The most cost-effective energy solution in renovating a multi-family house

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Abstract. The Swedish government aims to reduce total energy demand per heated building area by 50% until 2050. A large number of residential buildings, built within the so-called "Million homes program" in Sweden, need major renovations, which offers an opportunity to implement energy efficiency measures and thereby, reduce total energy demand. The best way to encourage the implementation of a major renovation is to demonstrate a practical method which reduces energy demand and provides economic benefits. Hence, this study aims to determine the most cost-effective energy solution in renovating a multi-family residential building. Multiple energy renovation measures were simulated on a case study to reduce the space heating and domestic hot water by 50%. The case study building was built within the "Million homes program" and is located in Växjö, Swedish climate zone 3. Design Builder software was used for analysing the pre-renovation energy performance of the building. The renovation measures comprised different insulation thicknesses of external walls, attic and ground floors, windows with different U-values, a mechanical ventilation with heat recovery system, and solar system for supporting space heating and domestic hot water. Later, a multi-objective optimization was accomplished for analysing every possible combination of renovation measures. The most cost-effective energy solution was obtained by calculating the net present value in a lifetime of 30 and 50 years and discount rate of 1%, 3% and 5%. Comparing the implications of two different lifetimes on net present value with implications of three different discount rates on net present value shows that lifetime has more influence on net present value. Furthermore, the results show the capability of the multi-objective optimization method in analysing multiple renovation solution.

Keywords: Net present value, Energy renovation measures, Multi-objective optimization

1 Introduction

The latest recast of the EU Energy Performance of Buildings Directive (EPBD) asks all member states to implement changes in building regulations to reduce the total energy demand [1]. Although EPBD's requirements target mostly new buildings, the directive asked all EU members to determine cost-effective energy solutions in renovating existing buildings [1], because the existing older buildings within the EU region have significant energy savings potential [2]. Furthermore, the annex to the EPBD has mentioned that the minimum comfort thresholds, defined at national level, should be ensured in calculating the energy demand [1]. In Sweden, actions have been taken by the government to reduce the total energy demand per heated building area by 20% and

50% until 2020 and 2050 respectively, compared to the energy demand in 1995 [3]. The total energy demand of the existing residential buildings in Sweden was about 147 TWh in 2013, which corresponds to 40% of the total energy demand in this country at the same year [4]. A large share of the existing residential buildings in Sweden were constructed in 1960s and 1970s, known as “Million homes program” [5]. According to Swedish energy agancy [6], over half of the total energy consumption in Swedish residential buildings is for space heating and domestic hot water. Major renovation of these buildings can provide a significant opportunity to implement energy efficiency measures and thereby, reduce the energy need for space heating and domestic hot water. At this point, Mahapatra and Olsson [7] and Dodoo, et al. [8] discussed that renovating buildings to passive house standard can significantly reduce energy demand for space heating and domestic hot water. Janson [9] listed energy renovation measures, which can be implemented in renovating Swedish residential buildings to reduce energy need for space heating and domestic hot water. The list comprised energy renovation measures such as improved airtightness of buildings’ envelopes, energy efficient windows and doors, efficient water taps, improved thermal insulation, installation of energy efficient mechanical ventilation system, energy-efficient home appliances [9], and other renewable-based energy systems such as heat pumps and solar energy systems [10].

But, according to Niemelä, et al. [2], the best way to encourage the implementation of a major renovation is to demonstrate a practical method which reduces energy demand and also provides economic benefits. Bonakdar, et al. [11], Bonakdar, et al. [12] and Gustafsson, et al. [13] discussed about energy and cost effectiveness of implementing energy renovation measures in Swedish residential buildings. Although these studies presented useful results, but they have mainly considered a few renovation measures in Sweden, without analysing all possible combinations of the measures [12-14]. For instance, Gustafsson, et al. [13] analysed five different renovation measures including insulation of external walls (with U-value of 0.6 and 0.26 $W/m^2. K$), roof (with U-value of 0.6 and 0.15 $W/m^2. K$), energy efficient windows (with U-value of 2.58 and 1.2 $W/m^2. K$), doors (with U-value of 2.72 and 1.38 $W/m^2. K$), and four different energy-efficient mechanical ventilation systems. However, only three renovation solutions were defined based on *combination* of the renovation measures. The effectiveness of each solution was later analysed with respect to life cycle cost, primary energy consumption, payback time and carbon dioxide emission. Such analyses are limited to a small number of solutions (based on combination of measures), hence limits the feasibility of finding *the most* cost-effective energy renovation solution [2, 14]. Bonakdar, et al. [11] studied the contribution of Swedish climate zones to the cost-optimal renovation strategy. Four renovation measures were defined and analysed in a multi-family house building, including insulation of external walls, basement walls, attic floor and the installation of energy-efficient windows. However, they analysed the effectiveness of an individual renovation strategy on cost but not the effectiveness of combination of measures, where there may exist the most cost-effective energy renovation solution.

In line with previous studies, Chantrelle, et al. [15] attempt to develop a tool by using an optimization method, which was used to specify a cost-effective energy solution in renovating an educational building in France. The renovation measures included renovation on external walls, roof, ground floor, intermediate floor, internal partition wall and windows. Furthermore, they analysed the performance of the renovation solutions in improving thermal comfort. The presented results indicate that optimization can be used as an aid in specifying a cost-effective energy renovation solution. Because, it can analyse a large number of renovation solutions based on combination of measures, that increases the likelihood of finding the most cost-effective energy renovation solution. Niemelä, et al. [2] used a multi-objective optimization method to specify the most cost-effective solution in renovating an educational building to near zero energy building in Finland. The renovation measures comprised the renovation of existed ventilation system, installation of windows with smaller U-value, using additional insulation layer for external walls and roof, installation a ground source heat pump system and PV-panels for electricity production. The results show that multi-objective optimization is a beneficial method in analysing multiple solutions and specifying the most cost-effective energy renovation solution. However, no study, to the best of authors knowledge, have used a multi-objective optimization as a method in renovating a multi-family building in Sweden.

Considering the abovementioned limitations, this study aims to find the most cost-effective energy renovation solution in renovating a multi-family residential building, constructed during the "Million homes program". Multiple energy renovation measures, suggested by Janson [9] and Kjellsson [10], were implemented to reduce the energy need for space heating and domestic hot water by 50%, compared to 1995[1]. Later, a multi-objective optimization was accomplished for analysing every possible combination of renovation measures. The most cost-effective energy solution was obtained by calculating the net present value in a lifetime of 30 and 50 years and discount rate of 1%, 3% and 5%.

2 Case study

The multi-family building was located in Växjö municipality in Swedish climate zone 3. The building was constructed between 1966-1968. It has three residential-floors above the ground with four separate apartments in each floor. The total heated area of each floor is about 375 m², with ventilated volume of 937.5 m³. The forth floor, which includes some storage unit for the apartment, had a wooden pitched roof and considered as an unheated area.

[1] Between 1990 and 2000, the energy demand for space heating and domestic hot water in multi-family house buildings was about 130 (kWh/m²) [16]

2.1 Energy performance simulations

The energy performance of the building was studied using Design Builder software, version 5.0.3.007 [17]. Design Builder is a graphical user interface for EnergyPlus. EnergyPlus is one of the frequently used tools in analysing the energy performance of a building [18]. The energy performance evaluation was started by constructing a 3D model and providing data regarding material specifications of envelopes including windows, doors, external and internal walls, ground floor and attic floor. Furthermore, building's location, geometry, occupancy schedule, heating and ventilation system were specified for executing simulations. The building was connected to the district heating system to cover the demand for space heating and domestic hot water. Table 1 presents a summary of the simulation layout of the building, applied in Design Builder software.

Table 1. Simulation layout of the studied building in initial status[2]

General properties	Values
U-value of Windows	2.90 (W/m². K)
U-value of Doors	3.00 (W/m². K)
U-value of the attic floor	0.51 (W/m². K)
U-value of the east and west façade	0.367 (W/m². K)
U-value of the north and south façade	0.279 (W/m². K)
U-value of the ground floor slab	2.70 (W/m². K)
Efficiency of fan for ventilation	0.5
Air tightness	0.8 (l/m². s) at differential pressure of +/- 50 Pa
Electrical lighting	Fluorescent 9.9 (W/ m²) power

The internal gain from occupants was assumed to be 60 W/ person, which corresponds to activity level of seated at rest [19]. Furthermore, the heat gain from electrical lighting was assumed to be about 82% of the energy used by lighting system[3]. The thermal resistance of clothing follows ISO7730 Standard and was set to be 0.5 (clo) in summer and 1 (clo) in winter [20]. The building was assumed to be occupied 24 hours during weekends and 16 hours (between 16:00 pm to 08:00 am) during working days. Furthermore, the density of occupancy was assumed to be 0.03 (person/ m²). The simulated initial energy demand before implementing energy renovation measures for space heating, domestic hot water and electricity for ventilation was about 95 (kWh/ m²), 24.8 (kWh/ m²) and 5 (kWh/ m²) respectively.

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[2] The presented information in table 1 was an assumption regarding initial status of the building and was provided by Växjöbostäder.

[3] In Design Builder database, it has been stated that visible fraction of a fluorescent lighting system is about 18%, while the radiant and convictive fractions are 42% and 40% respectively.

2.2 Renovation measures

In this study, the renovation measures were comprised of improving the U-value of the building's envelopes, upgrading the ventilation system and installing solar heating system for supporting space heating and domestic hot water. Table 2 lists the renovation measures analysed in this study. The U-values of the measures were equal or lower than the requirements of the Swedish building code for new buildings (BBR 2015) [21]. The heating system was kept unchanged, because this type of biomass-based district heating systems has low environmental impact and about 80% of the multi-family buildings in Sweden are connected to such a system [13]. The U-value of external walls, attic floor and ground floor were improved by replacing the old insulation layer with a cellulose insulation layer having a conductivity of 0.04 (W/m². K). Because old insulation layers can be degraded after their lifetime, which has negative impact on conductivity of insulation layer [22]. Cellulose was selected due to its small environmental impact compared to Rockwool insulation material [23]. The pitched roof, which had initially no insulation layer, was not considered in defining renovation measures. Because the forth floor (area under the pitched roof) is indeed an unheated area. Furthermore, adding some insulation layer in pitched roof may have negative impact by accumulating moisture in the roof [24].

The existing ventilation system was upgraded by using a heat recovery system with an efficiency of 76% [25]. A solar heating system, comprised of 18 vacuum solar collectors, was installed on the roof with a 50º slope of surface and facing south.

Table 2. Renovation measures

Building envelop component	Simulated alternatives	BBR 2015 requirement U-value (W/m². K)	U-value (W/m². K)	efficiency
Windows	**-**	1.3	-	
	Type 1		0.8	
	Type 2		0.9	
	Type 3		1	
	Type 4		1.1	
	Type 5		1.2	
External walls	**-**	0.18	-	
	Type 1		0.09	
	Type 2		0.1	
	Type 3		0.12	
	Type 4		0.14	
	Type 5		0.18	
Attic floor	**-**	-[4]	-	

[4] No requirements have been found in BBR 2015 considering the maximum U-value for attic floor.

	Type 1		0.08	
	Type 2		0.09	
	Type 3		0.1	
	Type 4		0.12	
	Type 5		0.13	
Ground floor	**-**	0.15		
	Type 1		0.08	
	Type 2		0.09	
	Type 3		0.1	
	Type 4		0.12	
	Type 5		0.15	
Heat recovery	**-**		-	76%
Solar collectors	**-**		-	1119 (kWh/ year)

Combination of the above energy renovation measures resulted in 625 renovation solutions. There is a need to clarify that specifying the most cost-effective energy renovation solution may not necessarily include all abovementioned renovation measures. However, evaluating different renovation measures helps to monitor the degree of their effect in reducing energy consumption and increases the likelihood of finding the most cost-effective energy renovation solution.

Since simulating and analysing so many solutions is infeasible, multi-objective optimization was performed to evaluate the cost and energy performance of the 625 renovation solutions.

2.3 Multi-objective optimization

A multi-objective optimization involves in the minimization of optimization functions by interacting optimization variables [26]. In this study, the multi-objective optimization was accomplished by using the non-dominated sorting genetic algorithm-II (NSGA-II) in Design Builder software. The first step in performing the multi-objective optimization was to specify optimization variables. All considered renovation measures in table 2 were defined as optimization variables. Later, the thermal discomfort hours (all clo) $\leq$ 200 [h] was defined as constraints function [27]. This means that optimization process searched for renovation solutions in which the total thermal discomfort hours are less than 200 hours. This decision was made to fulfil the EPBD's requirements in terms of ensuring the minimum thermal comfort threshold in renovating the building. Furthermore, the execution time required for performing an optimization was recorded. The processor of the computer, used in running simulations and optimization was an AMD FX-7600P Radeon (4 cores, 2700 Mhz) with 8 GB installed physical memory (RAM).

The optimization process provided information regarding energy need for space heating, domestic hot water and electricity for running the ventilation system of all 625 renovation solutions. The total energy demand of the renovation solutions was later calculated as the sum of energy need for space heating, domestic hot water and electricity for running ventilation system.

Furthermore, the optimization process uses provided information in Design Builder regarding investment cost of each renovation measure and calculates the total investment cost for all 625 renovation solutions. The investment cost in this study, was based on material cost for each renovation measure. The investment cost for five types of windows was defined separately as price per unit window (SEK/m²) [28]. Design builder calculates automatically the total investment cost for five types of windows based on the unit price of the windows multiplied by the total windows area. The investment cost of insulation layer was defined as price per volume cellulose (SEK/m³) [29]. Design Builder quantifies automatically the required volume of cellulose for five types of external walls, attic and ground floors and calculates their respective investment cost. All results obtained from optimization processes were saved in excel files. A constant expense for installing heat recovery for ventilation [30-32] and solar heating system [33] was added to the investment cost of each of the 625 renovation solutions.

To find the most cost-effective energy renovation solution, the net present value of the 625 renovation solutions was calculated. Net present value shows the difference between total energy saving cost during a building's lifetime and investment and maintenance cost [34]. A higher net present value corresponds to the most profitable and cost-effective energy renovation solution. The net present value of the solutions with 50% reduced energy demand were calculated using equation 1 in Microsoft Excel.

$$NPV = \sum_{t=0}^{n} (D'_t) * \frac{1}{(1+r)^t} - (I_0 + U) \qquad \text{Eq. 1}$$

$$D'_t = (E_0 - E_t) * \alpha(1+\beta)^t \qquad \text{Eq. 2}$$

Where;
NPV is the net present value during lifespan of n year;
D'_t is energy cost saved annually;
E_0 is the initial annual energy demand before renovations
E_t is the annual energy demand after implementing renovations
α is energy price per kwh/m² in 2016
β is inflation in energy price (%)
t: lifespan of n years
r: discount rate
I_0 is the investment cost
U is the lifetime maintanence cost

In calculating the net present value, a discount rate of 1%, 3% and 5% with a lifetime of 30 and 50 years were considered [11, 13]. This decision was made to analyse the effect of the discount rate and lifetime of profitability of the 625 renovation solutions. The energy price for heating and electricity was 0.74 (SEK/ kWh) and 1.38 (SEK/ kWh) in 2016 respectively, including 1% of inflation rate [13]. The investment cost for heat recovery system, solar heating, windows and insulation layer were taken from [30-32][5], [33, 35], [28] and [36], respectively. At the end of the lifetime, the renovation measures were refurbished. Accordingly, the investment cost of refurbishment was also included in calculating the net present value. The maintenance cost for the ventilation system was assumed to be 1% of the investment cost [13]. The maintenance cost for the solar heating system was assumed to be 200 (SEK/ year) [37]. Table 3 shows the applied investment, maintenance and life time of the renovation measures.

Table 3. Investment, maintenance and life time of the renovation measures

Renovation measures	Investment cost	Maintenance cost	Lifetime
Windows [28]			
Type 1	4770 (SEK/ m²)	-	30
Type 2	4430 (SEK/ m²)	-	30
Type 3	4000 (SEK/ m²)	-	30
Type 4	3310 (SEK/ m²)	-	30
Type 5	2870 (SEK/ m²)	-	30
Insulation layer [38]	500 (SEK/ m³)	-	30
Heat recovery system [30-32]	140 (SEK/ m²)	15 (SEK/ m²)	15
Solar heating system [33, 35]	6950 (SEK/ m²)	200 (SEK/ year)	50

3 Results

The total required time for performing the optimization was about 60 hours, which can be considered as a long execution time. Thus, performing an optimization may require a computer with more powerful processor. Furthermore, the initial results showed that energy need for space heating and domestic hot water of all 625 renovation solutions were smaller than 75 (kWh/ m²) (50% of heating demand in 1995). The total thermal discomfort hours among all renovation solutions were less than 200 hours. Total energy consumption of the renovation solutions was varied between 24.1 and 35.6 (kWh/m²), which corresponds to 80.7% and 71.5% reduction in total energy consumption respectively. The minimum energy demand of 24.1 kWh/m² represents a renovation solution with a mechanical ventilation heat recovery system, solar heating system, window with U-value of 0.8 (W/ m². K), external wall with U-value of 0.09 (W/ m². K), attic floor with U-value of 0.08 (W/ m². K) and floor with U-value of 0.08 (W/ m².

[5] The investment cost for heat recovery system can vary greatly between different references. Therefore, the considered value in this study was taken to fit within the range.

K). The investment cost of this renovation solution was about 1860000 SEK, which corresponds to 1650 SEK/m². The maximum energy demand of 35.6 kWh/m² corresponds to the previously mentioned mechanical ventilation heat recovery system and solar heating system, but with installation of windows with U-value of 1.2 (W/ m². K), external wall with U-value of 0.18 (W/ m². K), attic floor with U-value of 0.13(W/ m². K) and floor with U-value of 0.15 (W/ m².K). The investment cost of this renovation solution was about 1520000 SEK, which corresponds to 1350 SEK/m².

Figure 1 shows the net present value of 625 solutions with a lifetime of 30 years and three different discount rates. Analysing the results show that, by increasing the discount rate from 1% to 3% and 5%, the net present value of the 625 renovation solutions decreased significantly. When the discount rate is 1%, the highest net present value was about 453 (SEK/m² of floor area), which represents the most cost-effective energy renovation solution. This renovation solution corresponds to the combination of the mechanical ventilation heat recovery system, solar heating system, windows with U-value of 1.2 (W/ m². K), external wall with U-value of 0.1 (W/ m². K), attic floor with U-value of 0.12 (W/ m². K) and floor with U-value of 0.08 (W/ m². K). The total energy demand of this solution was 31.3 (kWh/m²). However, by increasing the discount rate from 1% to 3% and 5%, the highest net present value fell about 507.8 and 847 (SEK/m² of floor area) respectively. With a discount rate of 3% and 5%, the net present value of all renovation solution was negative. Accordingly, none of the renovation solutions can be considered as cost-effective solutions.

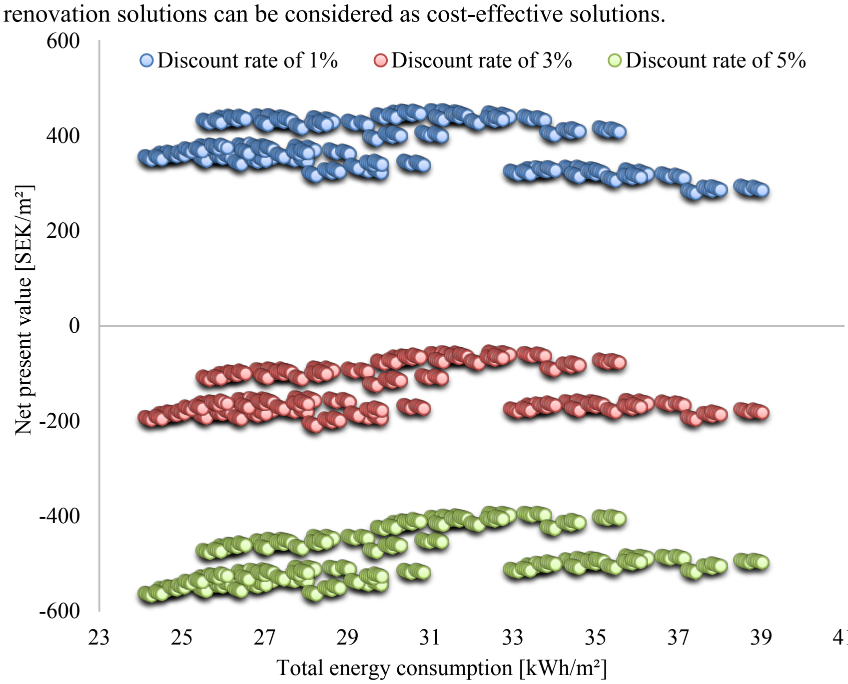

Fig 1. Net present value of renovation solutions in a lifetime of 30 years together with their respective total energy demand.

Figure 2 shows the net present value of 625 renovation solution with a lifetime of 50 years and three different discount rates. As was found earlier, increasing the discount rate from 1% to 3% and 5% decreases the net present values significantly. With a discount rate of 1%, all 625 renovation solutions had a positive net present value. The highest net present value, representing the most cost-effective energy renovation solution, was about 1869.5 (SEK/m² of floor area), which corresponds to the renovation solution with the mechanical ventilation heat recovery system, solar heating system, windows with U-value of 1 (W/ m². K), external wall with U-value of 0.09 (W/ m². K), attic floor with U-value of 0.08 (W/ m². K) and floor with U-value of 0.08 (W/ m². K). The total energy demand of this solution was 25.5 (kWh/m²). With a discount rate of 3%, highest net present value was changed to 558.8 (SEK/ m² of floor area), which corresponds to 1310.7 (SEK/ m² of floor area) fall in highest net present value. Furthermore, the most cost-effective energy renovation solution was changed to the renovation solution with the mechanical ventilation heat recovery system, solar heating system, windows with U-value of 1.2 (W/ m². K), external wall with U-value of 0.1 (W/ m². K), attic floor with U-value of 0.12 (W/ m². K) and floor with U-value of 0.08 (W/ m². K). The total energy demand of this solution was 31.3 (kWh/m²). By increasing the discount rate from 1% to 5%, the net present value of all renovation solutions was negative. Accordingly, none of the renovation solutions can be considered as cost-effective solution.

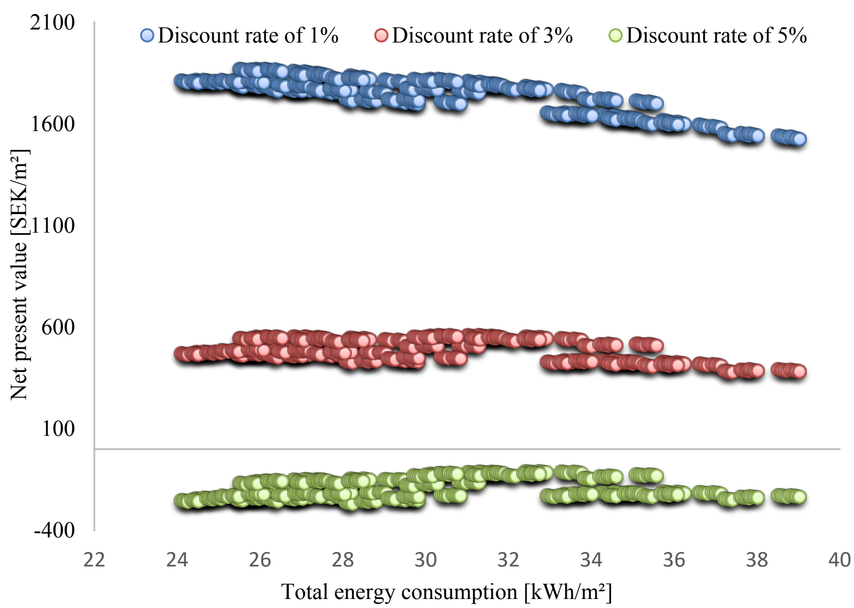

Fig 2. Net present value of renovation solutions in a lifetime of 50 years together with their respective total energy demand.

4 Conclusion

The aim of this study was to find the most cost-effective energy renovation solution in renovating a residential building in Swedish climate zone 3, Växjö. For this purpose, the initial energy performance of the building was analysed using Design Builder software. Multiple energy renovation measures were simulated to reduce the energy need for space heating and domestic hot water by 50%, compared to 1995. The renovation measures were comprised of improving the U-value of the building's envelopes, upgrading the ventilation system and installing solar heating system for supporting space heating and domestic hot water. Later, a multi-objective optimization was accomplished for analysing every possible combination between renovation measures. The most cost-effective energy solution was obtained by calculating the net present value in a lifetime of 30 and 50 years and discount rate of 1%, 3% and 5%.

As point of energy consumption, analysing the results show that a reduction around 80.7% in total energy consumption can be achieved by implementing energy renovation measures. Considering cost evaluations, net present value of the renovation solutions was sensitive both for changes in discount rate and lifetime period. However, comparing the implications of two different lifetimes on net present value with implications of three different discount rates on net present value shows that lifetime has more contribution on net present value. For instance, when discount rate was 1%, the highest net present value with a lifetime of 50 years was about four times greater than the highest net present value with a lifetime of 30 years.

When discount rate was changed from 1% to 3%, the fall in the highest net present value with a lifetime of 50 years was 2.6% greater than the fall in the highest net present value with a lifetime of 30 years. However, with a discount rate of 3%, the net present value of all renovation solutions, with a lifetime of 50 years, was still positive, while the net present value of all renovation solutions, with a lifetime of 30 years, was negative. Accordingly, implementing renovation solutions with a discount rate of 3% can only be cost-effective when the lifetime is 50 years. When discount rate was changed from 1% to 5%, the fall in the highest net present value with a lifetime of 50 years was 2.3% greater than the fall in the highest net present value with a lifetime of 30 years. With a discount rate of 5%, none of renovation solutions could be considered as cost-effective solution either with a lifetime of 30 or 50 years.

Furthermore, the results show the capability of the multi-objective optimization method (in this study NSGA-II algorithm) in analysing multiple renovation solution. However, one of the main concerns in performing an optimization using NSGA-II is the long execution time. Accordingly, performing an optimization may require a computer with more powerful processor.

The presented results in this study can be applied for buildings, which have similar characteristics and located in Swedish climate zone 3. Furthermore, the presented method in this study can be used for analysing the cost-effectiveness of other energy renovation measures and their combinations in Swedish residential buildings. This process may help to specify suitable renovation solutions, which fit for other climate zones. The future work of this study will include the analysis of required monetary instruments for implementing energy renovation measures, such as provided subsides by banks and studying how it affects the rental rates.

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