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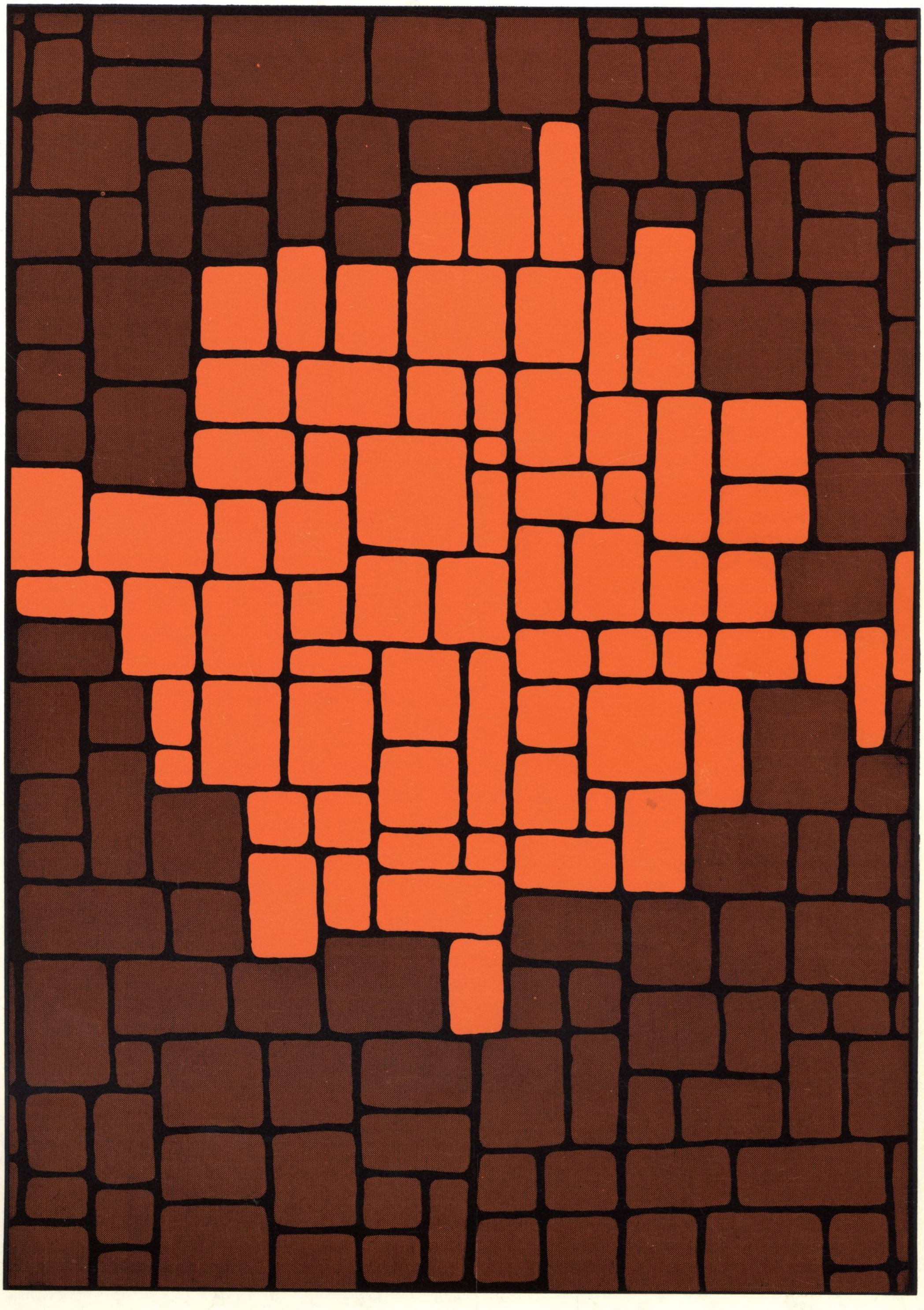

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Life-cycle Cost Minimization Considering Retrofits in Multi-family Residences

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ABSTRACT

When a building is to be renovated it is important to implement the optimal retrofit combination. If this strategy is neglected it might not be profitable to change the building in order to improve it as an energy system. This paper deals with energy retrofits and how the strategy can be optimized considering one specific building. The best solution is found when the life-cycle cost for the building is minimal, and building envelope, ventilation and heating system retrofits are combined.

In order to solve the problem, a mathematical model, OPtimal Energy Retrofit Advisory (OPERA), has been developed. Energy balance calculations are used in which the free energy from solar radiation and from appliances is taken into proper account. The interaction between different retrofits is emphasized. Provided that the optimal solution is implemented, the retrofits in the combination will have a minor interaction which, for most cases, could be neglected. This will also imply that the order of implementation is of no, or minor, importance. A case study for a real building sited in Malmö, Sweden, and a sensitivity analysis for some critical input parameters are discussed.

INTRODUCTION

The Swedish Council for Building Research and the municipality of Malmö, Sweden, have funded a research project which aims to develop a method for optimizing energy retrofits, i.e., renovation in order to achieve the lowest life-cycle cost (LCC). The LCC is the sum of the building costs, the maintenance costs and the operating costs. More details about life-cycle costing, and why it is a superior means for ranking different retrofit strategies, can be found in ref. 1.

As costs and savings occur at different times, they have to be converted to a base year. Let us consider a window retrofit, where the existing window has a remaining life of five years. If the window is changed now, before it is actually needed, this will incur a building cost. However, the future operating costs, for heating the building, might be reduced if a window with a better thermal performance is installed. This future decrease in the operating cost cannot be subtracted from the increased building cost without considering the time aspect. This is done by the net present value method, also described in ref. 1. The present values are calculated by use of the following expressions:

$$\mathrm{PV_s} = B(1 + r)^{-a} \qquad (1)$$

$$\mathrm{PV_a} = C\left[\frac{1 - (1 + r)^{-b}}{r}\right] \qquad (2)$$

where the first expression gives the present value $\mathrm{PV_s}$ for one single cost, B, appearing at year a, with a real discount rate, r. Equation (2) gives the present value for an annually recurring cost C, appearing for b number of years. The proper project life and discount rate cannot be chosen with perfect accuracy. However, their influence on the LCC can be studied by a sensitivity analysis. In a similar way, uncertainties in operation and maintenance costs can be dealt with.

The LCC concept has some constraints as the consequences of a retrofit measure must be expressible in monetary terms. Aesthetical

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reasons for retrofits are not dealt with here. Further, the OPERA model only deals with energy retrofits, while costs for cleaning, elevators, etc., are not considered.

STATE OF THE ART

This paper deals with a mix of three different, traditionally separated subjects:
— retrofitting of buildings
— life-cycle cost
— optimization.
Retrofitting can be subdivided into one part relating to the building envelope and one relating to installation. In each of the three subjects there is extensive literature, but almost nothing concerning the entirety. Surveys of the literature found in mid 1988 are given in refs. 2 and 3.

At the U.S. Department of Commerce/ National Bureau of Standards in Washington DC, much work has been done on LCC and buildings [4]. However, mainly new buildings are treated, but some reports about retrofitting exist. Unfortunately, none of these deal with the optimization procedure.

Other reports about LCC can be found in the proceedings from CIB conferences (Conseil International du Bâtiment pour la Recherche, l'Étude et la Documentation). Hall *et al.* [5] have calculated the LCC for retrofits implemented in a single-family house. The retrofit strategy is based on the lowest LCC but only few retrofits are tested, mainly for the building envelope. By a trial-and-error procedure some selected retrofits were chosen, and if they were found profitable, the LCC was calculated. However, since no changes were considered to the original heating system, no real optimization has been made.

Other authors have dealt with insulation optimization [6 - 8], but again no changes in heating system were considered. On the other hand, Björk and Karlsson [9] have investigated the effect of different heating systems combined with building measures, but for a new single-family building. A computer program dealing with energy retrofits, called CIRA, has also been described [10]. Here, the authors rank the different retrofits in saving-to-cost ratio. Again in this case, only the thermal envelope is treated and the importance of the proper heating equipment is not considered. The program tests a number of different envelope retrofits in a similar way to OPERA. However, the remaining life of the existing building parts is not taken into account and, consequently, the program will not find the optimal solution for the building.

A Swedish model that works almost in the same way is the MSA model [11]. The model, even if it does not optimize the retrofit strategy, has one big advantage: it can calculate the result of energy savings for the total Swedish building stock, and thus it was used in the project "Energy–85" study for Sweden.

There are several drawbacks with CIRA and MSA. They cannot handle differential rates or bivalent systems which often compete in the optimal solution. In addition, the models only deal with a constant energy price. Of course, inputs can be changed but correct forecasts about the future energy costs of such heating systems are difficult. The amount of extra insulation will also influence the optimal design of the heating system which complicates the problem.

Use of MSA or CIRA, even for ordinary heating systems such as oil boilers, may in fact lead to severe misoptimization, if they are used without expert knowledge about energy system optimization [3]. This is because they rank retrofits only in order of their saving-to-cost ratio. For example, MSA or CIRA nearly always considers weather-stripping to be a proper retrofit because of its cheapness. They will not, however, consider the fact that it could be cheaper to invest in an exhaust-air heat pump, which takes care of the extra ventilation flow if the windows and doors are left unchanged. The exhaust-air heat pump has a higher saving-to-cost ratio. However, MSA or CIRA might choose the heat pump also, but a smaller one than the optimal, due to the decreased ventilation flow.

THE OPERA MODEL

As can be seen from above, no model was available for optimizing retrofits on multi-family buildings. The OPERA model, however, provides such a means. The geometry of the building, the thermal status of the

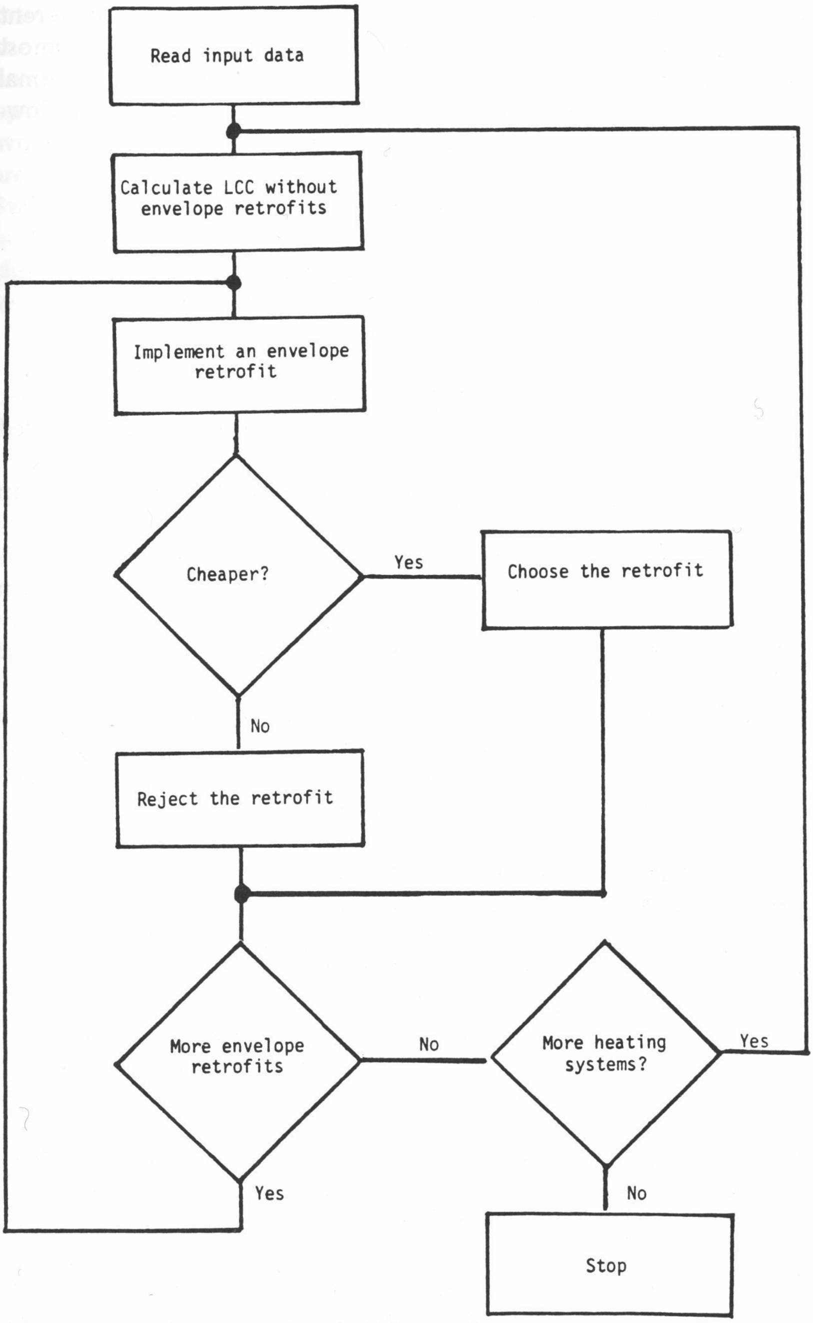

Fig. 1. Schematic view of the OPERA model.

envelope, and the climate conditions where the building is sited are input to the model. Other input data concern the building costs, the heating equipment costs for acquisition and installation, and energy costs for different systems implemented in the building. A complete list of the necessary input data can be found in ref. 3. Of course, it is possible to provide the model with dummy values, if only few possibilities exist in the situation studied, but no default values are stored in the model.

The process starts with calculation of the LCC for the existing building, as shown in Fig. 1. If nothing is done to the building there will be costs, nevertheless, for inevitable renovation during the project life, like replacement of rotten windows or of aged or worn equipment. If a retrofit is implemented, e.g., attic floor insulation, this is done in order to decrease the existing LCC. However, for some retrofits under consideration the LCC might, on the contrary, increase. Such a situation must be avoided, of course.

The OPERA model considers the following envelope and ventilation retrofits:

- attic floor insulation
- floor insulation
- external wall insulation
- triple-glazed windows
- triple-glazed windows, low-emissivity
- triple-glazed windows, low emissivity, gas-filled
- weatherstripping
- exhaust-air heat pumps.

In the model it is assumed that the building is equipped with double-glazed windows, which is normal in Sweden. The optimal amount of insulation is calculated for each building part under consideration. This uses a derivative method, assuming that the LCC depends on the insulation thickness according to a continuous function. The method is described in detail in ref. 2.

There are also some retrofits not present in the model such as solar panels, exhaust-air static heat exchangers, DHW tank insulation and improvement of regulation. Solar panels are not considered since they are not economically viable, as far north as Sweden. Heat exchangers are very expensive to install in multi-family buildings, due to difficulties with the warm air supply in different apartments. Tank insulation and better regulation are measures made inside the energy system and they do not affect the thermal supply or losses. The model considers the retrofits one by one, and if a retrofit results in a lower LCC, compared to the original one, it is considered a candidate for the optimal solution. If the retrofit leads to a higher LCC, it is rejected. The procedure is initially carried out for the existing heating equipment. When the last envelope and ventilation retrofit is considered, a number of candidates have been selected. It should be noted here that it is the optimal amount of insulation that is considered in the process. The original calculations are shown in detail in ref. 2. However, these are modified according to the theories in ref. 12, where it is shown that insulation optimization should be carried out for more degree hours than heating equipment optimization.

After this, OPERA selects a different heating system and the process starts almost from the beginning with the original thermal envelope and ventilation system. The following ten heating systems are considered:

- the existing heating system
- new high-efficiency oil boiler
- electricity heating, fixed rate
- district heating, fixed rate
- ground water coupled heat pump
- ground coupled heat pump
- electricity heating, time-of-use rate
- district heating, time-of-use rate
- bivalent oil boiler–ground water coupled heat pump system
- bivalent oil boiler–outside air heat pump system.

In ref. 2, the first eight systems are dealt with in detail, while system nine is dealt with in ref. 13 and system ten in ref. 3. Eventually all the heating systems have been treated and the different LCC are presented.

As mentioned above, there are now a number of competing retrofit strategies, but due to the fact that the envelope and the ventilation retrofits might interact, the one with the lowest LCC cannot yet be chosen. For instance, the savings from attic insulation and the savings from external wall insulation separately do not equal the savings from the combination of the two retrofits. This is partly due to the fact that the heating season is shortened after the first retrofit is installed. Thus, the second retrofit will not save as much money as could be expected. Some of the energy saving is of no value because it is not needed. The optimization process however, can be scrutinized with the OPERA model and examined if one or more retrofits should be excluded from the first solution.

Obviously the available amount of free energy must be taken into proper account. If the building could be heated solely with free energy no retrofit would be profitable, regardless of cost. But this is not the situation in residential buildings in Sweden. In OPERA, a number of energy balance calculations are made, for the building as it is, and for each retrofit implementation. A typical situation is shown in the case study below.

Another reason for closer attention to this was dealt with in ref. 14, where an electrically heated building is considered. The existing building used a tariff for electricity that was no longer applicable when the building was retrofitted, which made OPERA overestimate the savings. The operator of the program is, however, notified about the situation and the optimization can be examined in order to avoid mistakes. The tariffs used by OPERA are those used in the municipality of Malmö, Sweden. If the design of a new rate is similar to the one implemented, it is possible to change the tariff in the input file, otherwise some reprogramming is necessary.

CASE STUDY

In order to emphasize the possibilities in OPERA, a case study will be presented. The building studied is a rather small building containing 34 apartments in Malmö, Sweden. It must be noted here that a real building is considered in this case. All the input data have been presented by the OPERA operators in Malmö with the help of the different contractors concerned.

The thermal envelope is rather poor with the following U-values:

— the attic floor	$0.8\ \mathrm{W\ m^{-2}\ ^{\circ}C^{-1}}$
— the external wall	$1.2\ \mathrm{W\ m^{-2}\ ^{\circ}C^{-1}}$
— the floor	$0.5\ \mathrm{W\ m^{-2}\ ^{\circ}C^{-1}}$
— the windows	$2.5\ \mathrm{W\ m^{-2}\ ^{\circ}C^{-1}}$

These values lead to a total transmission value of $4780\ \mathrm{W\ ^{\circ}C^{-1}}$, which includes thermal losses from the ventilation system of $1094\ \mathrm{W\ ^{\circ}C^{-1}}$. In Malmö, Sweden, it is mandatory to construct the heating equipment to a design temperature of −14 °C, [15]. The inside temperature has been set to 21 °C so the thermal load will be 167 kW.

The energy balance for the existing building, assuming no free heat gain, is shown in Table 1. OPERA calculates the heating degree-hours for every hour the outside temperature is lower than the inside temperature.

The overall appearance of the building is acceptable so the remaining lifetimes of the building parts considered above are set to:

— the attic floor	0 years
— the external wall at the outside	15 years
— the external wall at the inside	10 years
— the floor	40 years
— the windows	0 years

The building, ventilation and heating equipment costs considered in this case study are based on practical experience in Malmö. However, it is not applicable to present all the input data here and thus only the result of the OPERA model is shown in Table 2.

TABLE 1

Energy balance in kWh for the building Ansgarius: no free gains

Month	Degree-hours	Energy losses	Hot water energy	Resulting energy
January	15996	76476	8333	84809
February	14712	70340	8333	78673
March	14582	69717	8333	78050
April	10800	51634	8333	59967
May	7440	35570	8333	43903
June	4320	20654	8333	28987
July	2827	13517	8333	21850
August	3199	15295	8333	23628
September	5400	25817	8333	34150
October	9002	43040	8333	51373
November	11592	55420	8333	63753
December	14136	67583	8333	75916
Total	114007	545067	100000	645067

In the Table the LCC, i.e., 4.59 MSEK, is presented for the building with its existing heating equipment (1 US \$ = 6 SEK). If an optimal thickness of attic insulation (0.24 m) for this heating equipment is introduced, 0.13 MSEK is saved during the projected life of 50 years of the building. Floor insulation is not profitable, for any of the heating systems considered and thus no values are presented. The optimal thickness of external wall insulation, also 0.24 m, saves 0.07 MSEK and weatherstripping 0.03 MSEK. Where retrofits are profitable for some heating systems, but not for all, as is the case for window retrofits, a dash is shown. The resulting LCC if the existing heating equipment is not changed will become 4.36 MSEK.

In this case where the free energy has been set to 0 kWh per month, the combination of the retrofits results in the same LCC, and no special attention has to be paid to the fact that different retrofits might interact. The fact that no free energy at all has been used might seem strange but experience from Malmö shows, however, that the free energy is very hard to utilize. The only result from the free gains is that the indoor temperature will rise. Thermostatic valves available on the market today cannot prevent this temperature rise and thus no energy is saved. It must be

TABLE 2

Retrofit strategy matrix: values in MSEK

	Existing oil boiler	Electricity heating	District heating	Ground coupled heat pump	Bivalent system
LCC with no envelope retrofits	4.59	5.41	3.78	3.90	3.53
Savings					
Attic floor insulation	0.13	0.18	0.07	0.09	0.05
External wall insulation	0.07	0.31	—	—	—
Triple-glazed windows, low-e	—	0.05	—	—	—
Weatherstrip	0.03	—	—	0.01	—
Exhaust-air heat pump	—	0.16	—	—	—
New LCC	4.36	4.71	3.71	3.80	3.48

noted, however, that it is possible to provide OPERA with values on free energy, from appliances as well as from solar radiation in different orientations.

The optimal solution in this case, as well as in many other cases, is to install a bivalent heating system where a heat pump provides the base load and an oil boiler provides the peak load. It is not economic to use only the heat pump because the high capital cost of a pump large enough to meet the peak load is not offset by the low running costs. The only profitable building retrofit in this case is attic floor insulation. Weatherstripping is a very cheap retrofit; here the cost is assumed to be 200 SEK for each item to be sealed, but the decrease in ventilation rate, from 0.6 to 0.5 air changes per hour, is too small to provide profitability. The optimal solution in the base case is thus to change the heating system to a bivalent oil boiler–heat pump system and to insulate the attic floor with an extra 0.19 m of mineral wool.

SENSITIVITY ANALYSIS

In the above example only one building retrofit was profitable. If the energy prices escalate at a real rate of 3% per year (0% is assumed in the base case), more retrofits will be profitable. Attic floor insulation of 0.23 m, external wall insulation of 0.24 m, and weatherstripping are then found optimal, combined with a bivalent heating system. Also, as in the original case of 0% price rise, there was no interaction between retrofits, so the LCC did not change when they were taken together.

If the free heat gains from solar energy, appliances and persons are increased, the situation might be different. In Table 3 the energy balance is shown for such a case. The free energy from appliances and persons is assumed to equal 5000 kWh per year and apartment, resulting in 14667 kWh per month for the total building. The solar gains are calculated according to the theories in ref. 16. The gains are also reduced due to different shading factors for the more complex windows considered in this case.

The optimal solution, assuming a 3% annual energy cost rise, is however almost the same as before, i.e., two envelope retrofits, attic floor insulation and weatherstripping to be combined with a bivalent heating system. The resulting LCC is identical for the combination and the incremental methods. The energy price must increase to 4% annually to show any discrepancies. External wall insulation will then be a candidate. However, the difference is very small, about 1% of the total LCC, and this does not influence the overall strategy.

If only the existing heating system was considered, the situation would be different. The oil boiler should be combined with four retrofits, i.e., attic floor insulation, low-emissivity-coated triple-glazed windows, weatherstripping and an exhaust-air heat pump. Also, here a 3% annual energy price escalation is considered, which results in the highest amount of envelope retrofits in the cases studied. The combination retrofit LCC is calculated to 3 710 000 SEK while the incremental method results in 3 842 000 SEK. The difference is about 3%. Once again, note that this is not the optimal solution. The same

TABLE 3

Energy balance in kWh for the building Ansgarius, Malmö, Sweden. Free gains 14 667 kWh/month and solar gains according to ref. 16

Month	Degree-hours	Energy losses	Hot water energy	Free energy from appliances	Solar gains	Resulting energy
January	15996	76476	8333	14167	4494	66147
February	14712	70340	8333	14167	7633	56873
March	14582	69717	8333	14167	14656	49228
April	10800	51634	8333	14167	18504	27295
May	7440	35570	8333	14167	24297	8333
June	4320	20654	8333	14167	25297	8333
July	2827	13517	8333	14167	24901	8333
August	3199	15295	8333	14167	21517	8333
September	5400	25817	8333	14167	17122	8333
October	9002	43040	8333	14167	11165	26040
November	11592	55420	8333	14167	7718	41868
December	14136	67583	8333	14167	4301	57447
Sum	114007	545067	100000	170000	181609	366567

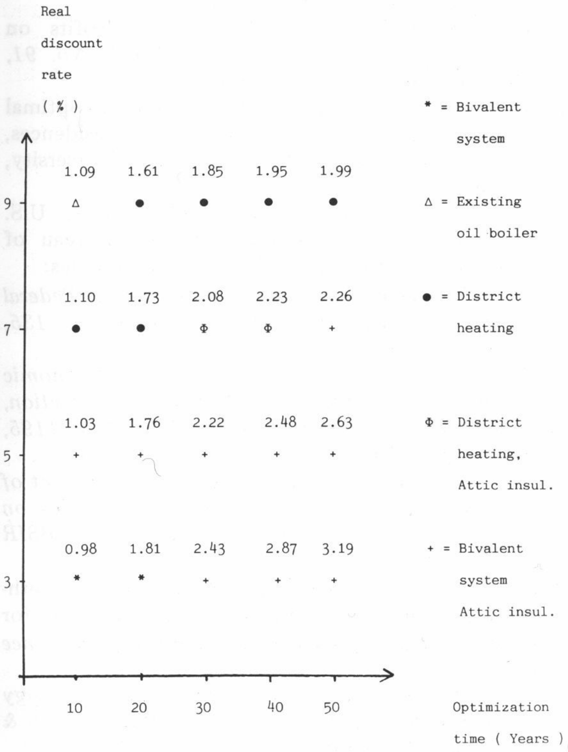

Fig. 2. Bivariate sensitivity analysis. Real discount rate versus optimization time. Values in MSEK.

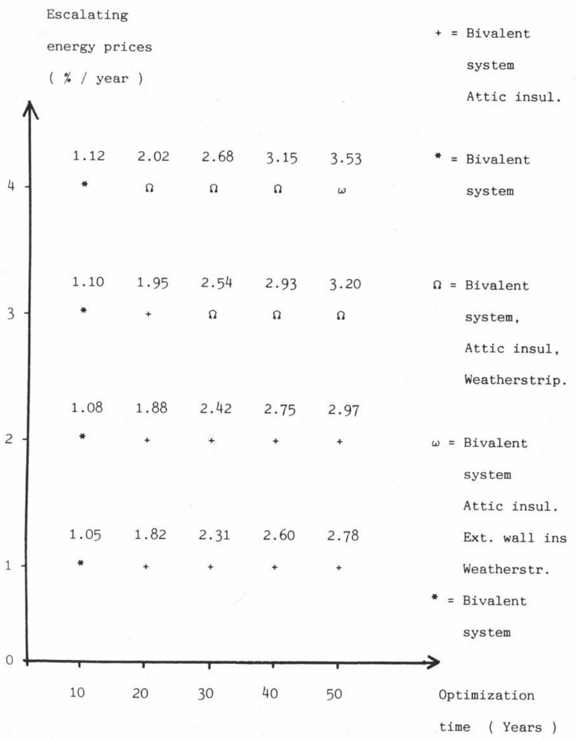

Fig. 3. Bivariate sensitivity analysis. Annual escalation of energy prices versus optimization time. Values in MSEK.

case but with less free energy results in even lower discrepancies.

In Figs. 2 and 3 the optimal solutions for a number of OPERA runnings have been shown. Obviously, the resulting LCC will change, due to the input values of the parameters studied, but the resulting retrofit strategy is almost the same in the vicinity of the base case. The bivalent heating system is the best one for almost all cases studied and this system should be combined with a few cheap envelope retrofits.

In Fig. 2 it is shown that more retrofits are profitable if the discount rate is low and the optimization time, i.e., the project life, is long. A high rate and a short project life, e.g., 9% and ten years, resulted in no retrofitting at all. The best thing to do was to keep the building unchanged. Note that the total LCC is decreased for high discount rates as long as the project life is not too short. This fact is dealt with in more detail in ref. 3. The LCC is increased for longer project lives.

In Fig. 3 the influence of escalating energy prices is shown. The bivalent system was always the best one but it should be combined with different envelope retrofits. For low escalation and a short project life, the envelope retrofits are not very profitable while more retrofits are optimal for the opposite situation.

Consider, however, that the discount rate and optimization time are changed with several hundred percent from the base case in Figs. 2 and 3. Small errors in input parameters do not change the retrofit strategy which is very robust. One envelope retrofit might come or go, but no severe changes will occur in the optimal solution.

CONCLUSIONS

This paper deals with an optimizing energy retrofit model, OPERA, for multi-family buildings. In the literature survey it is shown that this one is the first one ever developed that really can be used for optimizing the total energy system of a building. Complex heating systems, e.g., district heating with time-of-use tariffs or bivalent systems with heat pumps and oil boilers are dealt with. The model enables the operator to find the optimal combination of building, ventilation and heating equipment retrofits. The major conclusions are:

(1) The ranking of different retrofits due to their savings-to-cost ratio is inaccurate. It may be ultimately cheaper to install an expensive heat pump than inexpensive weatherstripping.

(2) Optimal energy retrofits should be implemented when the building is subjected to renovation for reasons other than energy conservation.

(3) A combination of heating system, envelope and ventilation retrofits leads to the optimal situation.

(4) The combined effects of several retrofits is only marginally different from summation of the individual effects and therefore interactions between retrofits can mostly be ignored.

(5) Bivalent heating systems and insulation measures can, and must, be optimized simultaneously.

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