Minimized life-cycle cost and optimal retrofit strategies for multi-family residences

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Abstract

This paper describes the OPERA-model (OPtimal Energy Retrofit Advisory model), which is elaborated in order to find the optimal combination of different energy retrofits for each unique building. Both building envelope as well as installation measures are dealt with. The model uses the minimized Life-Cycle Cost, LCC, as a ranking criterion. Having found this for the building and combination of retrofits no other solution can be found better, from the models point of view.

Input data to the model are e.g. the geometry and the thermal status of the building, the costs for different building and installation measures, the energy prices and tariffs, the climate and economic parameters.

The model calculates the LCC for the existent building and implements different retrofits to it. A new LCC is calculated and this one is compared to the existent one. If the new one is lower the retrofit is chosen, otherwise not. For each type of heating system there is an optimal combination of envelope and ventilation retrofits. These optimal strategies are elaborated for a number of heating systems and the best, i.e. the lowest resulting LCC, solution is selected.

Experience from a number of OPERA runnings for both conceptual and real buildings shows that a low running cost heating equipment is essential to reach the lowest LCC. This heating system shall be combined with cheap envelope retrofits or the retrofit shall be inevitable, e.g. three glazed windows shall be implemented only if the old windows are rot.

INTRODUCTION

Since April 1985 a research project has run funded by the Swedish Council for Building Research and the municipality of Malmö, Sweden. The aim of the project is to elaborate a method for retrofit optimization, i.e. how should different energy retrofits be combined in the best way when implemented in a unique building.

The first thing to do was to find a mathematical way to express the best solution. In Ref. [1] different ranking criterias are discussed and here is also shown the superiority of the LCC. This means that the best solution is discovered when the lowest possible LCC is found for the remaining life of the building.

The LCC is calculated with the present value method, i.e. all the costs for the building during its life is transferred to a base year, in our case to year 0 or now.

The model, which is a FORTRAN program implemented in a NORD 570 machine, starts with the calculation of the existent LCC for the building. This means that all the costs for running the building, heating costs and inevitable retrofit costs for the climate envelope and the installations are considered. However there are only costs related to the energy retrofits that are of any interest for the model.

A retrofit is after this implemented to the building and a new LCC is calculated. Only if this new LCC is lower than the existent one the retrofit is profitable, and chosen. If the new LCC is higher the retrofit of course is rejected. Retrofits dealt with are insulation, fenestration and ventilation measures such as weatherstripping and exhaust air heat pumps. All of these retrofits are tested keeping the existent heating system, and the optimal combination of the envelope and ventilation retrofits can be evaluated.

The heating equipment is after this changed to some other possible facility. The heating systems dealt with are oil- boilers, electricity, district heating, heat pumps and bivalent oil-boiler - heat pump systems. Differential rates for district heating and electricity are also treated.

The procedure starts with the calculation of the LCC for the existent building with no envelope or ventilation retrofits but with the new heating equipment. Eventually all of the heating systems are tested with all the envelope and ventilation retrofits and the best solution can be selected. The optimal strategy has been found.

INSULATION MEASURES

This paper only will deal with the insulation measures and how they will emerge if the minimized LCC concept is implemented. In Ref. [2] we have shown the influence of different discount rates, optimization periods, building and energy costs etc, on the optimal insulation thickness, but no concern was taken to the fact that the insulation thickness will influence the proper heating equipment. In Ref. [3] however this is done and it is shown that the LCC can be evaluated from an expression as:

$$LCC_{ins} = C_1 + C_2 \times t + \frac{C_3}{C_4 + C_5 \times t} \tag{1}$$

where LCC_ins = the life-cycle cost due to insulation measures, C_1 ,C_2 etc = constants and t = the extra insulation thickness.

The expression (1) shall be minimized and this is easily done with a derivative method. The lowest LCC will emerge for $t = t_*$ or when

$$t_* = \frac{C_4}{C_5} \pm (\frac{C_3}{C_2 \times C_5})^{\frac{1}{2}} \tag{2}$$

However, as mentioned above the LCC can be greater than the existing LCC and for those cases insulation is not profitable. This is a very common situation e.g. for external brick walls with very long remaining life. In Ref. [4] this is emphasized by OPERA runnings on two existing buildings in Malmö.

In C_3 above several important values are hiding, e.g. the energy prices, the climate and the heating equipment cost due to the insulation measure. Also important are the economic parameters such as the discount rate and optimization time. In OPERA the energy balances for the existing building as well as for the retrofit implementations are elaborated and because of this it is possible to decide the proper amount of degree hours to use for the optimization. This is emphasized in more detail in Ref. [5]. It is due to the energy balances also possible to evaluate the influence of solar gains and free energy from appliances.

The economic parameters can not be chosen by any mathematical methods, there is no ultimate discount rate or optimization time. This is in OPERA dealt with by making calculations for a number of different discount rates etc. A sensitivity analyzis can be elaborated, and by that it is possible to scrutinize the chosen retrofit strategies. However, for most cases the solution found seems to be very robust, e.g. the essential thing is a low running cost heating system.

The situation shall be depicted using an OPERA running for a conceptual building, see Table 1.

	Oil-boil	Electr-icity	Distr heat	Heat pump	Diff distr	Diff elect	Biv heat pump-oil
LCC no env. re-trofits	1.86	2.37	1.77	2.27	1.77	2.37	1.64
Savings: Attic insul.	0.08	0.17	0.05	0.08	0.05	0.17	0.02
Ext.wall insul	—-	0.08	—-	—-	—-	0.09	—-
Weather-strip.	0.14	0.21	0.12	0.17	0.12	0.22	0.10
New LCC	1.64	1.91	1.61	2.03	1.61	1.90	1.52

Table 1: Optimal insulation retrofits due to different heating systems. Values in MSEK (1US \$ = 7 SEK)

In this case the existing heating system was an oil-boiler with an approximate running cost of 0.25 SEK/kWh. Profitable envelope retrofits were only attic floor insulation and weatherstripping, i.e. the two cheapest retrofits. Important also, is the fact that the facade of the external wall and the windows have some years left of their remaining life-cycle. This is emphasized more in Ref. [6].

From Table 1 it is also obvious that a heating system with a higher running cost, e.g. electricity, will generate more envelope retrofits. In this case the energy price was approximately 0.30 SEK/kWh and thus also profitable external wall insulation.

Differential rates will advantage insulation measures however only obvious in the differential electricity rate. The two rates for electricity are normalized and the LCC is thus identical for identical thermal loads. This is described in detail in Ref. [7].

The best solution was however to change the heating system to a bivalent heat pump - oil-boiler system. The heat pump will take care of the thermal base load and the oil-boiler the peak load. Such a system provides a very low running cost, approximately 0.12 SEK/kWh, with an acceptable installation cost. The low running cost will disadvantage envelope retrofits but nevertheless attic floor insulation was found profitable. The optimal extra insulation thickness was calculated to 0.17 m.

SENSITIVITY ANALYZIS

Table 1 tells us how much money to be saved if e.g. extra insulation is implemented in the best case above, i.e. 20 000 SEK. This is not so much considering that the optimization period in this base case was 50 years. Changing this to 40 years will decrease the amount to 10 000 SEK and an insulation thickness of 0.16 m, and the fact is that the profitability will vanish if the optimization time is 30 years. The most profitable heating equipment however, was still the bivalent system and this will not change for an optimization time higher than 10 years.

A change of the discount rate, in the base case 5 %, inflation excluded, will of course influence the LCC. Using 3 % gives 0.21 m attic floor insulation and also 0.16 m of extra external wall insulation. The bivalent system still is the best. A higher discount rate will of course disadvantage the envelope retrofits and also expensive heating systems. No insulation measures were profitable if the rate was higher than 7 % and the bivalent system was abandoned when the discount rate was higher than 13 %, where the existing oil-boiler was most profitable.

Annual increases of the energy prices is of course very important to the LCC. The original strategy however, will not change very much. 3 % annual increase will generate attic floor insulation, 0.21 m, external wall insulation, 0.17 m, and weatherstripping. The bivalent system should be implemented combining these measures.

CONCLUSIONS

From the above discussion it is obvious that the LCC provides a very good means for evaluating energy retrofits. By minimizing the LCC for the remaining life of the building an optimal retrofit strategy can be found, i.e. no other combination of the retrofits can result in a lower LCC. Essential for the optimal solution is a heating system with a very low running cost combined with an acceptable installation cost. Such a heating system should be combined with some cheap envelope retrofits such as attic floor insulation and weatherstripping. If the retrofit is inevitable, e.g. bad windows that have to be changed anyway, also an energy retrofit may be profitable. A sensitivity analyzis shows that a solution like this is very robust, for a variety of discount rates and optimization periods.

(Note that not all papers in the reference list were published when this paper was originally written)

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