occupancy in the *EnergyPlus* model, taking into account the overall CO_2 emissions for different fuels and considering the local conditions.

2 Theoretical Framework

The following chapter introduces some important fundamentals of building physics, introducing the physical phenomena of heat transfer as well as the challenges linked to moisture in buildings. Important parts of the building envelope and their thermal behaviour are discussed in more detail. Finally, the concept of thermal comfort, aiming to understand the subjective perception of heating and cooling, is introduced. Designing a satisfying heating and cooling system for buildings requires an understanding of the physics behind, yet the subjective perception of well-being.

2.1 Building Physics

"Building physics studies the processes that occur in the building structures that influence the indoor comfort and safety of inhabitants [8, p. 59]."

The aim is not only to design energy efficient buildings. Moreover, ensuring safety of the construction as well as thermal comfort for the occupants is important. A variety of physical phenomena need to be taken into consideration when designing a building. This is where building physics starts, because it studies the physical condition of a construction and the material it consists of. Analyzing the transport process through a material layer helps to understand which energy transport and conversion processes can take place.

The challenge in building physics is the interaction of several physical phenomena [9]. Commonly building physics is divided into the following categories: heat transfer, humidity, acoustics, lighting and fire protection. All categories are closely linked and affect one another. In the scope of this work, a closer look into heat transfer mechanisms and humidity is done.

2.1.1 Heat Transfer mechanisms

Heat transfer is always related to a change in temperature. Temperature is a measure for the kinetic energy of particles inside a boundary system. There are three types of heat transfer mechanisms: conduction (transmission), convection and radiation. They are illustrated in *Figure 1* [5] [9, p. 14].

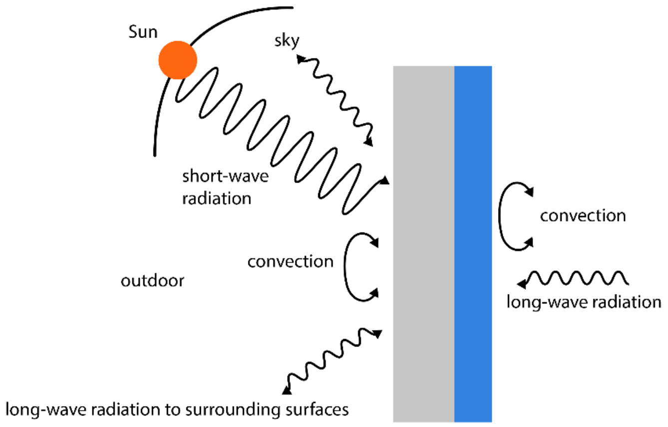


Figure 1: Heat transfer mechanisms

Even though heat transfer is always time-dependent and thus should be considered non-stationary, it is common practice to assume constant indoor and outdoor conditions. This simplification is acceptable for a first assessment of thermal insulation properties [8, pp. 60–63].
Therefore, the thermal resistance R is introduced *(see Equation 1),* where d represents the thickness of the construction layer in meters and λ the heat conduction. Thermal conductivity $\lambda\ (\frac{W}{mK})$ is a material property and describes how much heat (Q) is transferred through a material block (surface area 1m^2 and length 1m) at a temperature difference of 1 Kelvin. The thermal conductivity (λ) of a material is mainly influenced by the density of the respective material. Nevertheless, humidity and temperature also have an impact. For example, denser materials or increasing humidity favor heat conduction [10, p. 43].

$$R = \frac{d}{\lambda} \quad \left(\frac{m^2K}{W}\right)$$ *Equation 1*

In case of layered constructions, the individual thermal resistances *R* are added up and the overall thermal resistance R_t is calculated.

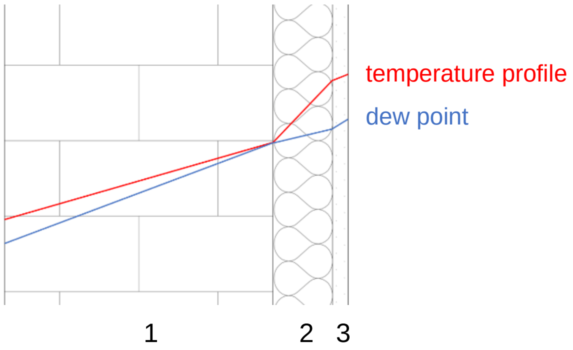
To assess the insulating quality, the heat transfer coefficient rather than the thermal resistance is considered. The heat transfer coefficient *(see Equation 2)*, also called U-value, is the reciprocal of the thermal resistance:

$$U = \frac{1}{R} \quad \left(\frac{W}{m^2K}\right)$$ *Equation 2*

“The U-value is defined as the rate of heat transfer (in Watts) through 1 m^2 of building structure at a constant air temperature difference of 1 K between both sides of the structure [8, p. 60].” A low U-value indicates good insulating properties, because the thermal resistance of the corresponding material layer is quite high. Typical U-values of important parts of the building envelope will be discussed later on in this chapter [10, 43-62].

2.1.2 Moisture

Another important aspect in designing and planning a building, is its ability to cope with various physical states of water (gaseous, liquid, solid) in different conditions.
The most relevant aspect to consider is water vapor and its movement through construction layers. As the dew point is temperature dependant, water might condensate on the surface or in between construction layers, as indicated in *Figure 2.* The red line represents the temperature profile, decreasing towards the outside of the building. The blue line displays the respective dew point. When both lines intersect condensation occurs. Thus, in the present example moisture can form between the interior wall insulation layer (2) and outside wall (3). Moreover, it is known since the 1980ies that already a relative air humidity of 80% over a period of three to five days is enough for mold to start growing [1, pp. 15–16].



With: 1) exterior wall 2) interior wall insulation 3) interior plaster

Figure 2: Temperature profile and dew point in wall construction with interior wall insulation

In open spaces, such as rooms or buildings, water gets in contact with air. Water in liquid state tends to evaporate on a surface. Latent heat, causing no change in temperature, is required for this phase change between liquid and gaseous state. How much actually evaporates depends on several external circumstances, such as temperature, air speed and surrounding air humidity.

The amount of water determines the air humidity and may be expressed in relative humidity measured in % or absolute humidity given in g/m^3. Water molecules count to the lighter elements in the air-water mixture. Hence, density decreases with increasing moisture. Furthermore, this affects the partial pressure ratio. The additional mass and movement of each water molecule puts pressure on the surrounding air volume (water vapor pressure). Water vapor pressure is temperature dependent. Once no more moisture can be absorbed, the air is saturated, and water falls out in liquid state.

To prevent harmful damage to a building and its envelope, moisture loads need to be assessed. For parts of the building, such as the basement, a hermetically sealed envelope is acceptable and necessary. Whereas in other spaces, the occupant wishes to be able and open windows and having permeable constructions to enable moisture transport. Furthermore, the activity inside a building largely impacts the amount of moisture, e.g. drying cloths and cooking. The risk of condensate increases. As mentioned earlier, the partial pressure for humid air raises. The pressure difference between inside and outside strives to reach equilibrium. Moisture starts to move through the construction envelope, like shown earlier in *Figure 2*. In case of permanent moisture, this can lead to damages in the construction and additionally destroy the heat protection of the building. Moreover, the humid conditions favor growing mold, which is harmful to humans [9, pp. 27–44]. Among others it can cause respiratory diseases or lead to allergic reactions.

Therefore, it is important to assess where condensate water can form as well as leave the building without causing huge damages. Thermal bridges are a great challenge, as their surface temperatures differ from the surrounding. *Figure 3* illustrates an example, where a cold surface (10°C) is exposed to a room with normal indoor conditions of 20°C and 70% humidity. As indicated, only 7.75 g of the 10.2 g/kg water at 70% is kept in the air, the remaining (2.45 g/kg) condensates on the cold surface [9, p. 34]. Thus, typical limits for surface temperatures are suggested at 12.6°C and 80% relative air humidity. The right insulation of the building envelope ensures, that temperatures of surfaces towards the outside will not drop below this value.

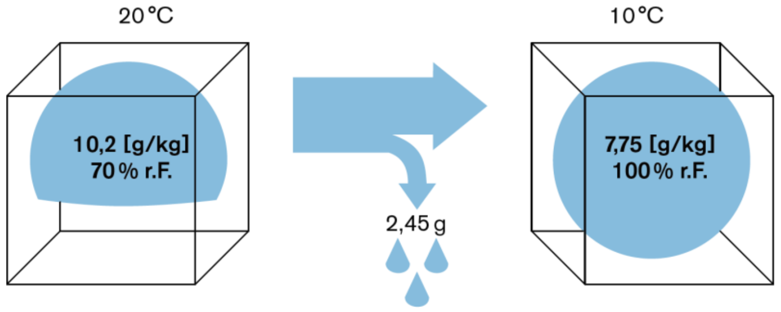


Figure 3: Condensation water due to temperature drop from 20°C to 10°C [9, p. 34]

Since they are more difficult to insulate anyway, windows can be used as heat sinks. In most cases they are made of water-resistant material, such as glass and a plastic frame. Condensate can precipitate here, before entering any other part of the building envelope. [9, pp. 27–44] [1, pp. 15–16] [10, pp. 171–248]

2.2 Thermal behavior for selected parts of the building envelope

Unlike technical appliances inside a building, such as lighting and HVAC, the building envelope is expected to have a much longer life of at least 50 years. It tremendously affects the energy use as well as the design of the building technology. Thus, the greatest priority should be given to the design of the walls, roof and floor of a building to achieve energy efficiency [11, pp. 15–16].

The building envelope is the interface between the outside environment and indoor comfort zone. Increasing demand of thermal comfort changed the design and function of the building envelope throughout the past centuries. Additionally, new technologies allow us to introduce smart solutions. One example is building integrated solar panels, that can function as shading devices as well as energy producers. The following aspects influence the design of the building envelope and shall briefly be discussed: usage, climate, construction and legal requirements [5, p. 82].
Depending on the **usage** of the building, the requirements can be very different. It is essential to know the desired thermal comfort level, to set the right thermal requirements. A theater or factory has very different requirements than residential housing. Weather independent indoor conditions are not necessarily an optimal solution. For a limited amount of time, deviation of the thermal comfort level can be justified, if this reduces the heating or cooling needs and therefore the installed air conditioning technology [5, p. 82].
Taken the **climatic conditions** into account, when designing a building, regains importance. Unlike in the “international style” in architecture, where climatic conditions are compensated with technology, we are getting back to the origins, adapting the building to its location [5, p. 82].
The **construction** of buildings has changed a lot. Nowadays, supportive elements and envelope elements are commonly separated. This technique was already used back in the days in warmer climate zones. Wood served as supportive structure and animal skin as cover for the envelope. In colder

climates, solid exterior walls were common as they had a higher thermal capacity. A breakthrough in steel and glass production changed the architectural design during the 20th century. To achieve better daylight conditions, architects introduced large window areas. Due to poor physical properties of glass at that time, it led to bad thermal comfort and high transmission losses. These resulted in high energy consumption [5, pp. 82–86].

First **legal requirements** to cut energy consumption for buildings in Germany were introduced in the 1970's. Three thermal protection regulations where passed by the government between 1978 and 1995. They defined limit U-values in order to reduce heat losses through the building envelope. In 2002 the laws where replaced by the energy savings regulations (EnEV). Directives for energy saving building technology, such as heating and cooling, were incorporated [4, pp. 5–11]. In parallel, the European directive on energy performance of building (EPBD) was negotiated and published in 2002. It includes regulations for energy consumption in buildings, support for renewable energy supply in the sector and introduces energy certification for buildings. In July 2007 the directive was adopted into national law and approved by the German government [12, pp. 22–33]. Subsequent changes in the EPBD (in 2010) were implemented into the German EnEV. Two amendments, in 2009 and 2014, now define the current status of the regulation.

Reducing primary energy consumption by 80%, compared to 2008, Germany wants an almost climate neutral building stock by 2050. EnEV 2014 supports that goal. Thus, requirements for the reference building[1] were increased by 25%. Following the European objectives, the government targets to introduce nearly zero energy buildings until 2021 [4, pp. 9–11].

Parallel to the legal actions, solar architecture and the desire to harvest passive solar energy for heating already rose back in the 1980's. Maximizing solar gains, measures to reduce heat losses through the envelope (insulation) and efficient ventilation manifested in the first passive house in the beginning of the1990's in Germany. Today, this design achieves an annual heating demand below 15 kWh/m² [5, pp. 82–86].

2.2.1 Exterior Walls

A measure for thermal insulation of a construction is the U-value, which was introduced in section 2.1.1. It depends on the thermal conductivity and thickness of the material layer. As they represent the largest surface area, the thermal quality of exterior walls significantly impacts the heat conduction losses. Depending on how the walls are composed, different insulation standards can be achieved.

In the past, construction of the exterior walls were carried out in, what today is called single-shell construction [5, pp. 87–88]. Even though walls reached thicknesses up to 600 mm and the massive construction offer great thermal storage capacities, U-values between 1.4 - 1.8 $\frac{W}{m^2K}$ are common. This is due to the good thermal conductivity of the built-in material. A common one would be solid brick (λ=0.68) [1, 11, 25] [13, p. 31].

[1] A reference building estimates the energy consumption of a specific building. The proposed building design is simulated with the reference values set by the respective regulation.

Studies by *Prof. Wagner (KIT)* [1, p. 27] proved critics wrong, who claim that insulation is unnecessary for thick walls of old buildings. *Prof. Wagner* and his team were able to show a significant reduction of heat losses, when applying insulation. Putting a 150 mm layer of insulation on a 365 mm thick solid brick resulted in a reduction of heat losses from 102 kWh/m^2 to 14 kWh/m^2 [1, p. 27] Today, a wall of 360 mm thickness made of highly porous bricks ($\lambda = 0.08$) can achieve a U-value close to 0.2 $\frac{W}{m^2K}$. Similarly, a wall composed of expanded concrete of a thickness of 400 mm reaches U-values close to 0.3. However, decreasing thermal conductivity also negatively affects the load carrying capacity of the support structure. This is why today multi-layer construction is common practice. Materials with low thermal conductivity, among them cork, hemp, mineral wool and extruded foams are added to the load carrying construction and help insulating the building envelope [5, p. 87]. Depending on the design of the exterior walls, three common types of insulation are briefly discussed.

Ideally, insulation is attached to the **exterior** *(see Figure 4 a))* surface of the walls. Thus, the wall mass can still act as a buffer and has positive impact on the indoor climate. Due to an overall increased wall temperature, risk of undesired mold formation is reduced as well. Insulating material is glued, if necessary, also screwed onto the existing wall. In addition, with a weather resistant layer, it protects the building envelope well.

In case of double shell wall constructions, a **cavity wall insulation** *(see Figure 4 b))* is possible. Since both shells need to be connected to the load carrying structure, the insulation layer is inevitably disturbed.

In some cases, such as listed buildings, external insulation is not possible. The goal is to maintain the ancient appearance. **Internal insulation,** *as shown in Figure 4 c)* offers a solution to improve the thermal behavior of the building envelope anyhow. A great challenge represents the moisture protection though. With insulation on the inside, the external wall does not gain heat from the inside anymore. This leads to lower temperatures of the inside surface of the exterior wall and increases the risk of condensate. Moreover, one needs to ensure that water vapor does not condensate, due to the low temperatures. To avoid moisture transport from the room side, a water impermeable vapor barrier is also put into place. Recently materials that can absorb and reject water vapor, such as clay, regain attention. If applied, attention needs to paid, to ensure enough ventilation so moisture can be transported back [5, p. 87].

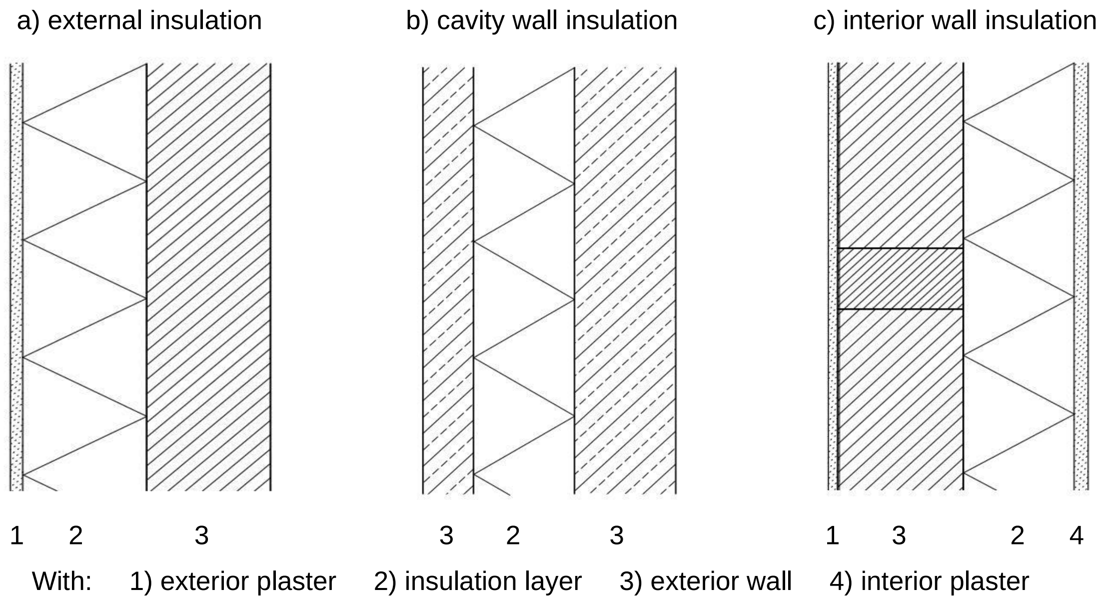


Figure 4: Common insulation structures, [5, p. 89]

Some overestimate the effect of façade greening. They do have a positive influence as they protect the exterior wall from direct UV-radiation, heat and heavy rain showers. During summertime, evaporation cooling reduces the surface temperature and the plants might provide shade. Furthermore, they offer habitats for insects, clean air and reduce dust. Nevertheless, they cannot directly replace a proper insulation. Moreover, damages of the wall are possible when plants climb along the outside wall of the construction. [14, p. 103]

2.2.2 Roof

Like the exterior walls, heat losses through the roof should not be underestimated, as the roof represents a large loss surface. Depending on the type of roof, different insulation methods are applicable.

Flat roofs, like illustrated in *Figure 5 a)*, are in most cases made of concrete. Regarding thermal improvements similar measures, as the ones considered for external walls are possible. The increased pressure load, compared to walls, especially for walk-on roof areas, need to be taken into account. U-values below $0.15\ \frac{W}{m^2K}$ require an insulating layer of approximately 200 mm. Another common insulation for roof structures is the insulation below or even between the rafters of the roof. In particular the vapor barrier needs to be done carefully, as indicated in *Figure 5 b)* [5, p. 88].

When outside temperatures exceed indoor temperatures in summertime, heat conduction towards the inside of the building takes place. Lower U-values help minimizing this effect. Next to the thermal conductivity, also the surface temperature influences heat transport. Ventilated walls and roof, or applying bright colors cool down the surfaces. Rooms on the last floor count the roof, next to the exterior walls, as additional adjacent surface connected to the outdoor environments. Evaporative cooling of green roofs reduces temperatures here [5, p. 96].

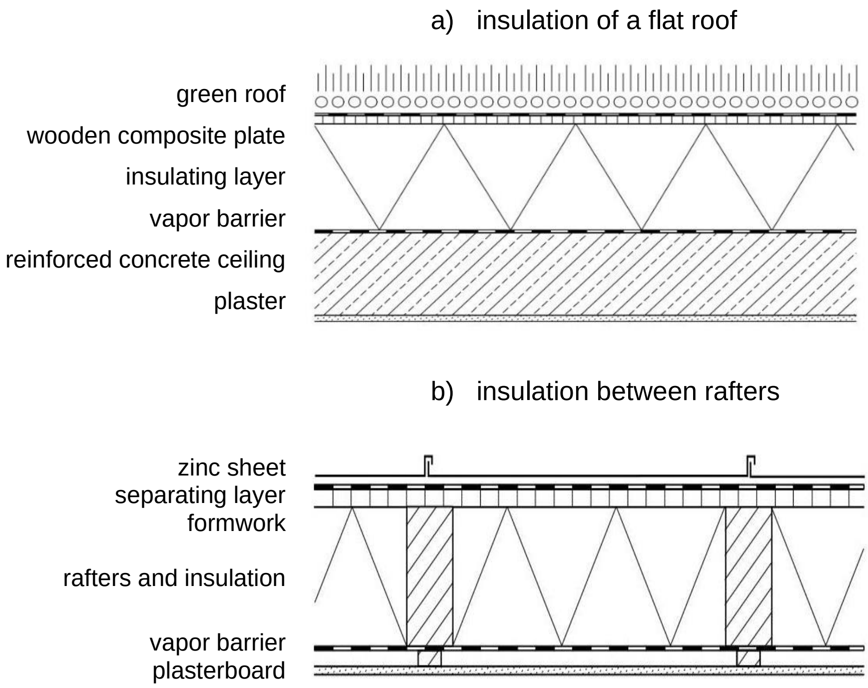


Figure 5: Sample constructions for roof insulation [5, p. 90]

2.2.3 Transparent Elements

Fenestration surfaces, such as doors and windows, are the key elements for a building to bring in daylight, outside air and support moisture escape. Especially the function of windows, to bring in daylight, is of great importance for indoor comfort. A drawback of windows though is their thermal behavior. On cold days their heat losses can represent up to 60% of the total heat losses. During summertime they can represent significant heat gains [11, 18-24] [5, p. 96].

The U-value for windows U_w is composed of the U-value for the glazing (U_g) and the frame (U_f). In moderate climates double glazed windows are common. Even though higher standards exist and achieve an overall U_w of $0.3\ \frac{W}{m^2K}$ in the case of coated, krypton filled quadruple glazing [5, p. 155]. However, only the increased surface temperatures positively affects thermal comfort, as it reduces indoor draft [14, p. 173]. For the energy balance, it is acceptable if the U_w matches the U-values of the other envelope surfaces.

Throughout the past decades, the glass industry has developed and U-values for insulating glass dropped by factor ten, compared to $3.6\ \frac{W}{m^2K}$ in the 1970's [5, pp. 152–155]. Including solar gains, thermal insulation glazing achieves the same or even better insulation quality than some insulating materials. This is due to the greenhouse effect. Solar radiation passes the transparent surface. Short-wave, infrared (IR) radiation is absorbed by the indoor material and emits back from the surfaces converted into long-wave, ultraviolet (UV) radiation. More heat is captured inside the room, since windows badly transmit UV-radiation. **Low emissivity** glass further reduces this effect. Emissivity is the ability of a surface to emit radiation. Compared to uncoated glass with an emissivity of 84%, high "low-e coated" windows achieve values below 4% [11, pp. 22–24]. Thin silver or titanium metal layers are coated onto the glass and act like a mirror, reflecting IR-radiation back to the room. The coated layer does not influence the visible transmittance. With state-of-the-art technology, the industry is capable to produce coated, non-insulated single glazed windows close to U-values of $3.6\ \frac{W}{m^2K}$.

To further reduce thermal transmission and thus heat losses through windows, multiple layers of glazing are applied. **Insulating glass** consists of two or more layers of glass. Gas in between reduces heat transmission and acts as soundproof. Due to their good availability, air and argon are used. However, xenon as well as krypton offer better thermal properties and are, even though more expensive in production, also considered. Vacuum insulation exists as well, but involves technical challenges, when assembling the window parts. [5, pp. 152–155] [8, p. 79] *Table 1* summarizes important values for wooden framed windows.

Table 1: Sample U-values for different assembly strategies of wooden framed windows [14, p. 172] [8, p. 79]

Type of glazing	**U_g in W/m²K**	**U_W in W/m²K, including wooden frame**
single	5.8	5.2
single, low-e	3.6	-
Insulating glass, double	3.0	2.6
double, air filled, low-e	1.3	1.5 – 1.7
Double, argon filled, low-e	1.1	1.3
Triple, insulated frame	0.7	0.8

A similar approach to the one mentioned above is the **multi-shell construction**. One common example are **casement windows**. The second layer improves insulation properties, however, does not change the existing window and frame structure. That is why this is a typical solution for renovation work of listed buildings.

Covering the existing building envelope with a second, transparent layer is referred as **double facade**. Transmission losses are reduced, as the space between the old and new envelope acts as a solar buffer. It is important to ensure enough ventilation and that the desired buffer during the heating period does not turn into undesired thermal loads in summer. One famous example is Strasbourg's, 2006-2007 renovated, main station [15]. The second layer improves thermal quality, protects and preserves the old structure and existing thermal bridges are weakened.

Temporary applicable heat protection, in form of window blinds, can also reduce transmission losses, especially when the view, e.g. during night time, is not important anyway [5, pp. 90–95].

2.3 Thermal Comfort

Room temperature, humidity and air circulation influence indoor climate. The human body feels comfortable, if the heat balance between room and body is in equilibrium. The ideal human body

temperature is 37°C. Depending on the activity people perform, and their cloths, heat transfer takes place to maintain the temperature at that level. One considers a heat flux of 100 Watts for an 80 kg person, seated at 20°C room temperature. Office and minor physical activities are quantified with a heat flux of 125 – 170 Watts per person, whereas heavy physical work can reach 360 – 490 Watts per person. Convective heat transfer between body and surrounding air, as well as radiation between skin and other surfaces, compensate any imbalance. [5, p. 55]
For residential buildings and offices, indoor environments with temperatures between 20 – 22°C, an air humidity ratio of 35 – 70 % and circulation of 0.15 m/s are perceived as comfortable for more than 80 % of the people *(see Figure 6)*.

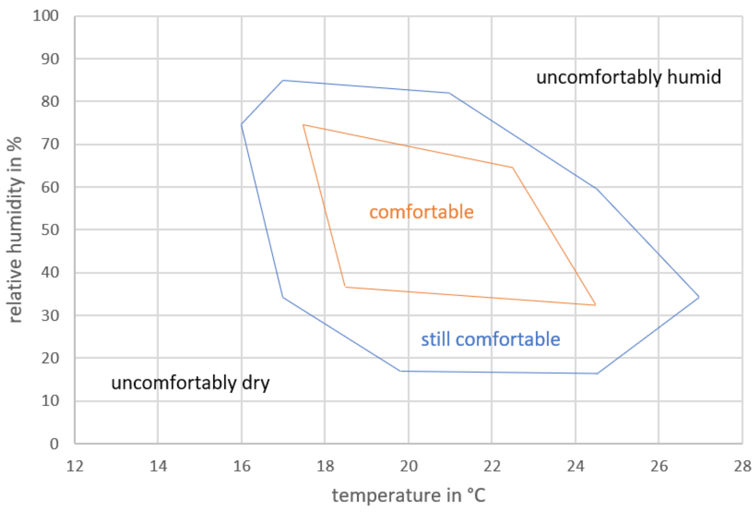


Figure 6: Thermal comfort zones for humans

Under those conditions, heat transfer between the human body and the environment is on a reasonable level. Moreover, deviations between surface and room temperatures should not exceed +/- 3°C. Warm surface temperatures have a positive effect on well-being of the occupants. Old buildings for example often reveal temperatures far below 17°C and thus, are regarded uncomfortable, as air cools down along these surfaces, drops and enhances natural draft, which is perceived negatively. Surface heating counteracts and significantly improves indoor thermal comfort. Floor temperatures up to 26°C and ceiling heating up to 34°C are enough to achieve cozy 20°C room temperatures [5, pp. 56–57].

This is why, *Meier* [16, 60-63] states, that energy-saving construction inevitably goes along with the effort to maintain temperature at a constant level. "Massive construction, such as solid brick or wood favor that, due to good heating capacity." Ensuring indoor thermal comfort with low additional energy supply characterizes energy-efficiently planned buildings. Hence, the design of the building envelope and energy supply system are linked and should be developed in common [5, p. 85], [14, pp. 30–31] [9, p. 13].

2.4 State of the art retrofit

The heat losses through the building envelope, due to transmission as well as infiltration, determine the heating demand of a building. They are estimated to be responsible for 70 % of the heating demand. Goal of an energy efficient retrofit is to improve the thermal performance of a building and reduce heat losses in winter and unnecessary heat gains in summer.

Roof insulation is expected to reduce heating demand by about 30%. Complementary exterior wall insulation and improved thermal performance of windows *Kolb et al* [17] believe to save 2/3 to 3/4 of the initial energy consumption for heating and cooling. *Kienzelen et al [1]* even claim values up to 90% with exterior wall insulation. Considering the walls with a thickness of up to 600 mm, as it is the case for most old building, exterior wall insulation also will not effect the big thermal mass which is beneficial for summer cooling [1, p. 25]. Insulation of the basement ceiling brings an additional benefit of 10%. [17, pp. 30–32]

In their case study for three different locations across Europe (London, Madrid and Tallinn), *Boyano et al [18]* also investigated the impact of "improving thermal insulation of the walls" with the help of an *EnergyPlus* simulation. Lowering the U-value of the external walls from $0.3\ \frac{W}{m^2K}$ to 0.18 or $0.12\ \frac{W}{m^2K}$, they were able to achieve energy savings of up to 20% for their London example. Due to the climatic differences, lower savings were revealed for their Madrid case study. [18, p. 25]

Official data for energy efficient retrofit and its energy saving potential for the existing building stock, constructed before 1949, does not exist. However, regarding an average heating demand, roughly between 200 and 300 kWh/m^2, for theses buildings, right insulation measures promise to achieve values below 100 kWh/m^2 as required by the current regulations [4].

3 Case Study

The following chapter introduces the practical approach and methodologies applied to develop different design proposals, in regard to energy efficiency for the renovation work of a listed courtyard-building located in Rudolfstrasse 5, Karlsruhe, Germany. An important part includes a detailed description on the development of the *EnergyPlus* model, which was necessary for the subsequent assessment of the refurbishment proposals.

3.1 Building Description

In 1895, the north and south wing in the backyard of Rudolfstrasse 5 in Karlsruhe - as indicated in *Figure 7* and shown in the photos in the appendix *(Figure 49 to Figure 51)* - were constructed. Until 1911 the buildings hosted a small cigar factory, containing production and storage facilities as well as offices. During the 1920's, a fruit and vegetable trader took over the place. After the second world war, when the roof in the north wing was badly destroyed due to fire, various people occupied the place. The building experienced all sorts of usages during the entire lifetime. Before the architect Patrick Häussermann *(MALO Architektur)* acquired the building complex in August 2018, the last owner ran a business recovering chemicals from photo and x-ray film materials until 2013.
Patrick Häussermann and his team usher in a new era continuing the versatile use. Picking up the old structure, a new building *(see Figure 7)* complements the U-shape and connects all parts of the complex. "With a visionary concept, the team aims to create new life in the courtyard, combing the renovation work with implementing a new living concept [19]", as displayed in *Figure 8.* The objective of the whole project, named *Rudolf 5*, is to bring people from different backgrounds together, to work, experiment, implement and show-case sustainable urban lifestyle.

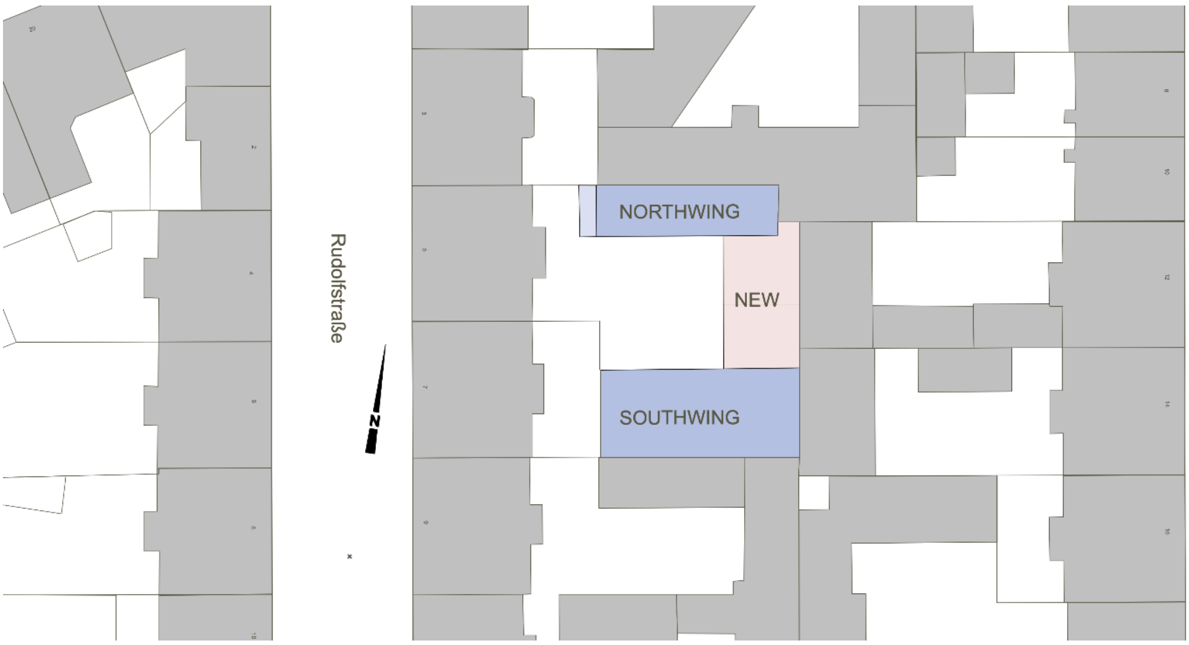


Figure 7: Location of the building complex in the eastern part of Karlsruhe, backyard of Rudolfstrasse 5

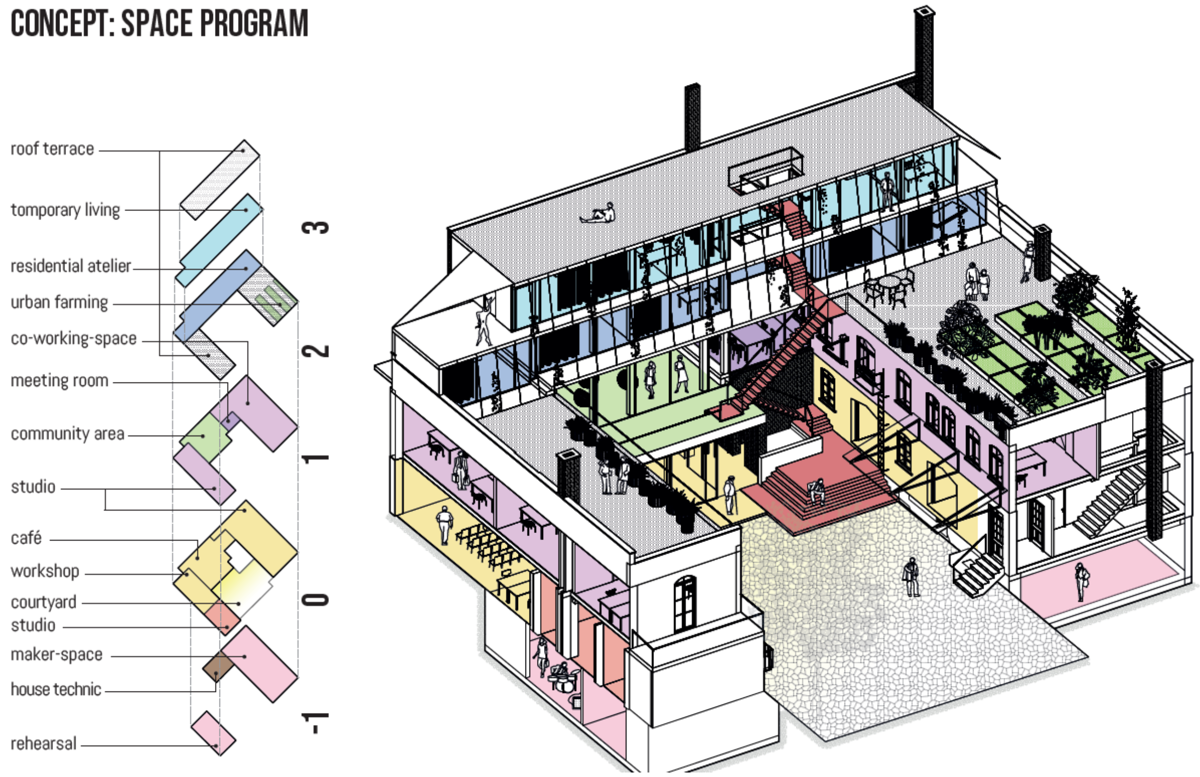


Figure 8: Concept of the future courtyard in Rudolfstrasse 5, developed by MALO Architektur

3.1.1 Inventory of the building

Since no accurate plans of the site were available, a measurement of the existing construction was necessary in a first step. We used a *Leica Builder 509* tachymeter[2] to manually record points outside and inside the buildings as well as the surrounding area. After setting a reference coordinate-system, using the same three points for each measurement, the tachymeter records the data in 3-D coordinates. With *AutoCAD,* the data points can be represented in a coordinate system on a computer. Superposing the points with the floor plans, exact values for all relevant distances and thicknesses were obtained and the plans could be adjusted accordingly *(see Figure 53 to Figure 58)*.

In a second step, all important components, including exterior and interior walls, roof, floors and ceilings as well as doors and windows of the building were investigated and documented. A detailed inventory analysis helps to point out weaknesses and damages of the construction. Moreover, the collected data was needed for the subsequent simulation. Comparing the existing structure with other references from literature, such as [20] [21] and [17, p. 51] helped to identify the materials and supported the decision process. In most cases, specific material data could be verified with *"Schneider - Bautabellen für Ingenieure"* [13, 10.42-10.50] and other sources.

[2] A tachymeter enables rapid surveying. It determines the horizontal and vertical position of points relative to one another, without using a separate reference or levelling instrument.

The exterior walls of the **basement** consist of 600 mm thick sandstone *(see Figure 53 and Figure 56)*. Typical for its time, the ceiling was designed as a cap ceiling [17, p. 51]. Drilling through the ceiling proved, that it is mainly made of screed/concrete. For the floor, a 150 mm concrete foundation was assumed. *Table 2* summarizes the collected material data.

Table 2: Material data for basement

	thickness (m)	thermal conductivity (W/(m*K))	density (kg/m^3)	heat capacity (J/kg*K)
exterior wall				
sandstone	0.6	1.1	2000	1000
floor and ceiling				
concrete	0.15,	1.95	2240	900
screed	0.20	1.4	2000	1000

On the **ground floor** level, the exterior walls measure an overall thickness of 440 mm, including 380 mm of bricks and a 30 mm layer of plaster on the out- and inside. Being the counterpart of the basement ceiling, the floors are made of screed and concrete. Interior walls of brick with plaster layer are found in the north wing. The south wing only includes one interior wall, separating the staircase from the main hall. This wall consists of various undefined material layers. For better understanding, *Figure 9 and Figure 10* illustrate the structure of the ceiling. The layers of the ceiling differ in the two buildings. In the south wing only beams and air make up the space between ceiling and the floor of the next level *(see Figure 9).* However, the north wing ceiling includes a sand-filling in between the beams *(see Figure 10)*. All materials properties for the ground floor level are summarized in tables below *(Table 3 to Table 5).*

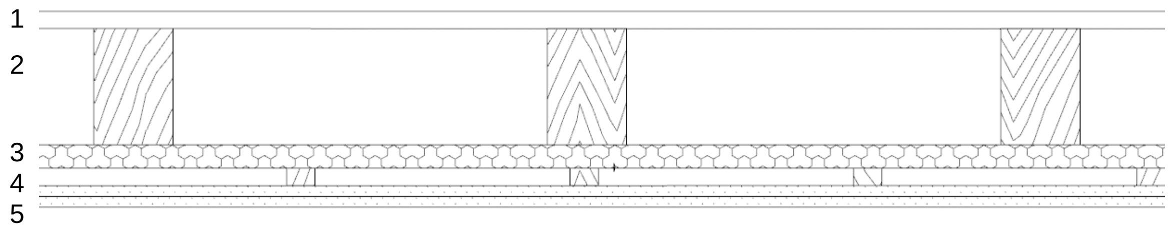


Figure 9: Construction of ground floor ceiling in the south wing

Table 3: Material properties, ground floor ceiling south wing

		thickness (m)	thermal conductivity (W/(m*K))	density (kg/m^3)	heat capacity (J/kg*K)	thermal resistance ((m^2*K)/W)
ground floor ceiling - south wing						
1	wood planks	0.025	0.13	500	1600	
2	rafters (140x160 mm), spacing 740 mm, air filled	0.200				0.47
3	wood-wool lightweight building board	0.035	0.075	400	2000	
4	air space					0.18
5	2x gypsum plaster boards	0.0125	0.27	1000	840	

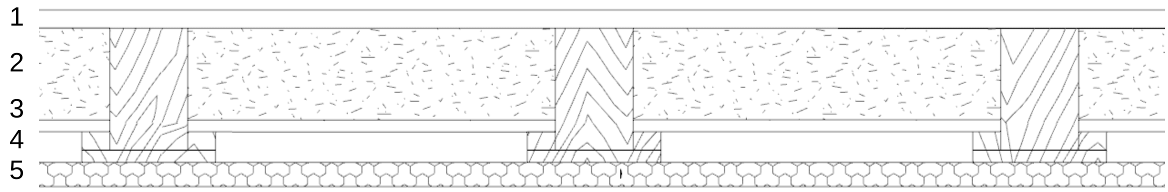


Figure 10: Construction of the ground floor ceiling in the north wing

Table 4: Material properties, ground floor ceiling north wing

		thickness (m)	thermal conductivity (W/(m*K))	density (kg/m³)	heat capacity (J/kg*K)	thermal resistance ((m²*K)/W)
ground floor ceiling - north wing						
1	wood planks	0.025	0.13	500	1600	
2	rafters (170x170 mm), spacing 800 mm, 150 mm sand fill	0.150				0.26
3	timber boards	0.020	0.13	500	1600	
4	air space					0.18
5	wood-wool lightweight building board	0.035	0.075	400	2000	

Table 5: Material properties, walls and floor, ground floor, south and north wing

	thickness (m)	thermal conductivity (W/(m*K))	density (kg/m³)	heat capacity (J/kg*K)	thermal resistance ((m²*K)/W)
exterior walls					
lime-gypsum plaster	0.030	0.7	1400	1000	
brick	0.380	0.68	1600	1000	
lime-cement plaster	0.030	0.87	1800	1000	
interior walls north wing					
plaster	0.030	0.38	1000	1000	
brick	various	0.68	1600	1000	
ground floor					
screed	0.100	1.4	2000	1000	

Common for older construction styles is the stepwise diminishing exterior wall towards the next level. A special characteristic of the two buildings in Rudolfstrasse 5 is that not all circumferential walls follow this pattern on the **first floor**. The north façade of the south wing maintains the thickness of 440 mm, like on the ground floor. All other walls in north and south wing measure the expected width of 250 mm.

The material properties of the walls are the same as stated in *Table 5* above (brick and plaster). Rooms on the northern side of the south wing are separated by 60 mm wooden walls, including indoor windows *(see Figure 52 as an example)*. Brick walls divide the first level of the north wing into three rooms *(Figure 58).* For the respective material data *see Table 5 – interior wall north wing*. *Figure 11* shows the side view on the south wing-roof and helps to illustrate its material layers, indicated in *Table 6* below. The roof of the north wing differs with a filling between the rafters; however, the layering of the roof structure is analog to the south wing. More details can be obtained from *Figure 12*. Material properties of all relevant components are stated in *Table 7* below.

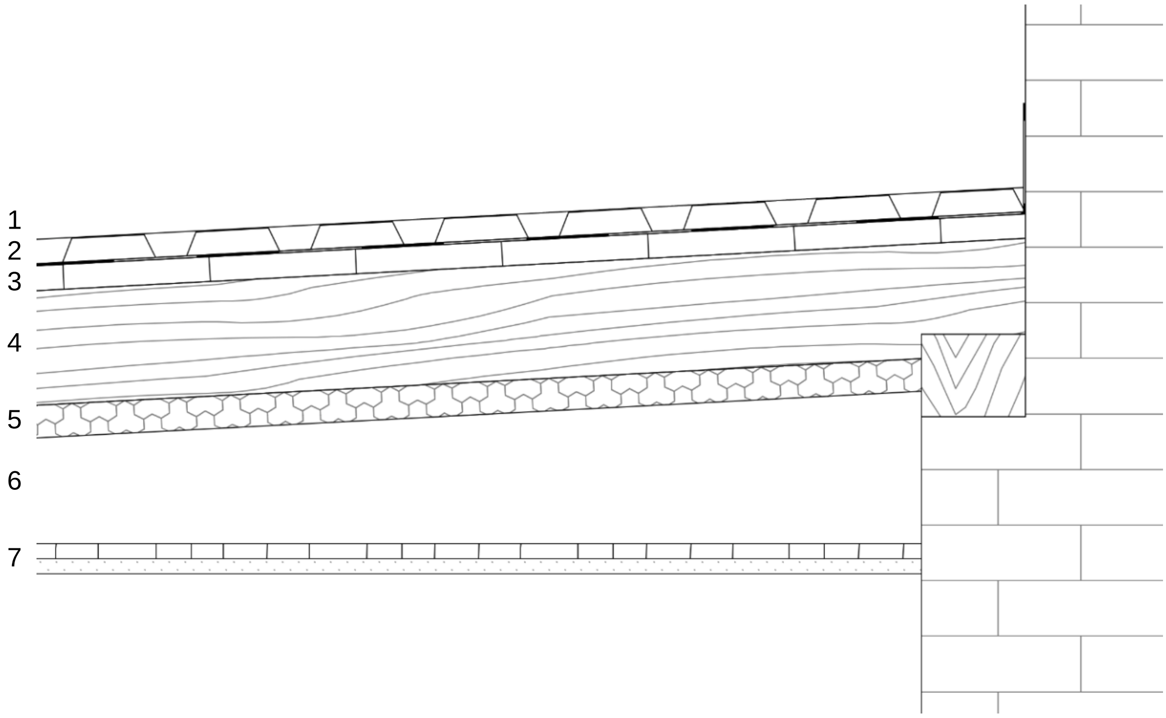


Figure 11: Current Roof construction with respective materials, south wing, sideview

Table 6: Material properties roof south wing

		thickness (m)	**thermal conductivity (W/(m*K))**	**density (kg/m^3)**	**heat capacity (J/kg*K)**	**thermal resistance ((m^2*K)/W)**
roof construction – south wing						
1	fibre cement/eternit	0.010	0.035	1700	1000	
2	bitumen membrane	0.005	0.17	1200	1000	
3	timber casing	0.020	0.13	500	1600	
4	rafters (140 x 160 mm), spacing 730 mm, air filled	0.140				0.38
5	wood wool lightweight building board	0.035	0.075	400	2000	
6	space, air filled with wooden construction for suspended ceiling					0.18
7	chipboard	0.010	0.14	600	1700	

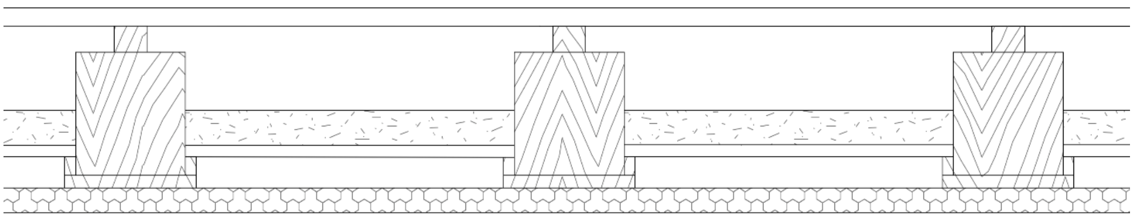


Figure 12: Current roof construction, north wing, front view

Table 7: Material properties roof north wing

		thickness (m)	thermal conductivity (W/(m*K))	density (kg/m³)	heat capacity (J/kg*K)	thermal resistance ((m²*K)/W)
roof construction – north wing						
1	PVC roof membrane	0.0015	0.18	1500	1260	
2	bitumen membrane	0.005	0.17	1200	1000	
3	timber casing	0.030	0.13	500	1600	
4	rafters (200 x 200 mm), spacing 670 mm, air filled space	0.005				0.33
5	rafters (200 x 200 mm), spacing 670 mm, sand/straw filled	0.015				0.16
6	timber casing	0.020	0.13	500	1600	
7	air space					0.18
8	wood wool lightweight building board	0.035	0.075	400	2000	

All **windows** in the building complex are old, single glass windows. The predefined values of *EnergyPlus* were considered *(see Figure 59 in Appendix)*. A metal door is the entrance to the basement of the south wing. On the ground floor level two, double leafed wooden gates enclosed by a metal frame *(shown on Figure 49*) are characteristic for the old warehouse style. All other doors, indoor and towards the outside are made of wood. Most of them include windows. For wood, the same material properties as mentioned above were considered.

3.2 Simulation with EnergyPlus

Among others, *EnergyPlus* is one of the most used building energy modeling tools. The software is funded by the US-American Department of Energy (DOE) and managed by the National Renewable Energy Laboratory (NREL). *EnergyPlus* is the combination of two former software that were started to be developed in 1996 [22, p. 7]. Today it can be used to simulate models for heating, cooling, lighting, water usage and other energy flows. Although the software does not have its own interface to visualize building geometry and its surrounding, it supports third party software. The *OpenStudio* plug-in for *GoogleSketchUp* was used in this work

A variety of parameters can be set in the software. The goal of this work was to assess to what extent different refurbishment proposals impact the heating and cooling demand of the building. Since some parameters are yet unclear, the input was limited to the most relevant. The following sections briefly explain the collected data or assumptions.

3.2.1 Thermal Zoning

Thermal Zoning is an essential concept when defining the building geometry. The boundary conditions of each thermal zone are characterized by its surface properties. Furthermore, clever thermal zoning positively influences the energy consumption for heating and cooling of a building.

A variety of concepts are conceivable. Zones can be grouped according to their size, boundary conditions, orientation or variation of internal load. It is an individual choice, depending on the goal of the simulation. However, one needs to be aware to make plausible assumptions. For small or medium size buildings, each room can represent a thermal zone, as the workload is manageable [23, pp. 102–106]. An advantage is that the zones can be directly defined from the floor plan and surface conditions are given by the building envelope. That approach was used in this thesis. Each room, as indicated in the floor plans *(Figure 53 to Figure 58)* was defined as a separate thermal zone. The surfaces are characterized by the materials they are made of. At first, all material data, as analysed and given in *Table 2, Table 5 and Table 7* in the previous section was put into *EnergyPlus*. After setting these material properties, e.g. thickness, thermal conductivity, heat capacity and density, they are used to specify construction elements. In fact, these represent the real structure, such as walls, ceilings and roof of the building.

With the *OpenStudio* plug-in the construction elements were assigned to the respective surfaces through the *GoogleSketchUp* interface. Considering shading from surrounding buildings, the close environment was included into the model as one can see in *Figure 13 and Figure 14.* Neighbouring buildings, directly in contact with the Rudolf 5, share the same surfaces and thus influence their thermal behavior. Therefore, heated adjacent thermal zones, e.g. from neighbouring residential housing were considered adiabatic.

Not all building surfaces of Rudolf 5 consist of homogeneous layers and are made up of one material. In such case, the shares of the separate materials are weighted on a percentage basis and added up. This method was applied for the ceilings and roofs, because these components include air (in the south wing), or air and sand filling (in the north wing), in the space between the wooden rafters. Knowing the dimensions of the beams and their spacing, the surface area covered by wood and air/filling was calculated. The obtained percentages were multiplied with the respective thermal conductivities of the materials. An overall thermal resistance for the complete layer resulted. The value is displayed in the last column of the previous tables.

All data was verified, comparing the U-value of a typical building of that time, as stated in [17, pp. 50–59]. At first, the U-values for roof and ceiling of Rudolf 5 achieved values too good for such an old building. Deeper investigation and literature review revealed the mistake. Even though, air is enclosed in the ceiling or roof structure its thermal conductivity cannot be assumed as good as $0.025\ \frac{W}{m\,K}$, As this changes due to convection [24, pp. 60–69]. Norm *DIN EN ISO 6946* [25, pp. 7–9] explains this phenomenon and therefore defines different thermal resistances depending on the dimensions of the layer of air. For layers thicker than 50 mm, it states a resistance of $0.16\ \frac{m^2K}{W}$ in vertical upward direction. *EnergyPlus* has a similar value, called *ceiling air space resistance* predefined with $0.18\ \frac{m^2K}{W}$. Using that, U-values much closer to the expected ones were obtained. *Table 8* on the next page gives a short overview of the important U-values.

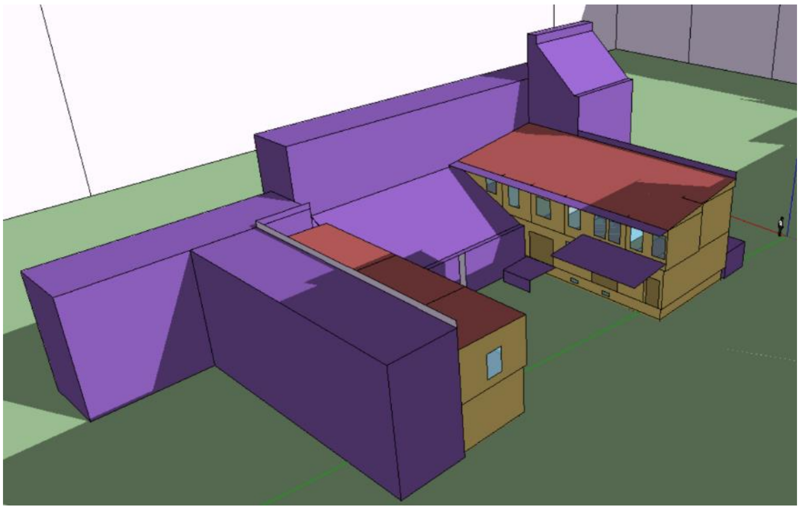


Figure 13: OpenStudio 3D model of the courtyard building “Rudolf 5” and its surrounding, view from north-west

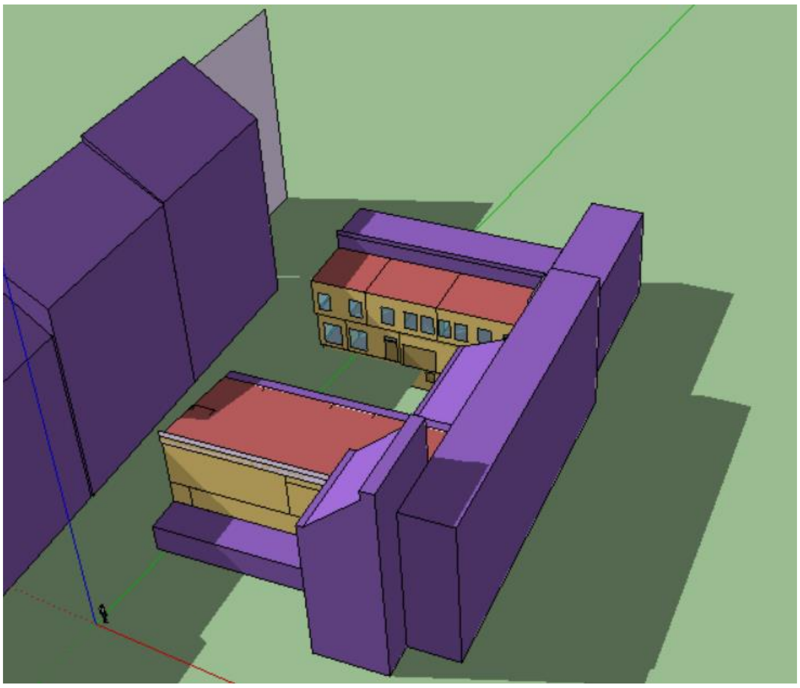


Figure 14: OpenStudio 3D model of courtyard building “Rudolf 5” and its surrounding, view from south-east

Table 8: Comparison of estimated and references U-values

	Calculated U-value	**Reference U-value**
exterior brick wall	1.67	1.46 – 1.71
ceiling between ground- and first floor, north wing	0.8	0.76 – 1.16
ceiling between ground- and first floor, south wing	0.72	0.7
roof north wing	0.66	0.76
roof south wing	1	2.06
windows	5.2	5.2

Since the original construction has been changed and replaced throughout the time, and literature only suggests some ideal constructions, an exact match cannot be expected. Still, the U-values give a good orientation. Especially the low thermal conductivity of wood wool lightweight building boards ($0.075\ \frac{W}{m\ K}$) influences the U-value of the roof quite significantly. The boards were added during a later renovation work in the second half of the past century. Until the 1920's, the typical building standard included simply layer of wood ($0.13\ \frac{W}{m\ K}$) beneath the roof, that also served as ceiling at the same time. Assuming the old standard construction layers higher U-values are achieved, compared to a U-value of $1\ \frac{W}{m^2 K}$ for the currently existing roof structure. Due to the large deviation between the calculated ($1\ \frac{W}{m^2 K}$) and expected U-value ($2.06\ \frac{W}{m^2 K}$) of the south wing roof, it was decided to work with the reference value *(see Table 8)*. *EnergyPlus* offers the possibility to enter the U-value via the *material:nomass* option, thus $2.06\ \frac{W}{m^2 k}$ was assigned to the respective roof surface.

3.2.2 Internal Gains

EnergyPlus allows the user to set several internal heat gains, by assigning specific loads and corresponding schedules. Predicting internal gains can be challenging, as they depend on the occupants and their behaviour. Most of all, the final design and use for the building in Rudolfstraße 5 can only be predicted at this point. The intended use as co-working and atelier area is incomparable with a typical office or workshop schedule. Nevertheless, the following assumptions were made.

Based on the ASHRAE Handbook of fundamentals, *EnergyPlus* proposes a range of metabolic rates depending on different activity levels for the internal heat gains of **people**. A wood workshop is planned and already partly in place in the south wing basement. Here, an activity level of 189 W/person was set. For the rest of the building "office activities" with an average of 120 W/person were assumed [26, pp. 388–390]. An average occupancy of 6 m^2 per person for the co-working places and 4 people in the basement were considered, since that reflects the current situation in the south wing. The assumed schedules can be found in the *appendix Figure 61*. They are vague, as the final use is uncertain.

Various numbers were found for the internal heat gains of **electrical office equipment**, to estimate the heat gains in the co-working spaces. A range between 7 – 15 W/m^2 is suggested in the literature, however it was unclear as some include lighting and other auxiliary services, such as fax, copying machine etc. The norm *DIN V 18599-10* suggests an average of 7 W/m^2 as maximum specific load for electrical equipment in shared offices, assuming a consumption of 100 W/person [27, p. 26]. The *Building Research Establishment Environmental Assessment Method (BREEAM)* [28, p. 15] concludes 15 W/m^2 as it estimated the average load density about 160 W/person, including auxiliary office equipment and assuming most of the people work with a computer. In contrast *Dentel and Dietrich* [29, p. 23] consider 15 W/m^2 high. For lighting this reference suggests a range between 8.5 and 14.5 W/m^2 [29, p. 21]. *BREEAM* [28, p. 13] presents values between 12 and 20 W/m^2. Since most of the lighting will be replaced by energy efficient LED at Rudolf 5, the heat gains due to lighting are almost neglectable. Therefore, an overall electrical heat gain of 20 W/m^2 was set in this thesis work. Since the majority of electrical heat gains will most likely be provided by laptops, the required fields in the *EnergyPlus* environment *(given in Figure 60)* for latent and radiative heat were set with 0.25 and 0.75 respectively [30, p. 19].

3.2.3 Air Exchange Rate

Two mechanisms, **infiltration** and **ventilation**, are responsible for the exchange of air in buildings. *EnergyPlus* allows the user to set both independently. Infiltration is understood as the unintended flow of air due to cracks around windows, small leakages through building elements or simply caused by opening and closing exterior doors. Ventilation refers to the intended airflow, caused by a mechanically driven ventilation system or natural ventilation (e.g. opening windows) [26, pp. 518–537]. The latter is the case in this study.

“The question of typical values for these coefficients is subject to debate. Ideally, one should do a detailed analysis of the infiltration situation and then determine a custom set of coefficients [26, p. 518].” To determine the **infiltration** rate, also called natural air change, two methods can be applied. The most common is a so called “blower door test”. A pressure difference of 50 Pa is created between the in- and outside of the building. From the pressure drop over time, the air tightness of the building can be calculated (n_{50}) [31, pp. 1–14]. Deeper research revealed a great range for the n_{50} values. *Wenzel* [32, p. 5] for example claims a range of n_{50} between 3 and 7 air changes per hour (ac/h). During their research, measuring air tightness of more than 30 year old buildings *Münzberg et al.* [31, p. 6] found an average n_{50} of 7.4 ac/h. Moreover, they claim a mean infiltration rate of n_{nat} = 0.26 ac/h. It is important to mention, that n_{50} and n_{nat} represent different situations. The first refers to a measurement under pressure and the second to the actual, everyday infiltration. Furthermore, infiltration is of course influenced by external factors such as temperature differences and wind outside.

In the scope of this work, an exact measurement of the infiltration rate was not possible. Even though, the German Norm *DIN 1946-6* [33, p. 18] proposes a calculation to estimate the infiltration some assumptions distort the result. Based on *Equation 3* given in *DIN 1946-6*, the infiltration rate can be estimated [34, pp. 2–8]:

$$n_{nat} = f * n_{50} * (\frac{\Delta p}{50})^{\frac{2}{3}}$$ *Equation 3*

DIN 1946-6/2 [35, p. 7] suggests an n_{50} of 4.5 ac/h. Considering the values found in literature, it is questionable if this assumption represents reality. Coefficient f changes according to the present type of ventilation system. *DIN 1946-6* [33, p. 18] defines 0.5 for natural ventilation here. Δp is adjusted depending on the type of building and its exposure to wind. From the table given in the norm, a value between 2 and 5 Pascal seems reasonable [35, p. 7]. According to this, we obtain n_{nat} = 0.48 ac/h. However, an infiltration rate of 0.8 ac/h is achieved when considering the mean n_{50} of 7.4 ac/h from *Münzberg et al*. [31, p. 6].The latter corresponds better with the proposal of EnEV, where 0.7 ac/h is assumed for non-airtight buildings [36]. Another source suggests similar infiltration ratios between 0.7 and 1.3 air changes per hour [37, pp. 2–4]. Although, *Münzberg et al* estimated the mean infiltration rate at 0.26 ac/h, the obtained numbers of this thesis match the range of data acquired during their research [31, p. 6]. Moreover, a difference of natural air exchange can be expected between ground floor and first floor [34, p. 8]. The roof typically shows greater leakages than other building components. Thus, the infiltration ratio set in *EnergyPlus* is adjusted during the calibration process. The final decision for the infiltration setting can be found in section ”*3.2.5 Calibration of the* model*”*.

To get an idea of the air flow, necessary and caused by natural **ventilation** *DIN 1946-6* was consulted. In order to avoid moisture, it suggests an overall air exchange of $15\ \frac{m^3}{h*m^2}$ for study rooms/offices in residential houses with low heat protection [33, p. 32]. Knowing the surface area (m^2) and dimensions (m^3) of the room, the air changes per hour are easily determined. Applied to Rudolfstrasse 5, an air exchange of approximately 4.5 ac/h is obtained. Furthermore, *DIN 18599* specifies a minimum fresh air volume flow of $4\ \frac{m^3}{h*m^2}$ [27, p. 26] for small group offices (up to six people). Hence, one needs to consider at least 1.33 air changes per hour. Respecting reference values, including the influence of various window positions for natural ventilation [24, p. 270], a ventilation value of 3 ac/h was assumed.

3.2.4 Weather Data Input

Mannheim, 60 km north of Karlsruhe, was the closest, predefined location available with weather data within the *EnergyPlus* software. Hence, external data for Karlsruhe was requested and converted into the required file *.epw format*[3]. The weather file conversion software, called *elements [38],* was used for this purpose. Data was acquired from the German Meteorological Service (DWD). They offer free, online access to all necessary parameters, such as temperature, humidity, wind and solar radiation etc. Current weather data as well as typical annual parameters, referred as TRY (Test Reference Year) are provided. The latter represents compiled and treated data over two decades, from 1995 until 2012, and was specifically developed for simulations purposes [39]. In Addition, future TRY data was extrapolated for

[3] *.epw* stands for *EnergyPlus weather file format* and represents the standard weather file format required to simulate with that specific software.

the period from 2031 until 2060. Given the occurrence of increasing temperatures, a comparison between the two data sets was considered in this work.

3.2.5 Calibration of the model

Due to the large number of independent as well as interdependent input parameters, the calibration of an energy model is a complex, over-parameterized process. Many factors can and need to be set, to accurately simulate the building's thermal behavior. Among them are the ones mentioned in the previous chapters. For the calibration, data from the simulation was compared with data from the real building. Ideally, energy consumption is tracked back with utility bills or sensors are installed in order to acquire additional data, such as temperature [40]. During the calibration process it is essential to verify the collected data, but also to define a reasonable level of accuracy required for the model [41, p. 4].

Today, statistical indices are calculated and used to state whether a model can be considered calibrated. The indices however, only determine "how well the simulation matches reality" and do not provide a guideline on how to calibrate a model. "It is quite common to use a "trial and error" method to calibrate a building model [41, p. 4]." Three international bodies have set reference criteria. All of them demand estimating the *mean biased error (MBE)* and *coefficient of variation of the root mean square error (cvRMSE)* as shown in *Equation 4 and Equation 7*. Since negative and positive values "contribute to reduce *MBE* final value", *cvRMSE* is an important addition stating the deviation between model and measured data. According to the ASHRAE guidelines, an hourly model is considered satisfying if *MBE is +/- 10%* and if *cvRMSE is below 30%*. Other bodies are more strict with their limits [41, p. 6].

$$MBE\ (\%) = \frac{\sum S - M}{\sum M} * 100\% \qquad \textit{Equation 4}$$

$$RMSE = \sqrt{\frac{\sum (S - M)^2}{N}} \qquad \textit{Equation 5}$$

$$A_{period} = \frac{\sum M}{N} \qquad \textit{Equation 6}$$

$$Cv(RMSE) = \frac{RMSE}{A_{period}} * 100\% \qquad \textit{Equation 7}$$

S represents the simulated data whereas *M* stands for measured data. *N* indicates the number of time intervals considered.

For the calibration process of this thesis work, four *EnergyOT Environment* sensors *(Figure 62)* were installed in the south wing to record indoor temperature over a period of six months (January 2019 – June 2019). In a five-minute interval the sensors log data. Connected to the WiFi network, the data of the sensor is sent to a website and available to download. Verifying the data with a thermometer revealed deviations between 3 – 4°C. In summer, when outdoor temperatures increased extremely, the sensors on the first-floor recorded temperatures up to 5°C higher than expected. Not all devices showed that discrepancy to same extend, however all did record an increased level of temperature. This can be traced back to the fact that the sensor is protected by a plastic casing. The warm casing is responsible for insufficient heat dissipation from the device and most likely the reason for the high temperatures. Therefore, the recorded data was adjusted accordingly for the calculation of the statistical indices.

Except for the temperature measurements, no other data was available for the calibration. Moreover, random, temporary occupancy including individual heating from gas heaters, due to lack of a working central heating system, influenced the record on the first floor. Furthermore, it was challenging to represent that in the model. As a result of the cold indoor temperatures during wintertime, the ground floor was practically not used. Thus, the temperature sensor there was used as reference for the calibration process. Sensors on the second floor were considered during May and June only, since a match between measured and simulated data before was not expected, based on the reasons mentioned above. Parameters for infiltration and ventilation were adjusted within their range *(see chapter 3.2.3 Air Exchange* Rate*)* until a satisfying result was achieved.

Figure 15 represents the course of the two graphs of the indoor temperature, the blue curve representing simulated data and the orange curve recorded temperatures from January until end of June 2019. For the sake of clarity, monthly segments are not indicated exactly on the horizontal axis. Several simulations were carried out adjusting the infiltration rates until satisfying results were obtained. Finally, an infiltration rate of 0.9 ac/h on the ground floor and 1.3 ac/h on the first floor were assumed. The increased infiltration on the first floor is justified, since the roof typically represents one of the leakiest parts of the building. Ventilation was set to 3 ac/h, as already mentioned earlier *(3.2.3 Air Exchange* Rate *- ventilation).* According to these settings, an *MBE of – 9.82%* and *cvRMSE of 13.66%* was obtained for the ground floor level, which is well within the acceptable range as defined by ASHRAE.

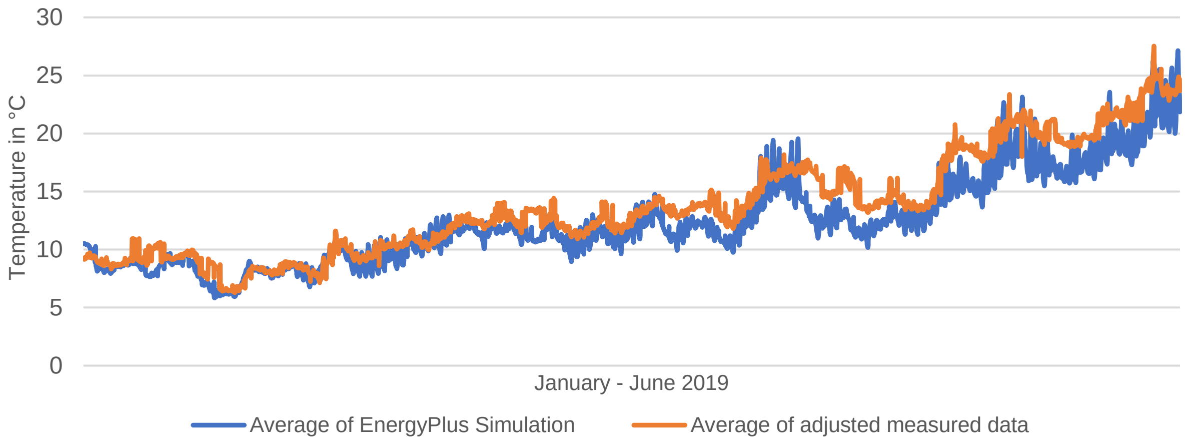


Figure 15: Deviation between measured and simulated temperatures on ground floor level, south wing

Figure 16 indicates the comparison of recorded and simulated temperatures on the first floor between May and June 2019. The recorded data is from the sensor that was installed in co-working space 02 *(Figure 55)*. There are periods, marked with a red circle, where simulated and recorded data match very well. The *cvRMSE* went down to *14.15%* for June, compared to *18.05%* considering both months, May and June together. *MBE* remained stable around + *9.5%* for both calculations. Uncertainties for internal gains, due to irregular occupancy and unknown indoor energy consumptions influence the results. Moreover, the amplitude of both graphs differs more compared to the ground floor level. Nevertheless, the obtained values were found to be within range and the model could be declared as calibrated.

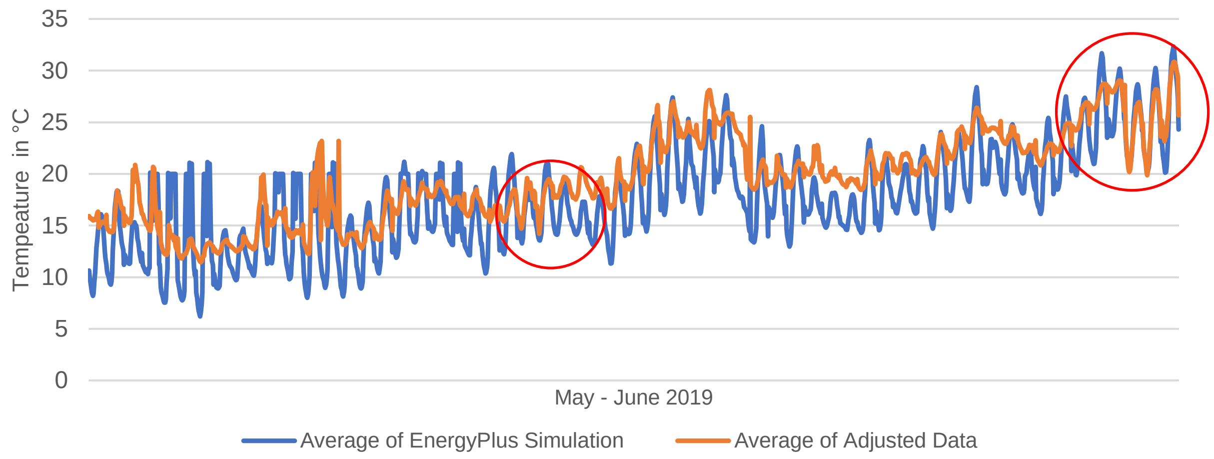


Figure 16: Deviation between measured and simulated temperatures, co-working 02 – first floor, south wing

3.3 Refurbishment Proposals

As mentioned in the beginning, the roof surface represents a big area of the building envelope. Exposed to sun, rain, snow and wind, it is prone to damages [17, p. 142]. Moreover, missing insulation greatly affects the indoor climate and leads to high energy consumption for heating. Therefore, three design proposals considering the **insulation of the roof**, were developed throughout this work and will be compared in the following sections.

Facing the requirements of the heritage authority, replacing of the old single glazed windows is not allowed. With a U-value of $5.2\ \frac{W}{m^2K}$, they represent a significant loss in the building envelope though. To keep costs low and at the same time achieving an energy efficient performance, a simplified version of a **casement windows** is planned. A framed windowpane is pushed onto the wall from the inside.

Interior insulation of the walls is considered as a last measure. Due to the requirements for listed buildings, exterior insulation is not allowed.

3.3.1 Detailed Design Proposals

Based on the typical designs and suggestions found in literature, the following **three refurbishment proposals for the roof** were developed. All proposals have a green roof structure in common. As part of the overall concept for Rudolf 5, the green roof offers space for urban gardening. Additionally, it has a positive impact on the surrounding atmosphere as well as the micro-climate, due to the evaporative cooling effect in summer. The structure for the green roof remains the same for all three roof designs and is consistent with the information of reference construction proposals found in literature [42] [17, p. 148] and [20, p. 52].

Figure 17 represents the first roof design proposal with a blow-in cellulose insulation. Keeping most of the existing roof structure is the great advantage. Only the roof cover and outside casing is replaced by the new green roof. For necessary static support, the rafters are doubled to 200 mm. 150 mm cellulose insulation is blown into the space between suspended ceiling and roof bottom (hence the name blow-in insulation). With this construction, a U-value of $0.18\frac{W}{m^2 * K}$ can be achieved. Detailed material data is appended in *Table 9* below.

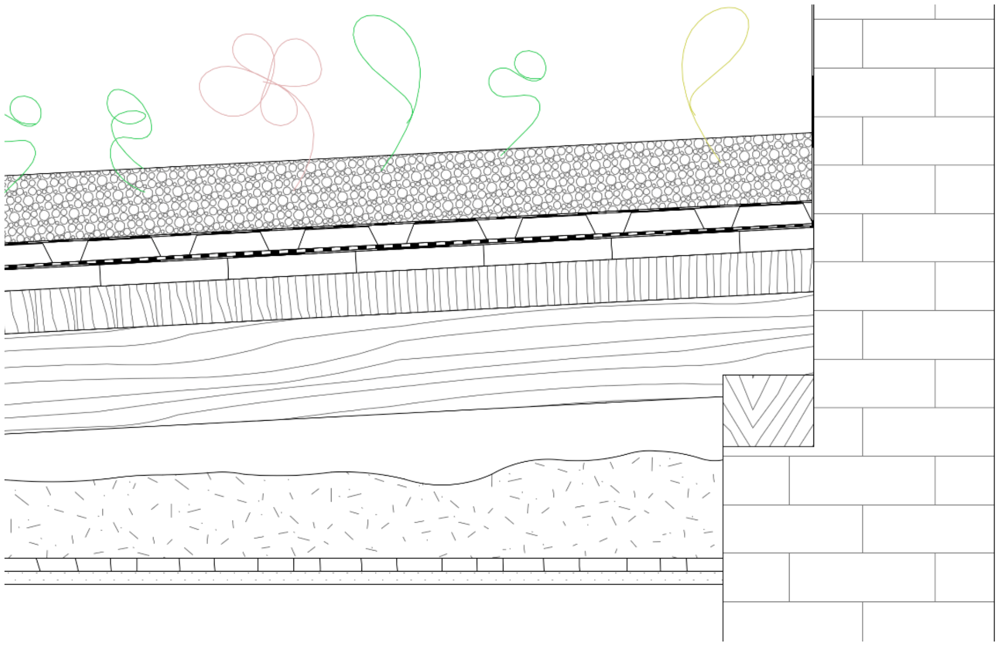


Figure 17: Refurbishment Proposal #1 - blow-in cellulose insulation for the roof

Table 9: Material properties #1 - blow-in cellulose insulation design proposal

		thickness (m)	thermal conductivity (W/(m*K))	density (kg/m³)	heat capacity (J/kg*K)	thermal resistance ((m²*K)/W)
#1 – blow in cellulose insulation						
1	soil green roof	0.07	1.4	1750	1000	
2	filter fleece	0.0015	1	1	1	
3	drainage	0.03	0.1	1	0	
4	protection layer (PP)	0.0036	0.22	910	1700	
5	roof seal (bitumen)	0.005	0.17	1200	1000	
6	protection layer	0.005	0.17	400	0	
7	wood casing	0.025	0.13	500	1600	
8	rafter doubling (60 x 140 mm)	0.06				0.2417
9	existing rafter (160 x 140 mm)	0.14				0.3765
10	cellulose insulation	0.15	0.04	40	1600	
11	chipboard	0.10	0.14	600	1700	

The second design involves more work, since the old structure will most likely not be kept. Wood fibre boards serve as insulation, like illustrated in *Figure 18,* and are placed between the rafters. In the course of this work, the existing rafter structure could be replaced completely by new ones with the required thickness of 200 mm. This has the advantage that the spacing of the beams could be adjusted to the structural specifications to support the green roof. Moreover, the suspended ceiling is not required anyway. It could be removed to have better access for inserting the wood fibre boards and place the vapour barrier. However, keeping parts of the old structure is of course also possible. The technical execution is not focus of this work. For this proposal, a U-value of $0.24\frac{W}{m^2*K}$ was estimated. *Kolb* gives similar U-values for this refurbishment proposal [17, p. 148]. A detailed drawing and corresponding material properties for this proposal is found on the next page, please refer to *Figure 18 and Table 10*.

The third and last proposal is a so-called timber board stacking ceiling. It captivates by its elegance; however, it involves replacing the entire existing roof structure. Solid timber boards, measuring a height of 200 mm, are installed as ceiling over the full length. Thus, no more additional rafters are required because, the solid surface serves as support structure itself. For insulation, an 80 mm layer of foam-glass is placed in between the timber boards and green roof construction. *Figure 19 and Table 11* display the construction and its details. An overall U-value around $0.24\frac{W}{m^2*K}$ was obtained for this structure.

Interior wall insulation can help to further reduce the energy consumption of the building. Wood fibre boards were chosen for a possible design proposal, shown in *Figure 20*. "Their capillary conductivity as well as hygroscopic properties prevent condensate formation and thus damages of the insulation layer [17, p. 92]." The boards are able to store accruing moisture and release it later. Clay plaster complements and supports this effect [17, p. 92]. Insulation up to 60 mm thickness is recommend, since a reduction of heat losses by more than 50% can be expected [17, p. 96]. Thicker layers of insulation are economically not viable. *Figure 20* shows the structure and

Table 12 includes its material data. With the described structure, the U-value of the exterior wall dropped from $1.67\frac{W}{m^2*K}$ down to $0.5\frac{W}{m^2*K}$. This represents slightly more than the references of $0.41\frac{W}{m^2*K}$ given by *Kolb* [17, p. 50].

Instead of the typical casement-**window** construction, a simpler solution was developed during this work. Rather than placing a complete second framed window, with all its additional components, in front of the old, listed one, only a simple double-glazed windowpane is temporarily pressed onto the window opening from the inside. This solution was developed as it represents the most affordable way to meet the requirements of the conservation authority in preserving the old window yet, achieving better thermal properties at the same time. Moreover, the temporary solution reflects the overall concept of Rudolf 5 striving to keep things simple, flexible, effective and at low budget. During the winter months the windows are equipped with the "additional layer" to reduce heat losses. During summer, the existing windows are enough. Currently, the U-value of the windows can be assumed to be $5.2\frac{W}{m^2*K}$. [14, p. 172]. With the complementary windowpane ($U = 3\frac{W}{m^2*K}$ [10, p. 66]) and the air space that results due to the space between new and old window, the new U-value of the window construction was calculated to be around $1.5 \frac{W}{m^2*K}$.

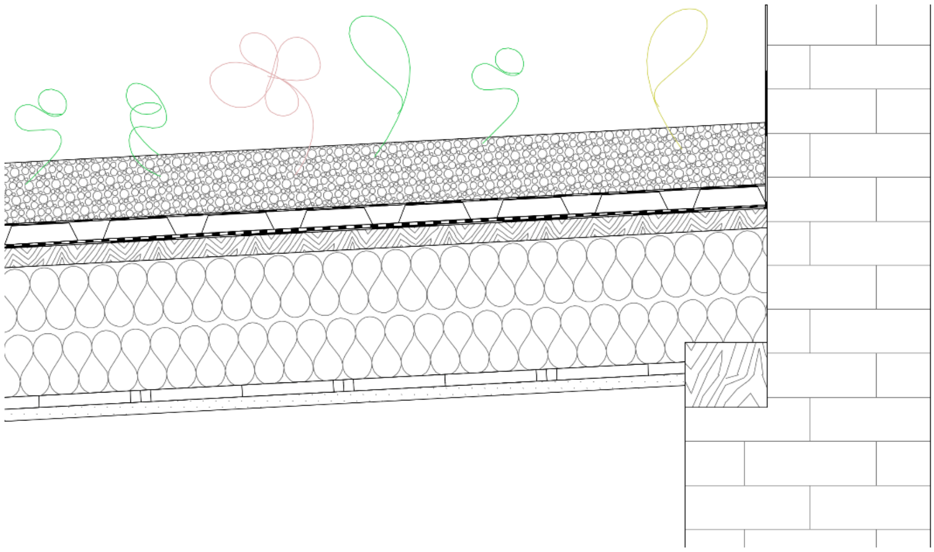


Figure 18: Refurbishment proposal #2 - insulation between rafters

Table 10: Material properties #2 - insulation between rafters' design proposal

		thickness (m)	**thermal conductivity (W/(m*K))**	**density (kg/m³)**	**heat capacity (J/kg*K)**	**thermal resistance ((m²*K)/W)**
#2 – insulation between rafters						
1	soil green roof	0.07	1.4	1750	1000	
2	filter fleece	0.0015	1	1	1	
3	drainage	0.03	0.1	1	0	
4	protection layer (PP)	0.0036	0.22	910	1700	
5	roof seal (bitumen)	0.005	0.17	1200	1000	
6	protection layer	0.005	0.17	400	0	
7	wood casing	0.025	0.13	500	1600	
8	rafter (200 x 160 mm) with wood fibre board insulation	0.2				3.44
9	vapour barrier	0.001	160	2700	896	
10	plywood board	0.012	0.17	700	1600	

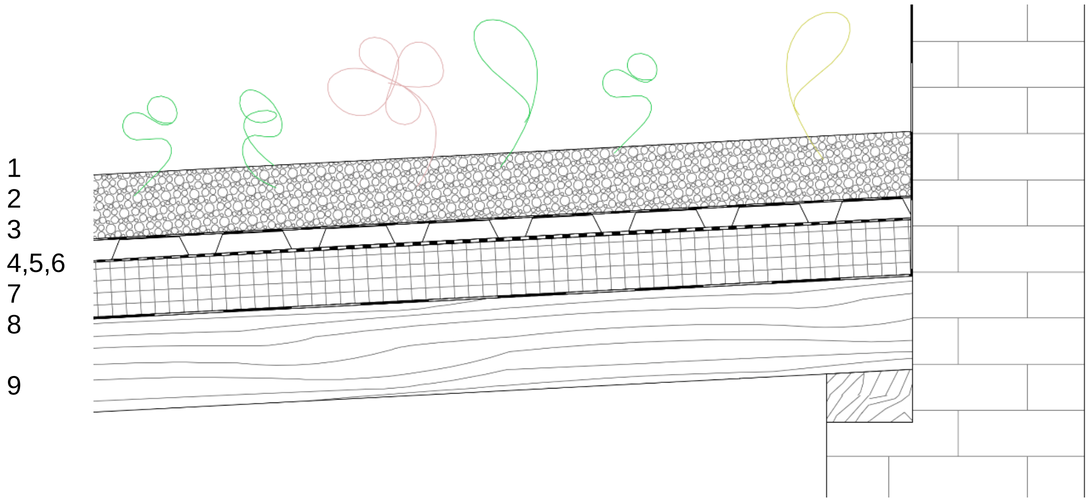


Figure 19: Refurbishment proposal #3 – timber board stacking roof

Table 11: Material properties, #3 - timber board stacking roof design

		thickness (m)	thermal conductivity (W/(m*K))	density (kg/m³)	heat capacity (J/kg*K)	thermal resistance ((m²*K)/W)
#3 – timber board stacking roof						
1	soil green roof	0.070	1.4	1750	1000	
2	filter fleece	0.0015	1	1	1	
3	drainage	0.030	0.1	1	0	
4	protection layer (PP)	0.0036	0.22	910	1700	
5	roof seal (bitumen)	0.005	0.17	1200	1000	
6	protection layer	0.005	0.17	400	0	
7	foam glass	0.080	0.037	100	1000	
8	vapour barrier	0.001	160	2700	896	
9	timber board stacking	0.200	0.13	500	1600	

Table 12: Detailed material properties for interior wall insulation

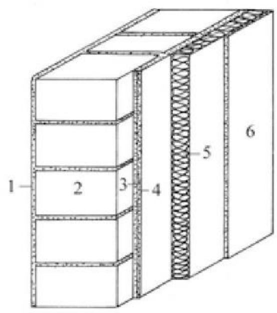


Figure 20: Interior wall insulation with wood-fibre board [17, p. 92]

		thickness (m)	thermal conductivity (W/(m*K))	density (kg/m³)	heat capacity (J/kg*K)
1	lime cement plaster	0.03	0.87	1800	1000
2	brick	0.38	0.68	1600	1000
3	lime gypsum plaster	0.03	0.7	1400	1000
4	clay plaster	0.005	0.91	1700	2100
5	wood fibre board	0.06	0.045	160	1000
6	clay plaster	0.005	0.91	1700	2100

4 Evaluation of Refurbishment Proposals

The following chapter summarizes the results of the simulation, for the different design proposals, carried out in *EnergyPlus*. Referring to the pillars of sustainability, the assessment of the environmental, economic and social impacts complements this section. All aspects aim to support the decision process in finding an overall sustainable and satisfying solution.

4.1 Simulated Energy Demand in EnergyPlus

The aim of the simulation with *EnergyPlus* was to find out which structural changes reduce the expected energy consumption for heating and cooling the most. Since the final heating system was unknown, the *ZoneHVAC:IdealLoadsAirSystem* was set in *EnergyPlus*. This setting allows the user to estimate heating and cooling demands without specifying a system. A heating and cooling schedule is required and was assigned accordingly (see *Figure 63*). The *IdealLoadsAirSystem* was appointed for all rooms in both buildings on ground- and first floor, expect hallway and staircase in the south wing. Monthly energy consumption was requested in the output file and used for the following analysis.

For comparison purposes, the current status of the building was simulated before the model was adapted to the different design proposals. Although, the U-value of the new roof constructions are very similar, the exact material layers were assigned, as mentioned in tables mentioned in the last section. The option *WindowMaterial:SimpleGlazingSystem* represents "an entire glazing system, rather than the individual layer [26, p. 166]." Since limited information about the real construction and behavior of the windows were available, this setting was considered to be reasonable.
The constructional changes also influence the air tightness of the building and reduce infiltration. *DIN 1946 – 6/2* [35, p. 7] suggests an $n_{50} = 2.0$ after renovation work. That includes replacing important parts of the building envelope such as windows. Compared to the original n_{50} of 4.5, this represents an improvement of more than 50%. *Equation 3,* introduced in the last chapter, shows that n_{50} and the infiltration n_{nat} behave proportionally. In this work, infiltration ratios of 0.8 ac/h on the first and 0.6 ac/h on the ground floor level were assumed after the refurbishment. They correspond to an improvement of 40% and 35% of the initial infiltration rates, respectively. Although the idea with the windowpane is innovative, achieving the same air tightness compared to new windows seems unlikely, which justifies the lower improvement of air tightness.

The simulation in *EnergyPlus* is carried out twice for each setting: one with the current, typical weather data indicated with "2015", the other with extrapolated future weather data, labelled "2045" in the following graphs. The objective is to account with the potential impact of climate change. Firstly, the heating and cooling demand of each floor is introduced before the global consumption of the building complex will be discussed. Energy consumption was converted into kWh/m^2.
All graphs follow the same structure, comparing the current building with the three roof design proposals of the previous section, labelled #1, #2 and #3. To be consistent throughout this work, it was decided to classify everything according to these three initial roof insulating designs. This explains labelling the

proposal with interior wall insulation: #2.3. Although interior wall insulation is a measure itself, model #2 - insulation between rafters - served as base model and was complemented with interior wall insulation. This was done, to better depict the improvement between only roof insulation and roof- as well as interior wall insulation.

Figure 21 displays the average heating demand for in the co-working spaces on the first floor of the south wing. *Figure 22* represents the energy demand on the same level in the north wing. It is interesting to notice that a difference between south- and north wing is only observed under the current conditions. After the implementation of the renovation proposals (#3, #2 and #2.3 - changing roof, windows and infiltration), both buildings show a similar performance, except for the first, blow-in insulation refurbishment proposal.

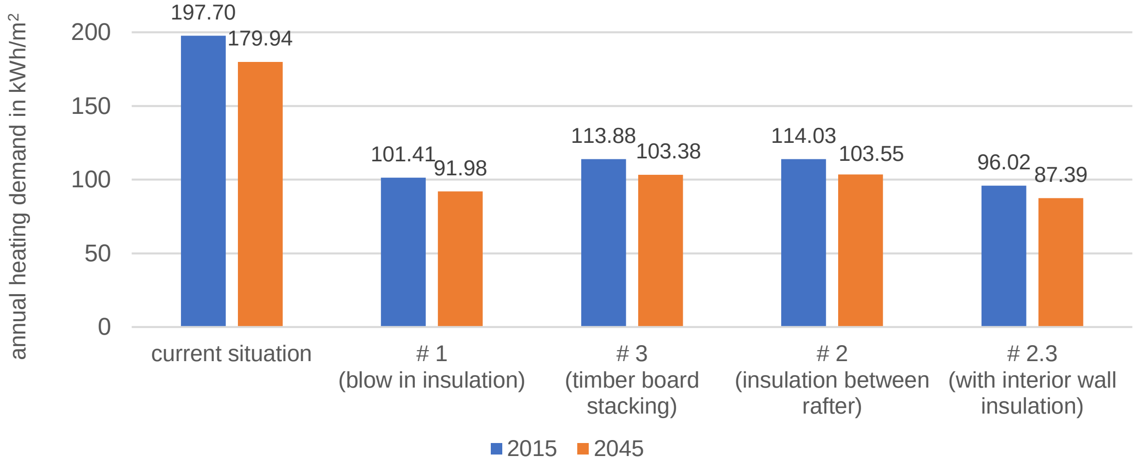


Figure 21: Heating Demand – first floor south wing

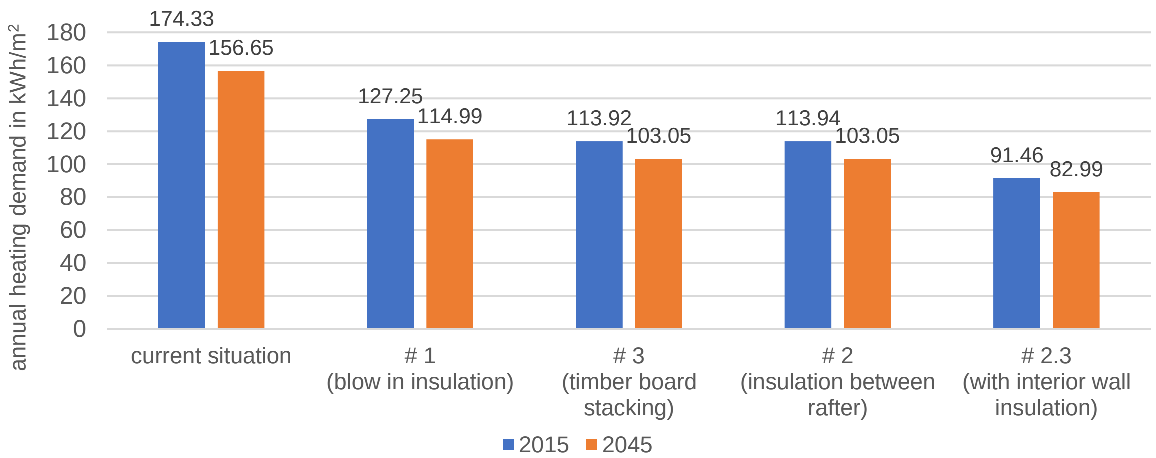


Figure 22: Heating Demand – first floor, north wing

The deviation between the two wings for proposal #1 – blow in insulation - is presumably due to the modelled roof-geometry in *EnergyPlus*. The triangular shape of the south wing roof *(see Figure 23)*, aiming to depict the plane suspended ceiling as well as the inclination of the roof, leads to better results. The material layers, defining a construction surface in the software, remain at the same thickness for their respective surface. That means the insulation is evenly distributed in the model, but in reality, it differs between southern and northern edge of the roof, because the space between ceiling and roof increases. Generally, better results were obtained by *EnergyPlus* for rooms at the northern façade of the south wing *(Figure 55 - co-working spaces 01 to 05)*.

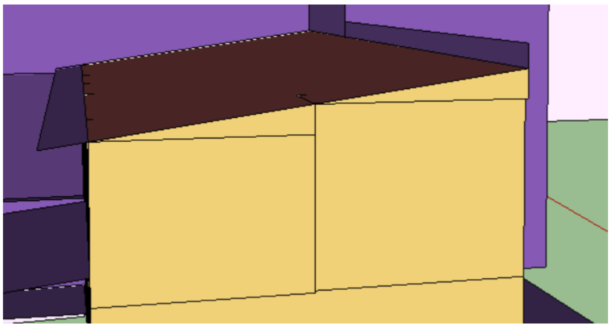


Figure 23: SketchUp model, side view of roof south wing

Achieving the same U-value, timber board stacking roof with foam-glass insulation (#3) and insulation between rafters (#2) obtained the same results *(see Figure 21 and Figure 22)*. In addition, another 16 – 20% savings are generated with interior insulation (#2.3). Moreover, the comparison between the 2015 and 2045 data indicates a decrease for heating energy of around 10% within the next 30 years. On the other hand, the cooling energy demand will double during the same time period, as it can be seen in *Figure 24 and Figure 25*.

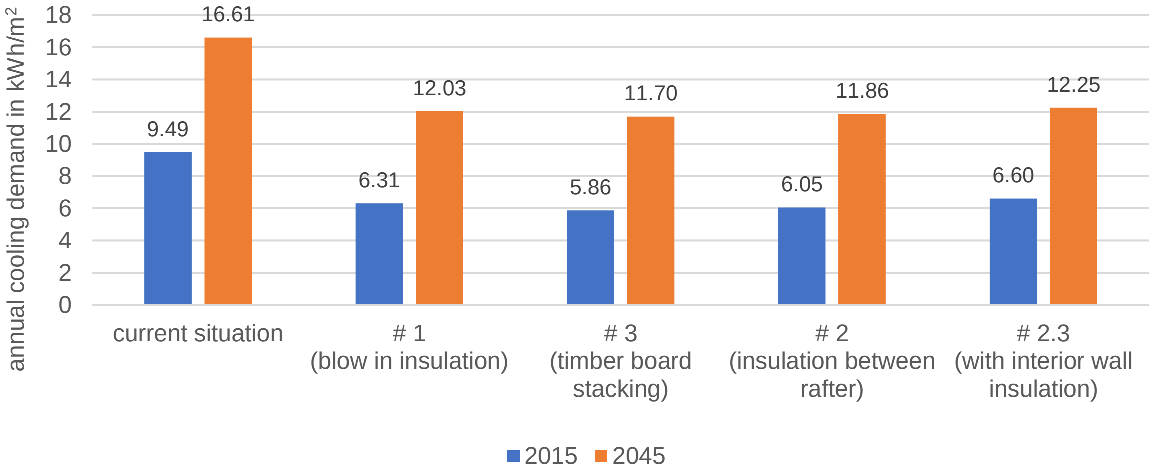


Figure 24: Cooling demand, first floor, south wing

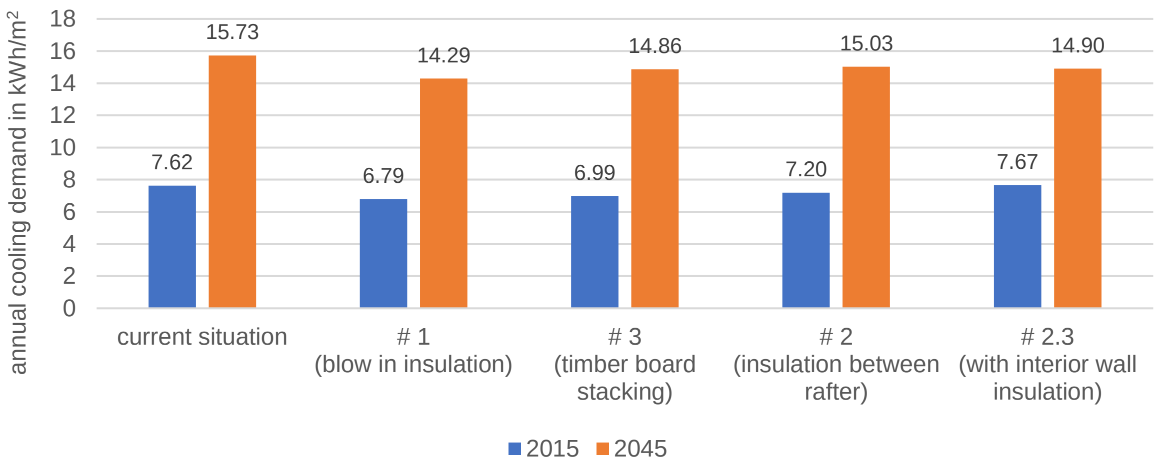


Figure 25: Cooling demand, first floor, north wing

Analyzing the simulated data of all thermal zones, it was observed that corner rooms, with two walls facing the outdoor environment, such as co-working space 01 *(Figure 55)*and room 01 *(Figure* 58*)* reveal higher heating demand. In the current status, it was found that they consume 20% more energy compared to the average value indicated in the graphs above (*Figure 21 and Figure 22)*. After, the roof renovation the deviation increases up to 35% for co-working space 01 in the south wing and 30% for room 01 in the north wing. With a complementary interior wall insulation, the difference decreases to only 18% and 14% more consumption, respectively.

Furthermore, the heating demand of around 155 kwh/m^2 for co-working space 06/07 *(Figure 55)* is 35% above all other rooms for the two renovation proposal, insulation between rafters and timber board stacking. The inclining roof and missing suspended ceiling contribute to more volume in that zone, which leads to higher energy consumption for the same surface area.

The graphs on the next page (see *Figure 26* & *Figure 27*) present the heating demand for the ground floor level for south- and north wing. Whereas the consumption could be reduced by 43% and 35% with insulation between rafters (proposal #2) on the first floor in south- and north wing, respectively, the ground floor only improves its performance by 17% and 22%. On the one hand, the overall energy consumption is lower, as there are only two surfaces exposed to the outdoor environment: walls and no roof. Moreover, only one wall includes two windows and gates. On the other hand, the thicker walls on that level favor stable temperatures. That was also recorded during the measurements, as shown before in *Figure 15*. From the baseline temperature, between 10°C and 12°C, less energy is required to heat up the entire volume compared to the upper floor, where the current situation revealed a higher temperature amplitude (*Figure 16*). Moreover, the smaller window surface as well as a lower infiltration rate, compared to the first floor, support reduced energy consumption. Both building parts show very similar performances for all three proposals on the ground floor level, reducing the demand by 17% and 22%. Another 8% can be saved installing an interior wall insulation, as depicted in the last proposal #2.3.

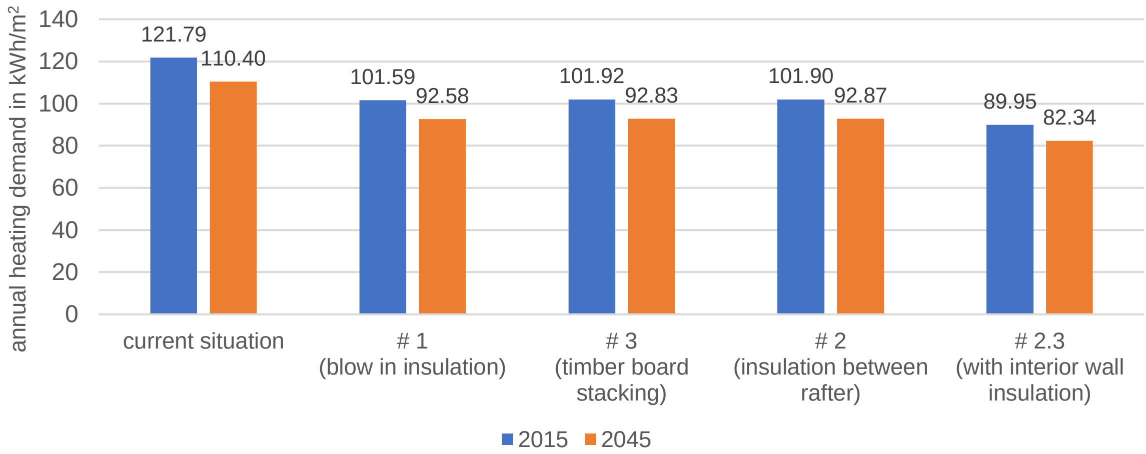


Figure 26: Heating demand – ground floor, south wing

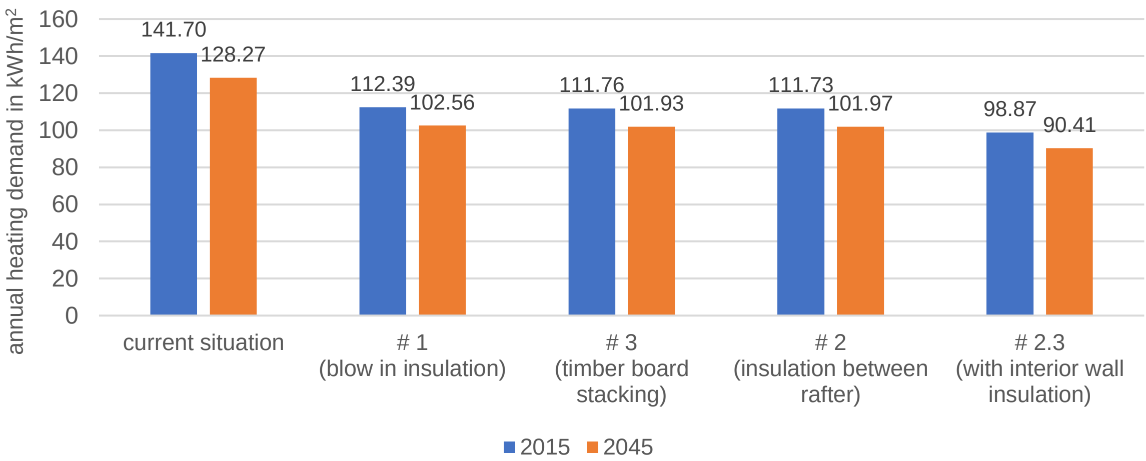


Figure 27: Heating demand – ground floor, north wing

Like on the first floor, the cooling demands increased significantly between the two simulations of 2015 and 2045. The results are displayed in *Figure 28 and Figure 29*. However, in comparison to the first level, the consumption is a lot lower, since the thick walls provide sufficient thermal mass and can also keep a moderate temperature level throughout the summer.

Unlike what would be expected, the cooling demand did not really change between the proposals without and with interior wall insulation *(see #2 and #2.3 of Figure 28 and Figure 29)*. On both, ground and first floor, the cooling demand remains on a similar level for all designs.

A comparison between the cooling loads of north- and south wing can be an indication for the impact the orientation of the windows can have. The north wing, with its windows facing south, records higher solar gains. Consequently, the cooling demand is higher in this part of the building compared to the opposite south wing, where windows face the north. The different energy consumption for cooling is found when comparing both building parts, as done in *Figure 24 and Figure 25* as well as *Figure 28 and Figure 29.*

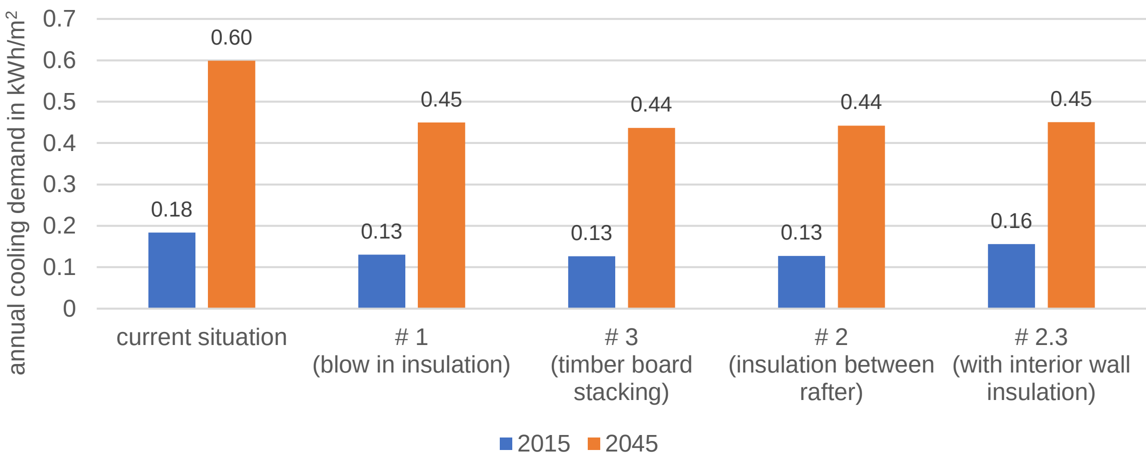


Figure 28: Cooling demand, ground floor, south wing

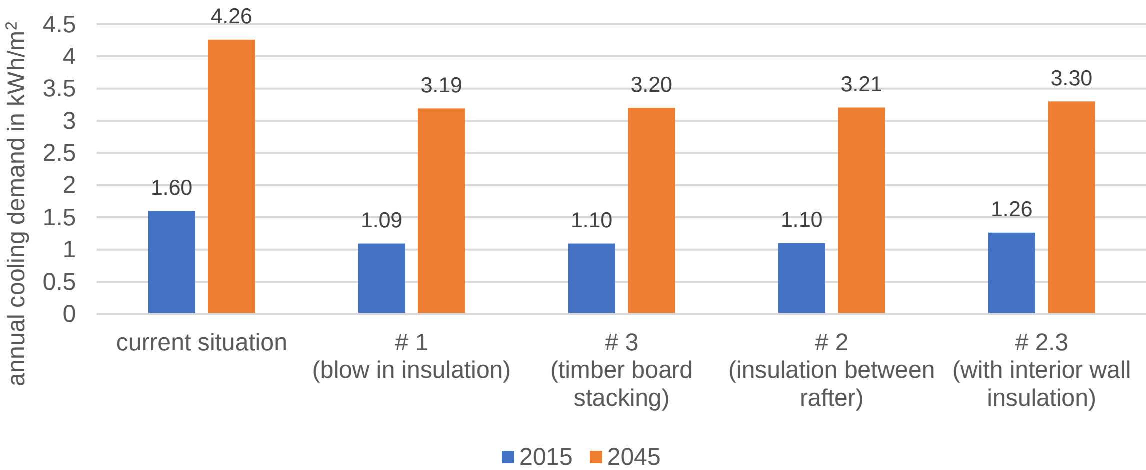


Figure 29: Cooling demand, ground floor, north wing

For the final, annual energy consumption of both, north and south wing, the overall heating and cooling demand is relevant. *Figure 30* summarizes the current and proposed, future situations. Next to ground- and first floor, the overall amount also includes a minimum heating for the basement of the south wing *(see appended schedules in Figure 61 and Figure 63)*. The basement of the north wing was neglected, as the final use is yet undefined and most likely will not include a heating system anyway. Moreover, the proposed changes on the upper floors, roof insulation and interior wall insulation, will almost have no impact on the energy consumption in the basement. From the graph in *Figure 30,* we can expect a decrease of around 25% in energy consumption for heating between the current and future, insulated design. Considering the increasing temperatures throughout the next decades, comparing 2015 to 2045, additionally 9% to 10% are gained. In contrast to the current (2015) global consumption of 83,574 kWh, a reduction by 30.7% down to 57,900 kWh (in 2045) is achieved with an insulation between rafters (#2) or a timber board stacking roof with foam glass insulation (#3). A complementary interior wall insulation makes the value drop down by 41.5% to 48,861 kWh, as it was shown for proposal #2.3.

Furthermore, *Figure 30* indicates that all renovation proposals have a positive effect on the cooling demand, i.e. the cooling load decreases. In general, more cooling energy is required for the north wing building. This is due to the solar gains in summertime, because all windows of the north wing face the south and thus are exposed to the sun. For the last renovation proposal, #2.3 - with interior wall insulation, we register again an increase of cooling energy. Covering the naturally, cold radiating brick walls with a layer of insulating material prevents the natural cooling effect of the old structure. Nevertheless, the initial cooling demand *(Figure* 30 - *current situation)* can be reduced regardless of the type of measure applied in the future.

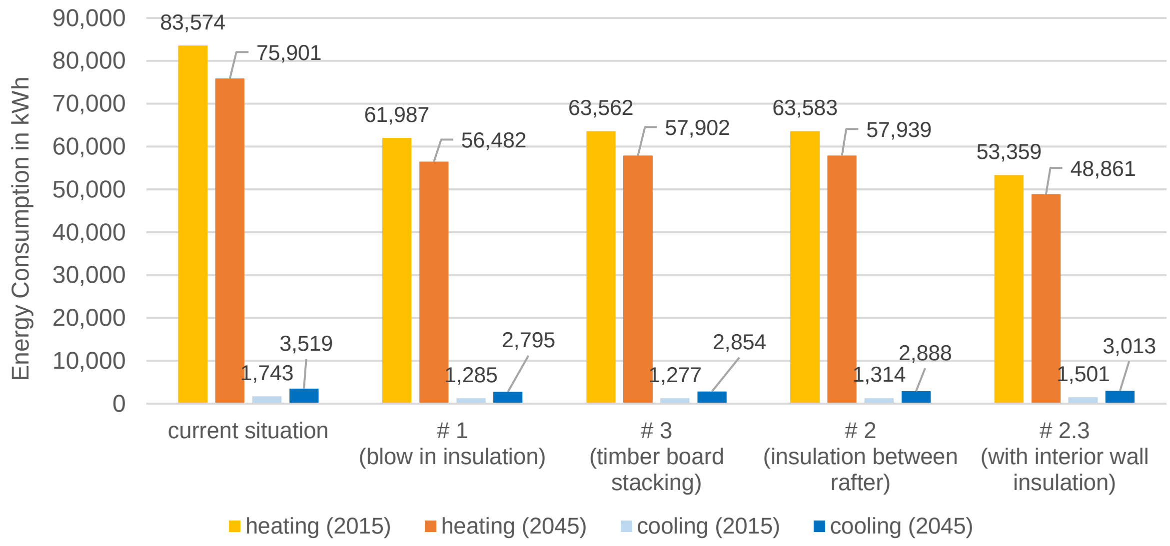


Figure 30: Overall annual energy consumption for heating and cooling, all thermal zones north- and south wing

4.2 Economical Analysis

By including the changing climate conditions over the next 30 years (2015 to 2045), energy savings for heating of 30.7%, for roof insulation, and 41.5%, for roof and interior wall insulation, were estimated. In comparison to the current condition of the building, savings between 14% to 24% were obtained for the cooling demand To support the decision process for the right design proposal, the following chapter addresses the costs for each refurbishment proposal.

The *building costs information center of German architects*, shortly BKI, annually publishes a book, listing prices for all relevant positions of civil construction works. Architects consult this compilation to estimate the construction costs of a building. For this work, the 2015 edition for old buildings [7] and 2017 edition for new constructions [43] was used. To get more accurate results, reflecting the current, local market price, the values are multiplied with two factors. One local factor, which adjusts the average price to the location where the construction work takes place. Depending on the two editions used in this thesis, 1.045 and 1.068 were applied for the 2015 and 2017 versions, respectively. The second factor represents the increasing costs, comparing todays with the ones of the time when the BKI compilation was published. With information from the federal statistical office, the BKI estimates the average increase in building costs four times a year. Present data is available online. Projecting the past prices into the second quarter of 2019, the costs were multiplied with a factor of 114.3 and 108.85 [44]. That represents in increase in costs of 14.3% and 8.85% compared to the prices of 2015 and 2017.

*Figure 27*Figure 31 summarizes the estimated costs for the three different roof renewals. They result from a detailed lists of expenses, which were prepared in the scope of this work and are attached in the appendix *(see Figure 64 to Figure 68)*.

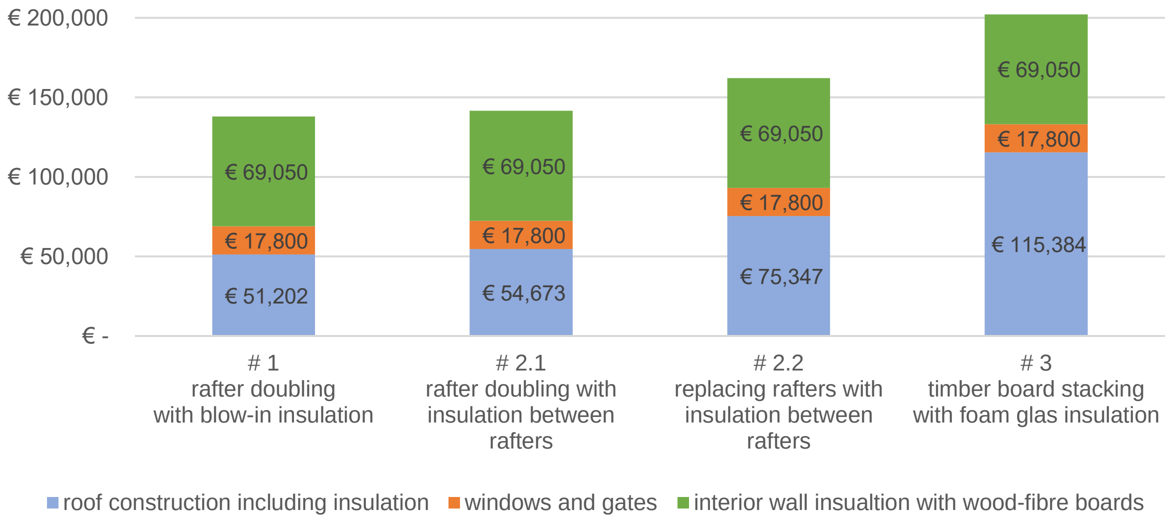


Figure 31: Initial investment cost breakdown for refurbishment proposals

The light blue bar of *Figure 31* corresponds to the costs of the constructional work for the different roof designs, #1, #2 and #3, as introduced before. The expenses are composed of preparation works, such as the demolition and removal of unnecessary roof structure, as well as all major construction measures involved for the new construction. The expenses vary between € 51,200 for #1 - blow-in insulation and € 115,380 for #3 - the timber board stacking roof. For better understanding the, the costs are divided into the two categories mentioned above and given in *Table 13*.

Table 13: Summary constructional costs for different roof designs

	#1	**#2.1**	**#2.2**	**#3**
preparation work	€ 8,127	€ 8,127	€ 19,033	€ 19,033
roof construction works	€ 43,075	€ 46,564€	€56,314	€ 96,351
sum	**€ 51,202**	**€ 54,673**	**€ 75,374**	**€ 115,384**

Apart from being a cheap insulating material *(54 €/m³ - see details in Figure 64)*, the design proposal #1 with blow-in insulation also involves less constructional work, as most of the old roof structure is considered to be kept. Both, insulation between rafter (#2.2) and timber board stacking (#3) involve more intervention into the existing building structure, which results in higher costs. The preparation costs are more than doubled, comparing proposals #1 (€ 8,127) to #2.2 and #3, with € 19,033. For this reason, proposal #2.1 was introduced. Smaller intervention into the building structure is required to place an insulation between rafters here, because the rafters are doubled and not completely replaced unlike proposed for #2.2. This reduces the overall costs by more than 25%, comparing #2.1 and #2.2 *(see Table 13).*

For better identification and separate cost analysis, the orange part of the bar in *Figure 31* indicates the additional expenses of the estimated expenditure for the complementary windows as well as renovation of the gates on the ground floor level. The costs amount sums up to € 17,800.

The top, green coloured part of each column in *Figure 31* represents the costs for the interior wall insulation and is estimated at around € 70,000. Throughout this work, another option for interior wall insulation was discussed and shall be mentioned for completeness. An interior wall plaster could offer an alternative to the design with clay and wood-fibre boards as mentioned before *(see Figure 20)*. The expenses for a wall plaster are estimated at a price of € 45,780 for north and south wing combined. Nevertheless, the savings of around € 23.300 compared to the interior wall insulation with wood fibre boards are at costs of a weaker insulation (U-value of $0.7\frac{W}{m^2*K}$, instead of $0.5\frac{W}{m^2*K}$).

In conclusion, the costs of the different design proposals can range between € 114,760 for proposal #1 with interior wall plaster and € 202,250 for #3 with conventional interior wall insulation.

4.3 Environmental Impact - LCA

Finally, the environmental impact was assessed. The ecological footprint of materials gets more and more important when seeking for a holistic approach to evaluate the overall impact of a construction work.

In cooperation with various research institutes, the German Ministry for environment, nature protection, construction and nuclear safety (BMBU) developed and published a data base, called Ökobaudat, to enhance life cycle assessment of building components. The data base includes most of the relevant materials used in building construction and for building technology appliances [45].
Based on *DIN EN 15804,* a product's life cycle is composed of different stages. *Figure 32* illustrates them. The first stage, A1-A3 represents the production. It includes the extraction of raw materials, transportation and manufacturing processes. Transportation to the construction site as well as the assembly and installation are part of the deployment phase in A4 - A5. The next part of the life cycle (B1-B7) represents all energy flows throughout the use phase. Among others, maintenance work, operational water- and energy consumption are part of these in- and outputs. The final "end of life" stage (C1-C4) is divided into four categories: C1 represents the demolition work, C2 the transportation to either waste treatment (C3) or disposal (C4) [46, p. 16]. In addition to these categories, a supplementary "module D" was introduced for credits and burdens of processes connected to the product, yet outside the system boundaries. This is the case, e.g. if further processing is required, before recycled material can replace primary resources or fuels in a another process [46, p. 28].

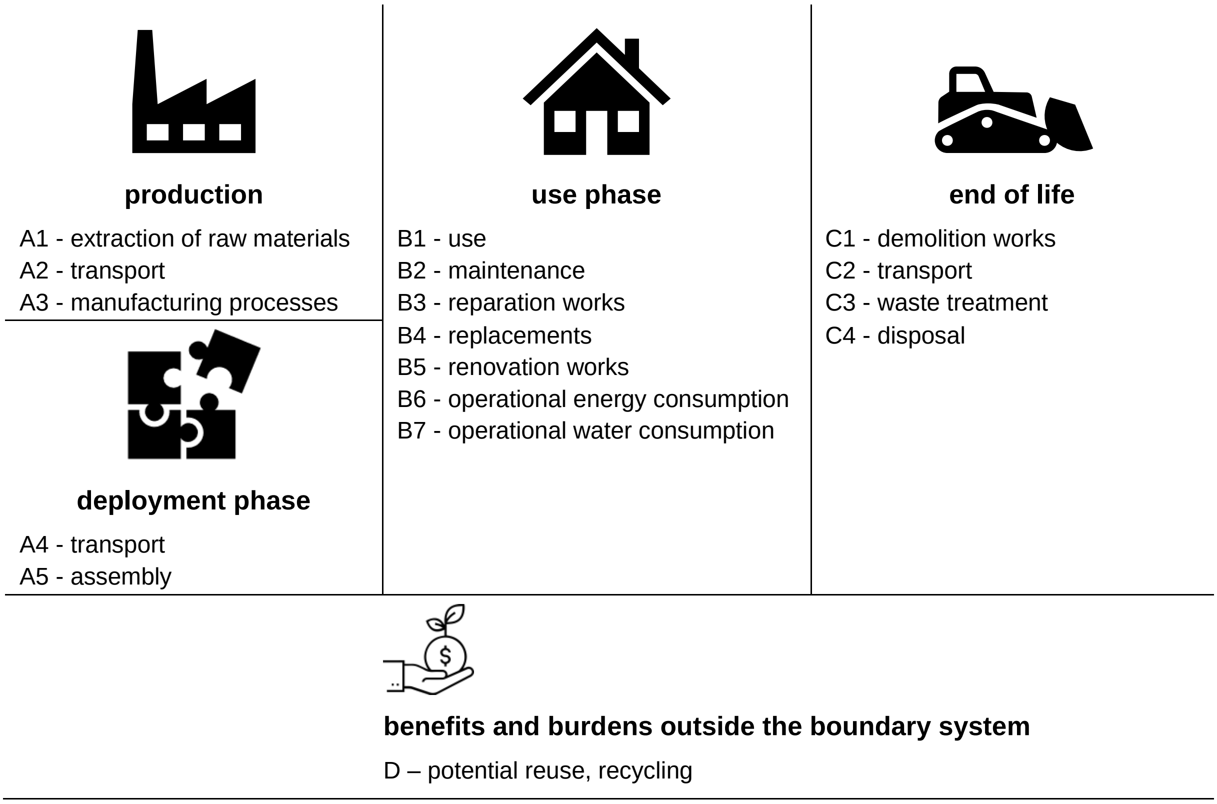


Figure 32: Life cycle stages

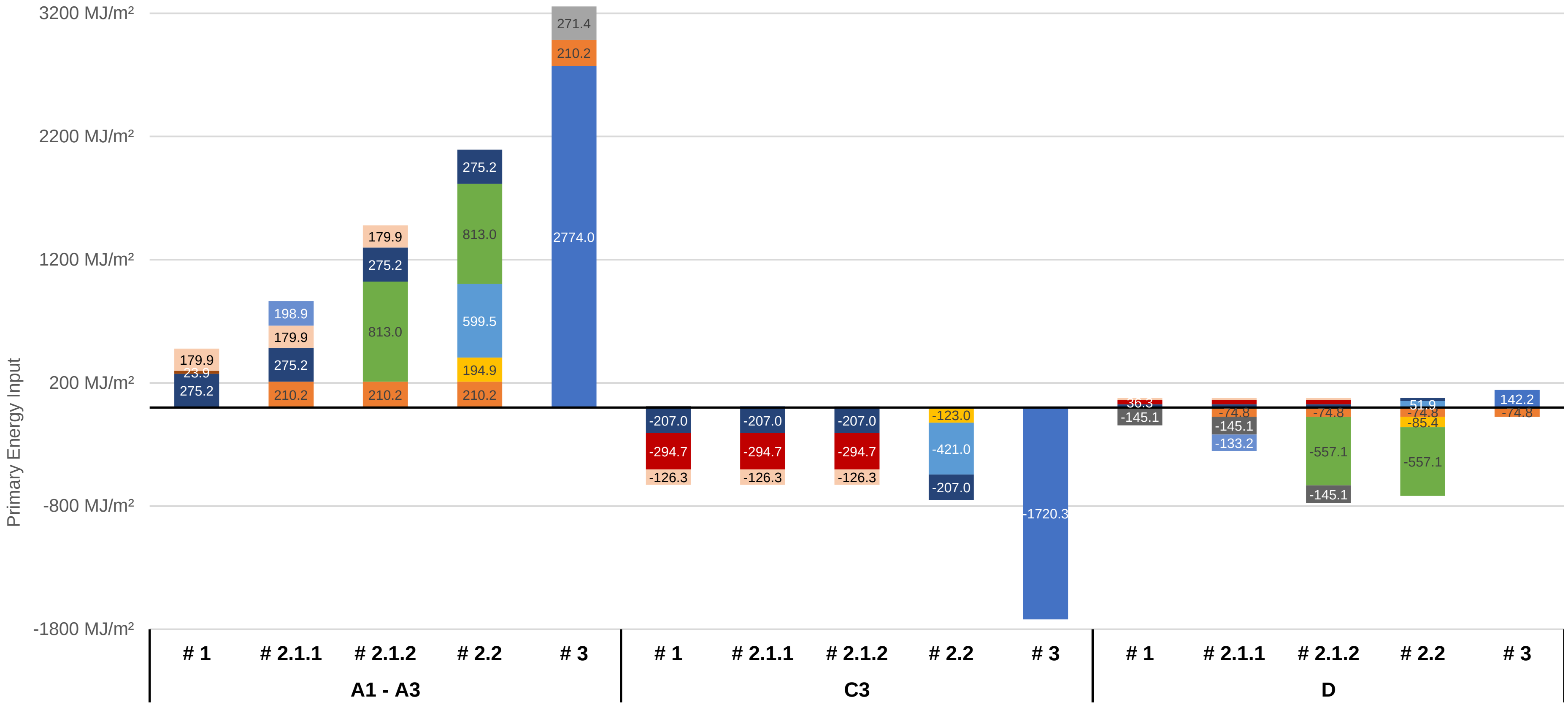
The primary energy consumption (PE) reflects the exploitation of resources required to produce a product. Thus, it is regarded as the input of the balance. Commonly the inputs are differentiated into renewable and non-renewable sources and quantified in mega Joules (MJ) or kilo watt hours (kWh).

The environmental impacts of the product or its production processes throughout the entire lifecycle, are considered as the outputs. Five aspects are evaluated in the scope of the Ökobaudat work. One of them, the Global Warming potential (GWP) quantified in kg CO_2 equivalents, is a measure for the anthropogenic contribution to the greenhouse effect, as enriching the atmosphere with CO_2 crystals and water molecules increases the natural greenhouse effect. Part of the infrared radiation is captured by these particles, absorbed and reflected back to the earth, which leads to a global warming effect. Even though the natural greenhouse effect is necessary for our ecosystem to exist, the anthropogenic addition of greenhouse gases, such as CO_2 and CH_4 (methane) creates an imbalance and has consequences for our climate [47, pp. 7–9]. Since primary energy consumption and GWP are considered to be the most relevant factors, the analysis of the remaining four environmental impacts was neglected in this work. They include the ozone depletion- and photochemical ozone creation potential as well as acidification and eutrophication potential [47, p. 19].

In the scope of this work, access was granted to the online tool “eLCA”. It incorporates the Ökobaudat data base and allows the user to easily define individual building elements. Since the execution of the construction process is still to be defined, the analysis was limited to the default parameters. These include material data for production phase (A1 - A3), end of life (C3 and C4), maintenance (B2) and

complementary in- and outputs in module D. In general, in- and output of the deployment phase (A4 – A5), transportation and assembly, show little relevance for the final result anyway [47, p. 6].
The roof designs discussed in the previous chapter were complemented with two additional proposals. Considering the ecological footprint, more insulating materials were studied. Although wood fibre boards are made of eco-friendly material and satisfy with good physical properties, straw also represents a good alternative. Less energy is required for production and more green house gases are bound according to [48, p. 25]. Straw is a waste product of cereal production. Moreover, its local availability around central Europe is a great advantage [48, p. 58]. Thus, an insulation between rafters, using straw (#2.1.1) as insulating material was analyzed next to a design with wood-fibre boards (#2.1.2) insulation.

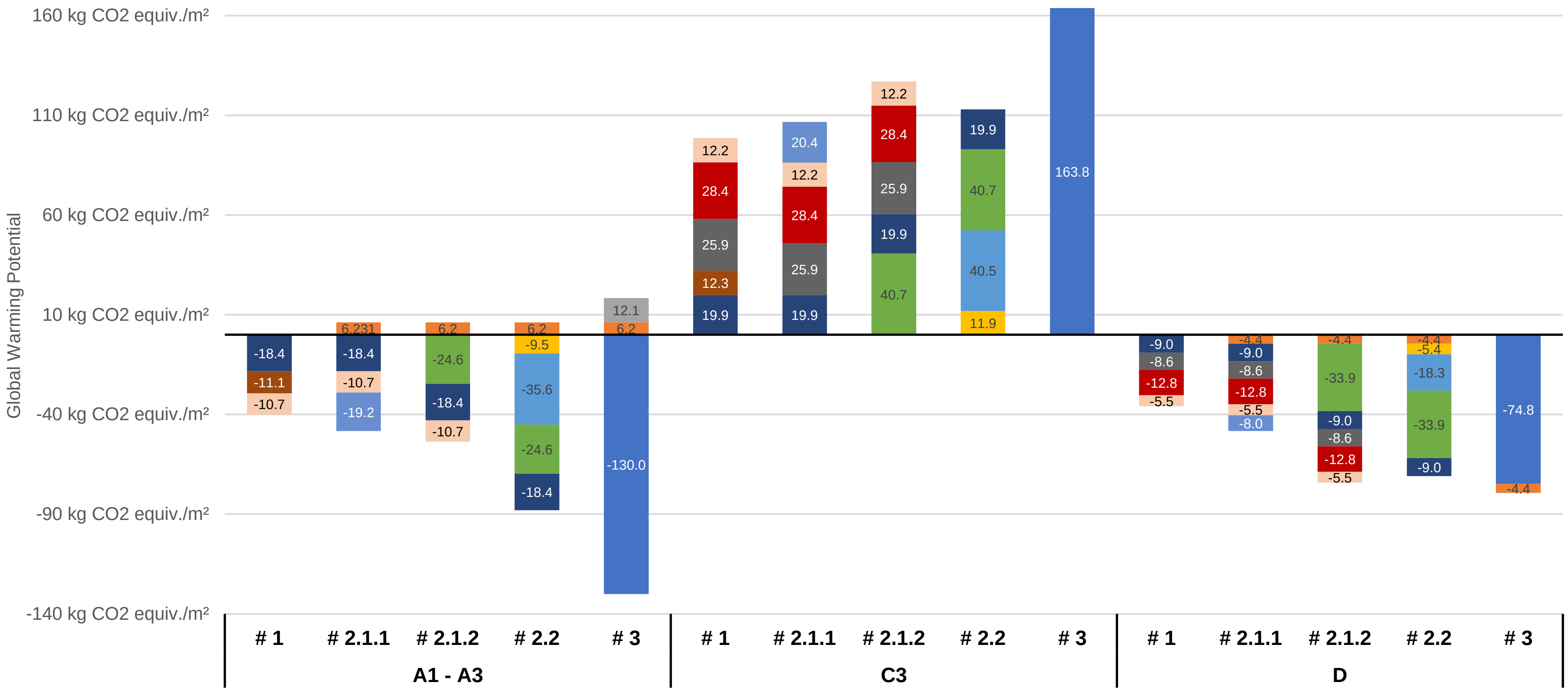
The roof construction, support structure and insulation, was analysed separately from the green roof cover. The latter remains the same for all proposals and was relevant for the final result. In addition, relevant data for interior wall insulation *(see Figure 39 and Figure 40)* and windows *(see Figure 37 and Figure 38)* is given in this chapter.
Figure 33 represents the primary energy input (MJ/m^2) and *Figure 34* the CO_2 output per square-meter roof surface (kg CO_2 equivalents/m^2) for the different design proposals. The manufacturing process (A1 – A3), waste treatment (C3) and credits and burdens (D), mostly due to C3, are also displayed. No maintenance is necessary for the supportive roof construction, since all materials last until the end of life. A lifetime of 50 years was considered. The *eLCA* tool suggests replacing the green roof cover after 30 years. Hence, maintenance is displayed additionally in *Figure 35 and Figure 36.*



 # 1 - rafter doubling on existing roof construction: blow-in cellulose insulation
 # 2.1.1 - rafter doubling on existing roof construction: insulation between rafters with straw
 # 2.1.2 - rafter doubling on existing roof construction: insulation between rafters with wood fibre boards
 # 2.2 - replacing rafters with new beams: insulation between rafters with wood fibre boards
 # 3 - replacing roof structure with timber board stacking roof: insulation with foam glass

- timber board stacking
- cross-laminated timber (inside casing)
- coniferous timber (outside casing)
- rafter (already in place)
- vapour barrier
- new rafter (wood)
- cellulose (blow-in insulation)
- new rafter doubling (wood)
- foam glass (insulation)
- wood fibre boards (insulation)
- wood-whool lightweight building board (already in place)
- straw (insulation)

Figure 33: Primary energy input for different roof constructions proposals throughout the life cycle stages



 # 1 - rafter doubling on existing roof construction: blow-in cellulose insulation
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- timber board stacking
- cross-laminated timber (inside casing)
- coniferous timber (outside casing)
- rafter (already in place)
- vapour barrier
- new rafter (wood)
- cellulose (blow-in insulation)
- new rafter doubling (wood)
- foam glass (insulation)
- wood fibre boards (insulation)
- wood-whool lightweight building board (already in place)
- straw (insulation)

Figure 34: Global warming potential (CO_2 emissions) for different design proposals throughout life cycle stages

During the first stage of the life cycle **(A1 – A3)** all new material in- and outputs are recognized. For all processes primary energy is consumed, which explains the positive input in *Figure 33*. Renewable resources bind CO_2, which is why CO_2 is credited and the output (GWP) can be negative. Hence, only the plastic made vapour barrier as well as foam glass insulating material emit green house gases, 6.2 and 12.1 kg CO_2 equivalents/m^2 respectively, during that stage *(Figure 34)*. Existing roof constructions, e.g. rafters and wood-wool lightweight building boards that are already in place (#1, #2.1.1, #2.1.2), and thus do not require any new input, are not accounted in the manufacturing stage.

Whereas **C3** describes the waste treatment, module **D** represents the benefits and burdens outside the boundary system. For better understanding the two are assessed together. Next to the in- and outputs of the preparation processes for waste treatment, some manufacturers also declare the energy content of a material itself in C3.

All timber is balanced with a negative primary energy input, which represents an energy output, in C3. As a result, a positive GWP output is accounted. Module D then includes the potential savings, resulting from an incineration at the end of life [49] [50]. Hence, the sum of C3 and D represents the "overall output". Unlike for timber materials, straw counts the preparation process (energy input of 2.3 MJ/m^2) and overall CO_2 output for the waste treatment process (20.4 kg CO_2 equivalents) in C3. The gains (133.2 MJ/m^2) and savings (8 kg CO^2 equivalents) from the thermal treatment are credited in D [51, p. 9]. The same approach was chosen for wood-fibre boards. [52, p. 4]. For foam glass and the plastic-based vapour barrier the waste treatment includes a recycling process. Therefore savings are accounted in D [53].

This emphasized the challenge of LCA. As the system boundaries for the environmental analysis are defined by the manufacturer, it takes time to understand where and why the in- and outputs are defined the way they are. To do so, the Environmental Product Declarations (EPD) of the different materials were studied for this work.

In the order of appearance the **overall energy input** *(see Figure 33)*, including all phases A1-A3, C3 and D, increases for the different design proposals. The first, #1 – rafter doubling and blow-in insulation, has the smallest overall primary energy input.

The comparison between #2.1.1 and #2.1.2 serves as an example to show the impact of the different insulating materials, wood-fibre boards and straw, for the ecological footprint. Even though, the same quantity of material is required, straw (#2.1.1) demands less energy compared to wood fibre boards (#2.1.2). An overall primary energy consumption of 188.8 MJ/m^2 and 376.6 MJ/m^2 for both insulating materials, respectively was estimated.

Greater constructional intervention, such as replacing the entire support structure as proposed in #2.2, comes along with a significant increase of primary energy input during the manufacturing stage. The same is the case for the last proposal: #3 – timber board stacking roof.

The use of new timber materials, as in #2.2 and #3, positively effects the **global warming potential** (GWP) outputs *(see Figure 34)*. Whereas the current structure in place is not accounted, the bound CO_2 of new material affects the results. The first three proposals (#1, #2.1.1 and #2.1.2) show similar results in the CO_2 output throughout all life cycle stages.

As already mentioned, the layers of the green roof construction remain the same for each proposal. By default, the materials will need to be replaced after 30 years, which is once during the defined lifetime of 50 years. That explains the high overall energy input of 4620.6 MJ/m² in *Figure 35* as well as the output of 184.5 kg CO_2 equivalents in *Figure 36.* All steps from A1-A3, C3 and C4 reoccur. Part of the plastic (blue bar – PE HD) can be recycled or is incinerated in the end *(see Figure 35 and Figure 36, part D)*. C4 accounts the disposal of material that is not processed any further.
A reduction of the ecological footprint is possible, when replacing the conventional plastic materials. No longer needed roof tiles could be crushed and used for the drainage. However, the choice and discussion of adequate material reuse for the green roof goes beyond the work of this thesis.

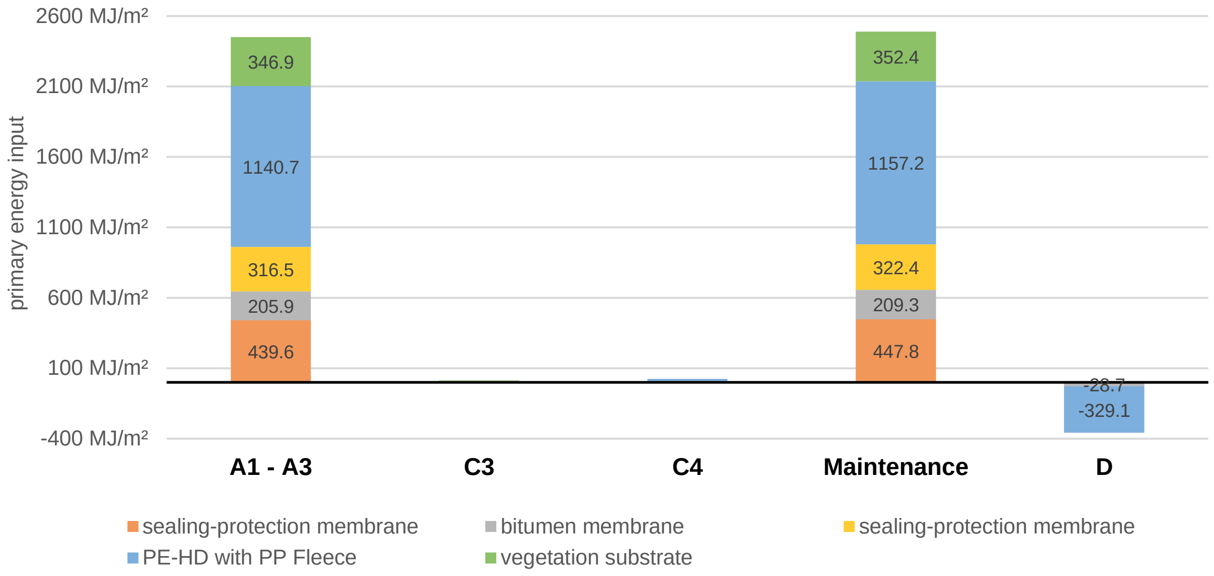

Figure 35: Primary Energy input for green roof layers throughout different stages of the life cycle

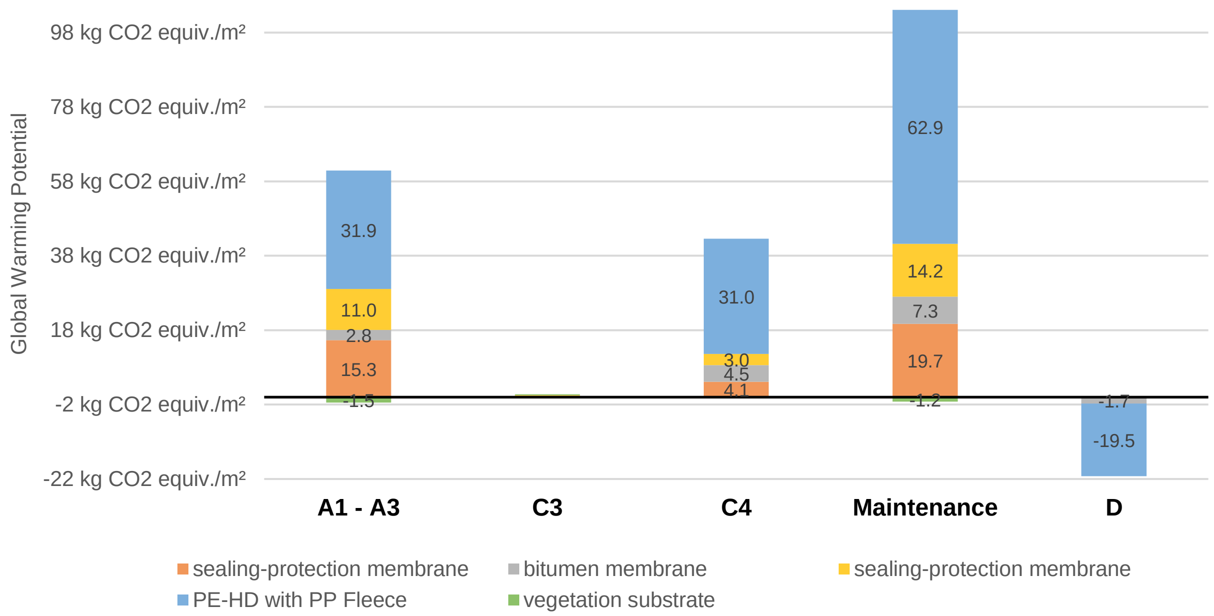

Figure 36: Output (CO_2 emissions) of green roof layers throughout different stages of the life cycle

Moreover, data about the energy input and GWP output for manufacturing double glazed insulating window was obtained from the data base. It is displayed in *Figure 37 and Figure 38*. Unfortunately, no details were given about further processing and only data for disposal (C4) was found. Studying other EPD's to get a better understanding of the obtained values, it was found that some manufacturers declare the recycling potential of glass in D [54], although one would expect to find it in C3.

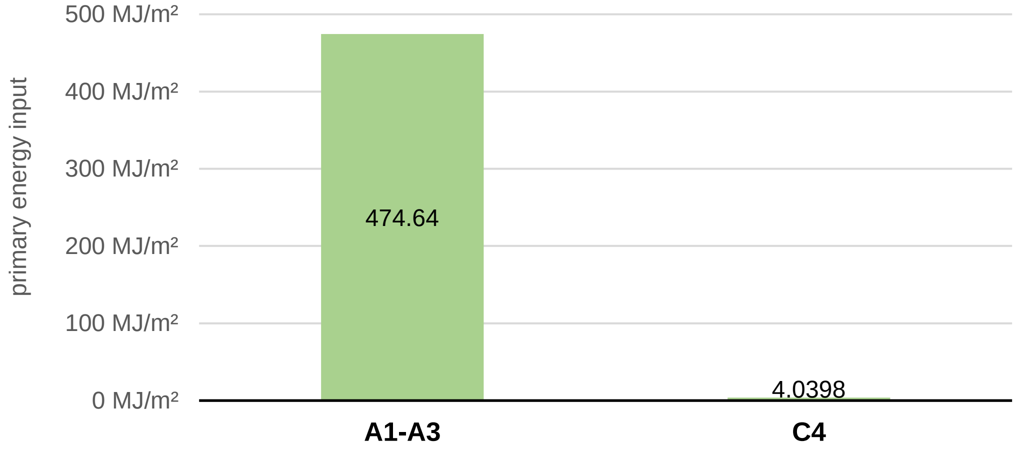

Figure 37: Primary Energy Input for double glazed insulating window throughout different stages of its life cycle

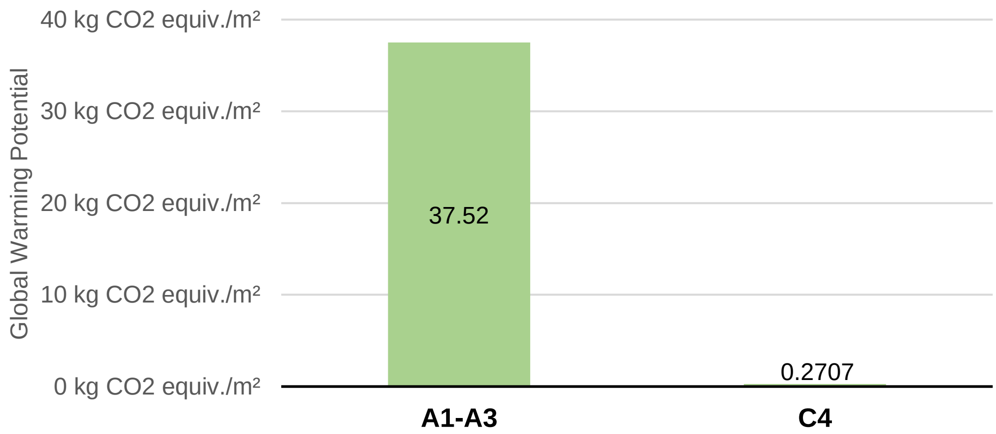

Figure 38: Output (CO_2 emissions) for double glazed insulating window throughout different stages of its life cycle

The energy consumption and CO_2 output, as well as their allocation into the different stages, for the interior wall materials *(see Figure 39 and Figure 40)*, clay plaster and wood-fibre boards, can be explained analogously as it was done earlier for the different roof constructions.

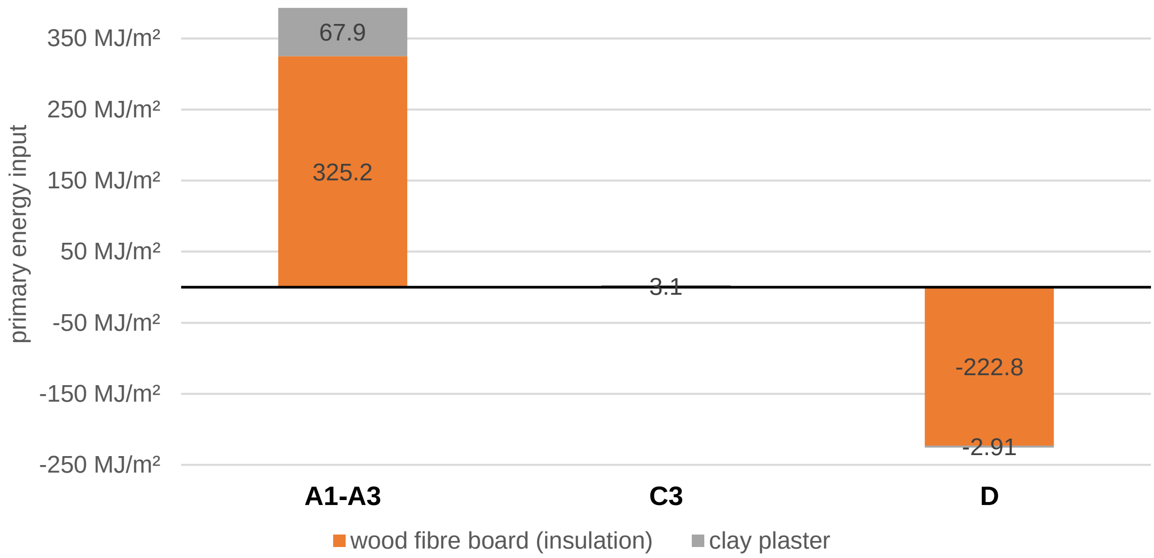

Figure 39: Primary Energy Input for interior wall insulation throughout different stages of its life cycle

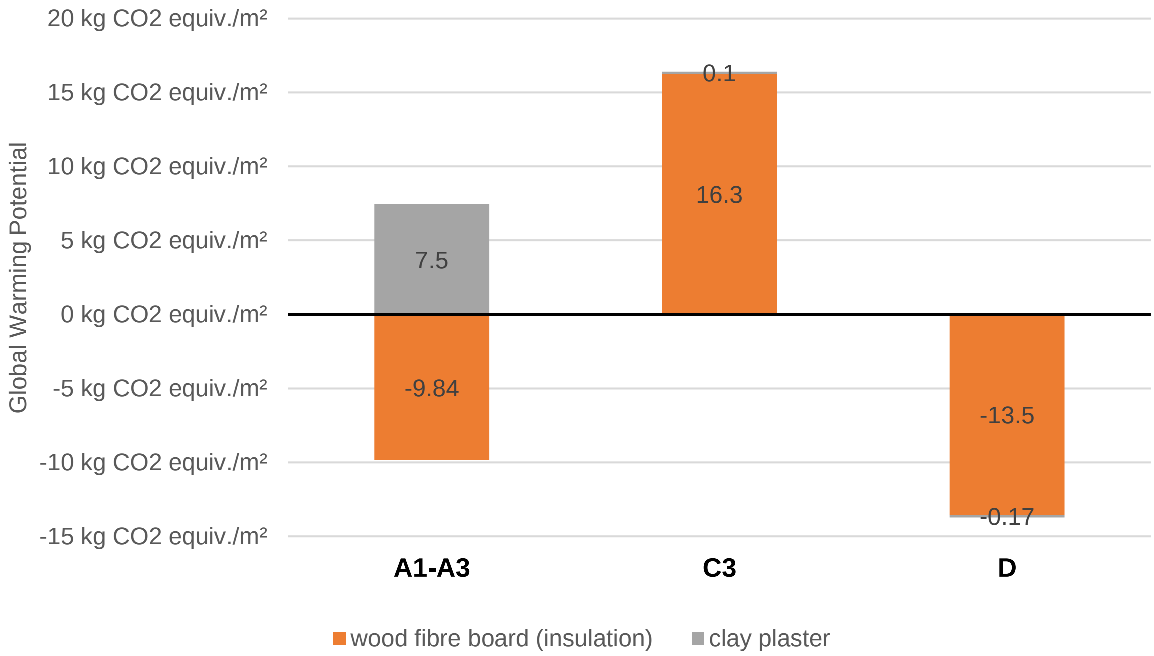

Figure 40: Output (CO_2 emissions) for interior wall insulation throughout different stages of its life cycle

In conclusion the LCA helps to identify trends, to support the decision process. Absolute values are not representative. Seeking for a sustainable solution, the smallest amount of resource input, achieving similar effective results compared to other solutions, should be targeted [55]. Aiming to cut our carbon dioxide emissions, this can lead to conflicts though. Although a timber board stacking roof, as proposed for #3, requires a lot of primary energy input, it also bounds a lot of CO_2, which is accounted positively.

4.5 Discussion of Results

Before introducing a possible heating concept for the building complex in Rudolfstrasse 5, the results obtained in the previous sections are briefly discussed.

The energy assessment showed that the annual energy consumption can be reduced by around 20,000 kWh *(see Figure 30)* when insulating the roof and placing additional windows, to further decrease the heat losses through leakages (infiltration). This represents energy savings of 25%, compared to the current condition of the building, and includes benefits for heating and cooling loads. An additional consumption of 10,000 kWh can be cut, in case interior wall insulation is installed. Furthermore, it was observed that future increasing temperatures will inevitably minimize the heating demand.

Even though the saving potentials for all the solutions are almost the same, due to the similar U-values of the construction proposals, their costs differ greatly. Two aspects influence the expenses: how much of the old structure is kept and the quantity of new material required for the specific design proposal. Hence, replacing the old support structure, as it is the case for proposals #2.2 and #3, involves more expenses compared to the other first three proposals. The least amount of material is required for doubling the rafters and adding insulating material (#1 and #2.1). This is also reflected in the costs for blow-in insulation (#1) and insulation between rafters (#2.1), which were estimated around € 51,000 and € 54,700 respectively. With an additional € 22,000 the rafters can be replaced, therefore € 75,400 were estimated for proposal #2.2. Determined with expenses of up to € 69,050, the interior wall insulation represents the most expensive constructional measure.
Considering the current prices for gas (0.06 €/kWh) and electricity (0.29 €/kWh) as well as their annual increase, the economic payback time could be calculated. The results are displayed in *Figure 41*. A yearly rise of 2% for gas and 3% for electricity was accounted. Further, the effect of climate change was taking into account. Based on the obtained data of *EnergyPlus,* a linear course between 2015 and 2045 was assumed. The annual decrease for heating as well as increase of cooling demand for each design was estimated accordingly.

Compared to the current state of the building, indicated in red in *Figure 41*, the economical payback varies between 34 and 55 years. For clarity and consistency, interior wall insulation was only added to the proposal with insulation between rafters and is again indicated with #2.23 – with additional interior wall insulation. However, with estimated costs of roughly € 70,000 interior, wall insulation leads to a negative shift in payback time for all proposals. Since the courtyard building is enclosed by several neighbouring buildings, it is important to mention, that applying interior wall insulation to all exterior walls is not required. About half of the walls are connected to warmer adjacent environments already. This effect was also considered in the *EnergyPlus* simulation, when setting the physical properties of the respective surfaces. Therefore, the costs for interior insulation, could be reduced. Nevertheless, they will still make up a significant amount of the overall sum.

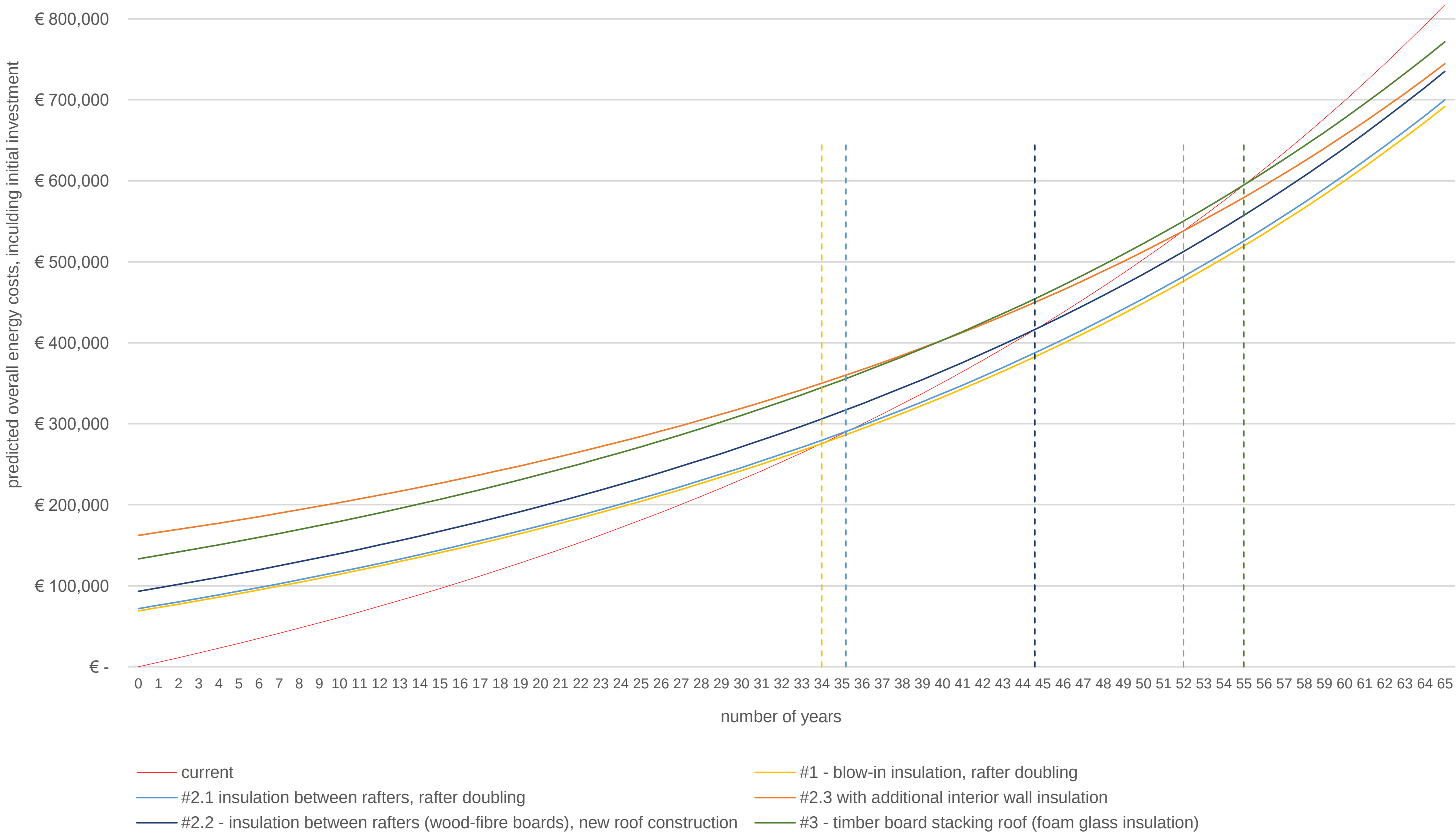

Figure 41: Overall predicted energy costs for the different design proposals

As mentioned in the previous section, primary energy consumption as well as the CO_2 emissions over the entire life cycle need to be considered. Both were again compared to the current state of the building in *Figure 42 and Figure 43*.

Figure 42 represents the primary energy input for each design proposal, including the energy input for new windows as well as the green roof construction. One can see, that the primary energy input correlates with the costs for most of the proposals. #1 (blow-in insulation) requires a small amount of work and a small energy input, whereas the timber board stacking roof (#3) again scores the highest value. Nevertheless, the graphs in *Figure 42* show, measuring the amount of years the energy savings take to pay off the initial energy and CO_2 input for the solution construction, it is a lot lower compared to the financial one in *Figure 41*. Furthermore, it is interesting to see that solution #2.3 already pays itself back after less than 14 years. Made of clay and wood-fibre board, the materials achieve low primary energy input. In addition, the reduced heating demand by around 10,000 kWh helps to significantly reduce consumption.

The combination of sustainable material choice as well as cutting energy consumption has even greater effect on the CO_2 emissions represented in *Figure 43*. Here the investment for roof- and interior wall insulation *(Figure 43: #2.3)* is worth after less than 5 years. To estimate the emissions, a gas heating and electricity based cooling was assumed with 300 g CO_2-equvialents and 550 g CO_2 equivalents [56, p. 13]. In general the CO_2 emissions are opposite, compared to the costs in *Figure 41* and primary energy consumption in *Figure 42*. This is due to the benefit of bound CO_2 in case of new constructions composed of renewable material, as it is the case for proposal #3 (timber board stacking roof) as well as the new rafters for solution #2.2.

The comparison between the three factors: costs, primary energy consumption and CO_2 emissions revealed conflicting points. Aiming to propose a sustainable solution, an optimum of all three is targeted. Although the first proposal (#1) revealed the best results with low costs and primary energy, constructional challenges could affect its implementation. A ventilated roof design requires a cross-section of up to 1500 mm^2 above the cellulose insulation [25]. Taking into consideration the slope of the roof, this requirement cannot be met on the northern edge of the south wing. Moreover, a steal beam of the support structure inside the insulating level, creates an undesirable thermal bridge.
With solid wood, the timber board stacking roof (#3) captures a big amount of CO_2. However, its costs and primary energy input are rated as a drawback of that solution.
In conclusion one of the solutions #2.1.1, #2.1.2 or #2.1, with an adequate insulation between rafters seem to be the most preferable one. Moreover, as *Figure 43* indicates, low annual energy consumption of course affects CO_2 emissions positively. In that point of view, it makes sense to think about interior wall insulation. With the smallest slope, *orange line in Figure 43* shows the best long-term saving potentials. Additionally, the comparison between rafter doubling (#2.1) and replacing rafters without a suspended ceiling (#2.2) revealed a complementary annual saving of 2,000 kWh, due to the reduced “heated volume”, because the old suspended ceiling is kept.

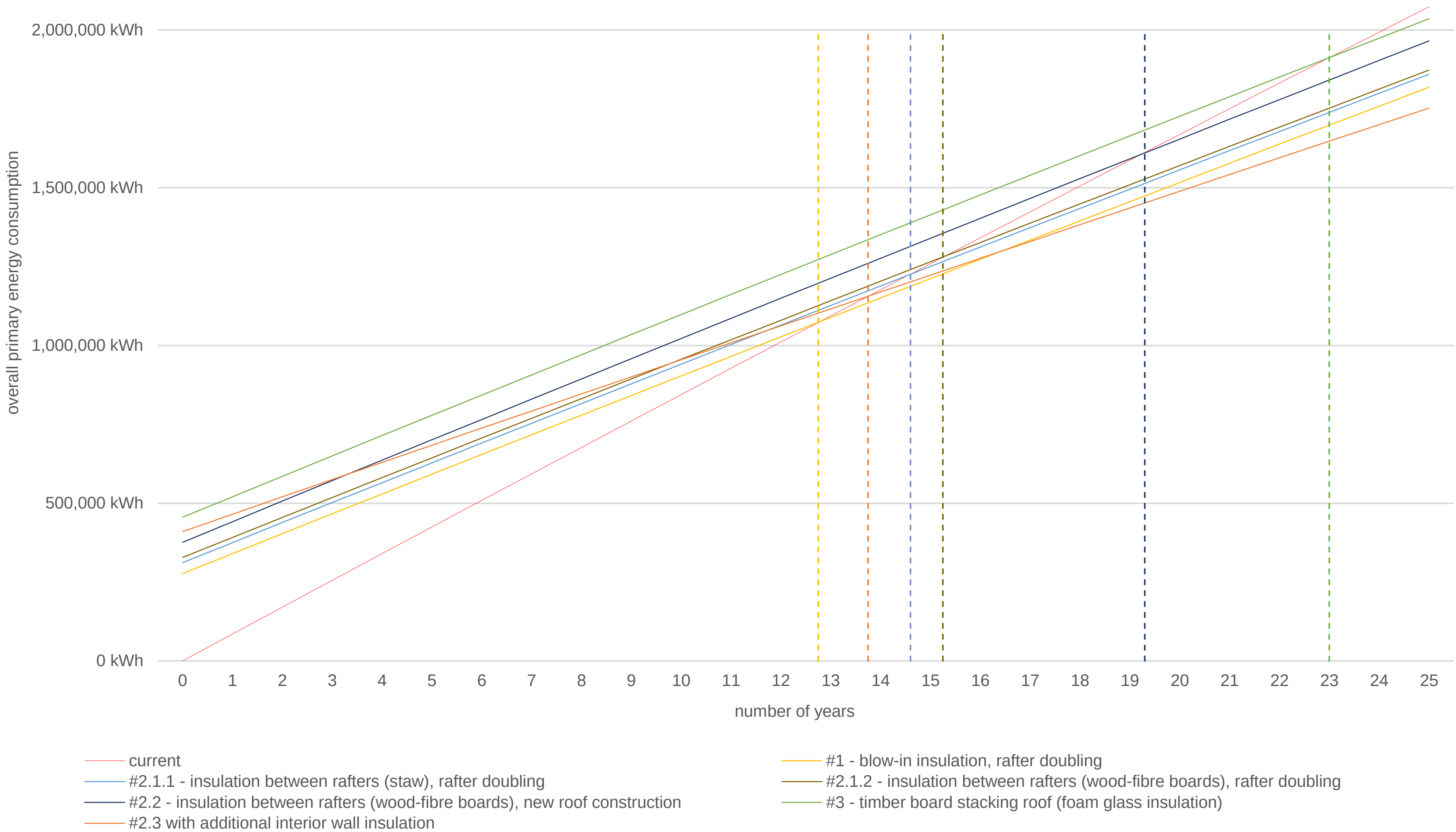

Figure 42: Overall primary energy consumption for the different design proposals

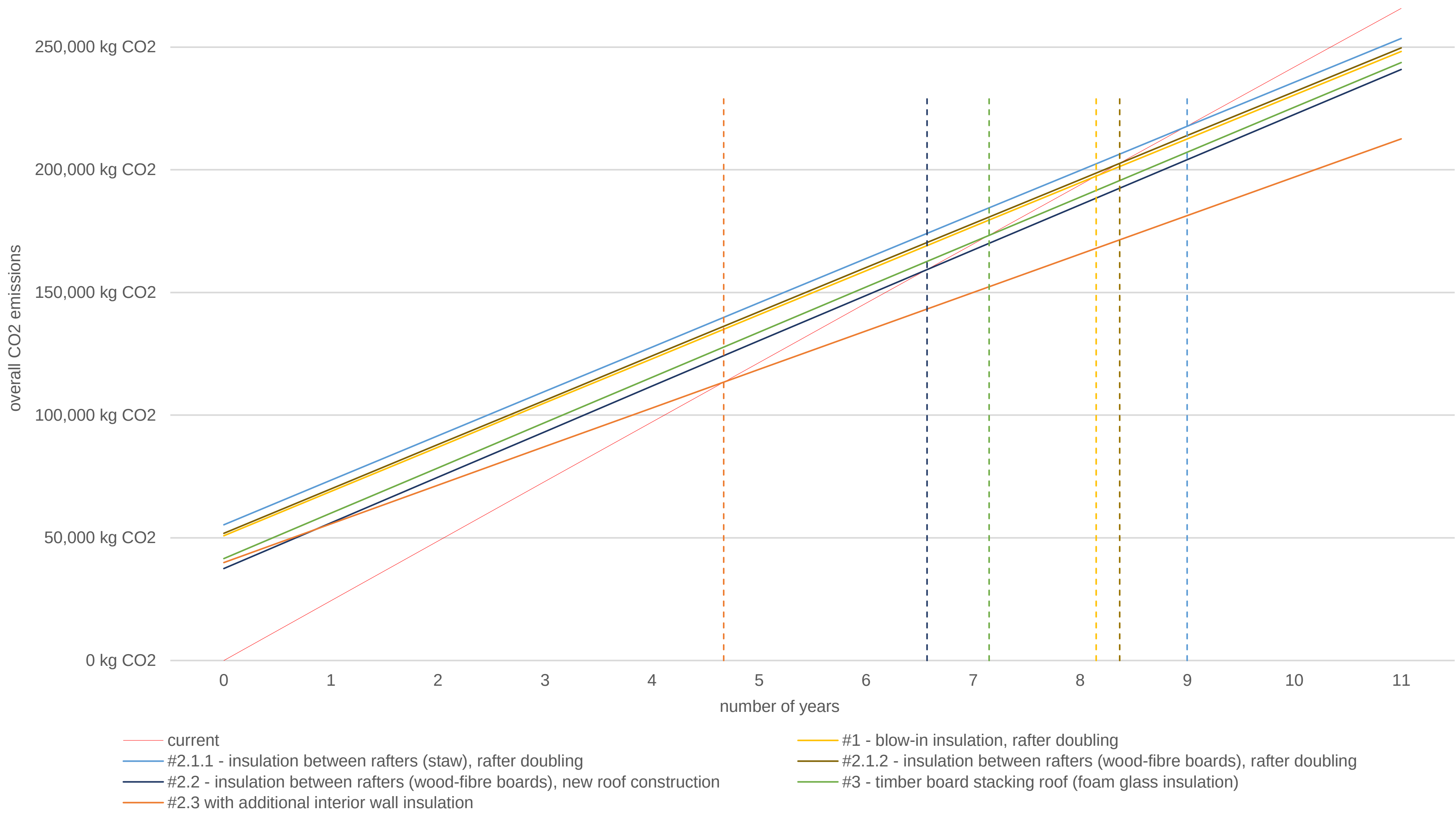

Figure 43: Overall CO_2 emissions for different design proposals, assuming gas heating

5 Final Heating System Design

This last chapter discusses a suitable heating concept for the building complex in Rudolfstraße 5. Given the intended use as creative workspace and the overall aim, seeking for effective and sustainable solutions, the main idea is to divide the heating system design into two sections. As shown in last sections reduced energy consumption has great impact on the CO_2 output.

5.1 Non - conventional solutions

There are various studies, investigating the impact of thermal sensation and comfort among individuals. All these studies proved a "relation between local thermal discomfort and local skin temperatures and heat losses [57, pp. 1–3]." Moreover, "local discomfort in a single body part often determines whole-body thermal comfort perception [58, p. 19]."
For most buildings, it is common to provide heating and cooling in a set range of temperatures for the indoor environment. The predefined temperature range, even though most are adjustable per room using thermostats, has two drawbacks. Firstly, a lot of energy is required to heat up an entire thermal zone or room. Secondly, everyone in a group has different comfort requirements. Therefore, the concept of Personal Comfort Heating Systems (PCS) was also considered in this work. Targeting specific parts of the body, such as the extremities hands, feet, face and neck, the perception of whole-body thermal comfort is given, even though the surrounding temperatures are lower compared to the typical 21°C. Thus, the experiments by *Maohui et al*. [58] revealed that 97.5% of the tested people were satisfied, when equipped with PCS, while exposed to a room with 18°C indoor temperature. Only 65% were OK without PCS at the same indoor temperature. [58, p. 13]

To support the first argument, the energy saving potential for lower indoor temperature was assessed. *Figure 44* displays the energy savings for different base temperatures, considering design proposal #2.1.1 – insulation between rafters with straw. Compared to the initial setting, with an indoor temperature of 21°C (62,218 kWh), a decrease by 3 Kelvin reduces the energy consumption by 24.66%. Moreover, this has a positive impact on the power of the heating system, since the peak power, relevant for dimensioning the heating system, is reduced for lower indoor temperatures. In addition, the heating unit is more likely to work close to its optimum operating point, due to a smaller temperature spread. All in all, lowering the energy consumption will be economically beneficial and goes along with the sustainability targets of the renovation project. Thus, a heating system providing 18°C indoor temperature for the building is proposed. A specific assessment and dimensioning of the heating unit itself goes beyond the scope of this work. However, a consideration of suitable technologies providing a base temperature follows later.

According to individual needs and desires, personal heating systems complement the basic heat provided. The individual solutions can be adapted as required for each person. For some it can be sufficient to put on another layer of cloths, others wish to get heat from a complementary source of heat. Next to small devices, directly in contact with the body such as a heated or cooled chair, wrist pad or

insole (for feet) [58, pp. 4–6] also external equipment impacting an entire thermal zone is considered. Electric heaters, hot air devices and gas heating could already partly satisfy the heating demand during the last winter for smaller thermal zones, such as the co-working spaces on the first floor. This also indicates the importance of thermal zoning. Large areas, e.g. south wing ground floor, can be heated more effectively when divided into thermal zones. *Arno Brandlhuber*, a famous German architect, claims a temperature difference of 5°C by simply dividing a large area into smaller sections with a curtain in one of his projects [59] [60]. Considering the final use of the ground floor level at Rudolfstraße 5, as a multifunctional, atelier space, a solution with curtains keeps the room flexible as well as warm in the specific sections occupied. In the scope of this work, more creative measures were discussed. One includes adding survival blankets to the curtains or walls. The reflective surface helps to radiate back heat into the room. Infrared coatings can reduce heat losses between radiators and badly insulated niches by more than 10%. On other indoor surfaces, an infrared coating is seen critically, as surface temperatures are reduced and could promote mould formation [1, p. 26]. In general, it is worth taking a look into infrared technology and IR heating devices [16, pp. 18–22]. Their great advantage, of directly heating surfaces rather than an entire volume of air, makes them very effective. Moreover, it reduces heat losses as there are no significant amounts of warm air in the building [61]. In a small experiment, part of the current heating supply was replaced by IR lights. Only a small impact was felt from the light bulbs. This was most likely due to limited power of the lights as well as the distance between body and light. However, a greater effect is expected installing powerful IR heating devices.
The individual heating, as well as occupancy of the rooms also mutually depend and define each other. More people result in more internal heat gains and higher temperatures. Less energy is required to raise the temperature to a comfortable level. Additional simulations, setting an overall average occupancy level of 6 m^2 per person for all working spaces were executed. The result revealed another drop of energy consumption, down to an annual heating demand of 37,200 kWh when targeting a base temperature of 18°C. A final evaluation can be done once the final user concept for the entire building complex is clear and it is knowns how many people can be expected in each zone.

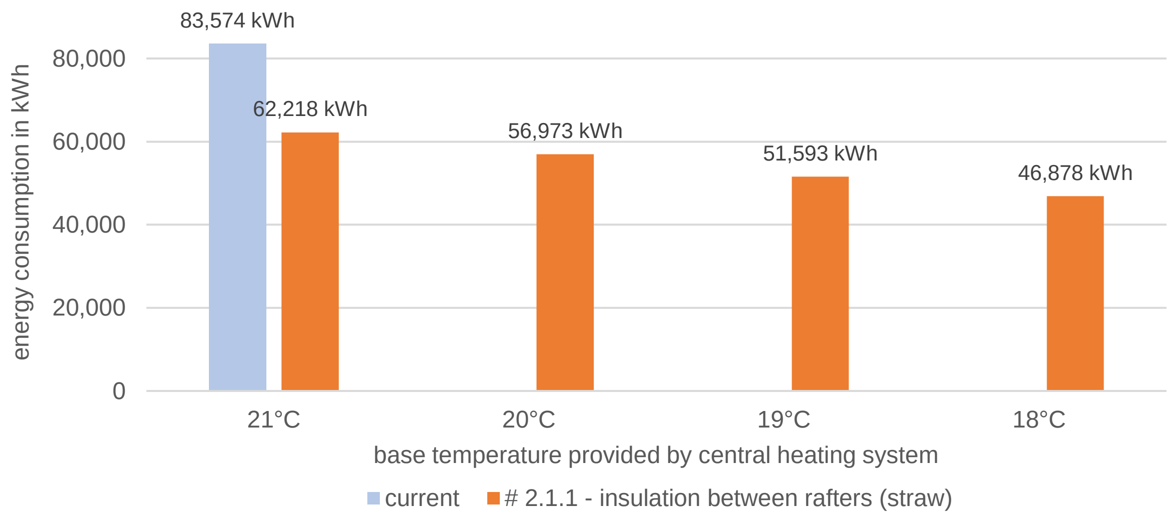

Figure 44: Overall annual heating demand in kWh for different base temperatures

The entire heating concept is designed and built around the concept of the whole complex “Rudolf 5”. Being flexible in using the space for different activities the individual heating concept makes sense. Furthermore, the stakeholders are invited to find their own personal preference on how to have a thermally comfortable workspace. It also creates awareness and makes them reflect and question our common habits and to what extent technology is necessary. In return rents can be kept low, as only an initial investment for a base load heating system is required. It is part of the concept and desired, that people adapt to the building and not the building is entirely adapted to its occupants. Especially while designing a concept for existing buildings, it is important to remind oneself of that. It also reflects the common approach in the combat of climate change: mitigation and adaption. Lowering the standards, energy consumption is reduced. Providing a base load heating system with additional heating devices the user adapts to the situation.

5.2 Base Load Heating System – Gas vs. Wood

As mentioned, a remaining amount of energy needs to be provided in order to ensure a level of 18°C inside the building. Therefore, a base-load heating system is required anyway. A comparison of two options, a gas and a wooden based heating system follows in this last section. Pioneering in urban, sustainable building renovation, the goal is to propose a non-fossil fuel-based system. Low temperature heating, such as heat pumps, were excluded since necessary surface heating in floors, walls or ceiling would involve major indoor constructions works. Moreover, an existing infrastructure in the south wing, including piping and radiators, can be brought back to function, providing a high temperature heat source.

5.2.1 Gas based heating system

Among energy sources for heating, gas is regarded as one with a good climate balance [62]. Therefore, it gained more importance throughout the past years. Nevertheless, it still is a fossil-based source. However, the Power to Gas (PtG) technology could help providing renewable gases in the future. Seeking for solutions to store excess energy from renewable sources, the PtG technology gained interest in the past years [63].

Consisting of about 500.000 km of pipelines and 22 billion m^3 underground storage [64, p. 39], Germany holds be biggest gas infrastructure in Europe. For comparison, the overall national natural gas consumption in 2017 was estimated at 87.9 billion m^3 [65]. The total storage capacity of 30,6 billion m^3 [63, p. 27] offers a huge potential to store gas from biogas and power to gas production and thus a great solution for the energy storage dilemma. Considering the challenges, the electricity grid faces (congestion, redispatch, balancing power etc.) due to an increasing amount of renewable energy production, huge investments are required. Experts argue that PtG offers a more economic alternative to the cost intensive work on the electricity grid. Moreover, flexibility is guaranteed, because stored gas is burned to produce electricity whenever needed, independent from its time of production.

The objective in this work was to find out the potential for renewable gas production. In case a comprehensive cover of renewable gases is in sight, a central gas-heating system for Rudolf 5 would be worth considering, as it would represent a long-term sustainable solution.

In 2017, a little more than 87% of the heating demand (1,262 TWh) was covered by fossil fuels. With 162,5 TWh final energy consumption, renewable sources held a share of less than 13%. Only a small fraction of that was provided by biogas [66, p. 4]. Among that, 9.84 GWh of Biomethane was fed into the grid, of which 3.8 GWh were converted into heat (coupled and uncoupled) and 2.7 GWh went into electricity production [66]. In general, the average, overall annual energy consumption for heating in Germany is estimated between 1300 and 1400 TWh per year. With around 590 TWh, natural gas covers almost half of the demand [67] [68]. Half of it, around 290 TWh, is consumed for residential heating [63].

A detailed assessment to define the potential for biogas production in Germany was carried out by *Adler et al*. [64] They claim a technically feasible, annual biogas-production of 100 TWh in the future. *Figure 45* displays the different sources for the production. Unfortunately, information about the PtG potential was rare. One study, discussing the potential for the European market, claims an annual potential of 1,072 TWh and 263 TWh for biogas and PtG respectively. Compared to the overall natural gas consumption of the EU with 4,500 TWh/a (~480 billion m3), this covers 1/6th of the entire demand [69].

Since natural gas makes up almost 50% of the primary energy consumption for heating, a direct use of renewable gases seems reasonable. However, lacking incentives do not promote direct use. In the scope of the remuneration policy by the government, biogas was not considered. Thus, it is economically not compatible with natural gas. A small fraction of biogas is used for district heating, since "heat from renewable sources" is subsidised in that case [66, p. 7]. For Rudolf 5 district heating is not an option, as the city of Karlsruhe does not intend to provide the necessary infrastructure any time soon around the area.
Even though, renewable gas represents an interesting option, currently lacking political incentives do not help in progressing the technology. Regarding the facts and numbers, it is questionable, if we will manage to produce a significant amount of bio- and synthesis gas and declare the energy source “renewable”.

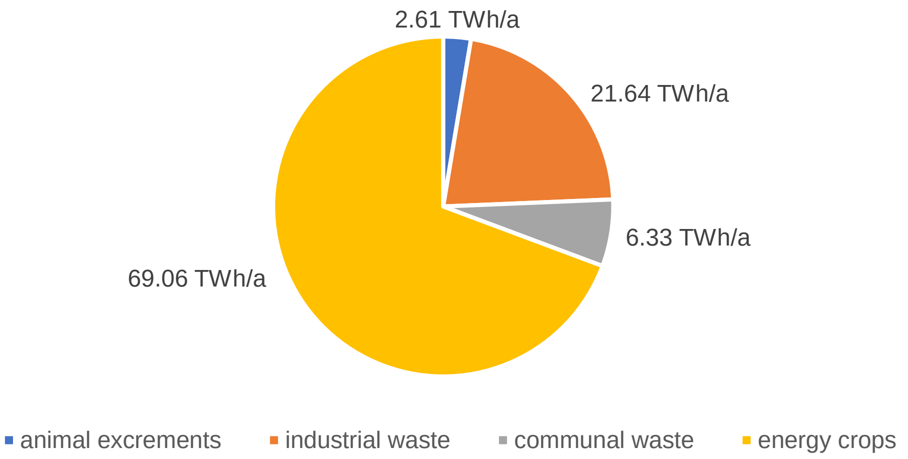

Figure 45: Distribution of biogas potential among the different sectors[64, p. 72]

5.2.2 Wood based heating system

Taking into account all aspects and stakeholders of Rudolf 5, as well as the neighborhood, a wood-based heating unit was also considered as one possible solution. Waste wood from the carpenter's workshop in the basement provides already a small stock of firewood. In addition, a lumberjack, across the street, is planning to offer firewood soon. Thus, local resources and short distances are guaranteed.

Two types of combustion processes are differentiated, complete and incomplete combustion. Products resulting from a complete combustion process, involving carbon (C) and hydrogen (H) of the fuel as well as oxygen (O_2), are carbon-dioxide (CO_2) and water-vapour (H_2O). Incomplete combustion forms undesired pollutants, such as carbon-monoxide (CO), hydrocarbons (C_nH_m) and soot. The reason for incomplete combustion is not only a lack of oxygen. Also, short residence time of the reactants and low temperatures in the combustion chamber favour incomplete combustion. For example, wood with high moisture content lowers the combustion temperature. Furthermore, the increasing volume flow of exhaust gases reduces the residence time of the reactants. Further, part of the bound nitrogen of the fuel (0.15% in case of wood) is converted into nitrogen-oxides (NO_x) [70, pp. 62–65].

Aiming to realize efficient, complete combustion processes, the technology for wood-based heating systems has evolved tremendously over the past decades. Two factors are important to consider for the overall efficiency of the heating unit: what type of fuel is used and what type of operation mode is considered. Both factors also depend on each other. Whereas pellet and woodchips make sense for automized systems, logs require manual effort to charge the combustion chamber. Next to the technical-operational question, the logistics are important to analyse for the decision process. The availability of wood, storage capacity on site and responsibility for operation, in case of a manual loaded heating system, are to be discussed. [71, p. 8]

For the assessment of the different possibilities, the technically relevant aspects, such as efficiency and pollutants are compared. In combination with the analysis of the local situation and availabilities, the preferred choice is limited.

In the literature, different results are found for pollutants emitted by the heating unit. In general, a central heating system is going to produce heat more effectively than several small single room combustion units. Bigger, central units are commonly equipped with technology to control the combustion process. Thus, emissions are mitigated effectively [72]. *Hartmann et al* [70, A] compared centralized gas-, hand-loaded logs-, pellets- and woodchips heating with respect to their exhaust emission. A comparison between conventional fossil-fuel based and wood-based systems represents difficulties, as the emissions "depend on the exhaust-reference states". This means the amount of oxygen required for the combustion process differs between different fuels and influences the chemistry of the combustion process [70, p. 114]. *Figure 46* represents their results for carbon-monoxide (CO), nitrogen-oxides (NO_x), soot and dust emissions for heating units up to 50 kW. Among wood-based heating's, pellets revealed the best results for all categories [70, p. 115]. Especially for log heating units, the range of values deviates a lot among the sources. *Uth* [71, pp. 23–24] claims an average of 103 mg/Nm^3 for CO-emissions and values below 12 mg/Nm^3 for soot particles[4]. Another source [56, p. 11] estimates the dust formation for a log-wood heating system between 18 and 60 mg/Nm^3. Deviation in the different studies can partly be explained due to the lack of consistency. Some measure the emissions in operation, some take data from the manufacturers. As mentioned earlier, the correct firing of the unit has great impact on the production of emissions and significantly influences the results.

The advantage of a pellet heating unit are its low exhaust emissions (*Figure 46*) However, given the local circumstances a logwood or woodchip heating unit makes sense. Fortunately, a combined solution of the two, logwood and pellet, exists. Moreover, such a solution simplifies the operation of the unit, as the system, depending on its size, can work autonomously on pellets for a certain amount of time before logs need to be inserted manually [71, pp. 110–113]. Overall, a wood-based heating system has the lowest climate impact comparing the emissions in CO_2-equivalents per produced kWh of heat between the different technologies, as displayed in *Figure 47* [56, pp. 12–14]. This is due to the fact, that wood is considered as a renewable resource as it emits CO_2 that was bound throughout its lifetime. Therefore, its emissions, regarding the entire life cycle: raw material extraction, preparation of the fuel, transportation and final use, are more or less balanced, compared to the other heat sources in *Figure 47.*

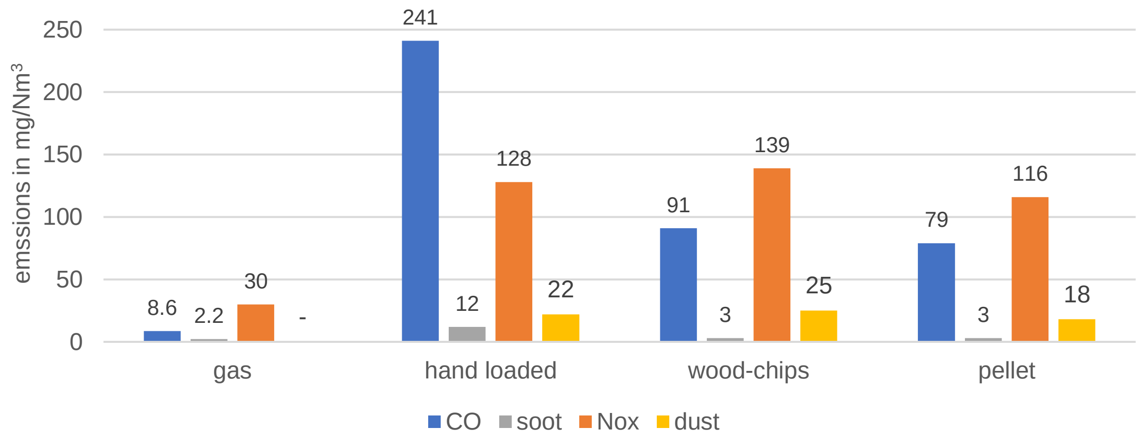

Figure 46: CO, NO$_x$, soot and dust pollution for different heating systems [70, pp. 113–117]

[4] Nm^3 stays for *normal cubic meter* and is a common unit for measuring gas emissions. The normal cubic meter refers to the volume of the gas at a specific temperature and pressure, defined by the norm.

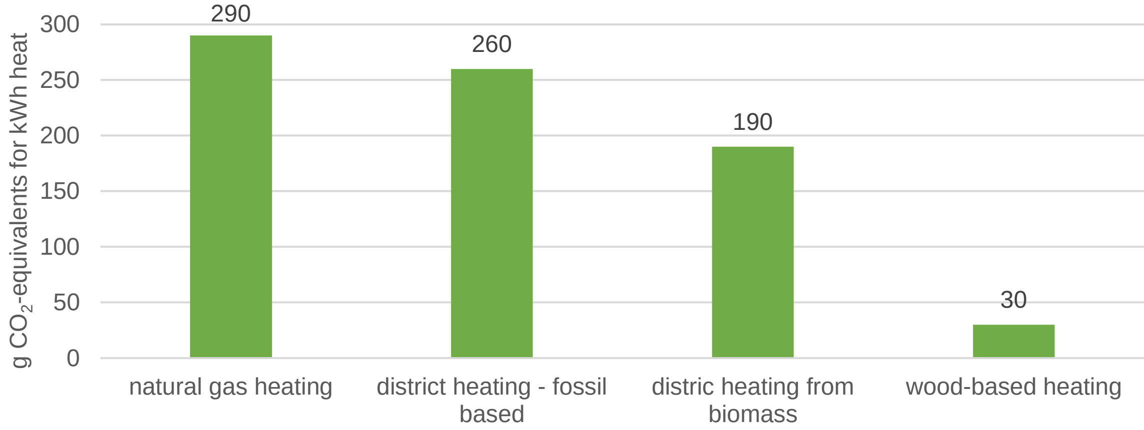

Figure 47: g-CO_2 equivalents produced per kWh of heat, throughout entire life cycle from resource extraction to combustion, for various heating systems [56, p. 13]

Given the heating value of dry wood logs (around 1890 kWh/m³ [70, p. 56]) and knowing the overall energy consumption of the building, the amount and costs for the fuel were estimated. The *EnergyPlus* simulation predicted an annual energy demand of roughly 47,000 kWh to provide a base heat of 18°C *(refer to Figure 44)*. Thus, a total amount to 25 m³ of wood was calculated. Regarding the local market, prices between 90 -115 €/m³ can be expected[5]. Fuel-costs between 5 – 6.25 cents/kWh were estimated and make wood a compatible alternative to gas heating. A combined wood log and pellet system with 50 kW is seen at around € 18,000 [71]. The cheaper option for only one type of fuel, e.g. wood logs, ranges from € 8,500 to € 14,000, depending on the size of the feed-chamber [71].Combined with a solar thermal unit and storage tank, the system is able to provide renewable sources of heat all year around. A detailed cost-analysis for all system components goes beyond this work

Considering all stakeholders involved, a wood-based heating system is regarded as the most preferable option. Although, in comparison to conventional gas heating emissions, carbon monoxide, dust, soot and nitrous oxides are a drawback. Nevertheless, the overall CO_2 performance is very good. Ensuring reforestation of cut firewood, the carbon cycle is fully closed. Then, wood represents a carbon neutral energy source. Moreover, already available waste-wood is incinerated on site rather than transported elsewhere for waste treatment.

Like all approaches in Rudolf 5, also the heating system invites people to take part and to actively contribute. The central unit will need to be fed regularly. Even though challenging, space for 25 m³ of wood can be found. Wood can be stacked along the walls in several areas of the building for temporary storage.

[5] Wood is commonly sold in stere. One stere represents a stacked cubic meter of wood logs. Considering the air-filled gaps, the volume of one stere is smaller than 1m³. For simplicity the price was converted into €/m³.

6 Conclusion

The objective of this thesis was to propose a suitable, energy efficient renovation concept for the listed building complex Rudolf 5. The methodologies applied exemplify an approach for sustainable building design by incorporating a technical, economical and environmental analysis.

This work involved carrying out the implementation and calibration of an *EnergyPlus* model, where various constructional proposals were analyzed.
With the help of the model, reduction of heat losses due to constructional improvements of the roof, windows and walls were confirmed. In addition, limiting the average indoor temperature to 18°C, the annual energy consumption could be reduced by almost 50% to 46,900 kWh compared to the current, uninsulated situation. Moreover, the model confirmed the impact of good occupancy of the building, as another 9,000 kWh are saved, increasing the occupancy to hypothetically 6 m^2/person for all working areas.
The results of the model serve as an orientation, as uncertainties remain, and an exact match of reality and simulation does not exist. Firstly, the internal gains could only be assumed, since the final use and occupancy of the building is not completely clear at that point. Secondly, many more variables influence the model. Using the recorded data from temperature measurements the model was adapted and calibrated according to the current situation. Higher temperatures were recorded because of the plastic casing around the sensor, so distorted temperature data was adjusted. It was found that the infiltration and ventilation settings had a great impact on the simulated results. Even though, a satisfying setting, with infiltration values of 0.9 ac/h and 1.1 ac/h and a ventilation of 3 ac/h, was found only a blower-door test on site would provide accurate results. Moreover, the exact impact of additional windows for better thermal performance of the building was difficult to define. Both U-value and lower infiltration losses improve the building envelope here. In general, the work proved, regarding literature and experts consulted throughout the process, that many parameters are set or assumed based on experience. Estimating the U-value for the south wing roof is one example. In a first attempt, considering the material layers, very low U-values were obtained. Further research and references revealed the wrong assumptions of ventilated and non-ventilated roofs.
Although uncertainties remain, the important factors could be analysed and showed satisfying results. Once defined and set, additional fine tuning is quite simple and helps to further improve the model. This was applied, when considering different insulating materials (cellulose blow-in insulation (#1), straw (#2.1.1), wood-fibre board (#2.1.2 and #2.2) and foam glass (#3)). Therefore, simulations offer a great potential quickly evaluate the impact of different solutions.

A detailed cost breakdown would have gone beyond the scope of this work, which is why only the most relevant parts were considered in the economic analysis. The exact measures and their execution need to be defined by the architect and the responsible craftsmen. They will define the exact expenditures. Nevertheless, it helped to emphasize the conflicting objectives between energy savings and initial insulating expenses. *Figure 41* depicted a payback time of more than 50 years for roof as well as interior wall insulation (#2.3). An insulation between the rafters pays itself back 8 to 18 years earlier (#2.1 and #2.2), compared to not investing anything. Regarding our goal to cut energy consumption, to reduce our carbon dioxide emissions, political incentives are inevitable to encourage energy saving measures. Especially promoting effective insulation for existing building structure, like Rudolf 5, requires subsidies. The ecological analysis revealed good CO_2 saving potentials *(see Figure 43)* for a solution with interior wall insulations, however its high investment is economically not viable.

The life cycle assessment concluded the chapter for different renovation proposals and underlines the conflict of reasonable economical and ecological decisions. Specific materials were compared with each other. Since the boundary systems are defined individually and the burdens and benefits are accounted into different stages of the life cycle, it is challenging to understand and directly compare different materials with each other. A good balance was found in comparing the two factors, primary energy consumption (input) and global warming potential (output) and to evaluate the performance throughout the life-cycle stages. This approach helped to see, for example, that the heating value of wood is counted as a benefit in C3 rather than as expected in D.
In conclusion, the LCA helps to give an orientation to what extent one solution is more sustainable than another. Accurate differences between various renewable resources and materials is challenging and requires a lot of detailed work. Moreover, the local availability influences the result and needs to be considered individually as it cannot be found in any data base.

This thesis work could point out that it takes several factors to develop a sustainable building design, as it requires the interaction of the three pillars that define sustainability: economy, ecology and society. With adequate calculations and simulations an assessment of the first two is possible. A lot of work was done throughout the past years. Data bases were developed, and software programmed to improve and simplify this aspect of work. Among them, *EnergyPlus* and *eLCA* which were used in this thesis. Yet, it takes time to collect, understand and verify respective data. Furthermore, every project has its individual requirements and solutions need to be adjusted accordingly. It was proven that the behaviour of the occupants has significant impact on energy consumption. This relates to the last pillar – society. Accepting lower temperatures (18°C) helped to mitigate CO_2 emissions. Moreover, a wood-based heating involves work of all stakeholders. In return a renewable, locally available fuel can be utilized. The advantage of this proposal compared to a typical gas heating is given in *Figure 48*. As mentioned earlier, lacking incentives to reduce heating demand and “limit our thermal comfort” for the sake of climate protection, do not make these approaches suitable for society. It takes a collective effort to obtain a sustainable solution.

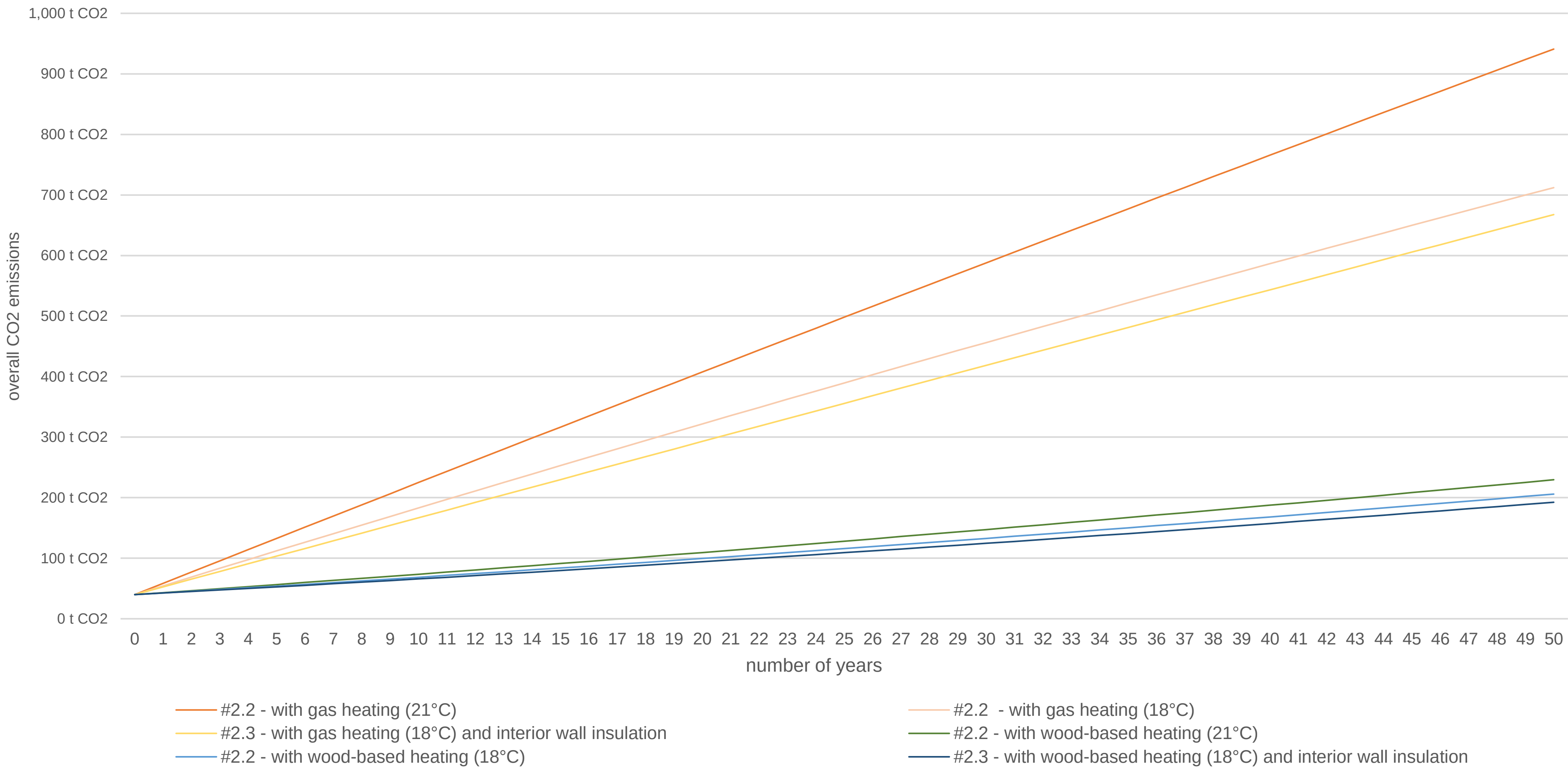

Figure 48: Comparison of gas and wood-based heating system for proposal #2.2 over 50 years

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8 Appendix

Figure 49: South wing of Rudolfstrasse 5, Karlsruhe Germany

Figure 50: Connecting building between north- and south wing, Rudolfstrasse 5, Karlsruhe, Germany

Figure 51: North wing of Rudolfstrasse 5, Karlsruhe, Germany

Figure 52: Co-Working Space on the first floor, south wing, Rudolfstrasse 5, Karlsruhe

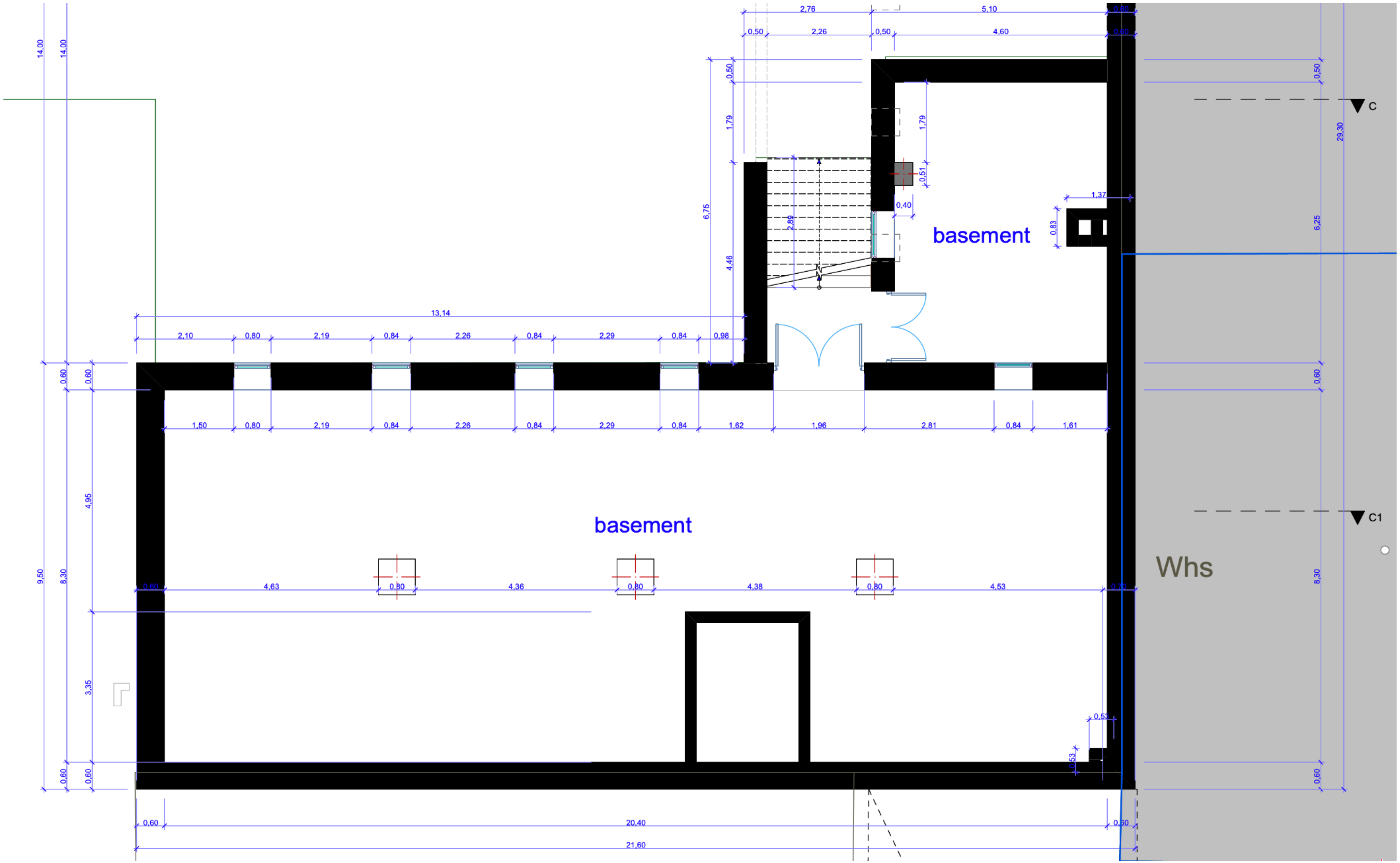

Figure 53: Floor plan, basement south wing

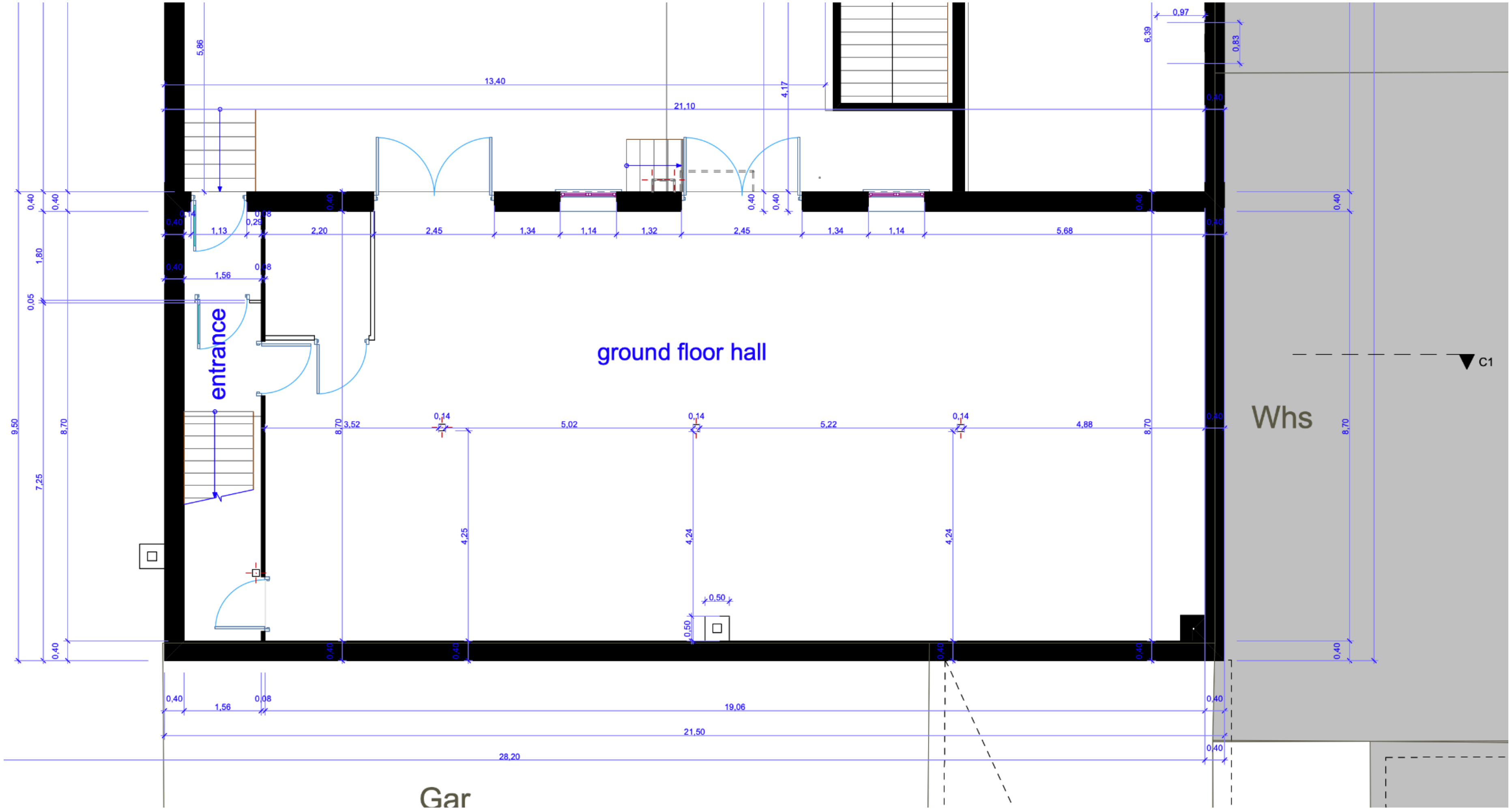

Figure 54: Floor plan, ground floor south wing

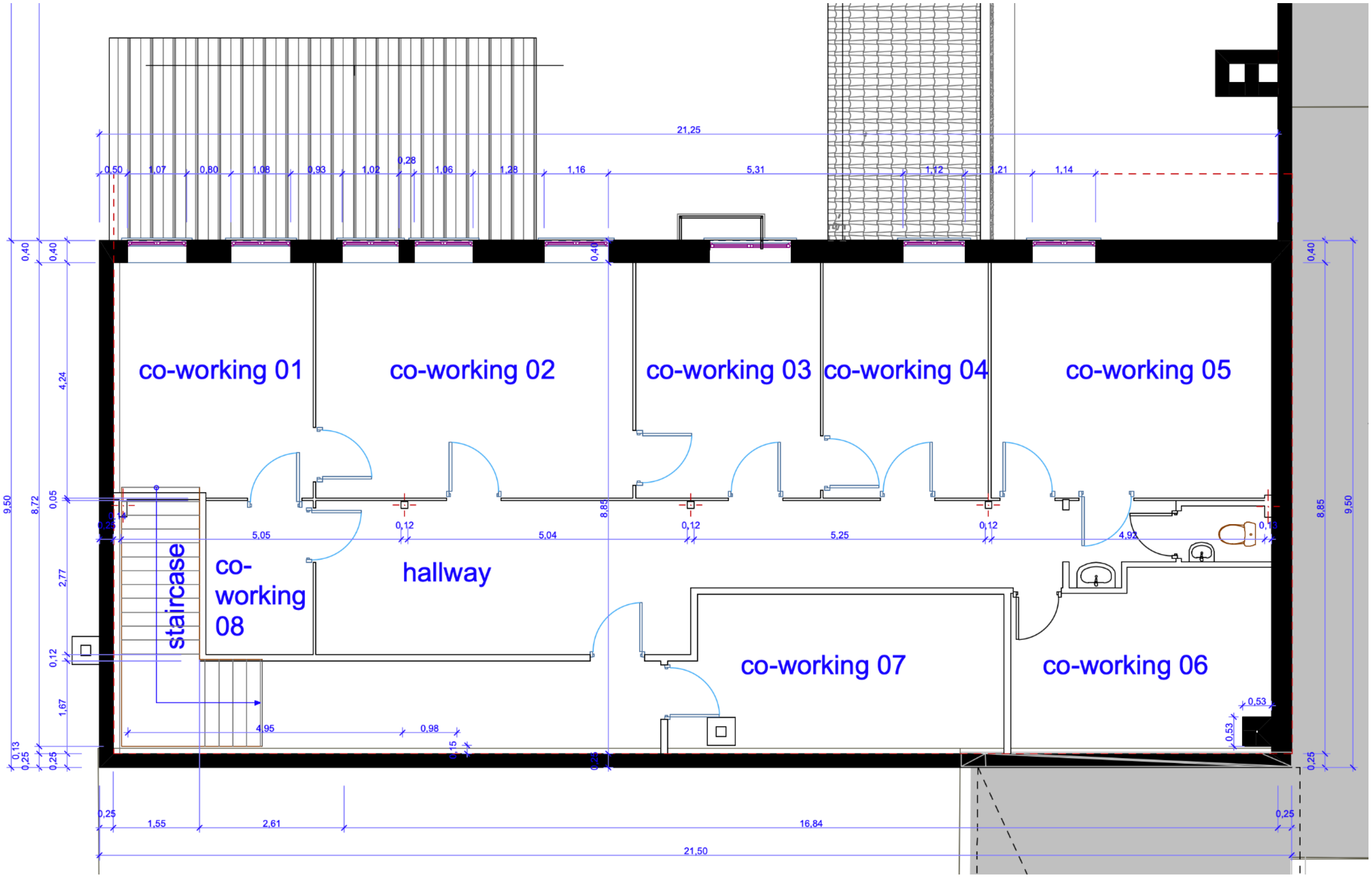

Figure 55: Floor plan, first floor south wing

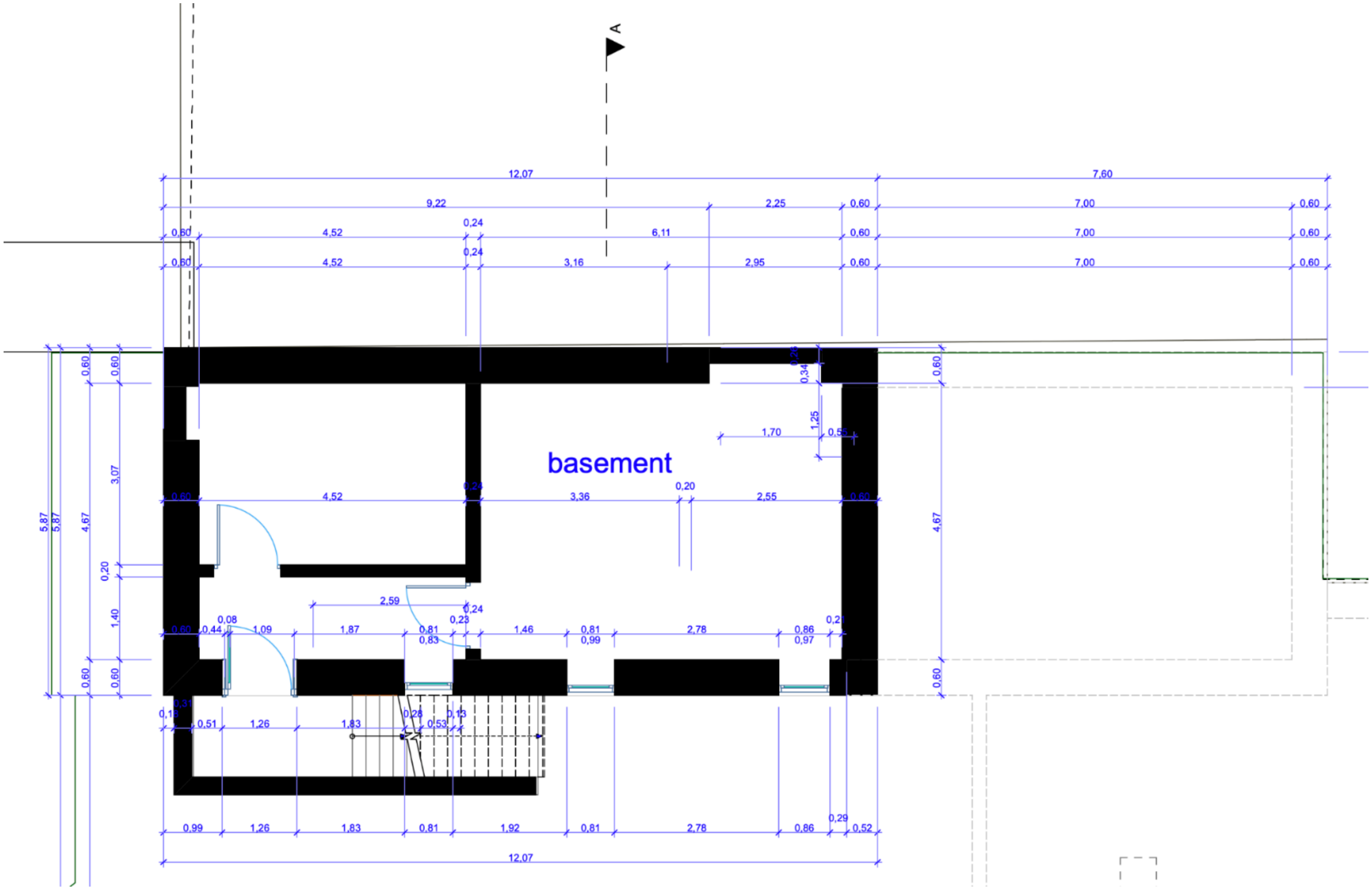

Figure 56: Floor plan, basement north wing

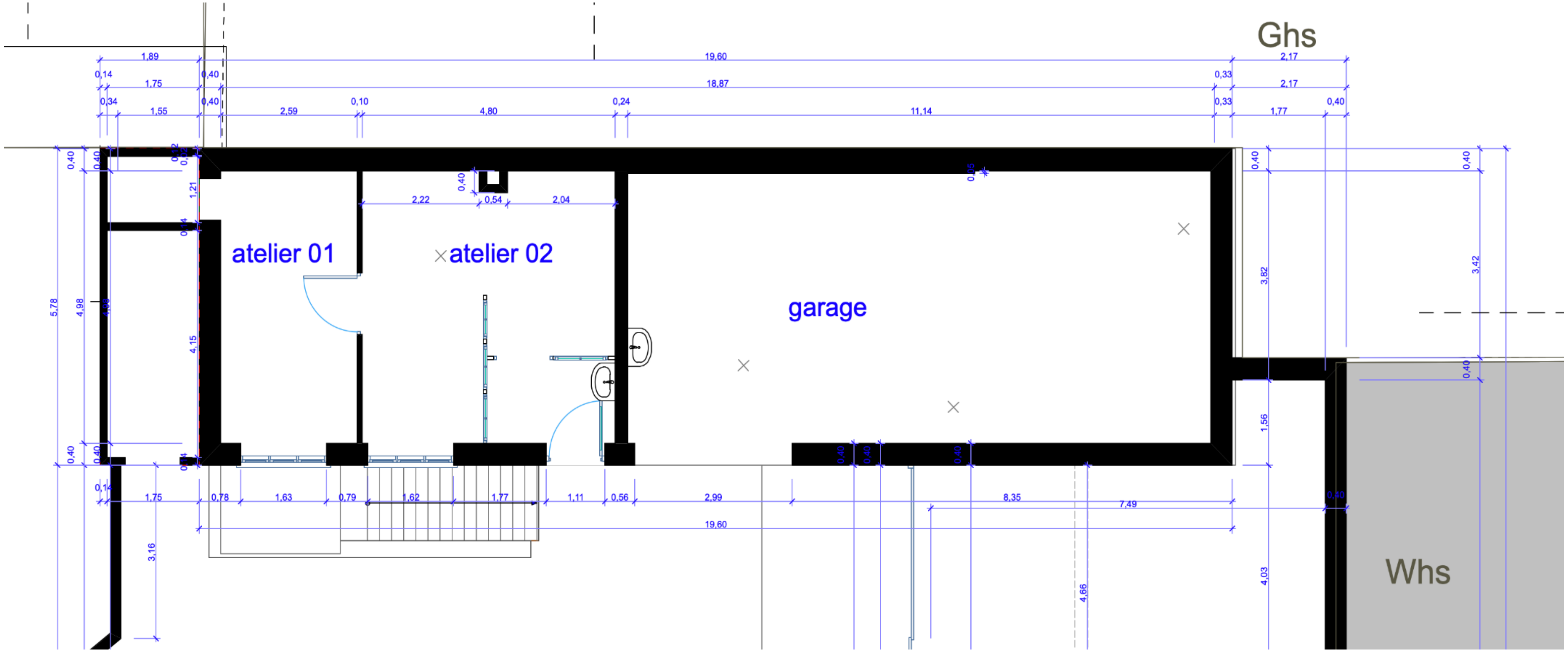

Figure 57: Floor plan, ground floor north wing

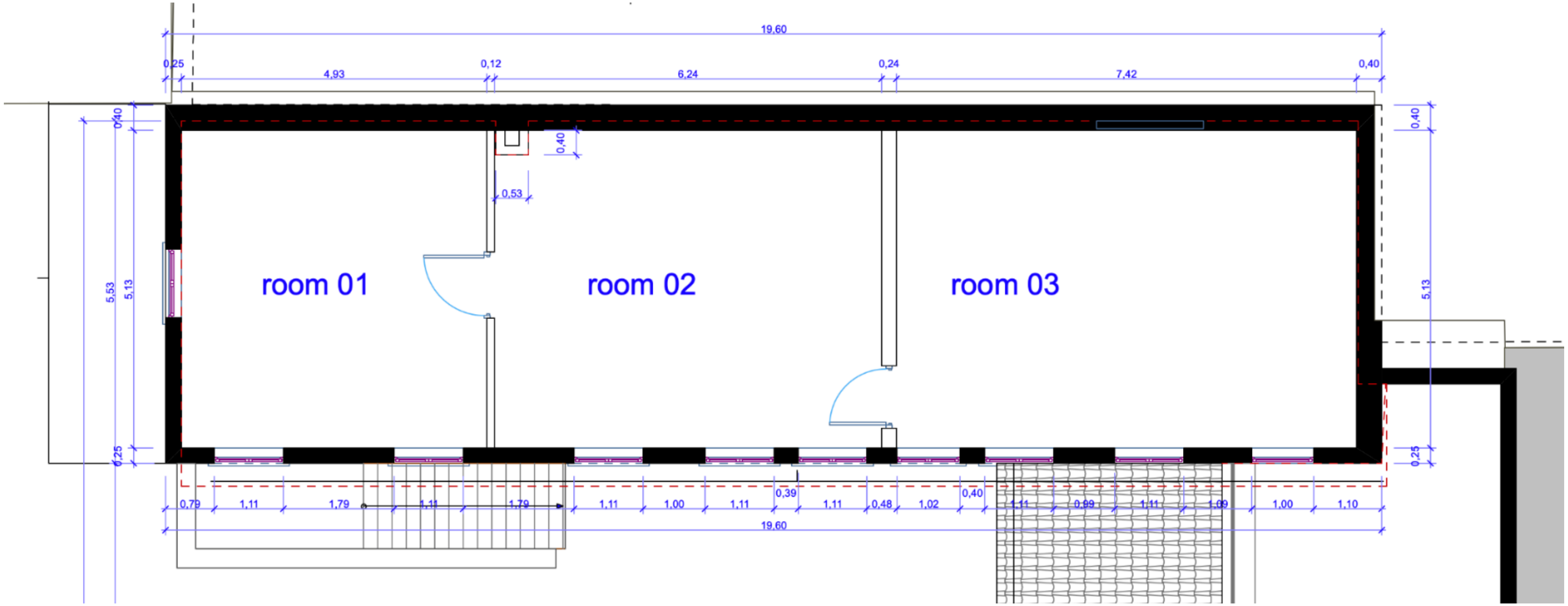

Figure 58: Floor plan, first floor north wing

Field	Units	Obj1
Name		Clear 3mm
Optical Data Type		SpectralAverage
Window Glass Spectral Data Set Name		
Thickness	m	0.003
Solar Transmittance at Normal Incidence		0.837
Front Side Solar Reflectance at Normal Incidence		0.075
Back Side Solar Reflectance at Normal Incidence		0.075
Visible Transmittance at Normal Incidence		0.898
Front Side Visible Reflectance at Normal Incidence		0.081
Back Side Visible Reflectance at Normal Incidence		0.081
Infrared Transmittance at Normal Incidence		0
Front Side Infrared Hemispherical Emissivity		0.84
Back Side Infrared Hemispherical Emissivity		0.84
Conductivity	W/m-K	0.9
Dirt Correction Factor for Solar and Visible Transmittanc		
Solar Diffusing		

Figure 59: Predefined material properties for window glass in EnergyPlus

Field	Units	Obj1
Name		Electrical Equipment - Co-Working 02
Zone or ZoneList Name		Co-Working Spaces - Southwing
Schedule Name		Office Equipment Schedule
Design Level Calculation Method		Watts/Person
Design Level	W	
Watts per Zone Floor Area	W/m2	
Watts per Person	W/person	20
Fraction Latent		0.25
Fraction Radiant		0.75
Fraction Lost		
End-Use Subcategory		General

Figure 60: Settings for internal gains from electric equipment

Obj14	Obj15
Occupancy Schedule_RUDOLF VERSION	WoodWorkshop_Occupancy Schedule_RUDOLF VERSION
Fraction	Fraction
Through: 12/31	Through: 12/31
For: Weekdays	For: Weekdays
Until: 09:00	Until: 09:00
0	0
Until: 10:30	Until: 11:00
0.7	0.5
Until: 17:30	Until: 17:30
1	1
Until: 21:00	Until: 21:00
0	0.5
Until: 24:00	Until: 24:00
0	0.05
For: Saturday	For: Saturday
Until: 10:30	Until: 09:30
0	0
Until: 17:00	Until: 17:00
0.5	0.4
Until: 24:00	Until: 24:00
0	0.1
For: Sunday Holidays AllOtherDays	For: Sunday Holidays AllOtherDays
Until: 24:00	Until: 24:00
0	0

Figure 61: Occupancy schedules for internal gains (people)

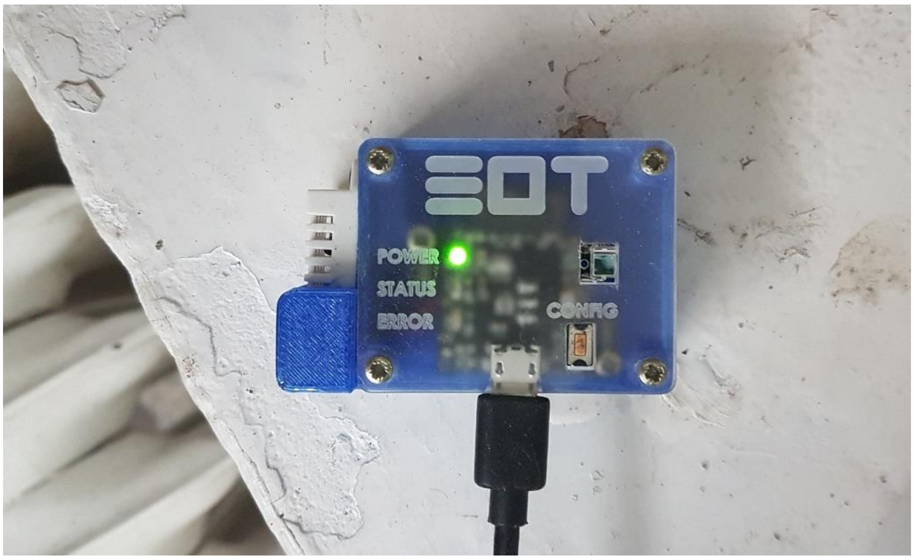

Figure 62: EOT sensor for temperature measurements, installed in Co-Working 02, south-wing

Heating Setpoint Schedule_Co-Working	Cooling Setpoint Schedule_RUDOLF	Heating Setpoint Schedule_Carpenters
Temperature	Temperature	Temperature
Through: 12/31	Through: 12/31	Through: 12/31
For: Weekdays	For: Weekdays	For: Weekdays
Until: 09:00	Until: 09:00	Until: 08:30
15	40	12.5
Until: 17:30	Until: 18:00	Until: 17:30
21	24	19
Until: 19:30	Until: 24:00	Until: 22:00
20	27	15
Until: 24:00	For: Weekends	Until: 24:00
15	Until: 10:00	12.5
For: Weekends	40	For: Weekends
Until: 11:00	Until: 16:30	Until: 11:00
15	24	12.5
Until: 17:00	Until: 24:00	Until: 17:00
21	40	19
Until: 24:00	For: AllOtherDays	Until: 24:00
15	Until: 24:00	12.5
For: AllOtherDays	40	For: AllOtherDays
Until: 24:00		Until: 24:00
15		12.5

Figure 63: Heating and cooling setpoint schedules for HVAC:IdealLoadsAirSystem

Costs - Blow-in insulation/ Rafter doubling (Southwing)

#	process	quantity	EP (BKI)	EP (Baupreisindex + RF Karlsruhe)	costs in €	source
210	**Preparation**				**4,063.47**	
212	**Demolition Measures**					
212.01	removing roof cover	189.0 m^2	9.00 €/m^2	10.75 €/m^2	€ 2,031.73	BKI - Altbau 2015, S.202, 1
212.01	removal of bitumen membrane	189.0 m^2	7.00 €/m^2	8.36 €/m^2	€ 1,580.24	BKI - Altbau 2015, S. 239, 8
212.01	removal of roof battens	189.0 m^2	2.00 €/m^2	2.39 €/m^2	€ 451.50	BKI -Altbau 2015, S. 203, 7
300	**Construction**				**63,808.00 €**	
330	**Exterior Walls**				**40,325.57 €**	
331	**Wall construction**					
331.01	inter wall insulation - plaster	**375.0 m^2**	**61.00 €/m^2**	72.86 €/m^2	**27,323.79 €**	BKI - Altbau 2015, S.283, 55
331.02					0.00 €	
334	**Transparent Elements**					
334.01	additional windows on the interior	22.5 m^2	94.00 €/m^2	106.93 €/m^2	2,404.33 €	BKI -Neubau 2017, S.580, 13
334.02	rubber sealing windows	65.7 m	8.00 €/m	9.10 €/m^2	597.45 €	BKI - Neubau, S.466, 35
334.03	gates groundfloor	2.0 Stk	5,000.00 €/Stk		10,000.00 €	offer manufacturer
360	**Roof**				**23,482.44 €**	
361	**Roof construction**					
361.01	rafter doubling material	4.0 m^3	513.00 €/m^3	612.75 €/m^3	2,444.85 €	BKI - Altbau 2015 , S. 170, 43
361.02	rafter doubling	315 m	13.00 €/m	15.53 €/m^2	4,891.21 €	BKI - Altbau 2015, S. 166, 29
361.03	blow-in insulation, cellulose	37.8 m^3	54.00 €/m^3	61.43 €/m^3	2,321.98 €	BKI - Neubau 2017, S. 302, 4
361.04	casing outside	189.0 m^2	19.00 €/m^2	21.61 €/m^2	4,084.97 €	BKI - Neubuau 2017, S. 207, 24
361.05	sealing membrane	189.0 m^2	18.00 €/m^2	20.48 €/m^2	3,869.97 €	BKI - Neubau 2017, S.297, 56
363	**Roofing Material**					
363.01	seperation, portection layer for green r	132.3 m^2	4.00 €/m^2	4.55 €/m^2	602.00 €	BKI - Neubau 2017, S.859, 124
363.02	drainage system, water storage	132.3 m^2	12.00 €/m^2	13.65 €/m^2	1,805.99 €	BKI - Neubau 2017, S.860, 128
363.03	filter fleece	132.3 m^2	3.00 €/m^2	3.41 €/m^2	451.50 €	BKI - Neubau 2017, S.860, 129
363.04	soil substrate	132.3 m^2	20.00 €/m^2	22.75 €/m^2	3,009.98 €	BKI - Neubau 2017, S.862, 137
	Estimated Costs				**€ 67,871.47**	

Figure 64: Detailed cost report for blow-in insulation proposal, south wing

Costs - Insulation between Rafters (Southwing)

#	process	quantity	EP (BKI)	EP (Baupreisindex + RF Karlsruhe)	costs in €	source
210	**Preparation**				**14,969.47**	
212	**Demolition Measures**					
212.01	removing roof cover	189.0 m^2	9.00 €/m^2	10.75 €/m^2	€ 2,031.73	BKI - Altbau 2015, S.202, 1
212.02	removal of bitumen membrane	189.0 m^2	7.00 €/m^2	8.36 €/m^2	€ 1,580.24	BKI - Altbau 2015, S. 239, 8
212.03	removal of roof battens	189.0 m^2	2.00 €/m^2	2.39 €/m^2	€ 451.50	BKI -Altbau 2015, S. 203, 7
212.04	remove roof beams	315 m	9.00 €/m	10.75 €/m^2	€ 3,386.22	BKI - Altbau 2015, S. 164, 22
212.05	remove ceiling cladding	189.0 m^2	16.00 €/m^2	19.11 €/m^2	€ 3,611.97	BKI - Altbau 2015, S. 161, 3
212.06	dismount interior wooden walls	218.1 m^2	15.00 €/m^2	17.92 €/m^2	€ 3,907.81	BKI - Altbau 2015, S.162, 9
300	**Construction**				**90,933.26 €**	
330	**Exterior Walls**				**54,211.43 €**	
331	**Wall Construction**					
331.01	leveling plaster for insultaion	375.0 m^2	14.00 €/m^2	16.72 €/m^2	6,271.03 €	BKI - Altbau 2015, S.281, 47
331.02	insulation wood fibre boards (assembly and mounting)	375.0 m^2	64.00 €/m^2	76.44 €/m^2	28,667.59 €	BKI - Altbau 2015, S.286, 73
331.03	organic plaster	375.0 m^2	14.00 €/m^2	16.72 €/m^2	6,271.03 €	BKI - Altbau 2015, S.297, 95
334	**Transparent Elements**					
334.01	additional windows on the interior	22.5 m^2	94.00 €/m^2	106.93 €/m^2	2,404.33 €	BKI -Neubau 2017, S.580, 13
334.02	rubber sealing windows	65.7 m	8.00 €/m	9.10 €/m^2	597.45 €	BKI - Neubau, S.466, 35
334.03	gates groundfloor	2.0 Stk	5,000.00 €/Stk		10,000.00 €	offer manufacturer
360	**Roof**				**36,721.83 €**	
361	**Roof construction**					
361.01	new rafters/beams	13.3 m^3	513.00 €/m^3	612.75 €/m^3	8,149.51 €	BKI - Altbau 2015 , S. 170, 43
361.02	assembly and installation of new beams	315.0 m	10.00 €/m	11.94 €/m^3	3,762.47 €	BKI - Altbau 2015 , S. 170, 46
361.03	counter battening	302.0 m	2.00 €/m	2.39 €/m^2	721.44 €	BKI - Altbau 2015, S. 224, 69
361.04	insulation between rafters	163.8 m^2	19.00 €/m^2	22.69 €/m^2	3,717.32 €	BKI - Altbau 2015 , S. 167, 32
361.05	interior casing/OSB	189.0 m^2	23.00 €/m^2	27.47 €/m^2	5,192.21 €	BKI - Altbau 2015 , S. 172, 53
361.06	casing towards outside	189.0 m^2	19.00 €/m^2	21.61 €/m^2	4,084.97 €	BKI - Neubuau 2017, S. 207, 24
361.07	sealing membrane	189.0 m^2	18.00 €/m^2	20.48 €/m^2	3,869.97 €	BKI - Neubau 2017, S.297, 56
361.08	vapour barrier	189.0 m^2	6.00 €/m^2	7.17 €/m^2	1,354.49 €	BKI, Altbau 2015, S.223, 65
363	**Roofing Material**					
363.01	seperation, portection layer for green roof	132.3 m^2	4.00 €/m^2	4.55 €/m^2	602.00 €	BKI - Neubau 2017, S.859, 124
363.02	drainage system, water storage	132.3 m^2	12.00 €/m^2	13.65 €/m^2	1,805.99 €	BKI - Neubau 2017, S.860, 128
363.03	filter fleece	132.3 m^2	3.00 €/m^2	3.41 €/m^2	451.50 €	BKI - Neubau 2017, S.860, 129
363.04	soil substrate	132.3 m^2	20.00 €/m^2	22.75 €/m^2	3,009.98 €	BKI - Neubau 2017, S.862, 137
	Estimated Costs				**105,902.73 €**	

Figure 65: Detailed cost report for insulation between rafter proposal, south wing

Costs - Insulation between rafters (Northwing)

#	process	quantity	EP (BKI)	EP (Baupreisindex + RF Karlsruhe)	GP	source
210	**Preparation**				**4,063.47**	
212	**Demolition work**					
212.01	removing roof cover	102.6 m²	9.00 €/m²	10.75 €/m²	€ 1,102.94	BKI - Altbau 2015, S.202, 1
212.02	removal of biutmen membrane	102.6 m²	7.00 €/m²	8.36 €/m²	€ 857.84	BKI - Altbau 2015, S. 239, 8
212.03	removal of roof battens	102.6 m²	2.00 €/m²	2.39 €/m²	€ 245.10	BKI -Altbau 2015, S. 203, 7
212.04	remove roof beams	173 m	9.00 €/m	10.75 €/m²	€ 1,857.59	BKI - Altbau 2015, S. 164, 22
300	**Construction**				**52,221.35 €**	
330	**Exterior Wall**				**32,629.19 €**	
331	**Wall Construction**					
331.01	leveling plaster for insultaion	253.4 m²	14.00 €/m²	16.72 €/m²	4,237.88 €	BKI - Altbau 2015, S.281, 47
331.02	insulation wood fibre boards (assembly and mounting)	253.4 m²	64.00 €/m²	76.44 €/m²	19,373.16 €	BKI - Altbau 2015, S.286, 73
331.03	organic plaster	253.4 m²	14.00 €/m²	16.72 €/m²	4,237.88 €	BKI - Altbau 2015, S.297, 95
334	**Transparent Elements**					
334.01	additional interior windows	24.9 m²	94.00 €/m²	106.93 €/m²	2,664.17 €	BKI -Neubau 2017, S.580, 13
334.02	window sealing	67.7 m	8.00 €/m	9.10 €/m²	616.10 €	BKI - Neubau, S.466, 35
334.03	gate groundfloor	1.0 Stk	1,500.00 €/Stk		1,500.00 €	own construction
360	**Roof**				**19,592.16 €**	
361	**Roof Construction**					
361.01	material for new rafters	7.7 m³	513.00 €/m³	612.75 €/m³	3,939.84 €	BKI- Altbau 2015, S.170, 43
361.02	assembly and installation of beams	172.8 m	9.00 €/m	10.75 €/m	1,857.59 €	BKI - Altbau 2015 , S. 171, 47
361.03	counter battening	302.0 m	2.00 €/m	2.39 €/m²	721.44 €	BKI - Altbau 2015, S. 224, 69
361.04	insulation between rafters	88.8 m²	19.00 €/m²	22.69 €/m²	2,014.71 €	BKI - Altbau 2015 , S. 167, 32
361.05	casing interior/OSB	102.6 m²	23.00 €/m²	27.47 €/m²	2,818.63 €	BKI - Altbau 2015 , S. 172, 53
361.06	casing towards outside	102.6 m²	19.00 €/m²	21.61 €/m²	2,217.55 €	BKI - Neubuau 2017, S. 207, 24
361.07	sealing membrane	102.6 m²	18.00 €/m²	20.48 €/m²	2,100.84 €	BKI - Neubau 2017, S.297, 56
361.08	vapour barrier	102.6 m²	6.00 €/m²	7.17 €/m²	735.29 €	BKI - Altbau 2015, S. 223, 65
363	**Roofing Material**					
363.01	seperation, portection layer for green roof	71.8 m²	4.00 €/m²	4.55 €/m²	326.80 €	BKI - Neubau 2017, S.859, 124
363.02	drainage system, water storage	71.8 m²	12.00 €/m²	13.65 €/m²	980.39 €	BKI - Neubau 2017, S.860, 128
363.03	filter fleece	71.8 m²	3.00 €/m²	3.41 €/m²	245.10 €	BKI - Neubau 2017, S.860, 129
363.04	soil substrate	71.8 m²	20.00 €/m²	22.75 €/m²	1,633.99 €	BKI - Neubau 2017, S.862, 137
	Gesamt Kostengruppe 300-400				**56,284.82 €**	

Figure 66: Detailed cost report for insulation between rafter proposal, north wing

Costs - Timber Board Stacking Ceiling (Southwing)

#	process	quantity	EP (BKI)	EP (Baupreisindex + RF Karlsruhe)	costs in €	source
210	**Preparation**				**14,969.47**	
212	**Demolition Measures**					
212.01	removing roof cover	189.0 m²	9.00 €/m²	10.75 €/m²	€ 2,031.73	BKI - Altbau 2015, S.202, 1
212.02	removal of bitumen membrane	189.0 m²	7.00 €/m²	8.36 €/m²	€ 1,580.24	BKI - Altbau 2015, S. 239, 8
212.03	removal of roof battens	189.0 m²	2.00 €/m²	2.39 €/m²	€ 451.50	BKI -Altbau 2015, S. 203, 7
212.04	remove roof beams	315 m	9.00 €/m	10.75 €/m²	€ 3,386.22	BKI - Altbau 2015, S. 164, 22
212.05	remove ceiling cladding	189.0 m²	16.00 €/m²	19.11 €/m²	€ 3,611.97	BKI - Altbau 2015, S. 161, 3
212.06	dismount interior wooden walls	218.1 m²	15.00 €/m²	17.92 €/m²	€ 3,907.81	BKI - Altbau 2015, S.162, 9
300	**Construction**				**118,022.93 €**	
330	**Exteroir Walls**				**54,211.43 €**	
331	**Wall Construction**					
331.01	leveling plaster for insultaion	375.0 m²	14.00 €/m²	16.72 €/m²	6,271.03 €	BKI - Altbau 2015, S.281, 47
331.02	insulation wood fibre boards (assembly and mounting)	375.0 m²	64.00 €/m²	76.44 €/m²	28,667.59 €	BKI - Altbau 2015, S.286, 73
331.03	organic plaster	375.0 m²	14.00 €/m²	16.72 €/m²	6,271.03 €	BKI - Altbau 2015, S.297, 95
334	**Transparent Elements**					
334.01	additional windows on the interior	22.5 m²	94.00 €/m²	106.93 €/m²	2,404.33 €	BKI -Neubau 2017, S.580, 13
334.02	rubber sealing windows	65.7 m	8.00 €/m	9.10 €/m²	597.45 €	BKI - Neubau, S.466, 35
334.03	gates groundfloor	2.0 Stk	5,000.00 €/Stk		10,000.00 €	offer manufacturer
360	**Roof**				**63,811.50 €**	
361	**Roof Construction**					
361.01	timber board stacking ceiling	189.0 m²	150.00 €/m³	170.63 €/m³	32,249.75 €	BKI - Neubau 2017, S. 266, 83
361.02	seperation layer	189.0 m²	4.00 €/m²	4.78 €/m²	902.99 €	BKI - Altbau, S.240, 20
361.03	foam glas	189.0 m²	72.00 €/m²	81.90 €/m²	15,479.88 €	BKI - Neubau 2017, S. 328, 16
361.04	casing outside	189.0 m²	19.00 €/m²	21.61 €/m²	4,084.97 €	BKI - Neubuau 2017, S. 207, 24
361.05	sealing membrane	189.0 m²	18.00 €/m²	20.48 €/m²	3,869.97 €	BKI - Neubau 2017, S.297, 56
361.06	vapour barrier	189.0 m²	6.00 €/m²	7.17 €/m²	1,354.49 €	BKI, Altbau 2015, S.223, 65
363	**Roofing Material**					
363.01	seperation, portection layer for green r	132.3 m²	4.00 €/m²	4.55 €/m²	602.00 €	BKI - Neubau 2017, S.859, 124
363.02	drainage system, water storage	132.3 m²	12.00 €/m²	13.65 €/m²	1,805.99 €	BKI - Neubau 2017, S.860, 128
363.03	filter fleece	132.3 m²	3.00 €/m²	3.41 €/m²	451.50 €	BKI - Neubau 2017, S.860, 129
363.04	soil substrate	132.3 m²	20.00 €/m²	22.75 €/m²	3,009.98 €	BKI - Neubau 2017, S.862, 137
	Gesamt Kostengruppe 300-400				**132,992.40 €**	

Figure 67: Detailed cost report for timber board stacking ceiling proposal, south wing

Costs - timber board stacking roof (Northwing)

#		process	quantity	EP (BKI)	EP (Baupreisindex + RF Karlsruhe)	GP	source
210	**Preperation**					**4,063.47**	
	212	**Demolition Measures**					
	212.01	removing roof cover	102.6 m²	9.00 €/m²	10.75 €/m² €	1,102.94	BKI - Altbau 2015, S.202, 1
	212.02	removal of biutmen membrane	102.6 m²	7.00 €/m²	8.36 €/m² €	857.84	BKI - Altbau 2015, S. 239, 8
	212.03	removal of roof battens	102.6 m²	2.00 €/m²	2.39 €/m² €	245.10	BKI -Altbau 2015, S. 203, 7
	212.04	remove roof beams	173 m	9.00 €/m	10.75 €/m² €	1,857.59	BKI - Altbau 2015, S. 164, 22
300	**Constuction**					**65,168.88 €**	
330	**Exterior Wall**					**32,629.19 €**	
	331	**Wall Construction**					
	331.01	leveling plaster for insultaion	253.4 m²	14.00 €/m²	16.72 €/m²	4,237.88 €	BKI - Altbau 2015, S.281, 47
	331.02	insulation wood fibre boards (assembly and mounting)	253.4 m²	64.00 €/m²	76.44 €/m²	19,373.16 €	BKI - Altbau 2015, S.286, 73
	331.03	organic plaster	253.4 m²	14.00 €/m²	16.72 €/m²	4,237.88 €	BKI - Altbau 2015, S.297, 95
	334	**Transparent Elements**					
	334.01	additional interior windows	24.9 m²	94.00 €/m²	106.93 €/m²	2,664.17 €	BKI -Neubau 2017, S.580, 13
	334.02	window sealing	67.7 m	8.00 €/m	9.10 €/m²	616.10 €	BKI - Neubau, S.466, 35
	334.03	gate groundfloor	1.0 Stk	1,500.00 €/Stk		1,500.00 €	own construction
360	**Roof**					**32,539.69 €**	
	361	**Roof Construction**					
	361.01	timber, board stacking roof	102.6 m²	150.00 €/m²	170.63 €/m²	17,507.00 €	BKI - Neubau 2017, S. 266, 83
	361.02	seperation layer	102.6 m²	4.00 €/m²	4.78 €/m²	490.20 €	BKI - Altbau, S.240, 20
	361.03	foam glas	102.6 m²	72.00 €/m²	81.90 €/m²	8,403.36 €	BKI - Neubau 2017, S. 328, 16
	361.04	casing towards outside	102.6 m²	19.00 €/m²	21.61 €/m²	2,217.55 €	BKI - Neubau 2017, S. 207, 24
	361.07	vapour barrier	102.6 m²	6.00 €/m²	7.17 €/m²	735.29 €	BKI - Altbau 2015, S. 223, 65
	363	**Roofing Material**					
	363.01	seperation, portection layer for green roof	71.8 m²	4.00 €/m²	4.55 €/m²	326.80 €	BKI - Neubau 2017, S.859, 124
	363.02	drainage system, water storage	71.8 m²	12.00 €/m²	13.65 €/m²	980.39 €	BKI - Neubau 2017, S.860, 128
	363.03	filter fleece	71.8 m²	3.00 €/m²	3.41 €/m²	245.10 €	BKI - Neubau 2017, S.860, 129
	363.04	soil substrate	71.8 m²	20.00 €/m²	22.75 €/m²	1,633.99 €	BKI - Neubau 2017, S.862, 137
		Gesamt Kostengruppe 300-400				**69,232.35 €**	

Figure 68: Detailed cost report for timber board stacking ceiling proposal, north wing