Window retrofits, interaction and life-cycle costing

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Abstract

This paper deals with the interaction between different types of building energy retrofits. The means for finding this interaction has been the OPERA model, which is used for energy retrofit optimization. The solution is optimal when the total life-cycle cost, LCC, for the building, i.e. the sum of the building, maintenance and operating costs, is as low as possible. The model finds the candidates for the optimal strategy, by calculating the total LCC for one retrofit after the other, an incremental method is used. All the measures are after this installed in the building and the resulting LCC is calculated. Mostly, the LCC for this combination is higher than the incremental LCC , i.e. the incremental way of calculation overestimates the savings. However, when window retrofits are of concern, the opposite might happen which is due to the use of shading factors. These factors show the decrease in solar radiation through a window when an ordinary one is changed to a window with enhanced thermal performance. The paper also shows that the interaction between different measures mostly can be neglected, as long as optimal retrofits are introduced.

INTRODUCTION

When a building is to be renovated it is important that the best strategy is introduced at this very occasion. If this is neglected it might be impossible to change the building once again, with any profitability, in order to reach the original optimal solution. In order to find this point a mathematical model has been developed. The model has been described in detail in Refs. [1], [2] and in a shorter paper, Ref. [3], and therefore it will only be shown in brief here, see Figure 1.

The building is described by use of an input data file, where the geometry, the building costs, the climate conditions etc are shown. Some 200 values are dealt with. When the file has been read the model calculates the LCC for the original building. At this moment the only retrofits of concern are the inevitable ones, e.g changing very poor windows to new ones because it is unavoidable. When the existing building LCC has been calculated an energy retrofit is introduced,

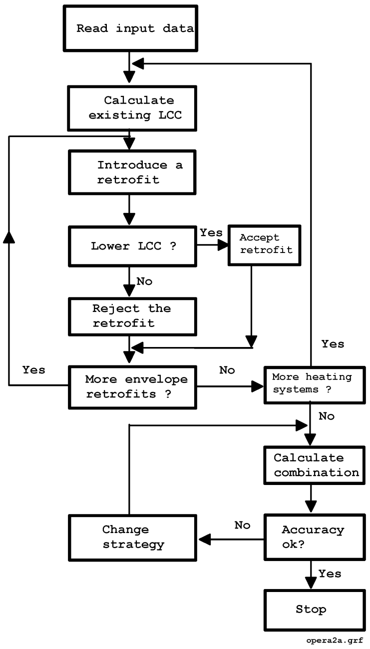

Figure 1: Schematic view of the OPERA model

e.g. attic floor insulation. The insulation thickness is now optimized by use of a derivative method. The best solution is supposed to be found when the new LCC is minimized. If this new LCC is lower than the original one the retrofit is selected as a candidate for the optimal strategy, otherwise it is rejected. The procedure continues by implementing new retrofits in the original building and examining the LCC. Insulation retrofits are examined by the derivative method while window retrofits, which cannot easily be depicted as continuous functions, use direct search optimization. When all building and ventilation retrofits are examined, the heating system is changed and the process starts again, almost from the beginning.

This means that the original LCC is decreased by the assumed amount of savings after each iteration, i.e. if the retrofit was found to be profitable. Assume that attic floor insulation was a profitable solution. The suggested monetary saving is subtracted from the original LCC resulting in a lower new LCC. The next retrofit, say external wall insulation, is after this tested in the same way. If the new LCC is lower than the original one the measure is selected. If the decrease in LCC from an external wall retrofit was calculated when the attic floor insulation already was implemented, the savings might be slightly lower than first could be expected, see also [4] for more details. This is so because of the energy balance calculations. The original building has a certain heating season, i.e. when the free gains cannot provide the necessary space heating. When the building is retrofitted the heating season gets shorter, and so does the applicable number of degree hours. If another retrofit is implemented the heating season is thus in reality somewhat shorter than was earlier expected.

The situation is emphasized if it is assumed that the first retrofit is so extensive that no space heating at all was necessary. The second one would in such a case not save any energy, or money at all.

It could thus be expected that the combined retrofit LCC will be somewhat higher than the incremental method suggested. Note, however, that this fact rarely will influence the optimal solution very much. This is so because the optimal solution very often contains only one or two building retrofits. The level of free gains, in buildings of concern for retrofitting, will also be very low and subsequently the heating season will not be changed very much when implementing a retrofit.

As we will show below in a case study, there are cases where the discussion above is not valid.

CASE STUDY

The OPERA model has been developed at the Institute of Technology in Linköping, Sweden. The example shown here, however, comes from Malmö where a lot of buildings have been used as testing objects for the model. Such a building is "Uppland 5" which is in a rather poor thermal and aesthetic shape. We will not show all the input values for the building but instead show the result from some OPERA runnings where the shading coefficient for a triple-glazed window is set first to 0.1 and then to 0.5. This means that the solar radiation through the window is decreased by 10 and 50 per cent respectively, if triple-glazing is used instead of double-glazed windows. The annual escalation of energy prices is set to 1.0 per cent and this, together with a real discount rate of 5 per cent, implies that some retrofits will be candidates in an optimal solution, at least for the more expensive energy sources. Table 1 shows the best building retrofit strategy when electricity heating is considered. It must be emphasized that the optimal choice was natural gas heating, with only a few building retrofits, but for that case the shading factor influence could not be observed.

Asset	Thermal load [kW]		Annual demand [MWh]	
	0.1	0.5	0.1	0.5
Original building	71.97	71.97	174.2	174.2
Attic insulation 0.19 m	65.92	65.92	158.6	158.6
Ext. wall ins 0.09 m	47.04	47.04	109.5	109.5
Triple-glazed w. east	43.07	43.07	100.6	105.9
Triple-glazed w. west	39.42	39.42	92.4	102.5
Weatherstripping	36.77	36.77	86.3	95.6

Table 1: Optimal building retrofits for electricity heating. Shading coefficients 0.1 and 0.5

The reason for only two orientations of the window retrofits is that the building does not have windows to the north and south. From Table 1 it is obvious that the shading factor will influence the energy demand for space heating. If a shading coefficient of 0.5 is used, 95.6 instead of 86.3 MWh will be the necessary heat demand, while the thermal load will be constant. The same building retrofits are chosen but because of the higher shading coefficient, and the subsequently higher annual energy demand, the total LCC will increase. Most interesting is however that the difference in LCC, between the two methods of calculation, will be reversed, see Table 2.

Calculation type	Life cycle cost [SEK]	
	0.1	0.5
Combination	1 571 094	1 677 990
Incremental	1 578 751	1 655 500
Difference	- 7 657	+ 22 489

Table 2: Life-cycle costs for incremental and combined calculations for shading coefficients of 0.1 and 0.5

Combining retrofits in the second case, with a shading coefficient of 0.5, will yield a lower LCC which up to now was not to be expected. The reason for this situation is to be found in the energy balance calculations. Note, that for both cases, the resulting LCC were found to be lower than the original one, and the window retrofits will be candidates in the optimal solution.

Energy balances

In the OPERA model, several hundred energy balances are calculated in order to find the best strategy. The first balance is naturally calculated for the original building, with no retrofits at all. This one can be found in Table 3.

Month nr	Thermal losses	Hot w. gains	Free gains	Solar free	Util. energy	Boil. energy	Insul.
1	32 893	3 500	4 167	1 201	5 368	31 026	32 893
2	30 254	3 500	4 167	2 609	6 766	26 978	30 254
3	29 987	3 500	4 167	6 078	10 245	23 242	29 987
4	22 209	3 500	4 167	8 998	13 165	12 544	22 209
5	15 299	3 500	4 167	12 717	15 299	3 500	0
6	8 883	3 500	4 167	13 200	8 883	3 500	0
7	5 814	3 500	4 167	12 933	5 814	3 500	0
8	6 579	3 500	4 167	10 900	6 579	3 500	0
9	11 104	3 500	4 167	7 712	11 104	3 500	0
10	18 512	3 500	4 167	4 109	8 276	13 736	18 512
11	23 837	3 500	4 167	1 561	5 728	21 609	23 837
12	29 069	3 500	4 167	778	4 945	27 623	29 096
Sum:	234 440	42 000	50 000	82 796	102 183	174 257	186 761

Table 3: Energy balance calculation, original building, Values in kWh

The shading coefficient does not influence on this original energy balance and subsequently the balance will be identical for the two cases. The total thermal loss coefficient is calculated to 2 056 W/m^2 K, the hot water energy need is

42 000 kWh each year, the free gains from applications is set to 50 000 kWh and the solar energy is calculated as shown in [5].

From Table 3 it is shown that the solar gains and the free energy have their maximum during the summer, but the utilized part of the free gains is maximized in May. Further the heating system does not deliver any heat for space heating during the summer months, only hot water heating is necessary. There is also a column called "insulation energy" showing the total amount of space heating needed in the building. The free gains are therefore included, and the values are used for insulation optimization. This is so because the free energy can be priced as coming from the original heating system as long as it makes it operate for fewer occasions. During the summer, however, the free energy of course is useless, because the extra heat saved by the insulation must be ventilated out through the windows. When OPERA considers if a retrofit is profitable, it calculates a new energy balance. Table 4 shows the energy balance for the original building with a triple-glazed east window retrofit implemented.

Month Nr	Thermal losses	Hot w. gains	Free gains	Solar free	Util. energy	Boil. energy	Insul.
1	31 079	3 500	4 167	888	5 055	29 524	31 079
2	28 586	3 500	4 167	1 930	6 097	25 989	28 586
3	28 333	3 500	4 167	4 496	8 663	23 170	28 333
4	20 984	3 500	4 167	6 656	10 823	13 661	20 984
5	14 456	3 500	4 167	9 406	13 573	4 382	14 456
6	8 394	3 500	4 167	9 764	8 394	3 500	0
7	5 493	3 500	4 167	9 566	5 493	3 500	0
8	6 216	3 500	4 167	8 063	6 216	3 500	0
9	10 492	3 500	4 167	5 704	9 871	4 121	10 492
10	17 491	3 500	4 167	3 039	7 206	13 785	17 491
11	22 523	3 500	4 167	1 155	5 322	20 701	22 523
12	27 466	3 500	4 167	576	4 743	26 223	27 466
Sum:	221 512	42 000	50 000	61 242	91 351	172 057	201 409

Table 4: Energy balance calculation, east window retrofit included. Shading coefficient 0.5. Values in kWh

If Tables 3 and 4 are compared it could be found that because of the thermally better windows, the thermal losses are reduced, with 12 932 kWh, but because of the high shading factor the heating season is prolonged, and further, the need for boiler heat is only reduced with 2 204 kWh.

If attic floor and external wall insulation are introduced before the east windows are changed, the thermal losses of course will be much lower than they are in the original case. Table 5 shows this.

From Table 5 it is shown that the thermal losses are decreased substantially, but so is the utilization of free energy, from 102 183 kWh in Table 3 to only 85 667 kWh here. When one of the window retrofits is installed the situation found in Table 6 will occur:

The utilization of free energy is decreased again and even if the thermal losses is decreased from 153 231 to 140 303 kWh, the electricity boiler heat is only reduced from 109 564 to 105 860 kWh, or 12 928 and 3 704 respectively.

Month Nr	Thermal losses	Hot w. gains	Free gains	Solar free	Util. energy	Boil. energy	Insul.
1	21 499	3 500	4 167	1 201	5 368	19 631	21 499
2	19 774	3 500	4 167	2 609	6 776	16 498	19 774
3	19 599	3 500	4 167	6 078	10 245	12 854	19 599
4	14 516	3 500	4 167	8 998	13 165	4 851	14 516
5	10 000	3 500	4 167	12 717	10 000	3 500	0
6	5 806	3 500	4 167	13 200	5 806	3 500	0
7	3 800	3 500	4 167	12 933	3 800	3 500	0
8	4 300	3 500	4 167	10 900	4 300	3 500	0
9	7 258	3 500	4 167	7 712	7 258	3 500	0
10	12 100	3 500	4 167	4 109	8 276	7 323	12 100
11	15 580	3 500	4 167	1 561	5 728	13 352	15 580
12	18 999	3 500	4 167	778	4 945	17 554	18 999
Sum:	153 231	42 000	50 000	82 796	85 667	109 564	122 068

Table 5: Energy balance with attic floor and external wall insulation implemented but no window retrofits. Values in kWh

The interesting thing is now to compare these differences with those found between Tables 3 and 4. If there are retrofits earlier implemented, as in Table 6, more heat is conserved than is the case where no preceding retrofitting was made, 3 704 compared to 2 204 kWh. A closer study shows that the difference emmanates from the prolonged heating season, see Tables 3 and 4. There are 882 kWh in May and 620 kWh in September which are not utilized if there were preceding retrofits.

When the other window retrofit, the one oriented to the west, is considered the difference is slightly larger, and the applicable values are 3 411 and 1 809 kWh.

OPERA found the east window retrofitting profitable but the difference in LCC was as small as 670 SEK during a 50 year period. This can be found by looking at the LCC and its contents in the following Tables 7and 8.

If windows to the west are installed the following LCC occurs, see Table 9:

The difference between Table 6 and Table 9 is 2 171 SEK and with the east window retrofit, OPERA will assume that 2 841 SEK will be saved during the optimization period of 50 years.

If the energy saving amounts are considered for both the window retrofits, the difference comes up to 3 102 kWh. In this case study the present worth of this heat is about 25 800 SEK and therefore it is obvious that the observed discrepance between the incremental and combining method found in Table 2 to most part is explained by the energy balance calculations above. The two values cannot be identical, because there are also influences by the utilization of the free energy leading to a lower LCC for the incremental method, as is the fact for lower shading factors.

Month Nr	Thermal losses	Hot w. gains	Free gains	Solar free	Util. energy	Boil. energy	Insul.
1	19 685	3 500	4 167	888	5 055	18 130	19 685
2	18 106	3 500	4 167	1 930	6 097	15 509	18 106
3	17 946	3 500	4 167	4 496	8 663	12 783	17 946
4	13 291	3 500	4 167	6 656	10 823	5 968	13 291
5	9 156	3 500	4 167	9 406	9 156	3 500	0
6	5 316	3 500	4 167	9 764	5 316	3 500	0
7	3 479	3 500	4 167	9 566	3 479	3 500	0
8	3 937	3 500	4 167	8 063	3 937	3 500	0
9	6 645	3 500	4 167	5 704	6 645	3 500	0
10	11 079	3 500	4 167	3 039	7 206	7 372	11 079
11	14 266	3 500	4 167	1 155	5 322	12 444	14 266
12	17 396	3 500	4 167	576	4 743	16 154	17 396
Sum:	140 303	42 000	50 000	61 242	76 442	105 860	111 769

Table 6: Energy balance with attic floor, external wall insulation and east window retrofits implemented. Values in kWh

Heating system retrofits	55 834
Inevitable building retrofits	407 633
Energy cost	1 451 390
Total LCC	1 914 857

Table 7: Life-cycle cost contents in SEK, original building

Heating system retrofits	55 315
Inevitable building retrofits	425 812
Energy cost	1 433 060
Total LCC	1 914 187

Table 8: Life-cycle cost contents in SEK, east windows retrofitted

Heating system retrofits	55 357
Inevitable building retrofits	424 369
Energy cost	1 432 960
Total LCC	1 912 686

Table 9: Life-cycle cost contents in SEK, west windows retrofitted

CONCLUSIONS

It is common to use an incremental process for finding profitable, and subsequently optimal retrofits, when a building is of concern for renovation. A building with one retrofit implemented, is compared with the same building without any retrofits. If the calculated savings for many retrofits are added to each other, the sum will not be identical to the one found if several retrofits are implemented at the same time. This incremental method will mostly overestimate the savings. The opposite situation, however, has been found when new windows are implemented in the building, i.e. when solar radiation transfer is reduced compared to the original window. This reduction is taken into account by use of a shading factor showing the magnitude of the reduction. The situation has been observed for a shading coefficient of 0.5, while lower coefficients will yield results that follows the traditional paradigm.

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