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Carbon-cost efficient retrofit of passive and active systems in residential buildings using genetic algorithm

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Abstract

In the past two decades, improving the energy performance of existing buildings is a major trend to reduce the environmental impacts since existing buildings make up for the largest share compared to new buildings. The energy consumed in a building consists of both embodied and operational form. However, most current conducted energy optimizations only consider operational energy and remain reluctant to the embodied energy invested in building materials and services during the life cycle of a building. The main innovation of this study is to address both types of operational and embodied energy together and consider building as a whole in order to optimize properties of the envelope and HVAC systems simultaneously. This approach shows a significant difference in optimal carbon-cost efficient retrofit scenarios.

The current research uses MOGA (Multi Objective Genetic Algorithm) to minimize CO_2 equivalent emissions, and costs in order to find optimal retrofit scenarios for a typical multi-family house (MFH06) according to TABULA building classification for Germany. Findings show four clusters of refurbishment scenarios that are mainly categorized based on the amount of insulation materials. It is also perceived that the most optimal carbon-cost retrofit options focus on increasing the thermal energy storage capacity and remain reluctant in insulating the envelope or changing the windows for a typical multi-family house of 1970s mainly due to high embodied energy in the insulation materials and devices.

Keywords

Operational and Embodied Energy, Carbon-Cost Efficient Retrofit, Life cycle Carbon Footprint, Life Cycle Cost, Genetic Algorithm

Introduction

Building sector is the leading energy consuming sector globally with approximately 33-40 % of energy consumption and 40 % of direct and indirect CO_2 emissions (International Energy Agency (IEA), 2019). The share of energy consumed in the building sector is approximately 35 % in Germany. In the building sector itself, residential buildings are responsible for 63 % of the end-energy-use (Deutsche Energie-Agentur GmbH, 2016). According to the German market building classification (2016), around 38 % of buildings are built between 1949 to 1978. The time spans in Figure 1 are mainly according to TABULA typology system. TABULA is a classification system for residential buildings throughout different European countries (EOISCOPE, 2012). The basis for this classification is based on size and age of buildings. The result is a matrix of buildings according to their construction date and type, with further information on their envelope and heating system characteristics. Since one generation of building is considered to be at least 30 years, in this study we focus on multi-family houses that are built during the period of 1969 to 1978 in Germany and tagged as MFH06. This group falls within the time span of the largest share of building stock in Germany.

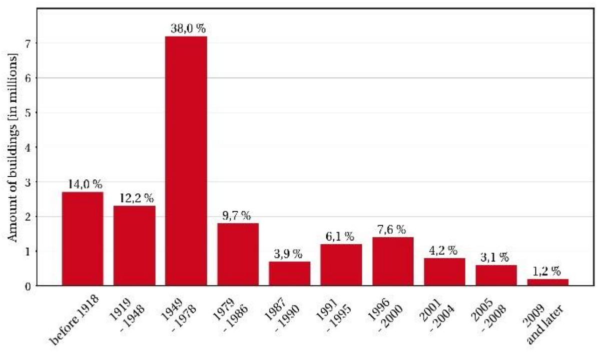

Figure 1. Share of residential buildings according to different age classes (Deutsche Energie-Agentur GmbH, 2016)

Most of the research around energy efficiency in buildings focus on optimizing operational energy. This approach only considers building in its operation phase. However, life of a building is not limited to the operation phase and spans from manufacturing the raw materials to the demolition and deconstruction of it. The energy used in these phases is usually hidden, therefore called embodied energy. The current study tries to integrate the knowledge of saving strategies in both operating and embodied energy and investigate the building as a whole.

Energy retrofit in the life cycle of the building

Buildings often undergo a retrofit process after their service life ends. This retrofit process often takes place using high energy-conserving upgrades that include both the envelope and HVAC systems of a building. This process is called energy retrofit. Assessing energy and environmental performances during an energy retrofit

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action is a sensitive matter because it consists of a trade-off between operational energy which is the energy being used by the HVAC systems, and the embodied energy which is the grey energy embedded in the building materials and components that are added to the building, utilized mainly in material extraction, transportation and manufacturing processes.

Life Cycle Assessment (LCA) is the method of calculating environmental impacts that a product can have. In Architecture, the product is the "building" and the metrics that measure its environmental impact are usually "Primary Energy Non-Renewable" and "Greenhouse Gas Emissions". LCA allows to estimate the possible reduction in operational energy and possible increase in the embodied energy within the span of building's extended life. Finally, one can understand whether the achieved energy benefits have overcome the environmental burdens of the retrofit action or not when we look at the life cycle of the building. A life cycle assessment quantifies the potential environmental impact of a product or a service and is defined in the DIN EN ISO 14040 and ISO 14044 standards. The LCA studies often show the relationship between the materials' embodied energy and the operational energy which is referred to as the energy required to maintain the building and its comfort conditions (Vilches, Garcia-Martinez, & Sanchez-Montanes, 2017).

Life cycle assessment according to DIN EN ISO, 14040 normally consists of a Life Cycle Inventory analysis (LCI), which is an inventory of all inflows and outflows. It is followed by a life cycle impact assessment (LCIA), in which the contributions from the different inflows and outflows to impact categories, such as climate change, human health, ecosystem quality, etc. are calculated. However, because of the uncertainties coupled to the models for calculating impact indicators, the LCA in this study is mainly limited to an LCI of energy flows and emissions. No impact indicators were considered, except for the global warming potential that calculates the cumulative climate change effect of the different emissions over a certain period (Verbeeck & Hens, 2007).

An LCA study usually contains three groups of life cycle phases: production, use phase, and end-of-life. The standard DIN EN, 15804 differentiates them into 17 clear stages. The B5 phase is the stage in which retrofit of a building takes place. However, when studying this stage alone, we should determine clear boundaries for input and output flows. In this study we consider the retrofit of both HVAC and envelope. Therefore, we have the inflows of new materials being inserted to the system both in the envelope and the new implemented HVAC system. With the same logic, we have the outflow of old materials that are taken out from the envelope or HVAC systems. Figure 2 illustrates the 17 different stages of LCA together with the boundary of this study.

The retrofit of an existing building has the potential to significantly improve its overall life cycle impact (Power, 2008 & Ding, 2013 & Goldstein et. al, 2013). LCCF is a measurement that accounts for all the processes that involve CO_2 inputs or outputs in buildings throughout their life cycle. According to life cycle energy analysis (Dixit et. al., 2012 & Ramesh et. al., 2010), CO_2 emissions flow in and out of building systems through embodied CO_2, operation-related CO_2, and CO_2 emissions due to demolition. Other processes including CO_2 emissions have been recently investigated (Kellenberger & Althaus, 2009 & Guignot et. al., 2015) which mainly focus on integrating renewable technologies which decease the CO_2 emissions during operational phase, and CO_2 savings during the recycling phase (Blengini, 2009).

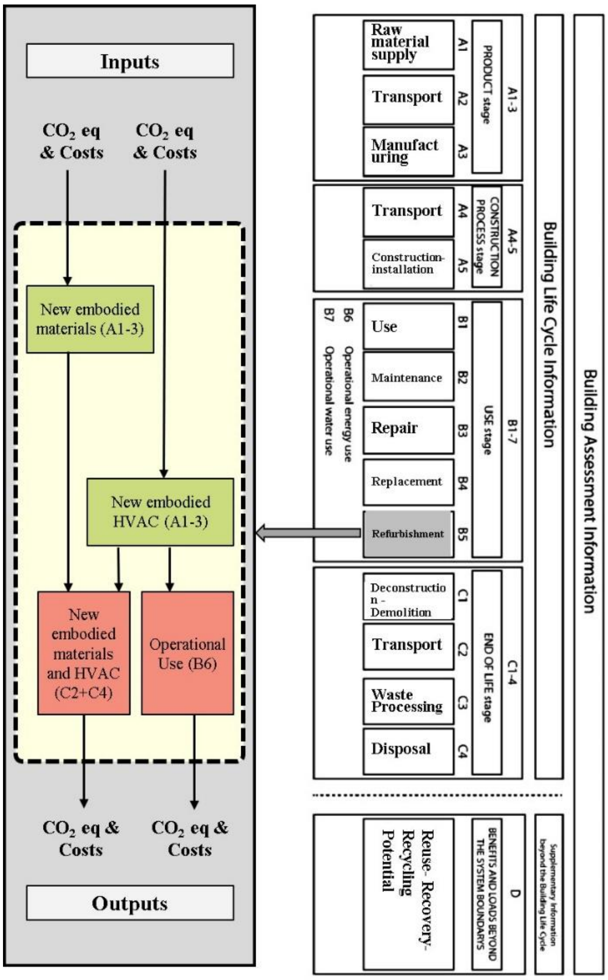

Figure 2. Existing building retrofit boundary based on (Vilches et al., 2017)

Retrofit Scenarios Optimization

There has been a notable increase of building optimization studies since 2011 (Evins, 2013), which is mainly due to the increased computational capacity of computers and industry interest into addressing more uncertainty while facing more stringent design problems. In this regard, many decisions in the building sector require a trade-off between conflicting parameters which makes it harder for the designers to address. Real-world optimization problems are usually therefore multi objective, meaning that we are interested in minimizing and/or maximizing more than one measure

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simultaneously. For such problems, Evolutionary Algorithms have shown a great capability into efficiently finding near-optimal solutions in a vast search space. In a study conducted by Evins (2013) it is shown that more than 75% of the optimization studies in the built environment is using evolutionary algorithms with Genetic Algorithm being the most popular accounting for more than half of the studies. As a result, we chose Genetic Algorithm for a holistic building optimization that enables investigation for the whole building elements, including passive envelope and active HVAC systems.

Methodology

We have developed an object-oriented model for modeling the building. Every building modeled, consists of smaller models of envelope elements as well as different HVAC systems written in Python. In the first step, the heat load is calculated according to the description of the envelope elements and based on a simplified thermal building model, DIN EN ISO, 13790. which is a dynamic resistance capacitance model. The resulting building heat load is the input variable for the system optimization. In the next step, we created different combination of retrofit interventions as our optimization individuals based on the following variables:

- Existence of a PV and/or solar thermal
- Hot water storage capacity
- Heating System
- U-value of Window
- Thickness and type of insulation material

Following that, we defined our cost functions. The study seeks to find out best solutions that are minimum in negative environmental impacts and are less costly. To define the environmental impacts, we take in CO_{2eq} as the most important greenhouse gas emissions to capture the global warming potential (GWP) of the retrofit action. This amount is called Life Cycle Carbon Footprint (LCCF) and is traced during the life cycle stages defined in Figure 2 as the study boundary. The life cycle carbon footprint during these stages is:

$$LCCF = LCCF_{Envelope} + LCCF_{HVAC} = CO_{2eq}\,(A1\text{-}3)_{Envelope} + CO_{2\,eq}\,(A1\text{-}3)_{HVAC} + CO_{2eq}\,(B6)_{HVAC} + CO_{2eq}\,(C_{2\&4})_{HVAC}$$

All global warming potential of insulation materials for each relevant envelope element, is calculated for the A1-3, B6 and C2&4 phases.

To define the costs of a system during its life cycle (LCC), we have to identify the investment efficiency of that system over time. This study uses the annuity method, recommended by German standard (VDI, 2067). In this method, both one-off investments and ongoing payments during a specific observation period, is calculated using the annuity factor. The costs aggregated in LCC should be investigated for both the building envelope and the HVAC system. The initial cost for building envelope elements, simply consists of the price of insulation material multiplied by the area of the retrofitted element. However, to address cost differences for various thicknesses of the same material, we interpolated a linear ratio based on normalized 2019 BKI[1] costs for different thicknesses of the studied materials. The one-off cost for envelope elements is:

$$LCC = LCC_{Envelope} + LCC_{HVAC} = Cost(A1\text{-}3)_{Envelope} + Cost(A1\text{-}3)_{HVAC} + Cost(B6)_{HVAC}$$

We calculated the annual heat load profile for every combination of retrofit scenarios for the envelope and further do an optimization calculation for the best combination of system und envelope retrofit and calculated the LCC and LCCF of it. Figure 3 depicts the process of optimization where calculations for LCCF and LCC are made for every single variant and the results are compared with the initial state of the building as reference case from TABULA. After that, the most fit variants found make up the pareto front as the best optimization solutions.

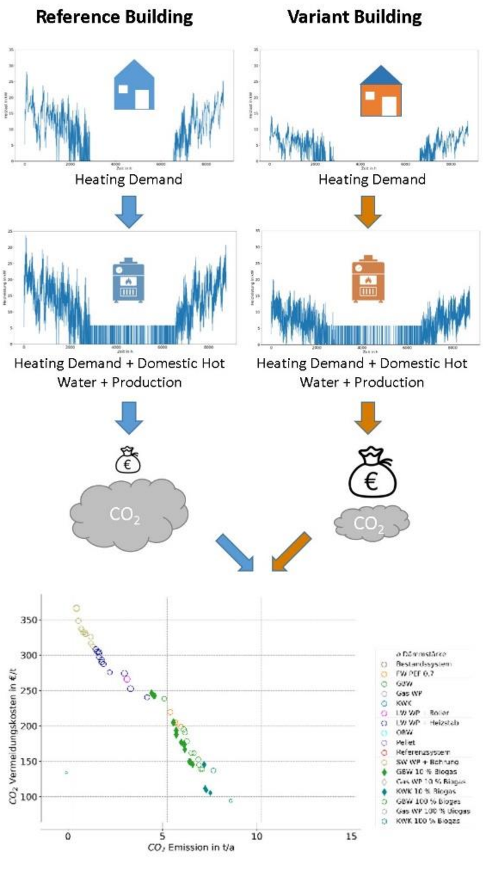

Figure 3. Comparison of optimization solutions with reference case during the optimization process

For the optimization of individuals, we used open-source Evolutionary Algorithm optimization packages in python, namely DEAP (Fortin, Rainville, Gardner, Parizeau, &

[1] Baukosteninformationszentrum: The German annual book of building costs

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Gagné, 2012). The model is fed in with additional data over weather condition, occupants and characteristics of the MFH06 building type. Table 1 shows the relevant data used for simulation of the model.

Table 1. Input data for simulation of the MFH06 building

Latitude in °	52.1
Longitude in °	12.4
German weather test reference year	Region 4
Heated area in m²	800
Inhabitants	10
DHW surcharge	1.25
Domestic hot water preparation	central
Existing boiler type	oil
PV slope in °	30
PV azimuth in °	45
ST slope in °	30
ST azimuth in °	45
Outdoor wall area in m²	568
Roof area in m²	300
Floor area in m²	200
Window area in m²	160
Solar area in m²	9
PV area in m²	40
Volume thermal water storage in L	200

The last part of the optimization is to conduct the genetic algorithm based on the parameters set on the previous stage. For this purpose, we first initialized a population of 500 random individuals. In the next step, the computer calculates the LCC and LCCF for all individuals of the population. At the end of the calculations for each population, the most fit individuals that have the least amount of LCC and LCCF are chosen as the parents for the next generations. These set of individuals are stored in a logbook, which is a chronological sequence of entries. At this point, if the number of generations has not reached a predefined amount, the algorithm goes on by mutating and breeding the selected individuals to create a new set of individuals as the next population. The most important aspect in this part is the calculation of LCC and LCCF where the costs and the environmental impact is being investigated during several stages of the building life cycle. In the following, we will explain the results from optimization of 500 individuals with the crossover rate of 0.7 and mutation rate of 0.2 over 80 generations.

Results

In the following, optimization result of the carbon-cost efficient analysis of a typical multi-family house from 1978 according to LCC and LCCF is illustrated using two methods. The first method with the results being presented by the orange dots is the conventional operational carbon-cost analysis of the building which only considers the B6 phase of the LCA. On the other hand, the proposed method of this research which is presented by blue dots shows the carbon-cost analysis when both embodied and operational energy is taken into account for a period of 30 years. In this regard, not only the operational CO_{2eq} produced in the building due to the burning of fuel by the HVAC system is calculated, but also the embodied CO_{2eq} in the HVAC devices as well as the embodied CO_{2eq} in the elements of the envelope such as windows and insulation material are considered. The more the solutions travel to the right side of the diagram and toward positive LCCF, the more CO_{2eq} is produced due to that retrofit scenario. Negative LCCF means that the building has less environmental burdens through emitting less CO_{2eq} compared to the reference building which is rendered by a blue dot in Figure 5.

It is perceived from Figure 4 that a better distinguish between the environmental impact of results will be achieved using the proposed method. Most solutions of the conventional method show little environmental impact which mainly vary based on the costs budget due to a wide selection of various HVAC systems and envelope elements. On the other hand, the solutions of the proposed model suggest a greater variation in environmental impacts which definitely influences the retrofit decision. It also consists of solutions that are significantly more limited in variety of selections for HVAC and envelope elements.

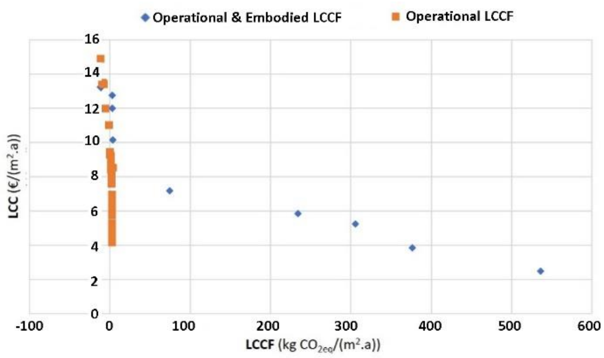

Figure 4. Comparison of results using conventional method based on operational energy with proposed method based on a combination of operational and embodied energy

Figure 5 shows the pareto front of the carbon-cost efficient retrofit scenarios for the multi-family residential building of type MFH06 of TABULA. In total, 77 optimal cases were achieved after 80 generations. Some of these solutions on the pareto front are very close to one another and therefore visible only as a single spot in the chart. The x axis represents the LCCF of every solution compared to the reference building which is the breakdown of CO_{2eq} that the system produces over the 30 years of the study

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and per square meter of the building. As a result, the unit is in kg $CO_{2eq}/(m^2.a)$. The y axis represents the LCC of the results which is the annual costs of any active or passive retrofit actions considered per square meter of building with the unit of €/(m^2.a).

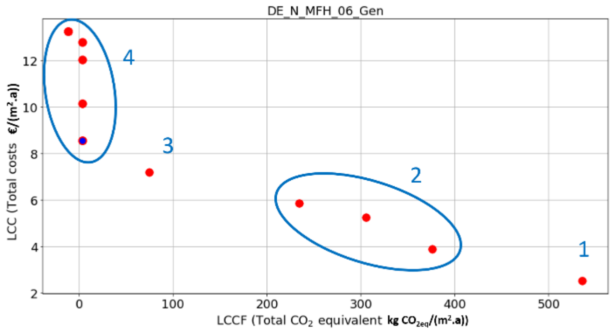

Figure 5. Pareto front of retrofit options for multi-family house of 1978

In general, four distinguished clusters of results are detected according to the environmental impact they create. The reference case is plotted with a blue dot. It is perceived from the first cluster that a minimum of approximately 2.5 €/(m^2.a) is required from a carbon-cost-optimal point of view. This will typically have the highest environmental burden of adding around 535 kg/(m^2.a) of CO_{2eq} emissions compared to the other optima with significantly less emissions. This scenario consists of keeping the existing window and HVAC system which is an oil boiler, and only adding 12 cm of Hemp fiber fleece insulation for the wall and roof and 8 cm of the same insulation material for the floor. Although these solutions decide against change of the old HVAC, they seem to suggest a capacity increase of hot water storage from 200 l to 750 l.

The second cluster is the retrofit scenario with 200-400 kg $CO_{2eq}/(m^2.a)$. This cluster shows a similar trend as the previous cluster, however, the amount of insulation on the envelope is relatively reduced which results in significant reduction of environmental impacts. The envelope insulation in this cluster is reduced to two out of the three elements of floor, roof, and wall.

The third cluster consists of solutions that are mainly insulating one element of the envelope, the floor. Apart from a lower amount of insulation, this cluster show not much more significant variation in other two prior scenarios.

Most solutions fall between -11 to 3.6 kg $CO_{2eq}/(m^2.a)$ which make up the fourth cluster. The most distinguishing aspect of this group is that none of them are using insulation on the envelope which explains the significant lower environmental impacts by a reduced kg CO_{2eq} production. Almost half of these solutions are using the existing HVAC system, whereas the other half show a switch to integrating CHP. Where a CHP is recommended, it is coupled with a sharp increase in the hot water storage, peaking to 1200 and 1500 l. However, this capacity is moderately increased to 750 l like many of the other solutions that are coupled with the existing boiler.

Figure 6 shows the total distribution of HVAC system selection in all four clusters with or without the use of insulation. In total, it is clear that with a CHP system, no insulation is required. Few cases of envelope insulation only happen with the existing boiler as the HVAC system.

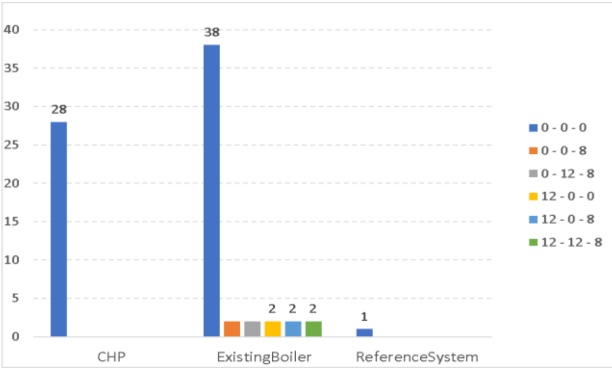

Figure 6. Distribution of HVAC system selection with regard to the envelope insulation thickness in all pareto solutions (W-wall, R-roof, F-floor)

Insulation of the envelope in general is not the most optimum solution for retrofit. It was reflected in Figure 5 that the main environmental burden of solutions come from the insulation material. Figure 7 shows the distribution of insulation material on different parts of the envelope among the 77 selected pareto solutions. It appears that none of the three envelope elements of floor, wall or roof, have priority over the other from a carbon-cost efficient perspective. Among different selection of insulation materials, hemp fiber fleece is determined as the most cost-carbon efficient insulation material.

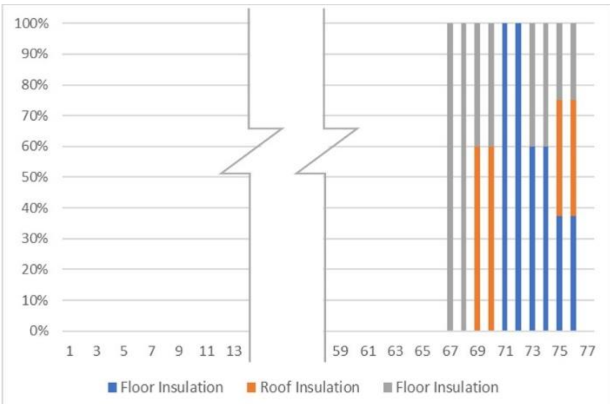

Figure 7. Distribution of insulation in different parts of the envelope

Overall, it is interestingly shown in Figure 7 that most of the optimal retrofit solutions have not selected insulation of the envelope. When other major aspects of solutions such as the HVAC system, U-value of the window and implementing PV or solar thermal systems, it was clear

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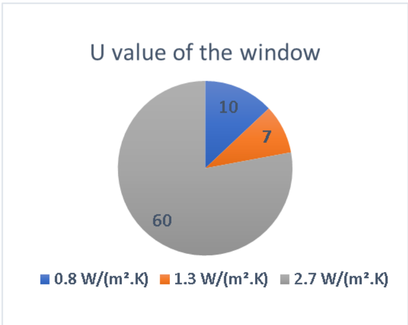
that in most cases these values had kept the initial values of the existing building which indicates that a retrofit focusing on these aspects is not the best practice.

Figure 8 reflects that most cases show a tendency of not changing the old windows with the U-Value of 2.7 and instead increase the storage size. Possible reason could be the very high embodied energy used in the complex materials of the frame, glass and sealers of the windows. It is also clear that all cases except for the reference case show a change of capacity of the hot water storage from the existing 200 l to mainly 750 l. Since there is no capacity size between 200 and 750 and a bigger size fits better to the consumption profile of 10 persons.



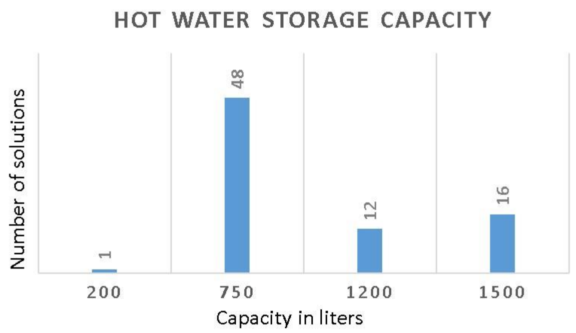


Figure 8. Suggested window selection (up) and hot water storage capacity for optimal retrofit options (down)

Conclusion

This paper proposes a binary discrete optimisation method using genetic algorithm to identify the most appropriate retrofitting options for a typical multi-family house according to TABULA classification. The proposed method combines the operational and embodied carbon footprint throughout the life cycle of the building. We took into account both building envelope together with HVAC systems to address the building as a whole. Results indicated that the proposed method show a better distribution of results regarding the life cycle carbon footprint and therefore more influential for the decision making. The best retrofit practice for multi-family houses built in the period between 1969 and 1978 is to increase the hot water storage capacity with the assumption of an installed storage size of 200 L and most likely to keep the existing windows and HVAC system. The optimization also highly decides against the insulation of the envelope when considering the massive area of retrofit and the global warming potential hidden in the material. This is contrary to what currently happens in the building stock. Although it is shown that the envelope insulation is the least expensive measure available, however, it has considerable environmental impacts when compared with more expensive solutions such as HVAC change to a CHP which are more environmentally friendly. Despite the decision against insulating the envelope, the best cost-carbon efficient insulation material for retrofit is shown to be hemp fiber fleece. The results initially refer only to the one selected TABULA building and no legal requirements to restrict the solution space were taken into account and effects of thermal comfort was also neglected. In the next step, it is planned to take into account the B2 and B4 phases of the life cycle as well as some of the end of life stages.

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