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OPTIMAL ENERGY RETROFITS IN MULTI-FAMILY RESIDENCES

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ABSTRACT

When a building is renovated it is changed as an energy system. Our paper shows the importance of implementing the optimal retrofit strategy when the building is the subject for a renovation anyhow. Neglecting this makes energy retrofits in many cases unprofitable. Very important also, is the heating equipment installed in the building. Systems with low running costs implie that only a few retrofits are profitable, e.g. caulking windows and doors. A heating system with high running costs e.g. electricity, should have an extensive shield retrofit.

The ranking criterion for the retrofit measures has been the minimized life-cycle cost, LCC, meaning that the optimal strategy is found only if the LCC for the unique building considered, is the lowest possible.

The paper also deals with different types of rates for both district heating and electricity e.g. cost accurate time-of-use rates. A sensitivity analysis has been elaborated in order to find out how the optimal solution changes for other values on the input parameters.

In order to solve this problem a mathematical model has been developed where the building, the climate, the cost functions, the economic parameters, etc are inputs. The model can be described as an integer, nonlinear program. Because of the difficulties to solve such a problem, both derivative and direct search methods are used.

Furthermore the paper shows the use of energy balances in order to evaluate the influence of free energy on the optimization procedure.

Key words: Life-Cycle Cost, Retrofitting, Optimization,
Installation, Boiler, Heat pump, Ventilation.

INTRODUCTION

Since 1985 a research project has run, funded by the Swedish Council for Building Research and the municipality of Malmö, Sweden. The aim of this is to find how each unique multi-family building shall be retrofitted in order to get the best profitability for the nation. However, only retrofits related to energy measures are treated.

We have found that a perfect means for optimization is the remaining Life-Cycle Cost, LCC, for the building /1/. The LCC contains the added installation, maintenance and running costs, and thus reflects the cash flow for the building. All of the costs are transferred to a base year using the present value method and they can thus be compared to each other.

Coming so far we can precise our aim:

> How shall different retrofits, both envelope and installation measures, be combined in order to find the lowest possible LCC for the remaining life of a multi-family building?

The OPERA model

In order to find the best retrofit strategy for a building we have developed a mathematical model called OPERA, which is an abbreviation of Optimal Energy Retrofit Advisory model. This model, now implemented in a NORD 570 machine, solves the optimization problem, which can be characterized as an integer, non-linear, mixed program /2/.

The model provides us with the best combination of envelope and heating equipment retrofits. The envelope retrofits implemented are e.g. attic floor insulation, external wall insulation and weatherstripping. Exhaust air heat pumps are also treated. Examples of the heating systems are oil-boilers, electricity, heat pumps, district heating and bivalent oil-boiler heat pump systems. Differential rates for district heating and electricity are also implemented.

However, there are uncertainties in the input data, e.g. the discount rate, the optimization period and the number of degree hours suitable for optimization. In this paper we shall emphasize how the degree hour problem can be dealt with.

Degree hours for optimization

In /3/ it is shown that a mathematical expression for the LCC, concerning an insulation measure, has the form:

$$LCC = C_1 + C_2 \cdot t + \frac{C_3}{C_4 + C_5 \cdot t}$$

where C_1 - C_5 are constants and t is the thickness of extra insulation. The constant C_3 contains among other values the number of degree hours for the site. It is obvious that this value has importance for the optimal insulation thickness and the situation is shown in /4/ for a big climate interval from 50 000 - 150 000 degree hours. For small changings in the number of degree hours the insulation thickness will only vary a little but the question is how many to start with. In /3/ the most simple concept is used, one degree hour is generated if the outside temperature is one degree lower than the inside temperature during one hour. The outside temperatures used are monthly mean temperatures and the inside temperature used is 20^{o}C. For Malmö in Sweden this means that one year contains 105 241 degree hours.

However, we know that it is not necessary to use the heating equipment during the summer, for space heating. The monthly mean temperatures are lower than 20^{o}C but due to solar gains and free energy from appliances and people the heating system can be turned off. Traditionally, at least in Sweden, this has been dealt with using a degree hour concept where no degree hours are generated during the summer when the temperature is above 11^{o}C and furthermore calculate with a lower inside temperature, 17^{o}C. The gap between the 17 and 20^{o}C is supposed to be filled in with free energy. For a detailed discussion about the degree hour concept see /5/.

However, this latter concept cannot be used for insulation optimization. During the months when the heating system works, the free energy of course is valuable. Implementing more insulation to e.g. an attic floor reduces the total energy losses whether the heat for to cover these losses comes from the heating system or from appliances etc.

For the heating equipment optimization, of course, the free energy must not be included. The situation is described in detail in /6/, for both single-family buildings and multi-family ditto.

In Table 1 the situation for a conceptual building is presented, using energy balance calculations. The building and solar gain calculations are described in detail in /3/.

Table 1. Energy balance for a multi-family building i kWh. (1kWh = 3.6 MJ).

Month	Energy losses	Solar gains	Free energy	From the heating system
Jan	59 947	2 069	11 800	46 122
Feb	55 200	3 471	11 800	39 131
March	54 425	6 413	11 800	36 219
April	39 645	7 837	11 800	20 011
May	26 335	10 533	11 800	4 484
June	14 159	10 327	11 800	---
July	8 192	10 214	11 800	---
Aug	9 656	8 977	11 800	---
Sept	18 406	7 393	11 800	---
Oct	32 479	4 984	11 800	15 699
Nov	42 760	2 402	11 800	28 561
Dec	52 670	1 482	11 800	39 394
Sum	413912	76 102	141 600	230 421

The free energy from appliances, people etc is calculated from /7/.

From Table 1 it is obvious that the heating system shall be optimized for 230 421 kWh because it does not produce more heat. In our case this equals 57 619 degree hours.

The insulation measures however shall be optimized for:

413 912 - (14 159 + 8 192 + 9 656 + 18 406) = 363 499 kWh.

The summer months when extra insulation is worthless are subtracted from the total energy losses. More saved heat only makes the inside temperature raise far above 20^{o}C, or more cooling is required. The 363 499 kWh equals 92 422 degree hours in our case.

However, if the attic floor in the building is extra insulated with a certain amount of mineral wool, one more month may be of no interest for the insulation optimization, i.e. May. This means that the proper amount of degree hours will change and can be considered as a variable. Fourtunately the number will change only with 6 695 degree hours in our case and thus the optimal insulation thickness can be considered as constant, however getting a little thinner. Furthermore, due to the uncertainties in the input data e.g. the degree hours, it is better to insulate a little too much then the opposite, as the LCC is raising faster on the thinner side of the optimum /8/. The problem thus is not too big and no overwhelming differences in the optimal insulation strategy will happen.

Considering the most profitable heating system strategy, it is of great importance to use the approximately 60 000 degree hours due to free energy, instead of 90 000 degree hours for the insulation optimization. Expensive heat pump systems will of course have a disadvantage from this, less cheap heat is produced in a 60 000, compared to a 90 000 degree hour system.

We shall depict the situation with the duration graph the figure below.

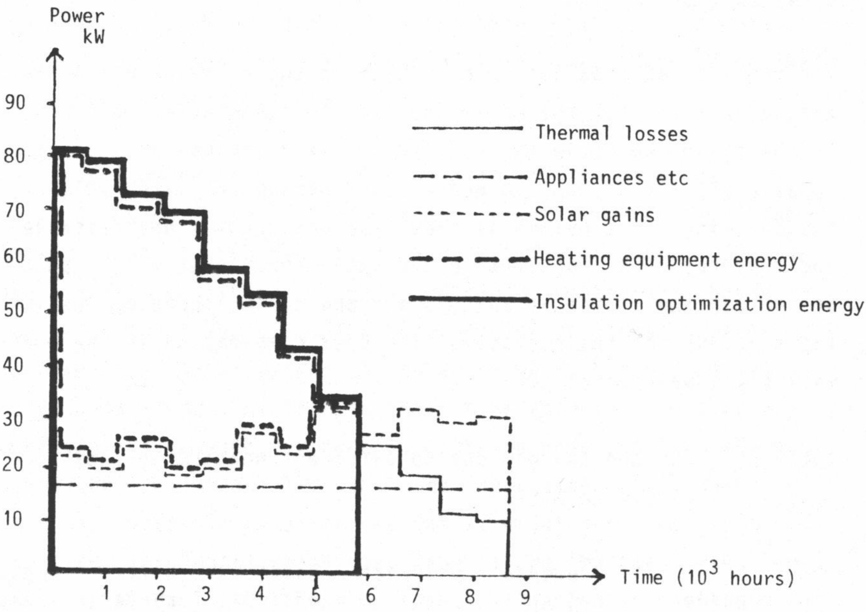

Figure 1. Duration curve for residential heating.

In Figure 1 it is obvious that the heating system can be turned off during the summer months, the amont of free energy is bigger than the thermal losses. The heating season is only about 5 800 hours during a year. However, some of the heat during the heating season is provided by free energy and thus the boiler only has to produce heat according to the heating equipment energy in Figure 1. For the insulation optimization, all of the thermal losses during the heating season have to be considered, no matter how the heat is produced. More insulation makes it harder for the energy to escape and this of course will save money. Note that domestic hot water heating is not considered in Figure 1.

Life-cycle cost tables

The money saved from less use of heat in the building of course must be higher than the money used for the insulation measures. In the following table the LCC for the existing building is calculated and after that the money saved during the life-cycle of the building. If a hyphen is shown the measure was unprofitable and thus rejected. Furthermore the table shows what will happen if the heating system is changed and the optimal envelope retrofit strategy for those systems. The best combination is the one with the lowest total LCC.

Table 2. LCC and savings due to different heating systems. The values in MSEK.

	Oil-boiler	Electric boiler	District heat	Diff. district	Diff. electric	Bivalent system
LCC with no envelope retr.	1.86	2.37	1.77	1.77	2.37	1.64
Savings: Attic ins.	0.08	0.17	0.05	0.05	0.17	0.02
External wall ins.	-	0.08	-	-	0.09	-
Weather-stripping	0.14	0.21	0.12	0.12	0.22	0.10
New LCC	1.64	1.91	1.60	1.60	1.89	1.52

Table 2 shows that the LCC for the existing building, where an oil-boiler with a running cost of 0.25 SEK/kWh is installed, equals 1.86 MSEK. (1 US $ = 6 SEK). Attic floor insulation and caulking windows and doors is profitable while external wall insulation is not. It shall be emphasized here that the optimal thickness of insulation is 0.18 m.

Changing the heating system to electricity, running cost 0.32 SEK/kWh, is not a preferable strategy, the LCC gets higher. However, it is important to notice that also external wall insulation is profitable if the electricity system was chosen in spite of the higher LCC. The thickness of the insulation of course also increases and the money saved is higher, but the result is worse. The fact is that it is essential to find a heating system with low running costs in order to find the most profitable solution. This has been emphasized in /9/ where heating systems with different installation costs have been treated. The installation cost tends to be important when the cost is about 1 000 SEK/kW or higher. This is the situation for many heat pump systems.

One heating system with low running costs is district heating. In the case above the cost is approximately 0.20 SEK/kWh, which is used as a firm rate in table 1, showing the normalized cost for Malmö, Sweden. The marginal cost theory and the normalization concept is treated in more detail in /10/. The running cost is rather close to the oil-boiler case and the strategy will not differ very much.

The differential rates for district heating and electricity will give almost the same strategies as the firm rates. For the building with no envelope retrofits the LCC of course is identical due to the normalization. The envelope retrofits only will have a minor advantage. Important however, is that the differential rates will disadvantage facilities as exhaust air heat pumps and solar collectors. In the case above those retrofits was not chosen for any heating system. The exstensive use of energy balances in the model also will ascertain that there realy is a need for the heat produced in the competing systems.

The best choise however, was the bivalent oil-boiler - heat pump system. The expensive heat pump is combined with an oil-boiler, taking care of the thermal peak load, while the heat pump produces the base heat. The running cost for the system is about 0.12 SEK/kWh. This very low running cost is combined with an acceptable installation cost. The single heat pump system is also treated by the OPERA model but the LCC resulted at 2.03 MSEK. The bivalent system should be combined with attic floor insulation and weatherstripping in order to reach the optimal result. However, the attic floor insulation only saves 20 000 SEK during the optimization period, 50 years in this case, and due to the uncertainties in input data it could be preferable to reject also this retrofit. The optimal solution will thus become: Do some weatherstripping and change the heating system. In /11/ this kind of a very simple strategy is proposed for some real buildings in Malmö, where weatherstripping was the only profitable retrofit. The existing heating systems in those cases were district heating with a differential rate.

Choosing other input data with minor differences from the first estimated makes it possible to do a sensitivity analysis. This can be very important in some cases but mostly the optimal solution found is very robust, a low running cost heating system shall be combined with a few cheap envelope retrofits if you not have to make a renovation anyhow, e.g. change to better windows if the old ones are rot.

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