Energy concept for a building refurbishment work in Karlsruhe, Germany

How to develop a sustainable building process

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***Abstract* — The objective of this work 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

I. 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. Cheap energy sources fueled today’s standard of full indoor heating. Moreover, an increase of living space from 8 – 12 m^2 up to 45 m^2 per person was recorded throughout the past 60 years [17]. Even though large improvements were made, supplying energy efficient technologies, the overall consumption in Germany increased enormously, making up 32% of the final energy consumption for heating and hot water supply in buildings in 2017 [16]. Including cooling and lighting, an average final energy consumption of 40% for the building sector is estimated. That includes 19 million residential- and 2 million non-residential buildings in Germany.
Nevertheless, 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, it dropped down to 140 kWh/m^2 by 2012. New buildings, under the EnEV 2009 regulation, require consumptions below 70 kWh/m^2. 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 counts 222.8 million tons of waste per year, which represents about 54 % of the overall German waste production [5]. 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. Many more include façades worth preserving. 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 [11] [14].

II. Case Study

The following section 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 the description on the development of the *EnergyPlus* model, which was necessary for the subsequent assessment of the refurbishment proposals.

Inventory of the building and design proposals

A detailed inventory analysis of the building was necessary to develop a respective model in *EnergyPlus* and the *OpenStudio – GoogleSketchUp* environment, as shown in *Figure 1*.

Since no accurate floor plans were available. the entire building was remeasured, and the floor plans were adjusted accordingly. Furthermore, a detailed analysis, of the build-in materials of all important building components, such as roof, floor, walls, windows and doors, was necessary. Comparing the existing structure with other references from literature, such as [21] [7] and [18] helped to identify the materials and supported the decision process. In most cases, specific material data could be verified with *"Schneider - Bautabellen für Ingenieure"* [2] and other sources. Moreover, the detailed inventory analysis also helped to point out weaknesses and damages of the existing construction.

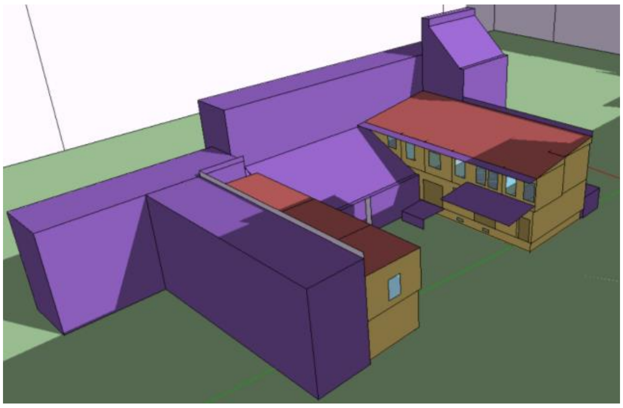

Figure 1: EnergyPlus model of the courtyard building

Further, various retrofit design proposals for the building envelope were developed, taking into account the requirements of the heritage authority.

The roof surface represents a big area of the building envelope. Exposed to sun, rain, snow and wind, it is prone to damages [18]. 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 and proposed in this work. All three show similar insulating properties, regarding all U-values were estimated between 0.18 $\frac{W}{m^2 * K}$ – and 0.24 $\frac{W}{m^2 * K}$. The roof insulations also serve to classify the proposals, discussed in this work, as given *Table 1* below:

Table 1: Design Proposals

#	Design Proposal
#1	cellulose blow in insulation
#2.1	insulation between rafters (construction with existing rafters)
#2.2	insulation between rafters (construction with new rafters)
#2.3	insulation between rafters with interior wall insulation
#3	timber board stacking roof with foam glass insulation

Facing the requirements of the heritage authority, replacing of the old single glazed windows is not allowed. With a U-value of 5.2 $\frac{W}{m^2 K}$, 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. In the subsequent simulations, this measure was combined with the roof insulation type: insulation between rafters. Hence the number #2.3 for the proposal with interior wall insulation.

Calibrating the model in EnergyPlus

For the calibration process, four *EnergyOT Environment* sensors were installed to record indoor temperature over a period of six months, from 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. 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 following statistical indices:

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

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

$$A_{period} = \frac{\sum M}{N}$$

$$Cv(RMSE) = \frac{RMSE}{A_{period}} * 100\%$$

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

Furthermore, the internal heat gains were included in the model. As the building is in temporary use at the moment, and the final use still needs to be defined, literature was consulted to obtain values for the internal heat gains. *Table 2* summarizes the assumptions considered for the model:

Table 2: Internal heat gains

Source of internal heat gains	Quantity	Value
Occupants in a carpenter's workshop	4 people	189 W/person
Occupants in co-working spaces	6 people/m^2	120 W/person
Heat gains from electric equipment	m^2 co-working	20 W/m^2

With an infiltration rate of 0.9 and 1.4 air changes per hour (ac/h) on ground- and first floor respectively, 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. A ventilation of 3 air changes per hour was set for all rooms.

III. Discussion of Results

The following part 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.

Heating and Cooling Demand

The design proposals introduced in earlier were simulated with two different sets of weather data. One represents the current weather conditions (2015) the other future conditions (2045), considering the effects of climate change. In addition, a proposal including interior wall insulation with wood-fiber boards was carried out (#2.3). *Figure 2* displays the results for heating and cooling demand for these proposals.

From the graph in *Figure 2*, a decrease of around 25% in energy consumption for heating between the current and future designs is expected. 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 the second and third design proposal. That means, timber board stacking roof (#3) or insulation between rafters (#2). A complementary interior wall insulation makes the value drop down by 41.5% to 48,861 kWh.

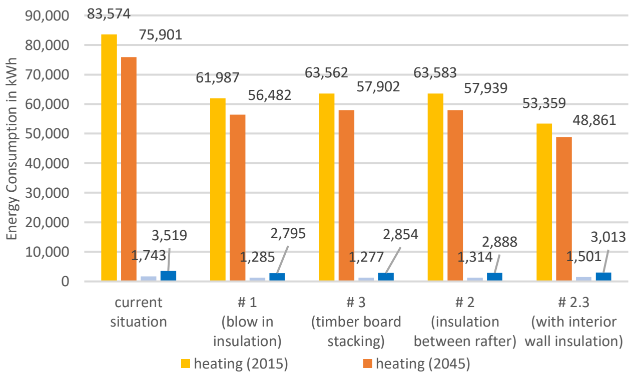

Figure 2: Heating and cooling demand of the building complex

Economic Analysis

In a second step the economic analysis followed, to assess the financial impact of each 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. For this work the 2015 edition for old buildings [6] and 2017 edition for new constructions [3] was consulted. The prices were adjusted by a local factor and another one that takes into account the increasing costs comparing 2015 and 2017 to today [4].
The constructional execution influences the expenses, therefore design proposal #2 was divided into two sections, as already displayed in *Table 1*. #2.1 represents a scenario were most of the existing roof structure is kept and the rafters are doubled for necessary static support. Proposal #2.2 represents the same type of insulation, however, includes a complete replacement of the old roof structure. A summary of all relevant costs is given in *Figure* 3.

Figure 3: Initial investment cost breakdown for refurbishment proposals

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. 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 (Figure 2)*, 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. *Figure 4* displays the results with an economic payback time, depending on the design proposal, between 35 and 55 years.

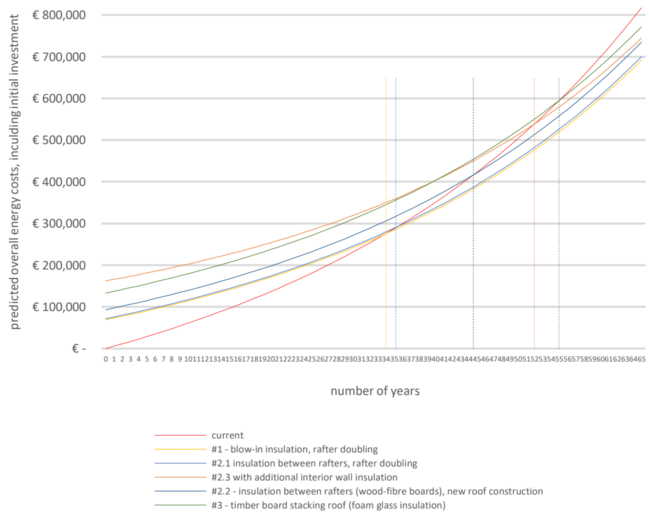

Figure 4: Economic payback time for retrofit measures

Environmental Impacts

The last step of the assessment involved the assessment of the environmental impacts with the help of the online tool *eLCA* which relies on the *Ökobaudat* data base. The output parameters of the LCA were limited to the CO_2 emissions. *Figure 5* represents the time it takes to pay off the initial “CO_2 investment” of each solution, through the reduced energy consumption achieved. To estimate the emissions, a gas heating and electricity based cooling was assumed with 300g CO_2-equivialents and 550g CO_2 equivalents per kWh of heat produced [10].

Considering all relevant impacts during the entire life cycle, a roof insulation with additional interior wall insulation represents the greatest CO_2 savings potential. This is because of the strict use of sustainable materials, such as wood-fiber boards for insulation. Its carbon footprint is very small. Moreover, the annual energy saving due to reduced heat losses result in a short “ecological payback time. Compared to the current condition of the building net savings are achieved after less than 5 years.

The use of new timber materials, as in #2.2 and #3, positively effects the global warming potential (GWP) outputs. 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) indicate a very similar starting point in *Figure 5*.

In general, the ecological analysis shows that all insulating measures have a positive impact, as all help to mitigate the CO_2 emissions. Compared to the current conditions of the building, net CO_2 savings are achieved after less than 10 years.

However, the great energy and emission savings conflict with the high investment costs solution #2.3 - with interior wall insulation demands. Regarding the current price for gas (0.06 €/kWh) and electricity (0.29 €/kWh) and considering an annual increase in costs the economic payback time was estimated with 52 years. Without interior wall insulation the time can be reduced to 35 years (#2.1) or 44 years (#2.2) for the same type of roof insulation. Moreover, two different materials, straw (#2.1.1) and wood-fiber boards (#2.1.2) were considered for the insulation between the rafters,

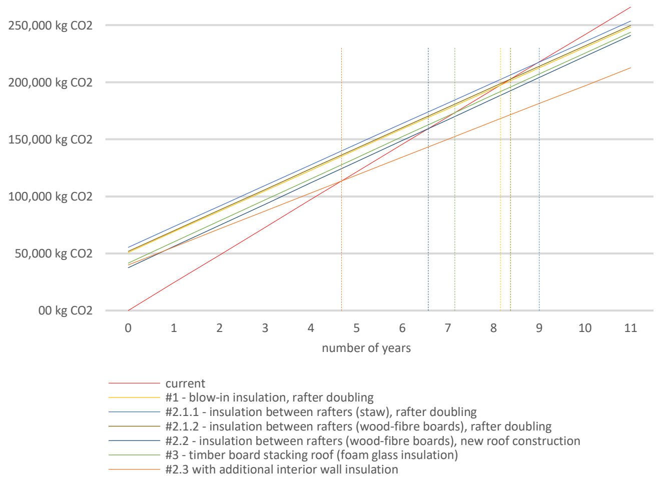

Figure 5: Overall CO_2 emissions for different design proposals

Figure 6 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 graph in *Figure 6* shows, 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 4*. Furthermore, it is interesting to see, that solution #2.3 already pays itself back after less than 14 years. Made of clay and wood-fiber board, the materials achieve low primary energy input. In addition, the reduced heating demand by around 10,000 kWh helps to significantly reduce consumption.

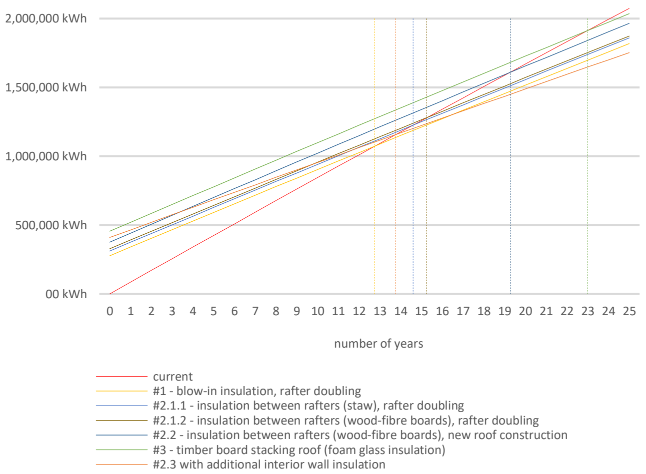

Figure 6: Primary energy input

IV. Final Heating System Design

Finally, an adequate heating concept for the building was proposed.

Firstly, energy savings for reduced indoor temperature were analyzed, using the *EnergyPlus* model. 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% as indicated in *Figure 7*.

To reduce energy consumption and mitigate emissions a system, prociding a base temperature, is suggested for the building complex. Complementary heat sources for individual heating, so called personal comfort systems (PCS) can be installed, if required. Among others, experiments by *Maohui et al*. [19] revealed, that 97.5% of a tested group were satisfied, when equipped with PCS, while exposed to a room with 18°C indoor temperature. 65% were OK without PCS at the same indoor temperature [19].

The combination of providing a base load of heat with additional individual heating fits the overall, flexible concept of the building complex as co-working space, workshop, atelier and event location.

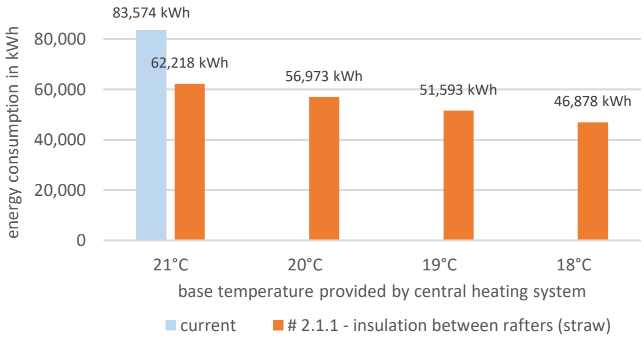

Figure 7: Energy demand for different base temperatures

Base Load Heating System – Gas vs.Wood

To meet the target of sustainable energy supply, gas and wood, as fuel for heating, were considered.

Gas Heating

Among energy sources for heating, gas is regarded as one with a good climate balance [9]. 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 [20].
Consisting of about 500.000 km of pipelines and 22 billion m^3 underground storage [1], 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 [15]. The total storage capacity of 30,6 billion m^3 [20] offers a huge potential to store gas from biogas and power to gas production and thus a great solution for the energy storage dilemma
In case a comprehensive cover of renewable gases is in sight, a central gas-heating system 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 [8]. 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 [8]. 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 [24] [22]. Half of it, around 290 TWh, is consumed for residential heating [20].

A detailed assessment to define the potential for biogas production in Germany was carried out by *Adler et al*. [1] They claim a technically feasible, annual biogas-production of 100 TWh in the future. 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 [12].

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 subsidized in that case [8]. 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 of the building.

Wood-based heating system

With the waste wood of a carpenter’s workshop in the basement of the building and locally available firewood, a wood-based heating system was an appropriate solution. Although the NO_x, soot and dust emissions of wood-based heating are worse compared to natural gas, its overall CO_2 balance is very good, as displayed in *Figure 8*. Furthermore, big central units are commonly equipped with technology to control the combustion process. Thus, emissions are mitigated effectively today [23].

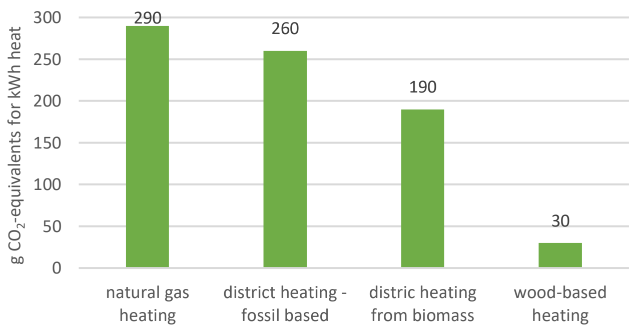

Figure 8: g-CO_2 equivalents produced per kWh of heat for various fuels [10]

Given the heating value of dry wood logs (around 1890 kWh/m^3 [13]) 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 *(Figure 7)*. Thus, a total amount to 25 m^3 of wood was calculated. Regarding the local market, prices between 90 -115 €/m^3 can be expected. 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 [25]. 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 [25].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

V. Conclusion

The objective of this work was to propose a suitable heating concept in the scope of the renovation work of a listed building complex. Moreover, the methodologies applied can exemplify an approach for sustainable building design. Incorporating a technical, economic and ecological analysis this work revealed the great complexity, partly conflicting objective of seeking holistic sustainable solutions.

With the help of the *EnergyPlus* 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.
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 yet unclear 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, 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 1.3 ac/h and a ventilation of 3 ac/h, was found only a blower-door test on site would provide accurate results. In general, the work proved, regarding literature and experts consulted throughout the process, that many parameters are set or assumed based on experience.
Although, uncertainties remain, the important factors could be analyzed 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-fiber board (#2.1.2 and #2.2) and foam glass (#3)).

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.
Regarding our goal to cut energy consumption, to reduce our carbon dioxide emissions, the juxtaposition of costs and LCA of the design proposals revealed the need for political incentives to encourage energy saving measures. Especially promoting effective insulation for existing building structure requires subsidies. The ecological analysis revealed good CO_2 saving potentials *(Figure 5)* for a solution with interior wall insulations, however its high investment is economically not viable.

An 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 work could point out that it takes several factors to develop a sustainable building design. It is 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 paper. 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 behavior 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 allows to use a renewable, locally available fuel. 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.

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