Optimisation and Simulation of Building Energy Systems

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Abstract

The Mixed Integer Linear Programming, MILP, technique is a useful tool for the optimisation of energy systems. However, the introduction of integers in linear models results in a severe drawback because the ranging process is no longer available. Therefore, it is not possible to study what happens to the solution if input data are changed. In this paper, we compare an MILP model of a building with a simulation model of an identical case. Both models describe a building with a number of possible retrofits. Using the MILP technique, the optimal retrofit strategy is calculated, after which certain input data are changed. The optimisation results in the lowest possible Life-Cycle Cost, LCC, of the building, and the paper describes how much the LCC will change if the property owner chooses other solutions. An increase in a particular data value may cause the LCC to increase or decrease. It may also be unchanged. Only a few data reduce the LCC when their values are increased.

Key words: Sensitivity analysis, MILP programming, Buildings, Energy Systems, Life-Cycle Costing, Retrofitting

INTRODUCTION

When a building is to be retrofitted, a number of measures are possible. For example, the existing windows can be replaced with new triple-glazed types or the existing boiler can be replaced with a district heating system, if such a system is available. Several hundred combinations exist and it is not easy to choose the best strategy. The Life-Cycle Cost, which sums all costs during a certain period of time, provides a criterion for finding the best solution, i. e. when the LCC is as low as possible. The strategy is thereby optimised and no solution with a lower LCC will be created as long as the input data are the same. Changing these data might, however, result in a different optimal solution. In MILP programming, the LCC is set up in a so called "objective function" which is to be minimised. A very simple solution is to choose the value zero for all the variables, although in this case no heating is provided in the building. A number of constraints are therefore introduced, all of which must be fulfilled in a valid solution. In most cases, only a few of the constraints are actually used for the specific optimal strategy, but it is not easy to determine them in advance.

Some of the costs of building equipment are not totally linear but instead show incremental behaviour. If a wall is retrofitted and extra insulation is to be applied, there is a "starting cost" which must be considered. Such steps are dealt with by using integers, i.e. if insulation is to be applied, a high price must be paid before the actual insulation retrofit actually starts. Such costs occur, for example, in the case of demolition of the existing facade. If the insulation is optimal, the integer is set to 1 and the cost is included in the optimal LCC. If the opposite is valid, the integer equals zero. LP and MILP programming from a mathematical viewpoint is dealt with in Reference [1] or [2] and is therefore not covered here in greater detail.

OPTIMISATION

The cost of heating a building varies according to the climate during the year. If electricity is used, which is common in countries such as Sweden and Norway, the cost also depends on the time of day. High cost periods apply on working days, while a lower price is charged in summer. District heating tariffs may also be divided into such time-of-use tariffs. Since the LP method is used, the energy need has to be split up into a number of segments and the energy in that segment multiplied by the applicable cost. The energy cost is incurred every year and thus a present-value factor must be introduced. For a 50-year project life and an interest rate of 5%, this factor will be 18.26. Our objective function therefore includes the following expression, where P_{1hdh}, P_{1hhp} and P_{1hob} indicate the thermal need in kW for a district heating system, a heat pump and an oil-boiler in the January high cost segment.

$$(P_{1hdh} \times \frac{0.26}{0.95} + P_{1hhp} \times \frac{0.94}{3.0} + P_{1hob} \times \frac{0.39}{0.7}) \times 368 \times 18.26$$

The district-heating price is 0.26 SEK/kWh and the efficiency is 0.95. The other values refer to the heat pump and the oil-boiler. Only one time segment is shown here and it has a length of 368 hours. Note that we do not know the actual values of P_{1hdh} et c., which instead are set by the optimisation. The model contains 22 time segments. The reason for this is firstly that monthly mean values are used for the climate. Twelve segments are used for this purpose. Secondly, according to the electricity tariff, the five winter months have a high cost and a low cost segment. In order to properly represent the use of a hot water thermal storage system, weekends must be treated separately and therefore each winter month, from November to March, is divided into three segments. The model is shown in detail in References [3] and [4] and in its present state it contains 183 variables and 152 constraints. Of the variables, 75 are binary integers. For pedagogic reasons, we start with a case where no building retrofits at all are performed on the climatic shield or ventilation system. In order to achieve this, we have set high values for the costs of such measures. The optimisation result can be studied in Figure 1, which shows that the oil-fired boiler should be used only in two segments, i. e. January and February nights between Monday and Friday.

The oil-boiler is also used for covering thermal peaks up to 72 kW. The heat pump should operate throughout the year. This is partly a consequence of the Swedish electricity tariffs of 1.01, 0.56 and 0.45 SEK/kWh for winter working

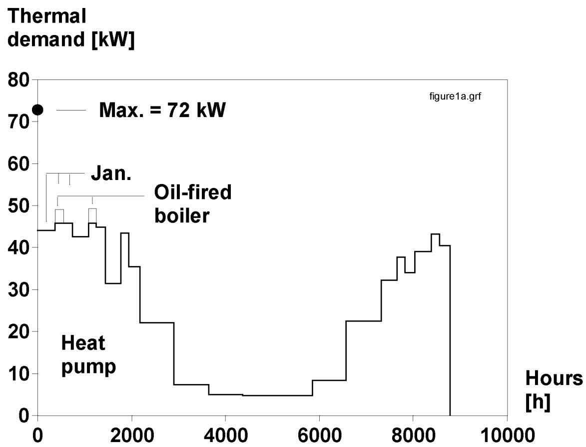

Figure 1: Thermal demand in the studied building and optimal use of the oil-boiler and heat pump.

days, winter nights and summer respectively. The price of oil in this study is set to 0.39 SEK/kWh. (1 USD equals about 8.3 SEK). The Coefficient Of Performance, COP, for the heat pump is set to 3.0, while the efficiency of the oil-boiler is 0.75. The running cost of the heat pump is therefore always lower than for the oil-fired boiler. The reason for using the boiler at all is that large heat pumps are very expensive compared to oil-boilers. In this study, the costs have been set to 55,000 + 60Pob SEK for the boiler and 60,000 + 5,000 Php SEK for the heat pump. These costs must, of course, be calculated as present values before they are inserted in the objective function, see 4 for details.

In the studied case, the thermal size of the boiler is 35.03 kW, while the heat pump is optimised to 15.23 kW. If the COP for the heat pump and the efficiency for the oil-fired boiler are considered, the total thermal power installed in the building is 71.96 kW, which is the actual need, see Figure 1. The total LCC is calculated at 1.566 MSEK.

SIMULATION

It is now assumed that the property owner chooses a heat pump of a different size. For the sake of consistency, the boiler should be changed accordingly. Figure 2 shows the resulting LCC for different electrical sizes of the heat pump.

If the property owner chooses not to use a heat pump at all, the LCC will be 2.39 MSEK. The incremental cost of the heat pump will thus not be present in the LCC. If only a very small pump is used, for example 1 kW as shown in Figure 3, the incremental cost is present, but at the same time the energy cost is reduced and the LCC becomes 2.35 MSEK.

However, the slope of the curve clearly changes at that point. If a theoretical heat pump with a size of 0.001 kW is chosen, the LCC will be 2.50 MSEK. The

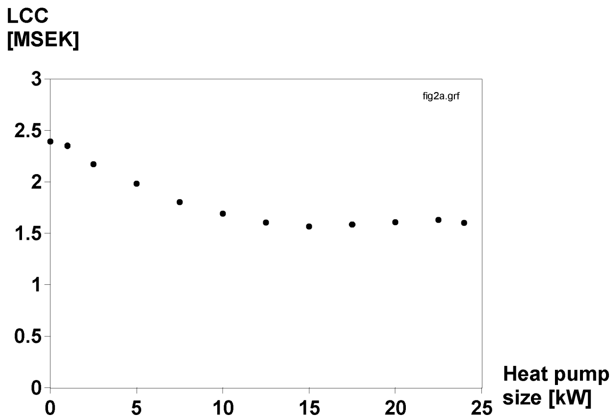

Figure 2: Life-Cycle Cost in MSEK of the studied building for different electrical sizes of a heat pump.

same effect can be seen at the other end of the graph. When the size of the heat pump exceeds 23.99 kW, there is no need for an oil-fired boiler and hence the slope changes again. This results in a LCC of 1.60 MSEK. The optimal LCC is, however, about 0.04 MSEK lower. From Figures 1 and 2, it is obvious that the size of the heat pump is not very interesting on the right-hand side of the optimum point, as long as its size, together with the size of the oil-fired boiler, is sufficient for meeting the thermal peak in the building. If too small a heat pump is chosen, the result will be unsatisfactory because the slope of the curve is much steeper on the left-hand side of the optimum.

COMPARING SIMULATION AND OPTIMISATION

One retrofit which is almost always profitable is weatherstripping. Hitherto, this type of retrofit has been prohibited by the very high cost, which we set to 25,000 SEK, for sealing each window or door. A more acceptable value would be 250 SEK. Weatherstripping is then included in the optimal solution and the LCC becomes 1.558 MSEK, i.e. slightly lower than before. At the same time, the new optimal sizes of the heat pump and oil-boiler become 14.63 and 33.90 kW respectively. In Figure 3, the change in LCC is shown for different values of the sealing cost. The squares show the LCC when weatherstripping is implemented, whatever the cost, while the dots show the result of optimisation. For low sealing costs, the two LCCs are identical, but when the weatherstripping cost exceeds 307 SEK per sealed item, the retrofit is excluded from the optimal solution. The dots in Figure 3 are subsequently located on a horizontal straight line, while the squares are located on a straight, but ascending, line.

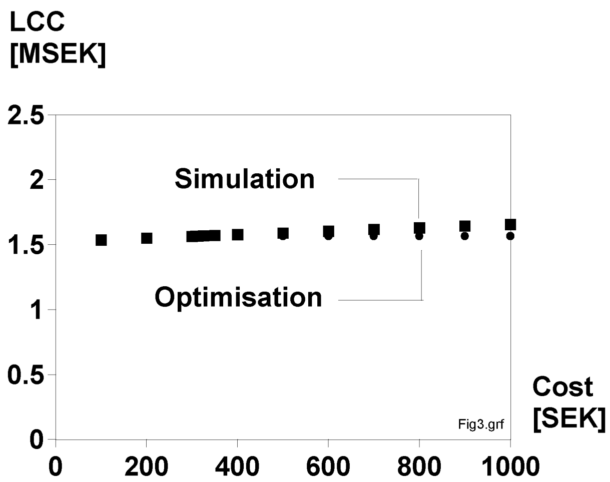

Figure 3: Life-Cycle Cost values for different costs of weatherstripping.

The same behaviour can be seen for fenestration retrofits. Until now, they have also been excluded from the optimal solution by high retrofit costs. Now a change from ordinary double-paned windows, with a cost of 1,100 SEK/m^2, to triple-glazed ones is assumed to cost 1,300 SEK/m^2.

If windows with a Low Emissivity, LE, coating are chosen, the cost increases to 1,500 SEK/m^2. The U-values for the three types are set to 3.0, 1.5 and 1.2 W/°C $\times$ m^2 respectively. The optimisation results in a strategy where LE windows are optimal. The sizes of the heat pump and oil-fired boiler are 12.32 and 29.60 kW respectively, and the optimal LCC is reduced to 1.467 MSEK. If the cost of changing to LE windows is reduced, the LCC must also decrease because it is always optimal to install them. If, however, the cost is increased, the next best solution will be optimal, i.e. to install triple-glazed windows without an LE coating, see Figure 4.

In Figure 4, the LE windows are abandoned at a cost of 1,600 SEK/m^2 and the LCC subsequently shows a horizontal line. Instead, triple glazed windows without LE become optimal. At the same time, a slightly larger oil-fired boiler and heat pump become optimal. If the cost of the now optimal windows is increased, two possibilities exist. LE windows may once again become optimal or double-paned windows should be used. The overall behaviour is, however, the same for weatherstripping and fenestration.

For our original data set, extra insulation on the attic floor was not optimal. The cost was assumed to be $(260 + 530t)$ SEK/m^2, where t is the extra thickness in m. The first value shows an increment in the cost, which does not affect the actual amount of extra insulation, but instead may indicate whether this amount is optimal or not, see Figure 5.

When the incremental cost is lower than about 250 SEK/m^2, it is optimal

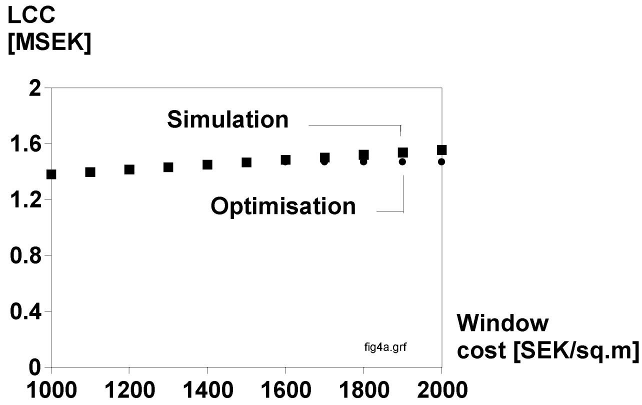

Figure 4: Life-Cycle Cost values for a varying window retrofit cost.

to apply an extra 0.16 m of mineral wool on the attic floor. At the same time, the optimal size of the boiler will decrease to 28.96 kW and the heat pump size to 10.53 kW. If the other part of the insulation cost varies, there is a change in behaviour. As the cost decreases, more and more insulation should be added, which affects the total thermal need in the building, see Figure 6.

At a cost of 150 SEK/m for each square metre, 0.34 m extra insulation should be added, while 0.18 m is optimal at a cost of 450 SEK/m$^2\times$m. When the cost exceeds 500, insulation is excluded from the optimal solution. To the left of the value 500, the dots have a small slope, while the LCC is constant to the right of that point. For the values 150 and 500, the LCCs are calculated at 1.446 and 1.467 MSEK respectively. The optimal heat pump size is constant, while the size of the boiler varies between 27.84 and 28.75 kW. As long as the property owner acts in an optimal way, the LCC can be held almost constant regardless of the cost of the extra insulation. Note that only optimal LCCs are present in Figure 6. If 0.34 m of extra insulation is applied and its cost is at the highest level in Figure 6, the LCC becomes 1.497 MSEK.

The same behaviour can also be found if varying energy prices are considered. In the case above, an electrical heat pump was found to be optimal. Figure 7 shows how the LCC varies for different electricity costs.

The electricity price differs according to the time of day. On working days during the winter, the price is 1.01 SEK/kWh, but in Figure 7 it varies from 0.5 to 1.5 SEK/kWh. For the lowest price, only triple-glazed windows are optimal. For 0.6, weatherstripping is added and for 0.8, LE-windows are used. When the price reaches 1.2 SEK/kWh, 0.18 m extra insulation on the attic floor should be added. The heat pump is abandoned for winter working days at a price of 1.40 SEK/kWh and district heating is used instead. At the same time, extra insulation is excluded from the optimal solution. After this, the LCC is constant.

Because of the dramatic change in optimal strategy when the electricity price is varied, three cases will be studied in more detail. When the electricity price is 1.10 SEK/kWh, the LCC includes the items in Table 1.

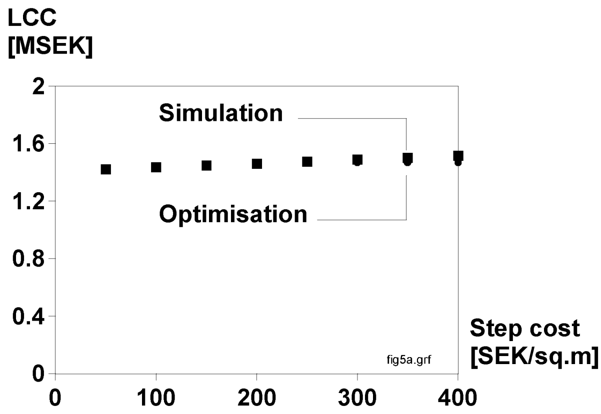

Figure 5: Life-Cycle Cost for varying incremental costs of extra insulation.

Unavoidable retrofit cost	407,633
Triple-glazed windows with LE coating	69,830
Weatherstripping	33,099
Energy cost	693,144
Heat pump cost (12.32 kW)	214,692
Oil-boiler cost (29.59 kW)	58,035
Insulation cost	-
Demand fee for electricity	21,268
LCC	1,497,701

Table 1: Life-Cycle Cost details when the high cost segment for electricity is 1.10 SEK/kWh. All costs in SEK.

An existing building must be refurbished from time to time. The windows must be replaced when they become dilapidated. This must be done even if the new windows have the same thermal performance as the old ones. All such costs, calculated as present values, are gathered in the unavoidable cost in Table 1. The largest cost item in the table is, however, the energy cost. When the cost of electricity is increased, another optimal solution comes into play as shown in Table 2.

If Tables 1 and 2 are compared, it is obvious that the energy cost in the latter case is lower. The same applies to the heat pump, the oil-fired boiler and the demand fee for electricity. Instead, a large sum is spent on insulation of the attic floor, where 0.18 m of extra mineral wool must be added. If the electricity price is increased to 1.40 SEK/kWh, the strategy in Table 3 becomes optimal.

The heat pump is no longer used throughout the year because of the high electricity cost on winter working days. Instead, district heating is used for those segments because of a lower energy cost than for oil, see Table 4.

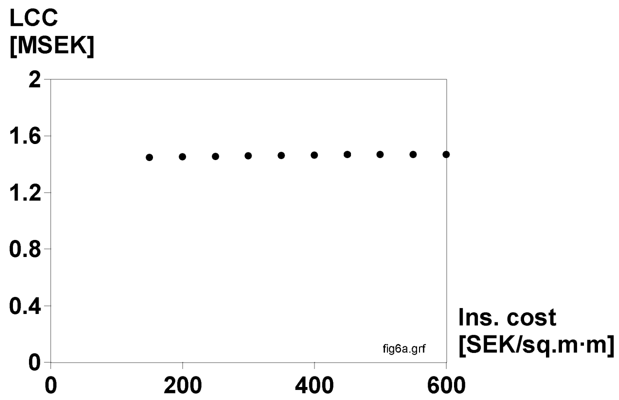

Figure 6: Life-Cycle Cost versus cost for extra insulation.

Unavoidable retrofit cost	407,633
Triple-glazed windows with LE coating	69,830
Weatherstripping	33,099
Energy cost	648,488
Heat pump cost (10.53 kW)	198,889
Oil-boiler cost (28.75 kW)	57,984
Insulation cost (0.18 m)	97,024
Demand fee for electricity	18,713
LCC	1,531,661

Table 2: Life-Cycle Cost details when the high cost segment for electricity is 1.20 SEK/kWh. All costs in SEK.

The optimal thermal size of the district heating system was found to be 35.29 kW in the January high cost segment. This segment includes 368 hours and hence 12,986 kWh are used. As mentioned above, the efficiency of the system is 0.95 and the cost of district heat 0.26 SEK/kWh. Thus the cost will be 3,554 SEK. The electricity cost is 0.56 for the winter months and 0.45 during the summer. The efficiency of the heat pump is assumed to be 3.0.

The annual energy cost, 33,793 SEK, must now be multiplied by the present value factor, 18.26, in order to obtain the cost for 50 years, which is found in Table 3. If Tables 1 to 3 above are compared, the energy cost is at its lowest value in Table 3. However, high subscription fees must be paid to the district heating utility and therefore the lower running cost must balance these fees if the district heating system is to be included in the optimal solution. When only a small amount of oil is needed, see Figure 1, this is not the case and the boiler is a better choice than the district heating system.

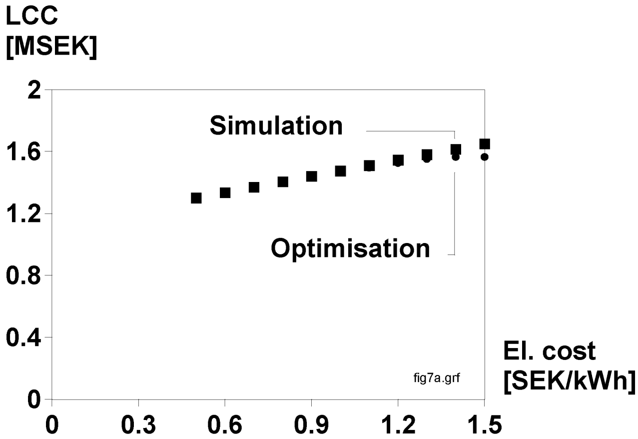

Figure 7: Life-Cycle Cost versus electricity cost on winter working days.

Unavoidable retrofit cost	407,633
Triple-glazed windows with LE coating	69,830
Weatherstripping	33,099
Energy cost	617,060
Heat pump cost (10.53 kW)	198,889
District heating equipment (37.16 kW)	54,700
District heating subscription costs	136,183
Insulation cost	-
Demand fee for electricity	18,713
Salvage value of discarded boiler	38,909
LCC in SEK	1,575,016

Table 3: Life-Cycle Cost details when the high cost segment for electricity is 1.40 SEK/kWh. All costs in SEK.

CONCLUSIONS

By using a mixed integer linear programming model, we have optimised the renovation strategy for an existing building. The existing oil-fired boiler should be combined with a heat pump run on electricity. In addition, weatherstripping and low emissivity triple-glazed windows were included in the optimal solution. The boiler was almost entirely used for covering the thermal peak during cold winter days. The heat pump should be used throughout the year. If the costs of the climate shield retrofits are increased, the life-cycle cost of the building increases to a certain level where the retrofit is excluded from the optimal solution. After this, the life-cycle cost becomes constant.

The use of incremental cost functions for the retrofit measures significantly changes the optimal solution. An extra amount of insulation on the attic floor, for example, will only be profitable if this amount exceeds a certain level. The

Month	Hours	District heating			Heat pump			Total cost
		Power	Energy	Cost	Power	Energy	Cost	
January	368	35.29	12,986	3,554	-	-	-	3,554
	184	8.76	1,612	441	31.63	5,819	1,086	1,527
	192	5.36	1,029	282	31.63	6,073	1,134	1,416
February	336	33.67	11,316	3,097	-	-	-	3,097
	168	8.93	1,500	410	31.63	5,314	992	1,402
	192	4.34	833	228	31.63	6,073	1,134	1,362
March	336	23.68	7,956	2,178	-	-	-	2,178
	168	4.03	677	185	31.63	5,314	992	1,177
	240	-	-	-	27.67	6,640	1,240	1,240
April	720	-	-	-	16.24	11,662	1,754	1,754
May	744	-	-	-	4.70	3,496	525	525
June	720	-	-	-	4.86	3,499	525	525
July	744	-	-	-	4.70	3,496	525	525
August	744	-	-	-	4.70	3,496	525	525
September	720	-	-	-	5.11	3,679	551	551
October	744	-	-	-	17.35	12,908	1,936	1,936
November	336	30.92	10,389	2,843	-	-	-	2,843
	168	-	-	-	30.92	5,194	969	969
	216	-	-	-	27.33	5,903	1,102	1,102
December	352	31.35	11,035	3,020	-	-	-	3,020
	176	3.86	679	186	31.63	5,567	1,039	1,225
	216	1.1	237	65	31.63	6,832	1,275	1,340
Total	8,784	-	60,249	16,489	-	100,965	17,304	33,793

Table 4: Energy usage in kWh and cost in SEK of district heating and the heat pump system.

same behaviour is shown for the heating system. If the utility uses a time-of-use rate for electricity, higher prices in one time segment support insulation of the attic floor, but when further increases are made the oil-fired boiler is excluded from the system and district heating is used instead. The heat pump is abandoned for the high price segments and insulation is no longer profitable.

By using a simulation program, we have also examined what happens to the life-cycle cost if the property owner chooses other than optimal solutions. For moderate discrepancies, the difference between these costs is small, but if, for example, the wrong heating system is used, significant divergences may occur.

ACKNOWLEDGEMENT

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