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Application and validation of a method to assess the energy reduction and environmental impact of renovation alternatives

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Abstract. The renovation of residential stock is one of the most promising areas, in terms of energy reduction, because these buildings are highly inefficient and represent the largest part of the building stock. However, the environmental impact assessment over the life cycle of building renovation is rare. It is more common to develop an assessment for new buildings. This study presents a method that combines the evaluation of the benefits of renovating residential buildings, considering cost, energy and environmental benefits using Life Cycle Assessment (LCA). The method is based on 3 stages of development. First, the database of energy certificates, costs and LCA was analysed. The second step is to develop a workflow in Rhino/Grasshopper/E-Plus to automatically model a residential building and feed the simulation model with the data obtained from the databases. Finally, a simulation campaign was carried out to obtain an optimal renovation package, minimising energy consumption and environmental impact. The research was carried out in a case study in Uddevalla, Sweden. The residential building has different measurements including energy consumption data before and after renovation. This was used to validate the proposed methodology. The validation shows that accurate results are achievable with potential for mass application.

1. Introduction

The residential sector in 2018 was responsible for 26.7% of the final energy consumed in the European Union (EU-28), being the second largest sector after the transport sector (31%) [1].Considering the construction, operation, transport and other emissions related to the building and construction industry, the building sector is responsible for the largest amount of CO2 emissions with 39% of all energy- and process- related emissions in 2017 [2]. Within these 39%, 28% are attributed to building operation, including heating, electricity, cooling, hot water and utilities, while 11% are associated with the embodied impact of buildings. Considering the overall contribution of buildings to the energy and process-related emissions, substantial reductions are necessary to avoid the risk of irreversible damage of climate change. While being one of the most emitting sectors, the building and construction industry has also the highest potential to substantially reduce emissions, decarbonize the building stock and ensure the green energy transition in the world. Because of the residential buildings' life cycle, which is expected to be several decades, a significant number of residential buildings will need to improve their energy performance in order to effectively reduce energy consumption and greenhouse gas emissions.

1.1. European goals

In order to mitigate climate change and reduce carbon emissions, the European Union (EU) has set a long-term strategy based on three milestones: reduced Greenhouse Gas emissions (GGH) by 20% in 2020, by 40% in 2030 and by 80-95% in 2050, compared with the 1990 emission level [3]. In a closer look at energy used, in 2017 around 27% of the total final energy consumption in the EU was used in the residential sector [4]. A great share of that energy, around 64%, is used for space heating [4]. Around 75% of the building stock is energy inefficient [5], since these buildings were constructed before adequate energy measures were mandatory. To this add that space heating is by far the largest energy end-use of households in Member States (64%), followed by hot water heating (15%) [4].

1.2. Swedish goal

Sweden has ambitions goal in terms of energy and CO2 reductions, according to the Swedish climate policy framework's long-term climate goal [6], it has been defined Sweden shall have zero net emissions of greenhouse gases into the atmosphere and should thereafter achieve negative emissions by 2045. This mean that activities in Sweden must be at least 85% less than the emissions in 1990. Due to this, the environmental impacts of the production and construction industry is the great concern, especially for policymakers, researchers, and industry practitioners [7]. Despite that the building sector has low CO2 emission, the energy index is lower than the average EU [8], Sweden is one of the countries that has always been a role model in terms of tackling climate change across the globe [7].

1.3. Importance of renovation of building stock EU

Besides the growing importance of building renovation, some level of renovation is carried out in Europe for only 11% of buildings per year and this renovation is usually not performed for energy reduction purposes [9] The deep energy-related building renovation that reduces the amount of energy by 60% is performed in 0.2% of buildings per year. The weighted annual energy renovation rate in European Union is low at some 1% [9]. Current renovation rate cannot ensure cutting the greenhouse gas emissions to net zero by 2050. For this reason, the European Commission has declared that the renovation of existing buildings is the greatest challenge for the coming decades, and at the same time represents the greatest opportunity for cost-effective energy savings in the EU [5]. The objective of the European Union is to at least double the current renovation rate by 2030 [9]. The Buildings Performance Institute Europe (BPIE) prepared a fact sheet [10] that gives an insight into this issue by stating that 97% of today's buildings need to be renovated. This is supported by the fact that the existing building stock is not considered energy -efficient today and that at least 40% were built before the 1960s, when most building codes did not include energy -efficiency requirements [11]. However, heating energy analysis in Sweden are supply -oriented and therefore, energy demand is generally not studied in depth [8]. This can be seen in a historical analysis of Sweden [12], where it has been stated that opportunities in terms of energy - efficiency are missed despite the large potential for energy reduction due to the focus on reducing oil dependency.

1.4. Importance of renovation of building under the million-home program

During 1965 and 1975, a large number of residential buildings were constructed in Sweden under the Million Homes Program [13], to meet the high demand for housing, reduce the overcrowding and to incorporate modern amenities in al the households [14]. It is estimated that 60% of the flats in Sweden were built between 1941-1980 [15], which means that these buildings are about to reach their useful life expectancy of 50 years, which translates into a great need for renovation and therefore opportunities for energy retrofitting [14].

1.5. Risk of retrofitting in the wrong way

Building renovation is clearly important, however, there is a risk of not getting the expected results. Many elements can cause renovations to fail to deliver the expected energy reductions and thus block further improvements from being developed, until the next renovation cycle, phenomenon also known as the lock-in effect. For example, the energy -efficiency gap, where potential improvements to redirect energy demand appear to be cost-effective energy -efficiency technologies but are not the optimal solution [16]. Because of this, it is important to be aware of the uncertainties and risks that cause gaps and to take action to prevent them.

1.6. Uncertainties on simulation and renovation

Another way in which a performance gap can arise is when renovations are carried out and the energy reduction is less than predicted once it is measured, i.e. the difference between the design stage (calculated) and the actual consumption measurement. This occurs as building simulation models in most of the cases rely on a set of simplifying assumptions that are usually validated a posteriori by experimental evidence [17]. Building simulation models rely on many input parameters, whose estimation can be inaccurate, or uncertain. Considering the overall life cycle of a building, many input parameters' uncertainties may occur, which can lead to wrong conclusions in a selection of the best renovation scenario. Such uncertainties can be varied and depends on several factors [18]. For instance, such as the accuracy of the input parameters, (geometry, boundary conditions) [19], occupants' behaviour [20], differences in the heating set points, unforeseen changes in climatic data, building materials with different thermal properties, , financial calculations with incorrect parameters, etc [21].

One of the actions Sweden has taken in closing the performance gap is by verifying compliance through building performance measurements. However, this is an optional measure of each municipality, if they do not opt for this mechanism, they will use to verify energy -efficiency through the calculation of energy demand. For example, it has been estimated in some cases that the measured energy exceeds the calculated energy by 250% [22].

1.7. Uncertainties or importance of LCA in retrofitting

Even a Life Cycle Cost Analysis (LCCA), can also present vague, incomplete and uncertain parameters [23-25]. For instance, average cost [26] and expected lifetime [27, 28], for building elements represent a challenge, especially for those items that have a shorter life span than the calculation period [29]. Other critical inputs are discount rate [25, 27] and calculation period [30].

The aim of the study is to propose a working model that allows residential buildings to be assessed accurately and with the minimum level of intervention: allowing automated assessments to be carried out. As a first part of this project the working method is presented in its basic form, but the next steps of this project are reported in this article.

2. Method

The methodology is based on 3 stages of development. First, the database of energy certificates, costs and LCA was analyzed. In this database, parameters and data were detected to describe the current building conditions as well as the elaboration of renovation scenarios. The second step is to develop a workflow in Rhino/Grasshopper/E-Plus to automatically model a residential building and feed the simulation model with the data obtained from the databases. Finally, a simulation campaign was carried out to obtain an optimal renovation package, minimizing energy consumption and environmental impact. The research was carried out in a case study in Uddevalla, Sweden. The residential building has different measurements including energy consumption data before and after renovation. This was used to validate the proposed method.

Step 1: A renovation catalogue was created based on studies carried out on buildings constructed in the million homes programme. Once the different renovation proposals had been defined, a database of costs and CO2 content of each material was created. An LCA was carried out to calculate the embodied emissions of the design measures studied. The calculation takes into account the initial phases of the life cycle, from raw material extraction to manufacturing (A1-A3) according to the European standard SS-EN15978:2011. The technical lifetime of the buildings was determined based on the value year, which is an estimation of the equivalent age for taxation [31], and for the lifetime of the measures it was used the Boverket's Climate Declaration material database. The cost for the material were collected from Wikells byggberäkningar, a standard reference from the local building industry [32].

Step 2: A simulation campaign was carried out to calibrate the baseline model and to obtain a sensitivity analysis. As a reference the measured heating energy demand during 2017, prior to the building renovation in 2020. The simulations focused on determining the most uncertain parameters of the building, being ventilation and air tightness. The rest of the parameters were known not from measurements but from field verification during the renovation work, such as insulation levels and the condition of the windows. The Monte Carlo method was used for calibration and the Morris's method and a regression.

Step 3: Finally, a workflow was developed between Rhino/Grasshopper/Octopus/Eplus to automate the optimization campaign in connection with the cost database. To obtain the geometrical model of the building, a CAD file was used, which shows the floor plan of the building. Then in Rhino, each level is automatically modelled according to the limits assigned to the drawing, such as height, number of floors etc. The model is exported to Grasshopper and a thermal model of the building is generated, where the materials, conditions of use, schedules etc. are assigned. At this stage of the process the databases are also incorporated as a CSV file, which Grasshopper reads and assigns to each simulation. The script is designed in such a way that the improvements that are assigned to the building can be done randomly for each component, floor, wall, roof, etc. The next tool is Octopus, which performs the optimization, between LCC and LCA. It basically manages the results and sends to Grasshopper the list of the next simulations to be performed always in the direction of minimizing both variables.

The selected building is located in Uddevalla, in the Västra Götaland region of southern Sweden, in a cold temperate climate zone. The building is owned by Uddevallahem and is part of a residential area with about 750 dwellings built between 1965 and 1975. The life expectancy of the building after the renovation is at least 50 years. Due to the cold climate, the renovation measures focus on reducing the energy demand for heating. The building was renovated in 2020, where the insulation in walls, floors and roof was increased and the windows were replaced. As a result of the renovation work, it was possible to verify the insulation levels and the energy reduction resulting from the improvements according to the measurements made for the Energy Performance Certificate EPC, which requires measured, not calculated energy.

The case study is a four-story building, including basement, mainly constructed with precast concrete. The building is heated by district heating. The ground floor consists of 250 mm concrete, the roof consists of 200 mm concrete and 400 mm insulation, the walls consist of precast concrete elements with 100 mm insulation and 90 mm concrete. A blower door test was carried out after the improvements were made, the result and the rest of the details of the building can be seen in the table below.

Table 1. Summary of the characteristics of the building

Description	Before renovation	After renovation
Wall	0,34	0,17
Floor	0,25	0,25
Roof	0,08	0,08
Window	2,40	0,93

Door	2,40	0,93
Ventilation ACH	-	0,35
Airtightness ACH at 50Pa	-	0,58
Energy consumption kWh/m2	140	118

3. Results and discussion

3.1. Data base

The databases consider materials rather than complete component solutions, each material was sourced from scientific articles proposing renovation solutions to buildings constructed under the Million Homes programme. Then in the optimisation phase, a solution is randomly created for floor, wall, roof and window. The solutions vary in the number of layers they can have, the maximum number of layers of the renovation solutions correspond to the maximum number of layers that were used in the selected studies. The studies considered are shown in the Appendix along with the material database.

3.2. Sensitivity analysis

A total of 698 simulations were performed with random variations in the parameters within the selected limit ranges, the distribution of the simulations can be seen in the Figure 1.

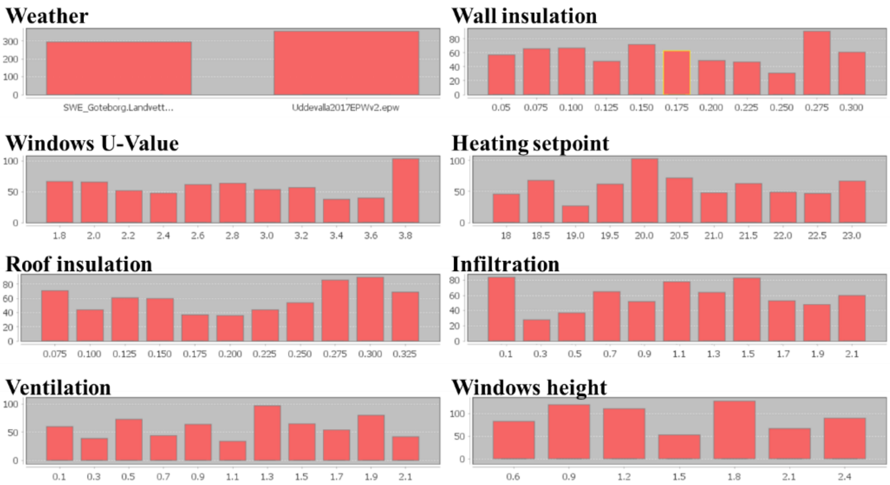

Figure 1. Shows the distribution of the parameters in the simulations performed in the sensitivity analysis.

According to the results of the Morris method, the most influential parameters in the simulation are ventilation and infiltration, which are the only unknown parameters. According to the Figure 2, ventilation is an influential parameter in the accuracy of the energy demand estimation. However, it has a high value in the standard deviation, which indicates that possible interactions with other variables and/or that the variable has a non-linear effect on the output. In the case of infiltration, the calculated value of μ shows that it is a sensitive value but its dependence on the other parameters is less than in the case of ventilation.

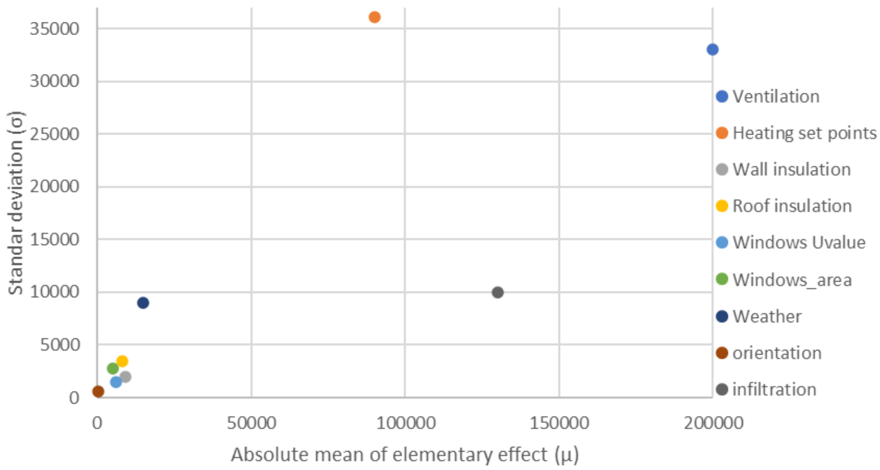

Figure 2. Shows the results of the Morris method

The results of the linear regression show a good fit, with an R2 of 0.98. with a similar pattern to the Morris method, indicating that both ventilation and infiltration are the most sensitive parameters in the estimation of energy demand. Both results also agree on the influence of the heating temperature range as the third parameter. The rest of the work shows only minor impact levels. The results are shown in the Figure 3.

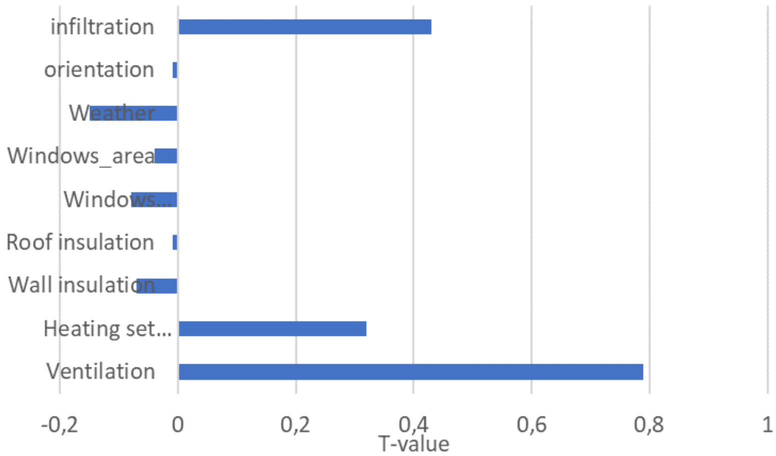

Figure 3. Shows the influence of each parameter according to its importance in the linear regression.

3.3. Calibration

The calibration seeks to adjust the energy demand through the iteration of the unknown parameters, in this case the ventilation and air infiltration flow rates. According to the results of the sensitivity analysis, these parameters are the most influential in the simulation. In order to reduce the uncertainty in the results, all parameters were randomised, and the results that were close to the measured energy demand, 176888 kWh, were revised. According to the results, the air infiltration at 50Pa, the value most likely to be correct is 3,5 ACH, since most of the simulations are in a range close to the measured energy demand values. Almost similar is the case for ventilation, although as the sensitivity analysis showed, the ventilation energy demand is dependent on its interaction with other parameters. This is consistent with the results, as it has a higher dispersion than infiltration. The ventilation flow rate that coincides most often with the measurements and has the smallest dispersion range is 0,5 ACH. Both results can be seen in Figures 4 and 5.

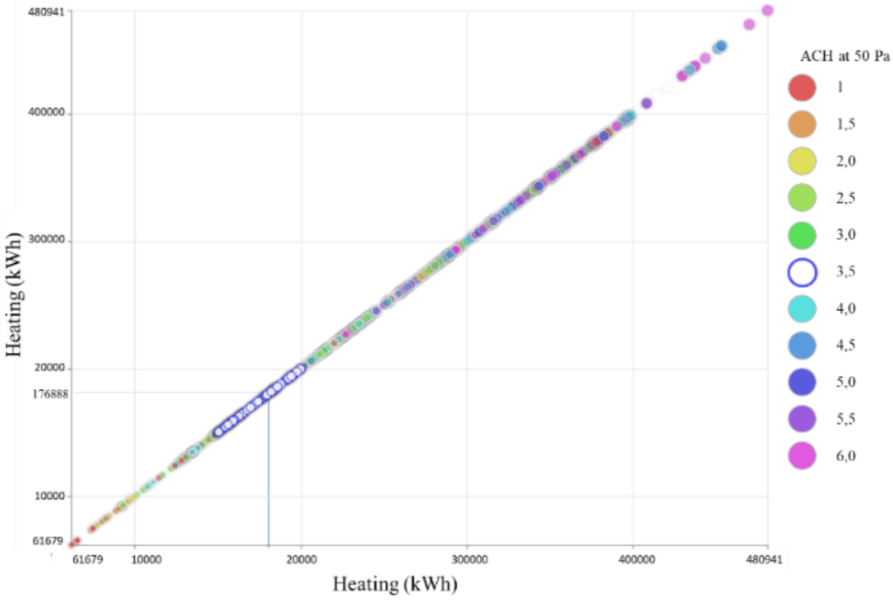

Figure 4. Shows the distribution of the results of the random simulations, where the air tightness at 3.5 ACH is the best fit to the measurements.

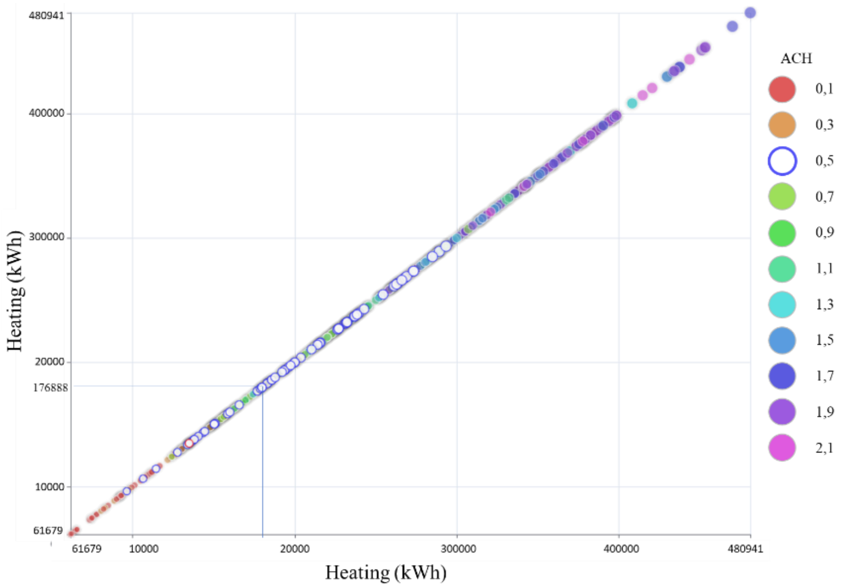

Figure 5. Shows the distribution of the results of the random simulations, where the ventilation at 0,5 ACH is the best fit to the measurements.

3.4. Optimization

The optimization results show that there are different options for renovating the building depending on the main variable to be minimized, cost or emissions. If we consider the results that minimize both, the solutions show that the energy demand can be reduced by 35.5%, this can be seen in the Figure. While in the LCA, the carbon contained in the materials represents 35.3% while in operations it represents 64.7%. The optimization shows that two layers is the optimal number between LCA and LCC. The materials that appear in the optimal solutions vary depending on the component. For walls, the use of rock wool and plasterboard was the most efficient. While for the ceiling, wood fiber and gypsum board performed best, for the windows, triple glazing was the best option. The details of the results of the simulations in the optimization stage can be seen in the Figure 6.

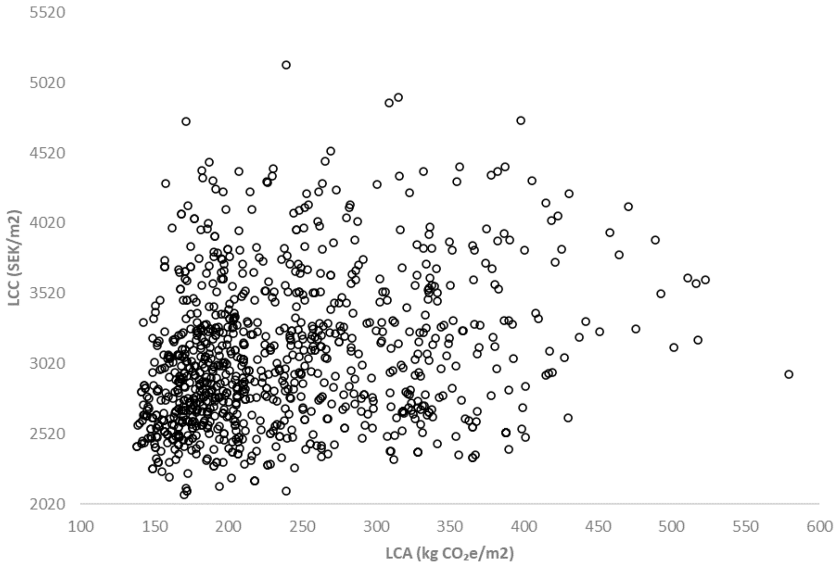

Figure 6. Shows the 6000 simulations performed during the optimisation campaign.

However, the results allow to propose renovation measures in residential buildings in an automated way. Some manual adjustments are required when some parameters are unknown, such as airtightness and ventilation levels in our case. However, the incorporation of calibration into the automated workflow is part of this project in the future. Another important factor to note is that the CAD file has to contain the three-dimensional information of the building, i.e., the number of floors and window heights. As mentioned above, the building was already renovated in 2020. Measurements show that it reduced its energy consumption by 16% by making improvements of the same size excluding the ground floor. Although the 2020 climate is different from the simulation, the difference is substantial compared to the calculated optimal solution, which predicts an energy reduction of 35.5%. In the next phase of the study, a comparison will be made with year-specific climates to verify the differences between the two solutions, in terms of energy and embodied emissions.

4. Conclusion

The proposed methodology allows automated assessment of residential buildings in Sweden, using LCC and LCA to derive optimal renovation solutions. The results show that several optimums can be found, and that it will be up to the stakeholders to decide which variable carries more weight. The savings in terms of energy can be up to 35.5% at a cost of 250 000 SEK per flat. The LCA and LCC analysis shows that the operational and embodied carbon emissions in the material over the 20-year analysis period do not differ much. This means that it is important to consider both aspects when aiming to reduce the environmental impact. The method used could be improved by including calibration work in the workflow, and the material database could be improved with more industry solutions.

5. Appendix

Table 2 shows the database used in the optimization process; information collected through the review of different scientific articles.

Table 2. Materials database.

Material	Conductivity	Cost	Embodied carbon	Density	References
	W/m*K	SEK	kg CO_2e/kg	kg/m³	[32-41]
Mineral wool	0.038	38.0	1.61	300	
Polystyrene with skin	0.04	81.2	4.0	250	
rock wool façade	0.02	53.2	1.61	80	
rock wool roof	0.02	53.2	1.61	180	
Wood fiber	0.038	56.5	0.371	50	
Glass wool	0.042	167.2	1.13	15	
Expanded clay aggregate insulation	0.07	88.9	0.243	400	
Plasterboard	0.4	60.6	0.333	760	
Gypsum board	0.21	39.4	0.333	760	
Particle board	0.1	113.0	0.488	300	
Gypsum fireboard MDF	0.07	102.0	0.32	250	
Gypsum floorboard	0.43	60.6	0.296	1120	
Cement fibreboard construction board	0.25	281.0	0.849	1080	
OSB	0.13	220.9	0.448	607	
light weight Concrete	0.1	550.3	0.291	1360	
Plywood	0.09	340.0	0.448	460	
Window wood/aluminium inward 3-glass (U-value)	1.1	6979.0	2.5	40	
Window wood inward 3-glass (U-value)	0.85	4967.0	2.13	36	
Window wood fixed 3-glass (U-value)	0.80	3816.0	2.13	35	
Window wood/aluminium side hung 3-glass (U-value)	0.60	7627.0	2.88	39	

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