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MINIMIZATION OF THE LIFE-CYCLE COST WHEN RETROFITTING BUILDINGS.

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Introduction.

When a building shall be renovated, there is an opportunity to change the house as an energy system. However, it is very important to choose a retrofit strategy which minimizes the remaining Life-Cycle Cost, LCC, for the building. If such a strategy could be found, the house as an energy system will be optimized, and no other retrofit can make the total cost lower. In order to elaborate a method that can find the optimal strategy for each unique building, the Swedish Council for Building Research and the community of Malmö, Sweden, have funded this research project which is running since april 1985. In Malmö we are co-operating with a group of seven building contractors, active all over Sweden, and thus it is possible for us to present the first result from our research concerning two existing buildings, owned by ABV and Svenska Riksbyggen AB. First, however, we will describe the mathematical model.

The OPERA model.

The problem to be solved can be considered as a mixed nonlinear and integer program. The objective function that shall be minimized describes the LCC for the building. However, ordinary programming methods can not solve such problems and at the same time find the true minimum with absolute accuracy. Thus we have developed a FORTRAN program where the LCC for each unique building can be calculated. An energy retrofit is after that implemented and a new LCC is calculated. Only if the first LCC is higher then the second the retrofit is profitable and chosen. If the reverse is valid the retrofit of course is rejected. It shall be noted that for the insulation measures the optimal insulation thickness is calculated using a derivative method. This is also the fact for the examined bivalent heating systems. The optimal distribution between e.g. an oil-boiler and a heat pump differs of course due to the thermal status of the building, which is influenced by the envelope retrofit strategy. This strategy however, depends on the heating system and thus the variables have to be considered simultaneously if a cumbersome iterative method shall be avoided. Using this kind of solving process for the problem ensures

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that the true minimum is discovered and by that an optimal retrofit strategy.

The input parameters to the model consists of e.g. the building geometry, the building costs for different retrofits, the installation costs for the possible types of heating equipment, the energy rates, the climate etc. The output from the model is presented in some tables where the influence of different discount rates, optimization time etc can be considered. In the tables the LCC for the existing building and the savings from different profitable retrofits are shown. The best solution are also presented and the resulting energy demand and so fourth are shown. By small changings in the FORTRAN code it is possible to get a lot of information about the optimal strategy and the solution can be studied in detail. The model and the necessary input parameters are described in (1).

Building 1. Hövitsmannen 6, owned by ABV.

This building, from 1934, contains 18 apartments and is located in the middle of Malmö. The facade is made of bricks while the foundation and the cellar floor are made of concrete. A rather big garage is located under and beside the actual building. This garage is also heated from the same boiler and it is thus difficult to get values for the energy demand etc that reflect ordinary multi-family buildings in Malmö. The garage is thus excluded from the calculations. The total apartment area is 1308 m^2. The building has 5 storeys over the cellar. The total window area is 160 m^2 type two glazed. U-values for the attic floor and external walls are 0.9 and 1.2 ($W/m^2,K$) resp.

The retrofit costs for different measures are:

$200 + 475 * t_{af}$	for attic floor insulation /m^2
$250 + 2500 * t_{ew}$	for external wall insulation/m^2

where t is the thickness of new insulation.
In this case there is no inevitable renovation to be made and the figures above thus only show the assumed insulation cost.

The costs for window retrofits are:

1300	for a two glazed window
2250	-"- three -"-
2650	-"- four -"-

Caulking windows and doors have an approximate cost of:

200	for caulking one window

An exhaust air heat pump costs about:

$30\ 000 + 6\ 000 * P$

where P = the thermal power of the heat pump. Pipes and ducts etc coupled to the pump are assumed to cost 2 000 SEK/apartment.

The different types of heating equipment costs are:

$30\ 000 + 200 * P_{OB}$	for a new	oil-boiler
$25\ 000 + 150 * P_{EB}$	-"-	el.-boiler
$30\ 000 + 70 * P_{DH}$	-"-	district heated boiler
$30\ 000 + 6\ 000 * P_{HP}$	-"-	heat pump

All the values above show the cost in SEK (1 US \$ = app.7 SEK) and are presented by ABV, Malmö.

Building 2. Jämtland 9, owned by Svenska Riksbyggen AB.

This object consists of two buildings containing 105 apartments with a total area of approximately 6500 m^2. The U-values for the wall, attic floor and the floor are 0.91, 0.55 and 0.83 $W/m^2,K$ resp.. The windows are two glazed with a U-value of 3.0 $W/m^2,K$. Building year is 1956. The external walls consist of bricks, the attic floor of concrete and mineral wool and the cellar floor of concrete and wood-wool slabs. The buildings are heated with district heating and have an installed power of 570 kW for the radiators and 670 kW for the hot water. The total energy demand during 1985 was 1.4 GWh, a little less then calculated.

The retrofit costs for the different measures are:

$200 + 200 * T_{af}$	for the attic floor insulation/m^2
$350 + 300 * T_{ew}$	-"- external wall -"-
$1000 + 800 * A_W$	for one two glazed window, area = A_W
$1100 + 900 * A_W$	-"- three -"-
$1200 + 1200 * A_W$	: four -"

Caulking windows and doors cost approximately 200 SEK/window etc., while an exhaust air heat pump costs about $30\ 000 + 3\ 000 * P$ SEK.

The heating equipment retrofits cost approximately:

$50\ 000 + 350 * P_{OB}$	for oil-boilers with the power P_{OB}
$20\ 000 + 100 * P_{EB}$	for electrical boilers, power P_{EB}
$100\ 000 + 400 * P_{DH}$	for district heated b., power P_{DH}
$150\ 000 + 3000 * P_{HP}$	for heat pump facilities, power P_{HP}

It shall be noted that the high firm cost for the oil boiler above depends on a very bad chimney that has to be renovated. All the costs etc, shown above, are delivered by Svenska Riksbyggen AB, Malmö.

Of course it is impossible to show all of the input data for the calculations and thus we recomend the interested reader to contact us for the complete input files.

Energy costs, differential rates e.t.c.

In the tables below, the LCC have been calculated for different heating systems. The energy cost for the building thus differs due to that equipment. The oil price used was 0.24 SEK/kWh considering the efficiency of the boiler. The price for electricity depends on the season and time for consumption. The power utility uses a differential rate. The mean value for one year is app. 0.30 SEK/kWh, taxes included. The district heating utility also uses a time-of-use rate since some years. The mean value for the energy price during one year is about 0.20 SEK/kWh. Information about the district heating rate and its influence on optimal retrofits are shown in (2). The heat pump equipment has an assumed COP = 3.0, and thus the energy cost is 0.10 SEK/kWh.

Economic parameters, climate etc.

The LCC is calculated using the net present value method. This is presented in detail in (1). However, in this method we have to use the proper discount rate and optimization time. Unfortunately there are no ultimate values for those parameters, but most recomendations tells us that the discount rate shall be between 3 - 10 % inflation excluded. The proper optimization time can not be determined with any accuracy but the influence from very time distant events are very small and thus the optimal retrofit strategy changes very little if the optimization time changes from e.g. 50 to 70 years.

The two objects are sited in Malmö, Sweden, and the number of degree hours thus can be calculated to 105 000. However, this number is decreased by the amount of free energy coming into the buildings with the sun and the use of electric equipment and thus studies also have to be made for other numbers of degree hours.

The problems mentioned above are not easy to solve and thus we have to study the strategies for some different input parameters, i.e. a sensitivity analyzis has to be made. In (3) this has been done for insulation retrofits.

Result.

The result from the calculations is shown in two tables. First the LCC is presented if no retrofits at all, exept for the inevitable ones, are done to the building. After that the amounts of money saved during the optimization period are shown for the different retrofits. If the amount is null the retrofit was found unprofitable, and thus rejected. The optimal strategy for the existent heating system by that has been found and the resulting LCC is shown. The procedure is then repeated for the other possible heating systems and the lowest resulting LCC can be found in the tables. The first table shows the situation for a base case where the optimization time is 50 years, the discount rate is 5 %, the annual increase in energy prices is 0 % and the number of degree hours is 105 000, showing the situation in Malmö without considering the influence of the free energy supplied to the building by people and electric equipment.

Table 1. LCC and savings for the object Hövitsmannen 6. The figures in 10^6 SEK. Base case.

	Oil-boiler	Elect. boiler	District heating	Heat pump	Bivalent oil-heat pump
LCC with no envelope retrofits:	1.71	1.96	1.30	2.01	1.53
Savings:					
Attic floor insulation:	0.03	0.06	---	0.07	---
External wall insulation:	---	0.06	---	0.08	---
Four glazed windows:	0.09	0.15	0.04	0.17	0.07
Weather-stripping:	0.16	0.21	0.11	0.25	0.14
Exhaust air heat pump:	---	---	---	---	---
New LCC	1.43	1.48	1.14	1.44	1.33

From table 1 it is obvious that the best retrofit strategy is to keep the existent district heating system and combine it with weatherstripping and four glazed windows. The fact that the windows shall be changed depends mostly on the bad quality at the existent ones. The windows have to be replaced with new ones whether they save energy or not. The optimal strategy however does not save very much energy. The demand is 87 kW and 328 000 kWh/year before the retrofits. After the optimal strategy has been implemented this decreases to 58 kW and 243 000 kWh/year. The annual demand per square meter decreases from 250 to 185 kWh/m^2. Table 1 also shows that it is the high running cost systems e.g. the electrically heated building that generates most envelope retrofits. The exhaust air heat pump, however, was not profitable what ever the heating system was. In this case this can depend on the rather small building. There is not very much heat to recover in the exhaust air.

A sensitivity analyzis tells us that the optimal solution above is very robust. The district heating is the best choise for:

* optimization periods from 0 - 50 years,
* discount rates from 3 - 21 %,
* less then 3 % annual escalation in energy prices. Higher not tested
* 70 000 to 130 000 degree hours type of climate

Weatherstripping was a profitable alternative for all the parameters above. It shall be noted that if there was another heating system in the building it could be more profitable to install an exhaust air heat pump and skip the stripping for some cases. This is so because the weatherstripping decreases the ventilation flow through the building.

Attic floor insulation is unprofitable as long as the

* Discount rate is higher then 3 %,
* the annual incrase in energy prices is lower then 1 %,
* the climate is warmer then 130 000 degree hours

The optimal new attic floor insulation thickness varies between 0.15 - 0.20 m..

External wall insulation are only chosen when the discount rate is 3 % or lower, the annual increase in energy prices is 2 % or higher. The optimal thickness of new insulation is about 0.07 m for those cases.

Four glazed windows are not chosen when:

* the optimization time is less then 10 years,
* the discount rate is higher then 7 %,
* the climate is warmer than 70 000 degree hours.

Due to the uncertainty for the discount rate, the four glazed windows maybe should be rejected. The old windows in such a case shall be replaced with new two glazed ditto. The optimal strategy will then become: "Do some weatherstripping and leave the building as it is".

The other building is presented in the next table:

Table 2. LCC and savings for the object Jämtland 9. The figures in 10^6 SEK. Base case.

	Oil-boiler	Electr-icity	District heating	Heat pump	Bivalent heat pump - oil-b
LCC with no envelope retrofits:	9.96	11.85	8.09	7.18	6.71
Savings:					
Attic floor insulation:	----	0.07	----	----	----
External wall insulation:	----	0.30	----	----	-----
Three glazed windows:	0.48	0.69	0.33	0.26	0.19
Weather-stripping:	0.78	1.07	0.57	0.48	0.37
Exhaust air heat pump:	----	----	----	----	----
New LCC	8.69	9.72	7.19	6.44	6.14

Table 2 shows the LCC for a much bigger building than table 1. In this case the most optimal solution was to change the heating system to a bivalent heat pump and an oil-boiler. The heat pump supplies the building with heat during base load conditions while the oil-boiler is working during the thermal peaks. This heating system is the best for all the parameters mentioned above exept for a climate warmer then 70 000 degree hours. The heating system retrofit shall be combined with weatherstripping and changing windows to three glazed ditto. This solution is so robust that it never changes for the tested parameters exept for the heating equipment change, mentioned above. Also in this case the existent windows are very bad and they have to be replaced immediately. Other examples showing the influence of the obsolescence can be found in (4).

As previous mentioned also the bivalent heating equipment has to be optimized. The thermal load, the oil-boiler and heat pump installation cost, the energy prices all influence on the most profitable solution. In (5) the optimization technique is described in detail. In this case the COP for the heat pump is considered as a constant, which can be tolerable for some heat pump installations. The procedure, however, is exactely the same when the COP is a function of the outside temperature. In this case the heat pump delivers heat during all the year and the oil-boiler is used only during peak conditions. Implementing the optimal envelope strategy makes the total power demand change from 449 kW to 332 kW. The energy demand decreases from 1 632 000 kWh/year to 1 291 000 kWh/year or from 251 kWh/m^2 to 198 kWh/m^2. It is obvious that the best solution is not to save energy but to make it cheaper. The heat pump in our case above shall have the power of 216 kW and the oil-boiler 116 kW. Allmost all of the heat produced in the system comes from the heat pump, while the oil-boiler delivers a minor part.

From the previous discussion it can be found that the lowest possible LCC almost always emerges if a low running cost heating system can be implemented in the building. However, if the building is rather small the more expensive installation costs for the heat pump alternatives can not compete with the differential rate of the district heating. If the thermal demand gets higher, this means that a bivalent system shall be considered. The envelope retrofits such as insulation measures can be profitable if the starting cost is rather low. Attic floor insulation sometimes is profitable. Windows in good condition are mostly unprofitable to change at least for energy reasons. Exhaust air heat pumps will not be profitable if a heating system with low running costs are installed. Weatherstripping almost always seems to be profitable because of the low "installation" cost. Sometimes, however, for heating systems with higher running costs it could be more profitable to install an exhaust air heat pump and reject the stripping. The lower ventilation flow makes the heat pump less profitable than it has to be. In (6) there are some examples about this situation.

In many cases in Sweden the buildings are retrofitted as if the heating system was a high running cost system. By this the thermal load gets too small to make the low running cost and subsequentely high installation cost heating system profitable. It is thus essential that the right retrofit strategy is implemented from the beginning.