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SESSION A · Methods of Economic Evaluation

Cost-benefit analysis, performance evaluation, life-cycle-costing, investment appraisal, economic aspects of building regulations

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Optimization of the Retrofit Strategy for a Building in Order to Minimize its Life-Cycle Cost

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In order to find an optimal retrofit strategy for a unique building it is suitable to use the Life-Cycle Cost, LCC, as a ranking criterion. Having found the lowest possible LCC implies that the strategy is optimal i.e. no better solution can be found. For many buildings this solution is mostly achieved with a low running cost heating equipment and almost no envelope retrofits e.g. district heating with a cost accurate rate. A high running cost equipment combined with an extensive shield retrofit can sometimes compete, at least if the building is rather small.

The life-cycle cost as a means for evaluating retrofit measures

A lot of ranking criterias have been used to rank different retrofit measures. Some of these are e.g. the savings-to-investment ratio and the discounted payback method. These methods and others are described in [1]. However those methods do not make us choose an optimal strategy without a tedious iterative process. The LCC for a building consists of both the building costs and the running costs for the house during the life of the building. The reccurring costs in the future is transferred to a base year using the Net Present Value method. Thus the different costs can be compared to each other. The process is thoroughly described in [2]. In figure 1 the situation is depicted for an attic flooor with an insulation retrofit.

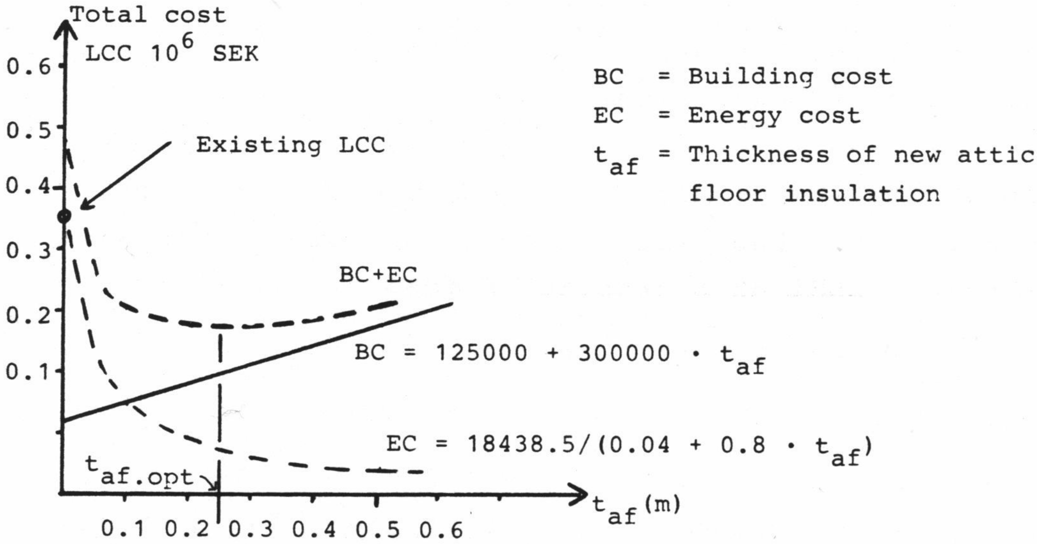

Figure 1. The total cost for an attic floor retrofit.

The example can be found in [2] where the energy price used was 0,30 SEK/kWh and the number of degree-hours was 105000 showing the situation in Malmö, Sweden. The existing U-value for the attic floor was 0,8 $W/m^2,K$ and the conductivity of the new insulation equals 0.04 W/m,K. The discount rate was 5% and the optimization period 50 years. To find the minimum cost and the optimal new insulation thickness, t_{af}, it is easy to derivate the total cost function BC + EC. In this case the lowest cost is achieved for t_{af} = 0,23 m. Of course the retrofit shall be considered only if the corresponding cost is lower than the existing cost for the attic floor. In [3] we have shown what will happen to the result if the input parameters are changed. This technique can be used for all the retrofit measures with a continuous total-cost function. This is not the fact for e.g. window retrofits. The cost for retrofitting will have discrete values according to the number of glasses etc. Thus we have to select the window construction with the lowest total cost among the other types of windows. The problem can be considered as an integer program using the terminology in [4]. The evaluation of the discrete values however are complex because of the cumbersome procedure to find adequate U-values for windows both during darkness and especially during daytime. In [2] this have been treated in more detail. Other kind of retrofits can be dealt with in the same manner e.g. exhaust air heat pumps or caulking windows and doors. However, using a constant energy price as above 0.30 SEK/kWh, is not very adequate. Changing the heating system in the building from e.g. an oil boiler to a heat pump makes it necessary to calculate with a totaly different price for energy, maybe three times lower. Of course such a measure changes the climate shield retrofit strategy very much. It is obvious that it is very important to consider the building as an energy system. Adding the different thermal losses together makes it possible to dimension a suitable heating equipment for the building. The cost for such an equipment to a great part is a function of the total power demand in the building. In [5] we have shown the aquisition and retrofit costs for some different heating systems, and the influence the heating equipment may have on the building envelope retrofits. Considering the heating equipment cost for an oil boiler makes it necessary to add an expression to the previous one in figure 1. The new LCC function thus will be: $LCC = 125000 + 300000 \cdot t_{af} + 18438.5/(0.04 + 0.8 \cdot t_{af}) + 729/(0.04 + 0.8 \cdot t_{af})$. The optimal attic floor insulation thickness only changes with about 0.005 m and the influence of the heating system in this case could be neglected. However considering a lake or an earth heat pump makes the expression, 729, about 10 times higher and therefore the heating equipment cost must be considered for such cases. From this discussion we think that it is obvious that using the LCC cost as a ranking criterion makes it possible to find the best retrofit strategy for each unique building.

The model

We have developed a mathematical model called OPERA (OPtimal Energy Retrofit Advisory model) which finds the minimized LCC and thus the optimal retrofit strategy for each unique building. Input to the model are the geometry for the building, the climate conditions, the economic parameters, the building costs, the energy prices etc. The model is implemented in a NORD 570-machine which solves the problem after about 30 seconds. The model, that may be called a mixed, nonlinear, integer program is solved with derivative methods for the continuous functions. The integer functions are solved using a comparative method because of the insecurity with ordinary integer programming methods [4]. Solving the model with our method thus ascertains that the optimal solution is found.

Case studies

Our building, which is fictional, is a rather small multi--family house with 20 apartments and 100 m^2 area in each. The highth of each of the two storeys is 2.4 m. The attic floor, the floor and the external wall area is 1000, 1000 and 700 m^2, the windows excluded. These are two glazed and have a total area of 140 m^2. The existing U-values for the attic floor, the floor and the external wall are 0.8, 0.6 and 1.05 (W/m^2,K). The U-values for the windows to the north, east/west, south and during darkness are 2.6, 0.8, -1.2 and 4.0 (W/m^2,K). We also have to take notice about the remaining life of the envelope which are for the attic floor, the floor, the external wall and the windows 50, 20, 10 and 10 years. A natural ventilation system is installed with 0.8 renewals/hour. The remaining life is 50 years. The building is oil heated with a boiler of 170 kW and the efficiency 0.7. The remaining life is 5 years. The energy consumption for hotwater is 80000 kWh/-year. The building costs have been calculated to $0 + 125 + 300 \cdot t_{af}$, $325 + 85 + 555 \cdot t_{ew}$, $250 + 195 + 250 \cdot t_{fl}$ (SEK/m^2) for the attic floor, the external wall and the floor. The figures 0, 325 and 250 show the cost/m^2 without any insulation at all the so called ineviteable retrofit cost. The retrofit costs for one window has been calculated to $1890 + 560 \cdot A_w$, $2350 + 790 \cdot A_w$, $2580 + 1020 \cdot A_w$, $2910 + 1250 \cdot A_w$ SEK for 2, 3, 4 and 5 glazed windows respectively, where A_w is the area of one window. Caulking windows and doors costs 200 SEK for each window or door and an exhaust air heat pump will have a calculated cost of $90.000 + 10.000 + 4.500 \cdot P_{EH}$ SEK. 90.000 SEK is the cost for caulking ducts and installing new pipes etc while the rest is the cost for the actual heat pump. P_{EH} is the thermal power of the heat pump. The economic life for the channels etc is 30 years while the heat pump has to be changed after 15 years. The retrofit cost for the heating equipment have been calculated to $20.000 + 350 \cdot P$, $20.000 + 100 \cdot P$, $75.000 + 75 \cdot P$, $30.000 + 3.300 \cdot P$ for oil boilers, electrical boilers, district heating and heat pumps respectively. The efficiencies are 0.7, 1.0, 1.0 and 3.0 for the systems above. The economic life for oilboilers etc have been estimated to 15, 20, 30 and 10 years. After all these values, which have been calculated in [2], we will show the result for this and other cases, where the input variables have been changed. The prices for energy is 0.18, 0.31, 0.19 SEK/kWh for oil, electricity and district heating. Note the efficiencies above for the different heating systems.

Result

In table 1 the result for the case above is shown.

Table I. Life-cycle cost and savings for the base case (10^6 SEK)

	Heating system						
	Exist oil	New oil	Electricity	District heat	Heat pump	T-O-U Distr.h.	T-O-U Electr
LCC with no retrofits	2.43	2.43	3.02	2.14	2.48	2.14	3.02
Savings							
Attic fl. insul.	0.11	0.11	0.20	0.06	0.12	0.06	0.21
Ext.wall insul.	0.3	0.2	0.10	-	0.04	-	0.12
Caulking	0.17	0.16	0.23	0.13	0.17	0.13	0.25
Exhaust air heat pump	0.03	0.02	0.17	-	-	-	0.10
New LCC	2.09	2.11	2.32	1.96	2.15	1.95	2.34

Floor insulation and the window retrofits where never found profitable and are thus excluded from table I.Two Time-Of-Use (T-O-U) rates have been tested both used in Malmö, Sweden. The district heating rate is 0,19 SEK/kWh during Nov-March and 0.10 SEK/kWh the rest of the year. The T-O-U for electricity is 0.42 SEK/kWh Nov-March, Monday to Friday, 0600-2200 and 0.232 SEK/kWh the rest of the time, taxes included. The ordinary rate for district heating and electricity have been normalized to the T-O-U rates. This means that the power company gets the same income from the different types of rates for the existing thermal load. The LCC for district heating and T-O-U district heating thus is identicial for the building with no climate shield retrofits. This is treated in more detail in [7].

The most expensive heating system was the electricity and the cheapest, the district heating. Adding retrofits to the building the LCC gets lower. Optimal attic floor insulation was always profitable, while floor insulation never was. External wall insulation was profitable for the high running cost systems. The optimal solution is a T-O-U district heating system with attic floor insulation and caulking. The LCC gets 290.000 lower just by changing the heating system and 190.000 SEK lower than this, if the climate shield retrofits are made. Keeping the existent oil boiler, implies that also an optimal external wall insulation should be made to the building and an exhaust air heat pump installed. In this case the retrofits at the envelope lowers the LCC with 340.000 SEK. However the resulting LCC is higher than the optimal one. From table 1 the influence of a T-O-U rate also is obvious. The insulation measures gets a better result and the exhaust air heat pump gets a lower amount of money saved. This is of course of great importance to the heating utility. During the winter when the energy production cost is high the utility wants the consumer to save energy. During the summer the cost for producing an extra unit of energy is low and thus there is no need for saving.

The base case above has a optimization period of 50 years. In table II this is changed to 10 years. Only the profitable retrofits have been noted.

Table II. Life-cycle cost and savings in 10^6 SEK. Optimization time = 10 years.

	Exist oil	New oil	Electricity	District heat	Heat pump	T-O-U distr.	T-O-U electr.
LCC with no envelope retrofits	0.86	0.85	1.10	0.76	0.87	0.76	1.10
<u>Savings</u>							
Caulking	0.07	0.07	0.10	0.06	0.07	0.06	0.10
Exhaust air heat pump	0.01	-	0.06	-	-	-	0.03
Total LCC	0.78	0.78	0.94	0.70	0.80	0.70	0.97

Changing the optimization time to 10 years means that a lot of the envelope retrofits are unprofitable. The optimal solution is district heating and caulking. Changing the optimization time to e.g. 90 years will not have a big influence compared to the base case because the far away costs does not imply very much to the LCC.

Using a higher discount rate (in the base case 5%) has a very big influence on the retrofit strategy. Table III shows this.

Table III. Life-cycle cost and savings in 10^6 SEK. Discount rate 15%.

	Exist oil	New oil	Electricity	District heat	Heat pump	T-O-U distr.	T-O-U electr.
LCC with no envelope retrofits	0.89	0.91	1.11	0.83	1.12	0.83	0.85
Caulking	0.05	0.05	0.07	0.04	0.08	0.04	0.08
Total LCC	0.84	0.86	1.03	0.79	1.04	0.79	1.03

Also in this case the shield retrofits were unprofitable. The expensive heat pump has a disadvantage of high discount rates.

3% uniform raisings of the energy prices makes of course the retrofits more profitable. This is obvious from table IV.

Table IV. Life-cycle cost and savings in 10^6 SEK. 3% annual energy price escalation.

	Exist oil	New oil	Elec-tricity	District heat	Heat pump	T-O-U distr.	T-O-U electr.
LCC with no envelope re-trofits	3.80	3.79	4.87	3.29	3.10	3.29	4.87
Savings							
Attic floor insulation	0.32	0.32	0.49	0.23	0.22	0.24	0.51
External wall insu.	0.22	0.21	0.37	0.14	0.12	0.15	0.39
3-pane windows	0.01	0.01	0.08	-	-	-	0.06
Caulking	0.32	0.32	0.44	0.26	0.24	0.26	0.47
Exhaust air heat pump	0.35	0.34	0.60	0.22	0.02	0.13	0.48
Total LCC	2.57	2.59	2.88	2.44	2.50	2.51	2.93

In this case the optimal solution was a heat pump if no envelope retrofits were considered. The district heating with some retrofits however was the best choice.

A mild climate makes of course a lot of retrofits unprofitable. Sometimes it was not even profitable to caulk the windows and doors. It is so because the caulking diminutes the air flow through the building. It was cheaper to install a little bigger exhaust air heat pump and use the higher ventilation flow to produce energy instead of caulking and install the heat pump. Cold climates naturally generates more envelope retrofits.

One more important parameter shall be discussed. The remaining economic life of the envelope. Table V shows what happens if the economic life for the external wall the floor and the windows are set to 0 years which means you have to renovate the envelope anyhow. Other values are identical to the base case.

Table V. Life-cycle cost and savings in 10^6 SEK. 0 year envelope life.

	Exist oil	New oil	Electricity	District heat	Heat pump	T-O-U distr.	T-O-U electr.
LCC with no envelope retrofits	2.89	2.89	3.47	2.60	2.94	2.60	3.47
<u>Savings</u>							
Attic floor insulation	0.11	0.11	0.20	0.06	0.12	0.06	0.21
Floor insulation	-	-	-	-	-	-	0.01
Ext. wall insulation	0.14	0.14	0.22	0.10	0.15	0.10	0.23
3-pane windows	0.05	0.04	0.09	0.02	0.06	0.02	0.08
Caulking	0.17	0.16	0.23	0.13	0.17	0.13	0.25
Exhaust air heat pump	0.03	0.02	0.17	-	-	-	0.10
Total LCC	2.39	2.41	2.57	2.30	2.44	2.28	2.60

Changing the economic life for e.g. the external wall to 0 years of course makes it more profitable to start the retrofit. In this case a lot of envelope retrofits are profitable also for the low running cost heating systems.

From the previous discussion it is obvious that a low running cost heating system is very important if the LCC shall be minimized. The heat pump provides a very low running cost but a big heat pump is very expensive. Using an oil boiler for the thermal peak load and a heat pump for the base load makes the installation cost for the system much lower. Such a bivalent system will thus be a very good solution in order to get a lower LCC. In [6] we have shown how such a system can be optimized also considering insulation measures at the climate envelope. Figure 2 show the LCC as a function of the heat pump thermal power and the thickness of insulation for the attic floor.

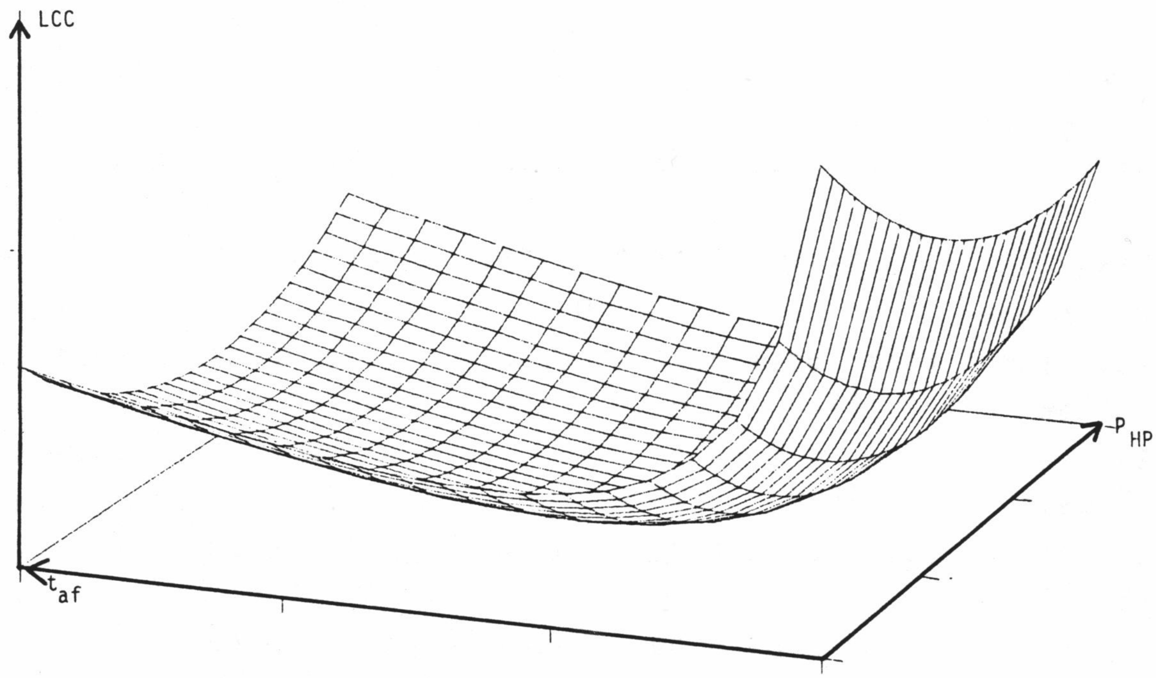

Figure 2. Optimization field for a bivalent heating system [6].

The minimized LCC for the bivalent system without any envelope retrofits is approximately 2.040.000 SEK. Combined with attic floor insulation and caulking the LCC becomes 1.880.000 SEK which also is the lowest LCC achieved for our case study.

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