Renovation of multi-family houses with minimized life-cycle cost

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Abstract

Our paper presents the OPERA - model, (OPtimal Energy Retrofit Advisory model), which enables the user to find the best retrofit strategy for each unique building. The model optimizes the implementation of both envelope, as well as heating equipment retrofits, in order to find the lowest possible Life-Cycle Cost, LCC, for the building studied. No other combination of insulation and installation measures thus can make the LCC lower.

Input to the model are e.g. the geometry and thermal status of the building, building and installation costs, the climate and prices or tariffs for energy deliveries.

The model can be characterized as an integer, nonlinear, mixed program and it is solved using both derivative and direct search methods.

Our results from calculations on both real and conceptual buildings show that a low operating cost heating system is essential to minimize the LCC. Such systems are e.g. district heating with a cost reflecting time-of-use tariff, or a bivalent oil-boiler heat pump system. These systems should be combined with cheap envelope retrofits e.g. weatherstripping and attic floor insulation. More expensive insulation retrofits e.g. external wall insulation or triple glazed windows can be a part of the optimal solution if a restoration has to made from other than energy conservation reasons. Only if a high running cost system e.g. electricity is installed in the building the exhaust air heat pump can be profitable.

Keywords

Retrofitting; Life-Cycle Cost; Optimization; Energy Conservation; Heating equipment; Heat pump; District heating; Time-of-Use rates; HVAC-systems; Fenestration.

INTRODUCTION

Since April 1985 there is an on-going study, dealing with retrofitting of residences and the minimization of the building LCC, at the Institute of Technology in Linköping, Sweden. The project is co-sponsored by The Swedish Council for Building Research and the municipality of Malmö, Sweden. It was initiated due to the decrease in building new residences and instead emphasizing the restoration of the existent building stock. However, there were also major uncertainties how the retrofits should be combined in order to find the most profitable solution, both from the point of society and from the owner of the house.

Traditionally the envelope retrofit strategy was decided by the building contractor and the heating equipment strategy by the installation contractor. Of course both of them wanted an extensive strategy to be implemented. However, this was also encouraged by the Swedish subsidiary system, the capital cost for the building was, and still is, subsidized to approximately 3 % the first year. Almost all types of retrofits thus is profitable to implement for the owner of the building, the capital cost is lower than the inflation. From the societal point of view, however, this lead to sub-optimations, e.g. in district heated areas. The district heating utilities were and still is sometimes to a part heated by burning refuse, and the short range marginal cost for producing an extra kWh was in the summer as low as 0.10 SEK, (1 US$ = 7 SEK.), see Ref. [1]. The municipality had to get rid of the waste, and if they could not burn it they had to store it at the refuse dump. At the same time the building landlords could get grants and loans to install sun collectors in order to heat domestic hot water. It was obvious that something had to be done to prevent such misuse with the scarce resources of the nation. A discussion in more detail can be found in Ref. [2].

THE OPERA MODEL

Above we did describe our problem as an integer, nonlinear, mixed program, following the terminology in Ref. [3]. However, there are no commercial algorithms which can solve such problems with an absolute accuracy. We have thus elaborated the model so it is solved during the generation of the problem itself. The model is now implemented in a NORD 570 machine which solves the base case problem in about 30 seconds.

The program starts with the calculation of the existent LCC for the building. A retrofit is implemented, e.g. attic floor insulation, and the program elaborates the optimal extra insulation thickness using a derivative method. A new LCC is after that calculated and it is compared to the existent one. If this new LCC is lower than the original one the retrofit is selected, otherwise not. The program proceeds with a new retrofit, e.g. external wall insulation, and the procedure is repeated.

However, it is extremely difficult to find an optimal window construction, see Refs. [4], [5], [6] and [7]. Such retrofits are tested, using a number of different alternatives. The existing LCC is tested against the LCC for triple and new types of energy conserving glazing. The procedure is identical for the evaluation of weatherstripping and exhaust air heat pumps. Either the measure is selected or not.

Coming so far the program has found the optimal retrofit strategy for the existent heating system in the building. This is now changed from e,g, an oil-boiler to an electrical heated device. The evaluation will now start from the beginning and a new optimal solution is found. This procedure is now repeated for all the heating equipment possible to install in the building. The model at this moment can work with oil-boilers, electricity, district heating, heat pumps, T-O-U rates for district heating and electricity and a bivalent oil-boiler heat pump system. Finally the lowest LCC strategy has been found.

However, there are some uncertainties in choosing the proper discount rates, optimization periods etc, and thus the program also evaluates the LCC for about ten different discount rates, optimization periods from 10 to 50 years, up to 3 % annual escalation of the energy prices and 5 different amounts of degree hours. This means that the optimal strategy can be meticulously scrutinized in order to do a sensitivity analyze. If there are more cases required, the FORTRAN code easily could be changed a little to provide this. In Refs. [8] and [9] the theoretical background is presented and the model and how it works can be studied in detail.

From the above discussion we think it is obvious that the main work has been emphasized on generating the mathematical problem. Less have been done to elaborate the optimization procedure. However, our method always finds the true minimum point of the problem and that is exactely what we wanted from the procedure to be used.

We also think it is obvious that we in the OPERA model have a perfect means to evaluate different retrofits, if they are profitable, and how they shall be combined in the best way. In the next part of our paper we will show examples from two existing buildings in Malmö, one small with 18, and one big containing 105 apartments.

CASE STUDIES

In Malmö we are co-operating with a group called the 7 - builders group, which consists of 7 housebuilders aktive all over Sweden and in many other countries. The 7 contractors are ABV, SKANSKA, BPA, JCC, Kullenberg, SIAB and PEAB. The municipality is aktive through Malmö Energy and Heating Utility. Due to this co-operation we have been enabled to calculate on two real buildings owned by ABV and Svenska Riksbyggen AB. In a paper of this length it is not fruitful to present all the input parameters, the interested reader can contact us and we will send the total input file. Instead we will show the retrofit strategies for a base case with 5 % real discount rate, optimization time 30 years and assuming the heating system is turned of if the outside temperature is higher than 17 °C. The desired inside temperature is assumed to be 20 °C. It shall be noted here that these buildings also are described in [10] but the calculations then were done for an other base case. Furthermore no sensitivity analyzis was made for different building or installation costs, but instead for various economical parameters.

In Tables 1 and 2 we will present the base case and below we will discuss how input changings will influence the optimal strategies.

All the starting values have been presented by ABV and SRAB, and no scientific study has been elaborated in order to examine the reliability of those values. In Ref. [8] however, there is a lot of references to Swedish literature, concerning building and installation costs. Nevertheless it is obvious that there is an immense lack of information about the costs for different retrofits due to various buildings and so fourth, and we hope that papers like this will initiate scientific studies about the topic. In Ref. [11] this is also emphasized.

From the presented table it is obvious that the existing heating system, district heating with a differential T-O-U rate, combined with weatherstripping is the best retrofit strategy for this building. The district heating with its low run-

	Oil boiler	Electr boiler	Distr heat	Heat pump	Bivalent oil heat pump
LCC without envelope retrofits:	1.22	1.40	0.86	1.48	1.32
Savings:					
Attic floor insulation	—	—	—	0.02	—
Four glazed windows	0.02	0.04	—	0.09	0.04
Weatherstripping	0.09	0.12	0.06	0.16	0.11
New LCC	1.10	1.23	0.80	1.20	1.16

Table 1: Optimal retrofit strategies due to different heating systems. The values in MSEK. ABV Building. 18 apartments

	Oil boiler	Electr boiler	Distr heat	Heat pump	Bivalent oil heat pump
LCC without envelope retrofits:	7.11	8.57	5.56	5.38	5.69
Savings:					
Three glazed windows	0.26	0.41	0.15	0.14	0.15
Weatherstripping	0.46	0.68	0.31	0.29	0.31
New LCC	6.40	7.48	5.09	4.95	5.23

Table 2: Optimal Retrofit Strategies due to Different Heating Systems. Values in MSEK. SRAB Building. 105 apartments

ning cost, 0.21 SEK/kWh during the winter and 0.10 SEK/kWh in the summer, makes almost all of the retrofits unprofitable. The cheap weatherstripping, 200 SEK/window,door, was the only one. The second best heating system is the oil-boiler, running cost 0.24 SEK/kWh, also combined with better windows.

In this case the four glazed windows had a better profitability then three glazed ditto. The costs presented by ABV are 1300, 2250, 2650 SEK for two, three, and four glazed windows respectively. The corresponding U-values were 3.0, 2.0, 1.5 W/m^2,°C.

Expensive exhaust air heat pumps, approximately 100 000 SEK, never was chosen by the computer. In Ref. [2] a minor study has been made about air heat exchangers, which are very profitable in new buildings. This study showed that it was very expensive to install new ducts, for the air flow transported into the different dwellings, and thus this equipment could not compete with the low energy prices nowadays, Feb. 1987.

The big building, will almost have a similar envelope retrofit strategy but the best one also includes changing the heating system.

Table 2 shows that three glazed windows and weatherstripping are profitable for all the examined heating systems. In this case the heat pump system was the cheapest which is not very expected. However, this can be explained by low prices for heat pumps in this case,

$$150000 + 3000 \times P \quad \text{SEK}$$

where P is the thermal power for the pump, and the fact that the existing building does not have any chimney due to the existing district heating system. Bivalent systems where the oil boiler is a part, of course will be less competitable in such cases.

It is also important to note that the existing district heating system LCC is very close to the cheapest one. Due to the uncertainties in all the input parameters we assume that it would be preferable to keep the existing heating system and only implement the envelope retrofit measures. Also in this case the expensive retrofits are rejected by the program.

SENSITIVITY ANALYZIS

From Table 2 above it is obvious that small changes in the input parameters can change the most profitable solution. For insulation measures the optimal thickness of extra insulation of course varies due to different energy prices etc, but the most important is that at one special point the profitability will vanish. The best solution will in such a case be to avoid the extra insulation. This point can emerge for rather thick insulations, more then 0.1 m, which is discussed more in Refs.[12] and [13].

In this paper we will instead emphasize the costs for the heating systems dealt with during the optimization. These are described by a straight line function:

$$C = A + B \times P$$

where C is the total cost for the equipment and installation in the building, A and B are two constants and P is the thermal power of the heating device. In Ref. [2] the process to evaluate such expressions is described in detail. The functions presented by the housebuilders are shown in Table 3.

	ABV	SRAB
Oil-boiler	$30000 + 200 \times P$	$50000 + 350 \times P$
Electr.boil.	$25000 + 150 \times P$	$20000 + 100 \times P$
Distr.heat	$30000 + 70 \times P$	$100000 + 400 \times P$
Heat pump	$30000 + 6000 \times P$	$150000 + 3000 \times P$

Table 3: Heating equipment costs in SEK

From Table 3 it is obvious that there is big differences in the cost functions especially for district heating equipment and heat pump ditto. It is important to note that district heating is the existent system in the two buildings which has many years of operating before it has to be changed to a new system. The costs for the changing will thus not influence so much, compared to the heat pump device which has a shorter life-cycle and also is much more expensive. In Tables 4 and 5 we present the optimal strategies when the costs for the heating equipment is ignored.

The cost functions are identical,

$$C = 10 + 10 \times P$$

which means that only the different running costs for the systems will influence the strategies.

	Oil boiler	Electr boiler	Distr heat	Heat pump	Bivalent oil heat pump
LCC without envelope retrofits:	1.10	1.30	0.85	0.47	0.57
Savings:					
Four glazed windows	0.02	0.04	—-	—-	—-
Weatherstripping	0.09	0.12	0.06	0.01	0.03
New LCC	0.99	1.14	0.79	0.46	0.55

Table 4: Optimal retrofit strategies due to different heating systems. ABV building. Heating equipment cost ignored

	Oil boiler	Electr boiler	Distr heat	Heat pump	Bivalent oil heat pump
LCC without envelope retrofits:	6.75	8.39	5.54	3.64	4.16
Savings:					
Three glazed windows	0.24	0.41	0.15	—-	0.04
Weatherstripping	0.43	0.67	0.31	0.07	0.15
New LCC	6.09	7.31	5.03	3.57	3.97

Table 5: Optimal retrofit strategies due to different heating systems. The values in MSEK. SRAB building. Heating equipment cost ignored.

Comparing Tables 4 and 5 with 1 and 2 it is obvious that setting the heating equipment cost to a very low value, almost free, will not change the optimal envelope strategy very much for the cheapest heating systems. The expensive ones, however, will lose some climate shield measures because there is no money to earn on decreasing the thermal load of the building. Of course the heat pump system is the cheapest, it delivers the energy for 0.10 SEK/kWh, and all the other systems to a higher price.

The important thing is that the situation is almost similar for heating systems that cost

$$1000 + 1000 \times P$$

	Oil boiler	Electr boiler	Distr heat	Heat pump	Bivalent oil heat pump
LCC without envelope retrofits:	1.41	1.60	0.87	0.82	0.92
Savings:					
Four glazed windows	0.04	0.06	—-	—-	—-
Weatherstripping	0.11	0.14	0.07	0.04	0.05
New LCC	1.27	1.40	0.80	0.78	0.87

Table 6: Optimal retrofit strategies due to different heating systems. The values in MSEK. ABV building. Heating equiment cost $1000 + 1000 \times P$ SEK

	Oil boiler	Electr boiler	Distr heat	Heat pump	Bivalent oil heat pump
LCC without envelope retrofits:	8.07	9.72	5.59	4.48	5.41
Savings:					
Three glazed windows	0.30	0.47	0.16	0.03	0.09
Weatherstripping	0.51	0.76	0.32	0.15	0.23
New LCC	7.26	8.49	5.11	4.70	5.09

Table 7: Optimal retrofit strategies due to different heating systems. The values in MSEK. SRAB building. Heating equipment cost $1000 + 1000 \times P$ SEK

We present this in Tables 6 and 7 and it is shown that the heat pump still is the best alternative due to its very low running cost. However, the existing heating system now gets very close and if the heating equipment cost only gets a little higher the best strategy will be to keep the existing system. The envelope retrofits differs not much from the earlier ones.

This situation changes a lot in our next two tables where the heating equipment cost is set to

$$10000 + 10000 \times P$$

valid for expensive heat pumps.

	Oil boiler	Electr boiler	Distr heat	Heat pump	Bivalent oil heat pump
LCC without envelope retrofits:	4.24	4.27	1.05	4.0	4.02
Savings:					
Attic floor insulation	0.09	0.09	—	0.08	0.08
Ext. wall insulation	0.11	0.12	—	0.10	0.09
Four glazed windows	0.20	0.19	0.03	0.19	0.18
Weatherstripping	0.28	0.28	0.10	0.27	0.26
New LCC	3.56	3.59	0.93	3.36	3.40

Table 8: Optimal retrofit strategies due to different heating systems. The values in MSEK. ABV building. Heating equipment cost $10000 + 10000 \times P$ SEK

From Tables 8 and 9 it is obvious that the existent heating system is the most outstanding solution. The expensive heating systems will influence the LCC very much, and a lot of envelope retrofits is generated by the program. It is important to observe that exhaust air heat pumps never are chosen due to small influence on the thermal load of the building. The tables above also implies that low cost heating systems, lower than 1000 SEK/kW, only will influence a little on the LCC and also on the chosen retrofit strategy, the running cost is essential. For very expensive equipment the opposite is true. In Tables 8 and 9 the LCC and savings tend to get closer to each other for the different systems, the district heating of course excluded.

This means that much work should be emphasized to find proper equipment cost functions for the expensive facilities i.e. heat pumps, while less may be

	Oil boiler	Electr boiler	Distr heat	Heat pump	Bivalent oil heat pump
LCC without envelope retrofits:	20.09	21.74	6.50	16.13	16.78
Savings:					
Attic floor insulation	0.15	0.26	—	—	—
Ext. wall insulation	0.53	0.85	—	—	0.05
Three glazed windows	—	—	0.26	0.51	0.59
Four glazed windows	0.89	1.15	—	—	—
Weatherstripping	1.29	1.53	0.46	0.81	0.92
New LCC	17.24	17.94	5.78	14.82	15.22

Table 9: Optimal retrofit strategies due to different heating systems. The values in MSEK. SRAB building. Heating equipment cost $10000 + 10000 \times P$ SEK

done to the cheap equipment. Unfortunately, there is very little experience, scientifically documented, about costs and life-cycles for heat pumps, but, some references are [8],[14] and [15].

The bivalent system has never been chosen by the computer. This can be explained by the rather mild climate in Malmö and the use of 17 °C as the inside temperature in the building. In the ABV case there is not enough heat to produce in such a low running cost system, the existent heating system will be the best. In the SRAB case the single system heat pump was chosen due to the low running cost. The installation cost was also acceptable. If the heat pump was more expensive the bivalent system gets advantages but so does the existent heating system, a low cost system with much less installation cost. In Ref. [10] the same building has been treated but with other base case parameters, e.g. a different inside temperature. The bivalent system was in that case the best.

(NOTE! Some of the references were not published when this paper was originally written)

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