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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 via the OPERA model, which is used for energy retrofit optimization. The solution is an optimum when the total life-cycle cost, LCC, for the building, i.e. the sum of the building, maintenance and operating costs, is minimized. The model finds the candidates for the optimal strategy by calculating the total LCC for one retrofit after another, i.e., an incremental method is used. All the measures are implemented with respect to the building and the resulting LCC is calculated. Usually, 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 considered, the opposite might happen due to the use of shading factors. These factors indicate the decrease in solar radiation through a window when an ordinary one is replaced by a window with enhanced thermal performance. The paper also shows that the interaction between the different measures usually 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 adopted. Otherwise, if this is neglected, it might be impossible profitably to change the building subsequently, in order to reach the original optimal solution. Thus a mathematical model[1–3] has been developed: see Fig. 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 used as inputs. When the file has been read, the model is used to calculate the

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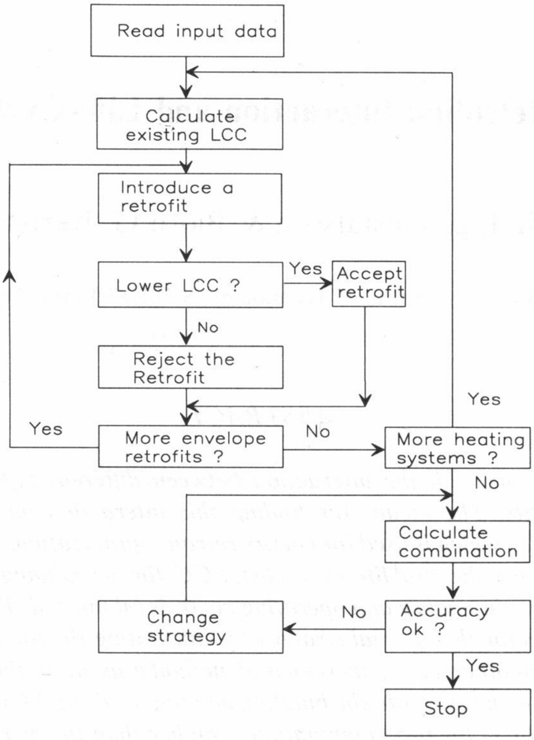

Fig. 1. Schematic view of the OPERA model.

LCC for the original building. At this moment, the only retrofits of concern are the inevitable ones, e.g., changing dilapidated windows because this is unavoidable. When the existing building's LCC has been calculated, an energy retrofit is introduced, 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 the 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 amount of savings after each iteration, i.e., if the retrofit was found to be profitable. It might be concluded that the 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 then 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 had already been implemented, the savings will probably be slightly lower than first expected.[4] 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 enough space heating. When the building is retrofitted, the heating season gets shorter, and so does the appropriate number of degree hours. If another retrofit is implemented, the heating season is thus in reality somewhat shorter than was earlier expected.

In the extreme, if the first retrofit is so extensive that no space heating at all is necessary, then 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. However, this will rarely influence the optimal solution very much. This is because the optimal solution 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 appreciably when implementing a retrofit.

However, as will be shown below, in a case study, there are cases where the above discussion is invalid.

CASE STUDY

The OPERA model has been developed at the Institute of Technology in Linköping, Sweden. The example shown here, comes from Malmö where many buildings have been used in testing the mathematical model. Such a building is Uppland 5 which is in a rather poor thermal and aesthetic shape. All the input values for the building will not be shown but instead the results from some OPERA runnings are given 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% and this, together with a real discount rate of 5%, implies that some retrofits will be candidates in an optimal solution, at least when using the more expensive energy sources. Table 1 shows the best building retrofit strategy when electric heating is considered. It must be emphasized that the optimal choice was natural gas

TABLE 1

Optimal Building Retrofits for Electricity Heating with Shading Coefficients of 0·1 or 0·5

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
External wall insulation 0·09 m	47·04	47·04	109·5	109·5
Triple-glazed window east	43·07	43·07	100·6	105·9
Triple-glazed window west	39·42	39·42	92·4	102·5
Weatherstripping	36·77	36·77	86·3	95·6

heating, with only a few building retrofits, but for that case the shading factor influence was not significant.

The reason for only two orientations of the window retrofits is that the building does not have windows on its north and south sides. 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, instead of 0·1, 95·6 instead of 86·3 MWh will be the necessary heat demand, while the thermal load will remain 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.

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. For both cases, the resulting LCC was found to be lower than the original one, and the window retrofits will be candidates in the optimal solution.

TABLE 2

Life-Cycle Costs for Incremental and Combined Calculations for Shading Coefficients of 0·1 and 0·5

Calculation type	*Life cycle cost (SEK)*	
	0·1	*0·5*
Combination	1 571 094	1 677 989
Incremental	1 578 751	1 655 500
Difference	−7 657	+22 489

TABLE 3
Energy-Balance Calculation for the Original Building
(All values are in kWh)

Month	*Thermal losses*	*Hot water*	*Free gains*	*Solar gains*	*Utilities free*	*Boiler energy*	*Insulation energy*
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
Totals	234 440	42 000	50 000	82 796	102 183	174 257	186 761

Energy balances

In the OPERA model, several hundred energy balances are evaluated in order to find the best strategy. The first balance is calculated for the original building, with no retrofits at all. This one can be seen in Table 3. The shading coefficient does not influence this original energy balance and subsequently the balance will be identical for the two cases. The total thermal-loss coefficient is calculated to be 2056 W/m^2 K, the hot-water energy need is 42 000 kWh each year, the free gains from appliances is set to 50 000 kWh and the solar energy is calculated as shown in Ref. 5.

From Table 3, it can be seen that the solar gains and the free energy have their maxima 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, then 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 or shorter occasions. During the summer, however, the free energy of course is an embarrasment 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

TABLE 4

Energy Balance Calculation, East Window Retrofit Included. Shading Coefficient = 0·5
(The values are in kWh)

Month	*Thermal losses*	*Hot water*	*Free gains*	*Solar gains*	*Utilities free*	*Boiler energy*	*Insulation energy*
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
Total	221 512	42 000	50 000	61 242	91 351	172 057	201 409

TABLE 5

Energy Balance with Attic Floor and External Wall Insulation Implemented, but no Window Retrofits
(The values are in kWh)

Month	*Thermal losses*	*Hot water*	*Free gains*	*Solar gains*	*Utilities free*	*Boiler energy*	*Insulation energy*
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
Total	153 231	42 000	50 000	82 796	85 667	109 564	122 068

new energy balance. Table 4 shows the energy balance for the original building with a triple-glazed east window retrofit implemented.

If Tables 3 and 4 are compared, it can be concluded that because of the thermally-better windows, the thermal losses are reduced by 12 932 kWh, but because of the high shading-factor, the heating season is prolonged, and further, the need for heat from the boiler is only reduced by 2204 kWh.

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

From Table 5, it can also be shown that the thermal losses are decreased substantially, but so is the utilization of free energy, i.e., from 102 183 kWh in Table 3 to only 85 667 kWh here. When one of the window retrofits is installed, the situation described in Table 6 will occur. The utilization of free energy has been reduced again and even though the thermal losses decreased from 153 231 to 140 303 kWh, the electric boiler's heat output was reduced only from 109 564 to 105 860 kWh. The interesting thing is now to compare these differences with those found between Tables 3 and 4. If the retrofits as in Table 6 are implemented as the initial measures, more heat is conserved than is the case where no preceding retrofitting was made, i.e. 3704 compared with 2204 kWh. A closer study shows that the difference emanates from the prolonged heating season, see Tables 3 and 4.

When the other window retrofit, the one oriented to the west, is

TABLE 6

Energy Balance with Attic Floor, External Wall Insulation and East Window Retrofits Implemented
(The values are in kWh)

Month	*Thermal losses*	*Hot water*	*Free gains*	*Solar gains*	*Utilities free*	*Boiler energy*	*Insulation energy*
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
Total	140 303	42 000	50 000	61 242	76 442	105 860	111 769

TABLE 7
Life-Cycle Cost Contents in SEK, Original Building

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

considered, the difference is slightly larger, and the applicable values are 3411 and 1809 kWh respectively. OPERA found the east window retrofitting profitable, but the difference in LCCs was as small as 670 SEK during a 50-year period. This can be seen by looking at the LCC and its contents as in Tables 7–9.

If new windows for the western wall are installed, the resulting LCC can be seen in Table 9.

TABLE 8
Life-Cycle Cost Contents in SEK, East Windows Retrofitted

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

The difference between the corresponding values in Tables 6 and 9 is 2171 SEK; with the east-window retrofit, OPERA will predict that 2841 SEK will be saved during the optimization period of 50 years.

If the energy savings are considered for both the window retrofits, the difference amounts to 3102 kWh. In this case study, the present worth of this heat is about 25 800 SEK. Therefore the observed discrepancy between the predictions via the incremental and combining methods found in Table 2 is explained principally by the energy-balance calculations above. The two

TABLE 9
Life-Cycle Cost Contents in SEK, West Windows Retrofitted

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

values cannot be identical, because the utilization of free energy leads to a lower LCC for the incremental method, as occurs when lower shading factors are employed.

CONCLUSIONS

It is common to use an incremental process for determining profitable, and subsequently optimal retrofits, when a building is to be renovated. The performance of a building, with a single retrofit measure implemented, is compared with the performance of the same building without any retrofits. If the calculated savings for retrofits implemented individually and alone are added, the sum will exceed the saving achieved had the several retrofits been implemented simultaneously. This incremental method will usually overestimate the savings. The opposite situation, however, has been found when new windows are introduced into the building, i.e., when the solar radiation transfer is reduced compared with that through the original window. This reduction is taken into account by the 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 follow the traditional paradigm.

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