LIFE CYCLE COSTING RELATED TO THE REFURBISHMENT OF BUILDINGS

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Abstract

This paper describes the use of life-cycle costing when a building is to be retrofitted. The Life-Cycle Cost, LCC, includes all costs that emerge during the life of a building, such as building costs, maintenance costs and operating costs. When the LCC is to be calculated, future costs must be transferred to a base year by use of the present value method. Albeit the LCC includes all costs, this paper will only deal with those costs related to the heating of the building, or the use of energy in one form or another. If the retrofits will yield a cheaper form of cleaning or not, will subsequently be out of the scope. One other confinement is that all the consequences must be expressed in monetary terms, i.e. money. If the building after the retrofitting has a different aesthetic shape, it is likewise not dealt with here. The paper, however, deals with the implemention of extra insulation on various building parts, changing windows for a better thermal performance, weatherstripping, exhaust air heat pumps and different types of heating equipment. The basic view is that the building is considered as an energy system and, at least sometimes, all the energy conserving measures must be dealt with at the same time if an accurate result will emerge. One more corner-stone in the paper is that the retrofit strategy shall be the one with the lowest possible LCC, i.e. the situation must be optimized in one way or another. Here derivative, direct search and linear programming methods are dealt with. Because of the limited length of the paper only a brief presentation of the methods can be made and therefore an extensive reference list is presented showing the state of the art in the middle of 1991. There are also many examples of real cases in order to highlight various aspects of the subject.

Chapter 1

INTRODUCTION

When a building is to be refurbished it is important to consider that it already has a Life-Cycle Cost, LCC, wether it is rebuilt or it is left as it is. If the LCC is to be the ranking criterion for deciding what to do it is therefore important to compare the new LCC to the old, or existing, one. If the new one is lower it is profitable to rebuild, if the opposite is true the building should not be refurbished at all. One of the basic consepts in life-cycle costing is the Present Value, PV, which is used for transferring future costs to one base year where they could be added properly. There are many papers and books about how to use the PV for life-cycle costing, e.g. Marshall or Flanagan et al., see Ref. [1], [2] and [3], and only the expressions for calculating the PV will be shown here. The first one (1.1) shows the PV for a single cost occuring once in the future, while the second (1.2) shows the PV for annually recurring costs.

$$PVs = Cs \times (1 + r)^{-n} \tag{1.1}$$

$$PVa = Ca \times \frac{1 - (1 + r)^{-m}}{r} \tag{1.2}$$

where r = the real discount rate, n = the number of years until the single cost Cs occurs and m = the number of years the annual costs Ca occur.

Expression (1.1) is suitable for calculating the PV for e.g window retrofits or insulation measures, while (1.2) is used for energy and other annually recurring costs. Before it is possible to start with the PV calculations it is necessary to find the costs Cs and Ca and proper values for r, n and m. Unfortunately, there are some difficulties here because of uncertainties both for the costs as well as for the economic factors. Cs might be found in certain price lists, see e.g. Gustafsson and Karlsson, see Ref. [4] for an example of the calculation, so if these are accurate the problem is solved to a part. Ca, however, is influenced by the thermal state of the building and further the uncertainties are larger due to fluctuating energy prices in the future. The real discount rate, r, cannot be set to an accurate value valid for all investors, and the fact is that different authors recommend values between 3 - 11 %. Van Dyke and Hu (1989), see Ref. [5], even show that some investors have dealt with negative rates.Note that inflation is excluded from these values. The value for n, the number of years until a retrofit is inevitable, is likewise not possible to accurately predict, and the same is valid for the project life of the building, m. From the above discussion it might seem hopeless to calculate anything at all and believe in the result. However, every time an investment is made, values for all the variables are set even if the investor is unconscious about them. A closer analysis will many times reveal limits where the values might roam and then it will be possible to calculate the result using slightly different values for each calculation. Without computers this is a very tedious task and this is also one of the reasons why life-cycle costing has not been used very frequently before. By use of modern computers large problems can be solved in a few minutes even in PC:s and MAC:s, and using mainframes will increase the calculation speed even more. It is nowadays possible to calculate the result for a number of different scenarios and then examine the situation in a so called sensitivity analysis. Several interesting results will then occur and general conclusions will be possible to be drawn in spite of uncertainties in input data. Below it is shown how different retrofits are dealt with in order to find the very best renovation strategy.

Chapter 2

INSULATION MEASURES

The optimal thickness of extra insulation is of course influenced by a number of variables e.g the building cost , the climate conditions, the energy cost etc. To start with the building cost it has been found suitable to describe the Building Cost as:

$$BC_{ins} = C_1 + C_2 + C_3 \times t_{ins} \tag{2.1}$$

where C_1 = the amount in £/m^2 for scaffolds, demolition etc, C_2 = the amount in £/m^2 for the new insulation, studs etc, C_3 = the amount in £/m$^2\times$ m for the new insulation, studs etc and t_{ins} = the thickness of new insulation in m.

The reason for splitting up the cost in three parts is because of the influence of the existing life of the building asset. As an example, consider an external wall. The facade is in a rather poor shape but nonetheless the retrofitting of it might not be necessary for say 10 more years. The C_1 coefficient shows the amount of money to be paid at year no 10 whether energy conserving measures are taken or not. This retrofitting is called inevitabe or unavoidable and is very important to take into consideration. Assume that C_1 equals 500 SEK/m^2 and that the wall must be retrofitted in year no 10 when it is unavoidable. The real discount rate is set to 5 % while the project life is assumed to be 50 years and the life of the new facade is supposed to be 30 years. Subsequently the PV of the retrofitting, see expression (1.1), will become:

$$500 \times (1+0.05)^{-10} + 500 \times (1+0.05)^{-40} - \frac{30-10}{30} \times 500 \times (1+0.05)^{-50} = 349.0$$

The PV calculation shows the value of the money invested year no 10 and no 10 + 30. Further the salvage value year no 50 is subtracted. The PV above must be added to the LCC for the existing building because it shows the inevitable retrofit cost. If the wall is retrofitted now, at present time, the PV calculation will become:

$$500 \times (1+0.05)^{-0} + 500 \times (1+0.05)^{-30} + \frac{30-20}{30} \times 500 \times (1+0.05)^{-50} = 601.2$$

From this it is shown that the increase of the cost for retrofitting now, instead for at year no 10, is 601.2 - 349.0 = 252.2 SEK/m^2. The cost 601.2 SEK/m^2

must be thus be added to the new LCC. Closer details about PV calculations can be found in Ruegg and Petersen (1987), see Ref. [6]. After this, the cost for the very insulation must be included. However, it is assumed that insulation is only applied once, at the base year, so it is not necessary to calculate the PV for the extra insulation. At this state of the examination it is not possible to tell how much insulation that is to be implemented and subsequently not to present the cost $C_3 \times t_{ins}$ in Eq. (2.1). It has been shown, Gustafsson (1986), see Ref. [7], that the new U-value for an extra insulated asset may be expressed as:

$$U_{new} = \frac{U_{exi} \times k_{new}}{k_{new} + U_{exi} \times t_{ins}} \tag{2.2}$$

where U_{exi} = The existing U - value in W/m$^2\times$ K and k_{exi} = The thermal conductivity in the extra insulation in W/m$\times$K

Multiplying the U-value with first the area of a building asset, second the number of degree hours for the building site and third with the energy price will result in the annual cost for the energy flow through the asset. Further the annual cost must be multiplied with the PV factor, calculated by use of Eq. (1.2), which will yield the total energy cost for a number of years. Using a real discount rate of 0.05 % and a project life of 50 years the PV factor will equal 18.26. In Malmö, in the south of Sweden, the number of degree hours for one year equal 114 008 and then it has been assumed that one degree hour is generated for each hour the desired indoor temperature, 21 °C, is higher than the outdoor temperature, see Gustafsson (1986), i.e. Ref. [7] for all details of degree hour calculations. Suppose the energy cost is 0.40 SEK/kWh, 1 US$ = 6 SEK, and the area of the building asset is 200 m^2 with an existing U-value of 0.8 W/m$^2\times$°C and a k-value for the new insulation of 0.04 W/m$\times$°C. The Total Cost in SEK for the energy flow through the building asset will subsequently become:

$$TC_{energy} = \frac{114\ 008 \times 0.40 \times 200 \times 0.8 \times 0.04 \times 10^{-3} \times 18.26}{(0.04 + 0.8 \times t_{ins}} = \frac{5\ 329}{0.04 + 0.8 \times t_{ins}}$$

When the building is extra insulated there also is a cost for the insulation and putting it at the proper place. Assuming the constant C_2 equals 100 SEK/m^2 and C_3 equals 600 SEK/m$^2\times$m, see Eq. (2.1), will result in the following building cost in SEK for the asset:

$$TC_{building} = 200 \times (601.2 + 100 + 600 \times t_{ins}) = 140\ 240 + 120\ 000 \times t_{ins}$$

The problem is now to minimize the sum of the energy and the building cost and this is utilized by use of the derivative of this sum which is set to 0. The way for doing this is shown in Gustafsson (1986), Ref. [7] but the result is that the optimal level of insulation in metres becomes:

$$t_{opt} = -\frac{0.04}{0.8} + \frac{5\ 329}{(120\ 000 \times 0.8)^{0.5}} = 0.186$$

Inserting this optimal level of insulation in the sum the resulting LCC will become 190 785 SEK. This cost is now to be compared to the LCC if the building is left as it is, and for the asset of concern this is:

$$LCC_{exi} = 200 \times 349.0 + \frac{5\ 329}{0.04 + 0.8 \times 0} = 203\ 025 \quad SEK$$

The existing LCC is thus higher than the new one, even if the difference is as small as about 13 000 SEK, and it is subsequently profitable to insulate the asset with, preferably, the optimal amount of new insulation. In Figure 2.1 the situation is shown in a graphical way.

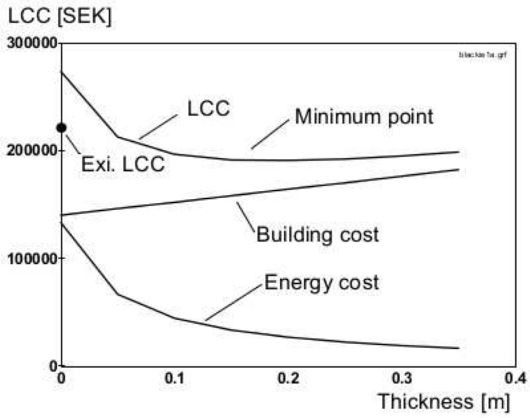

Figure 2.1: Graphical view of insulation optimization

As can be seen from Figure 2.1 the existing LCC is higher than the optimal new one. If, however, the inevitable cost would be decreased, for example by assuming that the remaining life of the envelope is longer than before, the existing LCC will also decrease, and for a certain point it is better to leave the building as it is. From Figure 2.1 it is also obvious that it is essential that enough insulation is applied. This limit is in the case above about 0.07 m, if less insulation is used the retrofit is unprofitable. If too much insulation is implemented the same might happen, but in the figure studied above this fact could not be observed. It is better to use 0.35 m of insulation than not insulating at all. In Gustafsson (1988), i.e. Ref. [8] a thorough examination is made for all the parameters of concern and therefore this will not be repeated here.

Chapter 3

EXCHANGING WINDOWS

When the exchange of windows is of concern it is not easy to find a continuous function to derivate in order to find the best solution, even if there have been some attempts for finding such a function, see e.g. Markus (1979), Ref. [9]. Instead it has been shown that it is preferable to compare different sets of windows with eachother. The existing LCC is thus compared to the new LCC for the number of different alternatives. It is very important to find, not only one solution with a lower LCC, but the lowest one of them all. It is also important to consider the fact that a thermally better window normally reflects solar radiation to a higher degree than simpler ones. This fact can be dealt with by use of a so called shading factor. The situation will subsequently differ for various orientations of the windows. The best solution may therefore be to keep the double-glazed windows oriented to the south while changing to triple-glazed windows to the north. Life-cycle costing and windows are dealt with in more detail in Gustafsson and Karlsson (1991), Ref. [10]. The Building Cost for Windows may, Gustafsson (1986), see Ref. [7], be expressed as:

$$BC_w = C_1 + C_2 \times A_w \tag{3.1}$$

where C_1 = A constant in £ for each window, C_2 = A constant in £/m^2 for each window and A_w = The area in m^2 for one window.

Here BC_w will appear whenever there is a change of the windows and the expression is subsequently used in a somewhat other way than expression (2.1).

Chapter 4

WHEATHERSTRIPPING

Mostly it is profitable to decrease the ventilation flow in the building. This can be accomplished by caulking the windows and doors. The cost for this measure is often very low compared to other energy retrofits but it is not always the best way to act especially when exhaust air heat pumps might be part of the solution. It is also important to consider that it is necessary to ventilate the building. Too much wheatherstripping might make the residences unhealthy to live in. In life-cycle costing these facts are hard to include in the calculus and thus only the energy costs are dealt with here. Suppose a building has 50 windows and doors to caulk. If the cost for caulking is 200 SEK/item the total cost will become 10 000 SEK. Further, assume that the wheatherstripping must be repeated after 10 years. The PV cost will thus become approximately 23 600 SEK if a 5 % discount rate and a 50 year project life are used. If the volume of the building is 5 000 m^3 and the ventilation rate is 0.8 renewals per hour the flow is 4 800 m^3/h. The heat capacity for air is about 1.005 $kJ/kg \times K$ and the density of the air approximately 1.18 kg/m^3. Subsequently the heat flow can be calculated to about 5 700 $kJ/K \times h$. If the same number of degree hour as above is assumed to prevail, i.e. 114 008, the energy flow will become 180, 5 MWh/year. Using the PV factor 18.26 and an energy price of 0.4 SEK/kWh, as above, the total energy cost will be 451 000 SEK. If the ventilation flow is decreased with, say 0.2 renewals per hour this cost will become 338 000 SEK and it is obvious that the wheatherstripping in this example will be profitable.

Chapter 5

EXHAUST AIR HEAT PUMP

One other means to decrease the heat flow from the ventilation is to install an exhaust air heat pump. This device takes heat from the ventilation air and, by use of electricity, transfers this heat back to the building again. One part of electricity may often result in two to three parts of heat. It is, however, very important to install a heat pump of the right size because the amount of heat in the ventilation air is a limited resource. In this paper no example is presented how to calculate the LCC for the heat pump. This because it is very rarely chosen as an optimal retrofit. It must nonetheless be emphasized that using a heat pump might make it unprofitable to caulk the windows in the building. Even if wheatherstripping is a very cheap retrofit it might be even cheaper to use a slightly larger heat pump in order to utilize the increased ventilation flow from not calking the windows.

Chapter 6

OTHER BUILDING OR INSTALLATION RETROFITS

Exhaust air heat exchangers are not dealt with here because of the high cost for distributing the air from the device to the different apartments in a building but the principle for calculation is of course the same as before. Water heater blankets and regulation of radiator thermostats might be important measures in order to decrease the energy need in the building. However, the blankets are only useful if the water heater is located outside of the thermal envelope or if the heating season is very short. Thermal thermostats will only try to set the desired inside temperature as close as possible and they will only be useful if the surplus heat is wasted by use of extra ventilation.

Chapter 7

HEATING SYSTEM RETROFITS

There are also a number of heating system retrofits that must be considered. If the building is eqiupped with an oil-boiler it might be better to change it to a new one with a better efficiency, or maybe district heating would be preferable if this possibility exists. At least in Sweden bivalent systems seems to be of interest when larger buildings are considered. A bivalent, or dual-fuel, system has an oil-boiler taking care of the thermal peak load and a heat pump used for the base load. Important is to optimize the size of this equipment and it has been shown that the level of extra insulation also in this case is essential for reaching the lowest LCC. See Gustafsson (1988b), Ref. [11], for all details. However, if the heating system is changed this will lead to a retrofit strategy that mostly differs from the one chosen when the original heating system is used and the strategy with the lowest LCC is to be chosen. The process is depicted in Figure 7.1.

Figure 7.1 also emphasizes that different retrofits might interact. Say that an attic floor insulation was found to be profitable. When the next retrofit, maybe extra external wall insulation, is examined the new LCC is compared to the original one, i.e. without additional attic floor insulation. Suppose also this retrofit is profitable. The problem encountered is that if the attic floor insulation already was introduced the external wall insulation might be unprofitable. Using an incremental method as above mostly will overestimate the savings actually made. The method for optimizatiom must subsequently include an examination of the combination of the retrofits. If the difference between the incremental and the combination retrofit is very small the accuracy is satisfied otherwise the insulation thickness must be changed and the resulting LCC be re-calculated. Perhaps the considered retrofit will fall out totally from the optimal solution. Fortunately, this interaction mostly is very small, at least if the best candidate for an optimal solution is examined. Sonderegger et al. (1983), i.e. Ref. [13] has calculated the difference to about 2 % for some cases and the fact is that for most cases the interaction can be neglected. It shall be noticed that sometimes the situations is the opposite, i.e. interaction leads to a lower LCC for the combination than for the incremental method. This has been observed for fenestration measures and is discussed in detail in Gustafsson and Karlsson

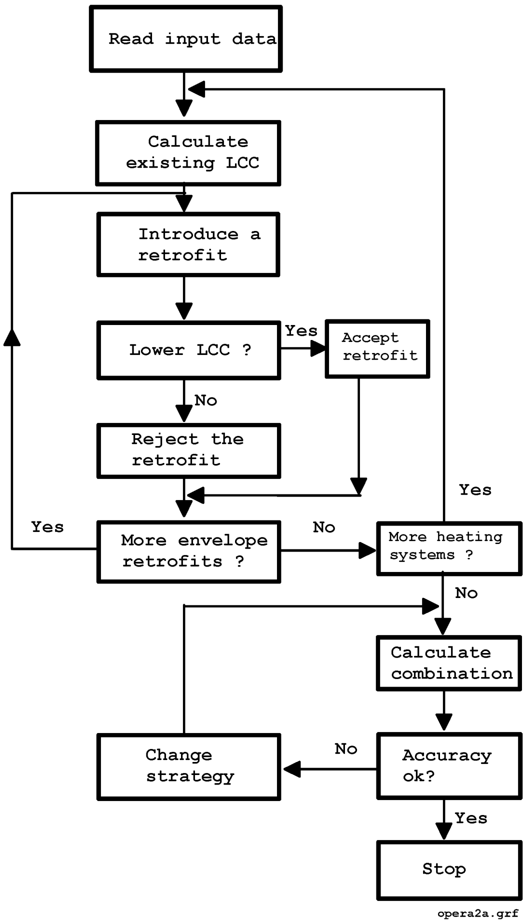

Figure 7.1: Optimization process, Gustafsson and Karlsson (1989), [12]

(1991), Ref. [10], but the cases where this fact has been observed are very rare and probably of scientific interest only. In Table 7.1 a case study is presented clarifying the above discussion.

The original LCC is calculated to 1.48 MSEK. The program has then checked if attic floor insulation was optimal but this was not the fact and thus the value .00 is shown on the line below. External wall insulation however was found profitable and the amount to save is calculated to 0.05 MSEK for the project life of the building. Triple- glazing and wheatherstripping were also candidates for the optimal solution. If the existing heating system was changed to a new oil-boiler the LCC is increased even if the money saved by retrofitting are raised and therefore this was not a very goog strategy. District heating, a ground water coupled heat pump and a bivalent heat pump - oil-boiler system were other heating systems with a lower LCC but the best one was natural gas. The

*** LCC TABLE FOR BASE CASE 1.00 ***										
VALUES IN MSEK										
	EXIS. SYST.	NEW OIL	ELE. HEAT	DIST. HEAT	GR.W HEAT	NAT. GAS	TOU DIST	TOU ELEC.	BIV. GR.HP	BIV.O. AIR HP
NO BUILD. RETR.	1.48	1.54	1.69	1.45	1.57	1.23	1.45	1.69	1.38	1.48
SAVINGS:										
ATTIC FL. INS	.00	.00	.01	.00	.00	.00	.00	.01	.00	.00
FLOOR INS.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
EXT. WALL INS.	.05	.05	.11	.04	.06	.00	.04	.11	.00	.03
INS. WALL INS.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TRIPLE-GLAZING	.06	.07	.09	.06	.08	.04	.06	.08	.05	.06
TRIPLE-GL. L.E.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TR.-GL. L.E. G.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
WEATHERSTRIP.	.01	.01	.02	.01	.01	.00	.01	.01	.00	.00
EXH. AIR H. P.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
SUM. OF RETRO.	1.36	1.41	1.46	1.34	1.42	1.20	1.34	1.48	1.33	1.39
SUM. OF COMB.	1.36	1.41	1.46	1.34	1.42	1.20	1.34	1.46	1.33	1.39
DISTRIBUTION:										
SAL. OLD BOILER	.00	.02	.02	.02	.02	.02	.02	.02	.02	.02
NEW BOIL. COST	.08	.10	.03	.06	.28	.09	.06	.03	.25	.31
PIPING COST	.00	.01	.00	.01	.16	.01	.01	.00	.07	.01
ENERGY COST	.60	.59	.62	.56	.28	.63	.56	.61	.34	.35
CONNECTION FEE	.00	.00	.00	.01	.00	.01	.01	.00	.00	.00
BUIL. RETROF. C	.43	.43	.54	.43	.43	.19	.43	.54	.40	.44
INEVITABLE COST	.25	.25	.25	.25	.25	.25	.25	.25	.25	.25

Table 7.1: LCC table from the OPERA model, Gustafsson (1990), i.e. Ref. [15]

only building retrofit to be implemented was triple-glazed windows and this because the old ones were dilapidated. It is also shown that the combination retrofit LCC and the incremental LCC have the same value for all the heating systems, except for electrical heating with a time-of-use rate which is of no interest for the optimal solution. More details and a thorough presentation of the input values for this LCC optimization are presented in Gustafsson (1990) or Ref. [14]. Experience shows that it is mostly optimal to use a heating system with a very low operating cost. The cost for the system, however, cannot be too high, as it is for solely a heat pump meeting the total demand in the house, see Table 7.1. There are only a few building and ventilation retrofits optimal to install and if they are the cost for them are low or otherwise their remaining life are very short.

Chapter 8

SENSITIVITY ANALYSIS

In the case shown above there is one solution showing a LCC much lower than the other. This is not always the situation and two or more of the strategies above may be very close to eachother making it hard to know which one to chose. A sensitivity analysis might solve this problem. The aim with such an investigation is to find out if the optimal solution will severely change for minor modifications in input data. Of special interest are changes in the discount rate and the project life of the building which values cannot be set with a total accuracy. Variations in energy prices must often be examined, as well as many other items in the input data file. The result may be presented by use of a bivariate diagram as found in Flanagan et al. (1987), i.e. Ref. [2]. One example is shown in Figure 8.1 found in Gustafsson (1989), Ref. [12]. Note that the two cases in Table 7.1 and Figure 8.1 are not identical.

From Figure 8.1 it is obvious that both the project life and the discount rate have a significant importance for the optimal strategy. Note also that the value of the LCC will change very much but this does not mean that a 3 % rate and a 10 year project life is the best to chose just because this alternative has the lowest LCC. Different strategies must subsequently be compared using the same rate etc. Important is to notice that for higher discount rates less complicated heating systems are chosen even if they have higher operating costs. For 3 % the bivalent system, which has a very low operating cost but a high acquisition cost, is the best while an oil-boiler is optimal for a rate of 9 %. Insulation measures will have an advantage of a long project life but will of course be less profitable also for a high discount rate. Of mostly scientific interest is the fact that the LCC mostly will get lower for higer discount rates but this fact is not valid for very short project lives. For a project life of 10 years the LCC is increased when the rate is increased from 3 to 5 %. This fact is dealt with in more detail in Gustafsson (1988), see Ref. [8]. In Sweden district heat is provided by burning a mix of fuels in the utility plant. During the summer most of the heat comes from burning refuse in an incineration plant while oil or coal must be used in the winter. The cost for district heat is subsequently mostly lower than the oil price, while at the same time the installation cost is higher than the cost for an oil-boiler, and that is why it is optimal to use it for some combinations of discount rates and project lives. It must also be noted that the amount of additional attic insulation is not the same in the optimal strategies. Longer project lives and lower discount rates implies more insulation. Important is also

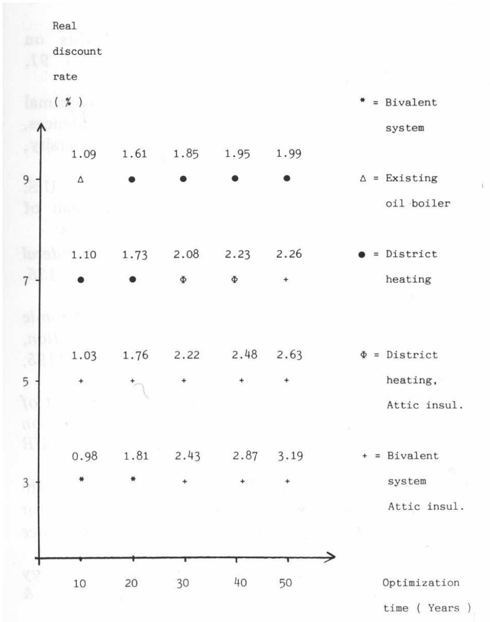

Figure 8.1: Bivariate sensitivity analysis, Gustafsson (1989), i.e. [12]

that optimal thickness of insulation is not a continuous function. When it is optimal to add insulation it is often necessary to apply more than 0.1 m or else it is better to leave the building as it is, see e.g Gustafsson and Karlsson (1990), i.e. [15]. The same reference also emphasizes the importance of the remaining life of the building asset. If this is very short it will mostly be optimal to add extra insulation to e.g. an external wall and in that case an extensive amount of insulation should be chosen, say 0.2 m. Such a measure will decrease the heat flow very much through the wall and this will also imply that if all retrofits are made when they are unavoidable, the thermal state of the building will become better and better, and the cost for achieving this will be lower than leaving the building unchanged. The influence of input data changes may be split i three different categories, one where the LCC will increase for an increase in input data, one where the LCC will decrease for an increase and the last one where the LCC will not change at all for changes in the input. Some examples of the first category are changes in building costs, installation costs etc. To the second category applies changes in e.g. the discount rate, the remaining life of a building asset and the outdoor temperatures. Some of the input data will apply to more than one of the categories. Consider for example a small increase of the oil-boiler cost. If the oil-boiler is part of the optimal solution the LCC will increase if the cost for the boiler is increased. However, when the cost passes a certain limit the oil-boiler will fall out of the solution and from that point further increases in the oil-boiler cost is of no interest. This fact is often used in the practical work with life-cycle costing. When a building is analysed for the first time input values can be chosen without a tedious examination process. The important thing is that the chosen values at least to some degree will reflect the real situation. After the first optimization have been elaborated only the strategies that are close to each other need to be scrutinized. This means that much of the first thought of work with input data might not be necessary, only some of the details must be examined more closely. In Gustafsson (1988), a sensitivity analysis of all the values used in an optimization is elaborated and it is not possible to repeat this here. Some of the facts found must however, be mentioned. It could be assumed that a small change in the resultimg LCC will not be as important as if larger differencies are encountered. This is not true. If a 5 % change in the discount rate is inroduced this led to about a 2 % change in the LCC which is one of the largest differencies found. However, the LCC for the existing building does also change to approximately the same amount and this mostly implies that the optimal strategy will be almost the same for small changes in the discount rate. A very high existing U-value for e.g. an external wall, i.e. a poor thermal status, might be supposed to influence the LCC very much and further the new optimal U-value. This is not so. The optimal new U-value is not influenced by the existing one, see Bagatin et.al. (1984), Ref. [16] or Gustafsson (1988), i.e. Ref. [8], and the fact is that as long as optimal insulation is introduced the resulting LCC is almost constant. The same thing is valid for the actual insulation cost. If this cost is increased the optimization results in a thinner insulation which in turn will decrease the new LCC. Annual increases in energy prices will naturally lead to a more extensive retrofit strategy, which will lead to a lower LCC than might first be expected. This will also mean that, if the proprietor knows in advance what the energy prices will become there is a possibility to make the effects smaller than if no action is taken at all. In some meaning the optimization leads to a model that is regulated by its own. The optimization makes the best of the situation and the result of a change might not be as bad as first assumed.

Chapter 9

LINEAR PROGRAMMING TECHNIQUES

In recent years there has been an increased interest in linear programming. The technique which was developed about 25 years ago has not reached common practice because of very tedious calculation procedures and the use of fairly advanced mathematics. However, nowadays when computers are on every desk the situation is different, and the design of mathematical software makes the solving of complex linear programs much easier than before. It must be noticed that linear programming is an optimization technique which is not confined to life-cycle costing. The reason for choosing linear programming is the fact that it is possible to mathematically prove that optimum, i.e. the best solution with the lowest LCC, has been found. The method is also suitable when discrete time or cost steps are included in the problem. Such things makes it harder to use a derivative method because of the need for continuous functions. This might seem to be of only minor interest but the tariffs for energy of tomorrow will probably always be of the time-of-use type where the price differs from one hour of the day to another. In the traditional methods, such as OPERA, these tariffs many times must be normalized and approximated by a mean value of the real price, which might influence the optimal solution very much. It is not possible to deal with linear programming in detail here and thus only a very brief presentation is made. The LCC must be expressed in a so called objective function. This function, which is the expression to be minimized, must be totally linear, i.e. it is not possible to multiply or devide two variables with each other. A variable must only be multiplied by a constant. The objective function is after this minimized under a set of constraints which also have to be linear functions. All of the constraints must be valid at the same time. The procedure for solving such problems includes the use of vector algebra and this is not at all dealt with here. See e.g. Foulds (1981), Ref. [17] for basic concepts and e.g. Murtagh (1981), see Ref. [18], for deeper insights in linear programming and how to solve such problems. In this paper it is instead presented how to analyse retrofit problems in order to use the linear programming technique. In Sweden it is common to describe the climat conditions for a site by use of mean values of the outdoor temperatures for each month of the year. The use of twelve mean values instead of a continuoes function makes it suitable to use the linear programming technique because it is not possible to derivate functions with discrete steps. The thermal load in kW and the need for heat in kWh will subsequently also follow the climate function, which implies that the steps are included also when the thermal situation is elaborated. In Table 9.1 the thermal load is shown for a building in Malmö, Sweden which can be considered as the situation to start with.

Month	Heat (MWh)	Month	Heat (MWh)	Month	Heat (MWh)
January	32.60	May	15.95	September	12.02
February	30.95	June	9.92	October	18.99
March	29.85	July	6.97	November	24.07
April	22.53	August	7.70	December	28.98

Table 9.1: Heat demand for a building sited in Malmö, Sweden

Suppose that only attic floor insulation is of interest here in order to make the problem shorter. The new demand for the building now to be calculated. One variable is thus introduced showing the themal load in the building for each month. Further, suppose that the building is heated by district heat using a time-of-use tariff where the cost for heat is 0.2 SEK/kWh during November to March and 0.10 SEK/kWh for other periods of time. The first part of an objective function might thus be presented as:

$$(H_1 \times 744 \times 0.2 + H_2 \times 678 \times 0.2 + H_3 \times 744 \times 0.2 + H_4 \times 720 \times 0.1 + \dots$$

$$\dots + H_{12} \times 744 \times 0.2) \times 18.26 \tag{9.1}$$

where H = The new optimal heat load in kW for each month 1, 2,... = The number of the month, 744, ... = The number of hours in each month, 0.2, 0.1 = The district heat price for various months and 18.26 = The present value factor. Note that the influence of lap years is considered for February. From Table 9.1 the existing themal demand is shown in kWh.

This demand must be covered in one way or another. The model is therefore supplemented by 12 constraints showing the situation for each month and the three first ones will become:

$$H_1 \times 744 \geq 32.60, \quad H_2 \times 678 \geq 30.95, \quad H_3 \times 744 \geq 29.85 \tag{9.2}$$

Above the cost for additional insulation was shown, expression (2.1) and the following, and furter the influence this insulation has on the thermal load, expression (2.2). From the last equation it is obvious that it is not a linear expression, t_{ins} is present in the denominator. However, it is possible to make this a linear function but in that case the expression (2.1) will be nonlinear. A method found in Foulds (1981), see Ref. [17], called piecewise linearization is thus used. In this method the value of a function is calculated for a number of discrete sizes of tins and each value for the function is coupled with a binary integer variable which only can have the value one or zero. All these binary variables are added and constrained as lower or equal to 1. This forces the model to choose one or none of the variables. The originally nonlinear function of tins is thus transferred to a linear function of the binary variables. The situation is

Added insulation	Variable	Existing U-value	New U-value	Decrease in U-value
0.05	A_1	0.8	0.400	0.400
0.10	A_2	0.8	0.267	0.533
0.15	A_3	0.8	0.200	0.600
0.20	A_4	0.8	0.160	0.640
0.25	A_5	0.8	0.133	0.667

Table 9.2: Decrease in U-value for five discrete steps of additional insulation

depicted by the following example. The decrease of the heat demand is shown by expression (2.2) and for five steps of insulation magnitudes the decrease will become as presented in Table 9.2, see also Gustafsson and Karlsson (1989b) or Ref. [19] :

Suppose the area of the attic floor is 200 m^2. The number of degree hours in Malmö for January has been calculated to 15 996 and subsequently the decrease in heat flow, in kWh, through the attic will become:

$$10^{-3} \times 15\,996 \times 200 \times$$

$$(0.4 \times A_1 + 0.533 \times A_2 + 0.6 \times A_3 + 0.640 \times A_4 + 0.667 \times A_5) \tag{9.3}$$

The expression (9.3), and eleven more for the rest of the months, must be added to the left hand sides of the constraints in (9.2). Note also that:

$$A_1 + A_2 + A_3 + A_4 + A_5 \leq 1 \tag{9.4}$$

and that the A variables all are binary integers. One or none of them must be chosen due to (9.4). Lacking is now only the building cost for the additional insulation. Using the same values as above for derivative optimization, the cost will be as a function of A_1 - A_6 instead of t_{ins}:

$$200 \times [(100 + 0.05 \times 600) \times A_1 + (100 + 0.10 \times 600) \times A_2 + \ldots$$

$$+ (100 + 0.25 \times 600) \times A_5] \tag{9.5}$$

The model is now totally linear and therefore it is possible to use ordinary linear or mixed integer programming methods for optimization. By the use of more binary integers it is possible to add the influence of the inevitable cost as well, i.e. when one of the A variables is chosen a certain amount is added to the objective and if none is chosen another amount should be added instead. As can be found from the example above the number of equations and constraints will become very large for real world problems, and nowadays the tedious work of generating equations and constraints is dealt with by designing separate computer programs which are used for writing the large input data files. More details and a complete model can be found in Gustafsson (1992), see Ref. [20].

Chapter 10

SUMMARY

Two different methods are shown for optimizing the retrofit strategy for a building. The first one uses a method where the LCC is actually calculated for a number of cases and the lowest one is after this selected. The other shows how to design a mathematical model in the form of mixed integer programming. The latter method demands a more scilled mathematician because of the use of vector algebra when solving the problem. However, there are advantages using this method due to the possibilities of solving discrete problems, i.e. the functions must not necessarily be continuous. One major drawback is that the problems to solve must be totally linear but by the use of piecewise linearization this can be dealt with at least to some extent.

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