OPTIMISATION OF INSULATION MEASURES ON EXISTING BUILDINGS

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Abstract

In Sweden, the activity on building new residences has been decreased for a number of years. The building stock as an average has therefore become older and in the future it will be subject for refurbishment. This paper deals with how to optimise retrofit measures, i. e. how to act in order to minimise the Life-Cycle Cost of a building. Insulation measures are emphasized but also other retrofits are dealt with such as changing the heating system. It is shown that the heating system has a vital influence on the optimal amount of extra insulation which is to be applied. District heating is common in Sweden at least for larger buildings such as multi-family block of flats sited in urban areas. The tariffs for district heat must therefore be properly addressed in order to find out if extra insulation is profitable or not. As an example the Navestad area in Norrköping is used. This residential area is now the subject for extensive retrofitting.

INTRODUCTION

The production of new residential buildings in Sweden has declined for the latest ten to twenty years. This is to a part a result of decreasing subsidies from the government because of the large deficit in the state finances. The average building stock therefore gets older and refurbishment must be initiated whether the proprietors like it or not. Some years ago there were special loans also for refurbishment where the state guaranteed an interest rate as low as 2.25 %. At the same time the ordinary interest was about 15 % when a loan was obtained from an ordinary bank. These refurbishment loans therefore gained some popularity. Because of the state finances also these loans were abolished but nowadays the interest rate for mortgage loans are a little more moderate even from the banks. When a proprietor considers refurbishment a number of questions arise. One of the more common is if energy prices will fall or increase in the future. Insulation measures hopefully reduce the energy bill and this decreased cost must at least balance the cost for applying e. g. extra insulation on the external walls. Predictions of future energy prices and other input data are always hazardous but when a retrofit strategy is selected some conditions are thought to be more plausible than others. By use of the concept Life-Cycle Cost, LCC, these considerations are dealt with in a more thoughtful way.

The LCC adds all costs which emerge for a number of years and if this cost is minimised the situation is optimal at least from a mathematical point of view. The LCC concept has been in use for several years and one of the first papers we found is Reference [1]. Economic optimisation of insulation measures was dealt with in Reference [2] but the actual LCC was not explicitly calculated. LCC calculations at that time was very tedious because of slow and difficult-to-use computers but when the PC was introduced things changed. One paper dealing with LCC and where both insulation measures and heating systems are considered is Reference [3]. The strategies are optimised but the process is not shown in close detail and, further, only more or less rudimentary heating systems are dealt with. Time-of-use tariffs for electricity and district heat were not used. In spite of these shortcomings the paper might be useful because it shows how to find input data for the calculations.

OPTIMAL U-VALUE

From text books in heat transfer, such as Reference [4] p. 26 or [5] p. 9 it is shown that the heat transferred by conduction through a wall can be calculated as:

$$q = -k \times A \times \frac{T_2 - T_1}{t}$$

where q is the heat in W, k is the thermal conductivity in W / (K × m), A is the area in m^2, $T_2 - T_1$ the temperature difference and t the thickness of the wall in m. The rate k/t is called the U-value and is expressed in W / (m^2 K) while the inverse is called thermal resistance. As in electric circuit theory you can add several resistors and in the sum find the resulting resistance, R_{new}. In our case there is an existing wall with an existing U-value, U_{exi}, or overall heat transfer coefficient. If extra insulation is added on that wall the new R-value will become:

$$R_{new} = \frac{1}{U_{exi}} + \frac{t}{k}$$

and the new U-value:

$$U_{new} = \frac{1}{R_{new}} = \frac{1}{\frac{1}{U_{exi}} + \frac{t}{k}} = \frac{U_{exi} \times k}{k + U_{exi} \times t}$$

There are also so called convection boundary effects but these are assumed to be included in U_{exi}. Heat is transferred through the wall as long as T_2 differs from T_1 but it only costs money if T_2 is larger than T_1, i. e. if not an air condition system is present. This fact has led to the degree hour, D, concept and here one such degree hour is generated each hour T_2 is larger than T_1. It is now possible to calculate the cost for the heat transfer, E_c:

$$E_c = \frac{U_{new} \times A \times D \times Ep}{\eta \times 1000.}$$

where E_p equals the cost for each kWh and the efficiency of the heating system. This cost is incurred each year and therefore a so called present worth,

PV, factor must be multiplied. For a discount rate of 5 % and a total life of the building of 50 years this factor equals 18.26, see Reference [3]. If extra insulation is implemented, a somewhat smaller boiler can be used. The thermal size, P_b, in kW will become:

$$P_b = \frac{U_{new} \times A \times (T_2 - T_3)}{\eta \times 1000.}$$

where $T3$ is a so called dimensional outdoor temperature. The boiler cost B_c, is assumed to be reflected by the expression $C_1 + C_2 \times P_b$ which also has to be calculated as a present value. Finally there is an insulation cost which is assumed to be reflected by the expression $A \times C_3 \times t$. For normal conditions the insulation is thought to be present for the rest of the building life and no PV factor is applicable, i. e. it equals 1.0. The costs must now be added forming the LCC which in turn must be minimised. This is fulfilled by ordinary calculus where the derivative is set to zero. All the constants, i. e. those values which not affect t, in the expressions above will by that become zero. Other parts of the expressions occur twice or even three times. These values are collected in the value F. The problem, therefore, is reduced to find the minimum point for the expression:

$$\frac{F \times U_{exi} \times k}{k + U_{exi} \times t} + C_3 \times t$$

which equals to solving the equation:

$$\frac{-k \times U_{exi}^2}{k^2 + U_{exi}^2 \times t^2 + 2 \times k \times U_{exi} \times t} + \frac{C_3}{F} = 0$$

The solution is:

$$t = -\frac{k}{U_{exi}} + (\frac{k \times F}{C_3})^{0.5}$$

The value of k for e.g. mineral wool is easily found in text books on heat transfer, U_{exi} is calculated for the existing wall and C_3 is the insulation cost which is obtained from the building contractor. The complicated thing is therefore to find the value of F.

THE ENERGY COST

One part of the F-value is the energy price E_p. For ordinary oil boilers this is easy to find and many times you just have to divide the oil price with the efficiency in order to find a usable value. When district heating is used the cost depends on the tariff and several different tariff structures is in practice in Sweden. For Norrköping, and hence Navestad, Table 1 applies for multi-family buildings.

The value E is calculated by dividing the annual purchased kWh divided by a so called category number which now equals 2,200. The proprietor also has to pay VAT of about 25 % but this tax can be withdrawn from the profit and is therefore not applicable here. The flow cost applies to the amount of water that passes the district heating meter. The actual price for the district heat therefore depends on the size of the building and also on the amount of insulation added to the climate shield. (One US$ equals about 8 SEK.)

Capacity price [SEK]	E-value	Flow cost [SEK/m^3]	Energy cost [SEK/kWh]
$(234 \times E) + 1{,}030$	6-112	1.5 (Nov. - March)	0.179
$(204 \times E) + 4{,}120$	113-338	-"-	-"-
$(170 \times E) + 15{,}450$	339-2,100	-"-	-"-
$(158 \times E) + 41{,}200$	2,101-	-"-	-"-

Table 1: District heating tariff for Norrköping, 1999.

THE DEGREE HOURS

Traditionally, the heating season also influences the number of degree hours and values for different climates can be found in text books. The building itself, however, also affects the number of degree hours. Consider a foundry where surplus heat is available throughout the year. If extra insulation is added to the existing factory walls the only result is that the windows must be opened longer periods of time in order to cool the premises. This is also the reason why insulation retrofits interact. If extra insulation is added to the attic floor of a building a certain amount of money is supposed to be saved each year. If other parts of the building is retrofitted first this amount will be lower because the building climate shield will get closer to the foundry case. In Table 2 and Figure 1 an example is shown of a building originally presented in Reference [6].

MONTH NO	DEG.- HOURS	ENERGY- TRANSM	HOT- WATER	FREE ENERGY	SOLAR HEAT	UTILIZ. FREE	FROM BOILER	INSUL. OPTIM.
1	17856.	36718.	3500.	4167.	633.	4800.	35419.	36718.
2	16340.	33600.	3500.	4167.	1679.	5846.	31257.	33600.
3	15847.	32587.	3500.	4167.	4344.	8511.	27579.	32587.
4	11376.	23393.	3500.	4167.	6386.	10553.	16344.	23393.
5	7514.	15452.	3500.	4167.	9127.	13294.	5663.	15452.
6	3888.	7995.	3500.	4167.	9349.	7995.	3500.	0.
7	2009.	4131.	3500.	4167.	9342.	4131.	3500.	0.
8	2976.	6120.	3500.	4167.	7680.	6120.	3500.	0.
9	6192.	12733.	3500.	4167.	5224.	9391.	6851.	12733.
10	10267.	21113.	3500.	4167.	2625.	6792.	17831.	21113.
11	13104.	26946.	3500.	4167.	790.	4957.	25501.	26946.
12	15624.	32128.	3500.	4167.	343.	4510.	31131.	32128.
TOTAL	122993.	252918.	42000.	50000.	57522.	86900.	208096.	234672.

Table 2: Energy balance, in kWh, for the test building, sited in Navestad, Norrköping.

The building is the same but now this is thought to be sited in Navestad, Norrköping. The climate, solar conditions and so on are changed to values for Norrköping. (Values for clear and overcast days, however, are fetched from Örebro about 100 km away, because no such values are presented for Norrköping.) The figures in Table 2 are presented in detail just for "pedagogic" reasons. During January the energy demand is supposed to be 36.7 MWh for space heating, i. e. transmission and ventilation. The use of hot water is assumed to be 3.5 MWh while "free" energy from appliances and persons is 4.2 MWh. Solar radiation through the windows has been calculated to 0.6 MWh and therefore 35.4 MWh must be provided by the boiler.

For three months, July - August, no space heating by use of the boiler is required, free energy from appliances and solar radiation is sufficient. In Figure 1 a duration graph is presented, i. e. the thermal demand has been sorted in

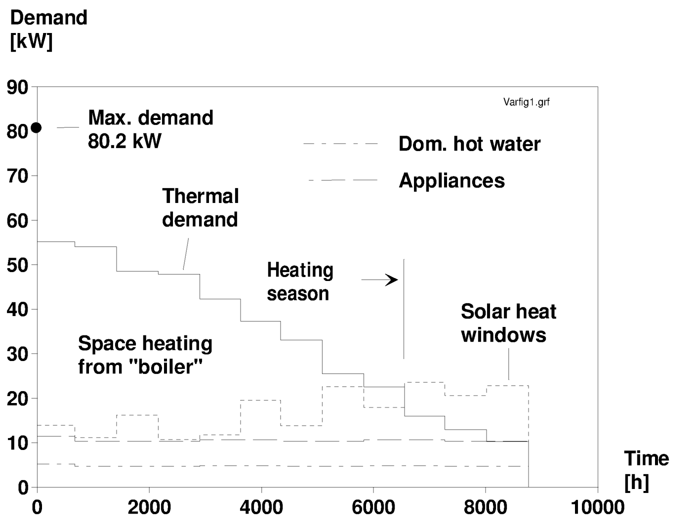

Figure 1: Duration graph for the thermal demand in the "test" building.

descending order. The maximum demand, 80.2 kW, is present for short periods of time and is calculated by use of a so called dimensioning outdoor temperature, which in Norrköping is - 18 °C. In February the need for space heating is 33.6 MWh while the energy demand for hot water is 3.5 MWh. In February 672 hours are present and hence the thermal demand starts at 55.2 kW, see the left part of Figure 1. Solar radiation through the windows is 1.7 MWh which result in 2.5 kW starting from about 11 kW which in turn emanates from hot water heating and free energy from the appliances. The heating season is 6,552 hours, i. e. when hours from July - August have been withdrawn from one full year. From Table 2 it is obvious that 208 MWh must be provided from the heating device, e. g. a boiler. This corresponds to approximately 101,000 degree hours in this case. (The heat demand has been calculated as 2,054 W/K.) The climate shield, however, also saves those kWh not coming from the boiler and even if they are free they are valuable for the proprietor. It is therefore necessary to calculate the total amount of kWh used during the heating season for space heating. The value is shown in Table 2 under "Insuation Optimisation", or 234.7 MWh corresponding to 114,000 degree hours which is the value to use when calculating the level of optimal extra insulation.

THE ENERGY COST, AGAIN

It is now possible to calculate the cost for district heat according to Table 1. The demand covered from the boiler has been calculated to 208 MWh, see Table 2. District heating systems have a high efficiency and here a value of 0.95 is thought to be appropriate. The E-value in Table 1, will thus become 99.6. This in turn results in that the first line applies, and the capacity cost becomes 24 kSEK. The flow cost is set to 1.5 SEK/m^3, see Table 1. The heat capacity for hot water is about 4.2 kJ/(kg × K, see Reference [4], p. 646. Assuming that the temperature drop in the district heating device is 35 K, this leads to 5,833 SEK/year. The energy cost for one year will therefore become:

Capacity cost	24,328 SEK
Flow cost	5,833 SEK
Actual energy cost	39,209 SEK
Total	69,370 SEK

which in average will be 0.32 SEK/kWh. This cost can be used for calculating the LCC but it must be wrong to use it for insulation optimisation without any consideration. The capacity cost is not totally linear but problems are larger if the E-value would have been e.g. 114 before extra insulation has been added and 112 after this has happened, see Table 2. It is therefore necessary to check what happens if extra insulation is applied. The problem, however, is that we do not know how much to add. This calamity is solved by assuming that the building asset is heavily insulated, so much that no heat passes at all. Above it was mentioned that the heat demand has been calculated to 2,054 W/K. If the attic floor is considered, the heat passing through that asset shall be withdrawn and in our case this results in a demand of 1,835 W/K. A new energy balance must be calculated because the heating season is now a little bit shorter. These calculations are not shown here but the resulting total energy cost was found to be 61,218 SEK. The amount of district heat was decreased to 183.2 MWh and hence the marginal cost can be calculated to 0.31 SEK/kWh, i. e. almost the same as the average price. This is, however, not always the case.

THE OPTIMAL INSULATION LEVEL

The LCC for the building and especially the building asset of concern includes the operating cost, the boiler cost and the actual insulation cost. The first of these is easily found by multiplying the cost Ec with the present value factor PV which in our case equals 18.26. A district heating device is supposed to cost 40,000 + 60Pb with a life span of 25 years and auxiliary equipment with a span of 50 years and a cost of 300 $\times P_b$. The present value factor for a single occasion 25 years distant is 0.29, and the temperature difference 39 K. Hence the present value for the boiler cost will become 377 $\times P_b$, which sets part of the F-value to 15.5. The other part is:

$$PV \times D \times \frac{E_p}{\eta \times 1000.} = 680.1$$

and the total F-value will become 696.6. The original insulation level for the asset was 0.8 W/(K×m^2) and k is 0.04 W/(K×m), i. e. for mineral wool. The C_3 value is supposed to equal 530 SEK/(m^2×m). The optimal insulation level in this example will therefore be 0.18 m.

THE EXISTING LCC

The building has a LCC even if it is not retrofitted. If this original LCC is lower than the new one, where retrofits are applied, it is better to keep the building as it is. One starting point is to find out the existing LCC just for the climate shield, here called the unavoidable cost. Assume that the cost for changing windows is 100 kSEK. No enhancement in thermal performance is achieved. Further, suppose that the existing windows still can be present for 10 years before the must be changed because they have dilapidated, and that new windows last for 15 years. If a rate of 5 % and a building life of 50 years are assumed this will lead to:

$$100. \times (1.05^{-10} + 1.05^{-25} + 1.05^{-40} - 0.33 \times 1.05^{-50}) = 102 \quad kSEK.$$

If, however, the windows have to be changed immediately the same calculation will be:

$$100. \times (1.05^{-0} + 1.05^{-15} + 1.05^{-30} - 1.05^{-45} - 0.66 \times 1.05^{-50}) = 177 \quad kSEK$$

The level of deterioration is therefore very important for the LCC. In our case study, see Reference [6] the added total of all those unavoidable climate shield costs equals 407 kSEK. The energy cost, if district heating is used is:

$$208,096 \times 18.26 \times \frac{0.317}{0.95} = 1,267 \quad kSEK$$

The boiler cost depends on the installed thermal power and for the existing building the necessary demand is 84 kW. We mentioned that one part of the boiler cost had a life span of 50 years and therefore this part will become 300. × 84 = 25 kSEK. The other part has a span of 25 years and hence 58 kSEK must be added. There is also a salvation value from the existing boiler of 20 kSEK and therefore the total present value for the boiler cost totals 104 kSEK. (The 25 year life span boiler cost is assumed to be reflected by 40,000 + $60 \times P_b$) Adding the costs above yields the existing LCCe which equals 1,778 kSEK.

THE NEW LCC

The retrofit under consideration is attic floor insulation with an assumed life of 50 years, i. e. the same as the building as a whole. No retrofit is necessary so in this case the unavoidable cost will not change. About 0.18 m of new insulation should be added and hence the U-value decreases from 0.8 to 0.17 W/m$^2\times$ K. The cost for this insulation effort has been calculated to 95 kSEK. The energy demand of 188 MWh results in a present value cost of 1,149 kSEK while the boiler cost is calculated as 89 kSEK with the salvage value for the old boiler included. The LCC with insulation applied is therefore supposed to be 1,740 kSEK, i. e. lower than the original LCC. The insulation measure is therefore profitable and should be included as a plausible retrofit. Other heating systems might yield still lower operating costs and the attic floor insulation might then become too expensive compared to the savings.

Note that the calculated optimal amount of extra insulation decreased the annual energy demand to 188 MWh. This is very close to the value used for calculating the applicable energy price, i. e. when the heat transfer through the attic was entirely excluded. The true energy price which should be used for the optimisation is therefore very close to the approximate price we had to use instead.

DUAL FUEL HEATING SYSTEMS

In Sweden, where electricity nowadays is purchased on a deregulated market, the price is subject for negotiations. A price of the magnitude 0.13 SEK/kWh, taxes excluded, is applicable for ordinary household customers according to the internet page www.kundkraft.se where such trade occurs. There is also a price for using the electricity grid which is not negotiable. In Navestad, the electricity grid is owned by the company Norrköping Miljö & Energi and for a multi-family building a time-of-use rate called T17 seems applicable. The prices used here are those valid for 1999 where the negotiable part was 0.6162 SEK/kWh during high price conditions November - March, Monday - Friday, 0600 -2200. Other times the price was 0.4162 SEK/ kWh. Here all taxes are included, 0.189 SEK/kWh. The cost for using the electricity grid was at the same time 0.15 and 0.10 SEK respectively. If the VAT is excluded the prices used during 1999 will become 0.613 and 0.413 SEK/kWh respectively. If the prices from the internet site are applied this leads to 0.43 and 0.38 SEK/kWh.

The cost for electricity is to a part dependent on the necessary current in Ampere, A. This is set by the installed fuses but the level for the existing test building is not known. The subscription covers only the need for those areas which are shared by all the inhabitants in the building. Each tenant has an own subscription for the precise apartment of his/her own. An applicable level for the proprietor of a small multi-family block of flats is therefore assumed to be 63 A and a this implies a cost of 5,875 SEK each year.

Because of the electricity prices in Sweden today, heat pumps might be of interest for heating purposes in buildings. The heat pump use one part electricity and delivers about 2.5 parts of heat. This extra heat comes from low grade heat in outdoor air or from a ground water well. Unfortunately, heat pumps are very expensive and therefore it is not preferable to use a heat pump which is able to cover the total demand in the building. The performance also drops significantly when the heat source temperature decreases too much, e. g. outdoor air during cold winter nights, Reference [7], p. 339. The thermal peak is instead dealt with by use of e. g. an oil-fired boiler. The high operating cost of the boiler is not a major drawback because it is used only for a few hundred hours during a year. The optimisation of such dual fuel systems has been dealt with e. g. in Reference [8] and is therefore not repeated here. Instead we will use the district heating system as a thermal peak provider. Such systems are probably very bad for the district heating utility because they must provide heat only during the worst of conditions, i. e. when the utility has a peak. They must invest in high capacity but only gets a low income due to the tariff. Such heat pumps have therefore not been allowed if the building owner wanted to apply for subsidised loans. These subsidiaries are today almost abandoned and hence, the proprietor only looks into his own wallet when deciding which system to use. If the district heating prices are too high such systems will get more and more common. This is precisely what has happened in Navestad and the buildings are now subject for extensive retrofitting. Solar collectors and heat pumps are supposed to take care of the base load while district heating only is used for the peak. Further, extra insulation is applied. It must be noted that the district heat origins from a Combined Heat and Power, CHP, plant and hence the buildings act like a cooling device when electricity is produced, see Reference [9], p. 371. The thermal performance of the test building is shown in Figure 1. For "pedagogic" reasons the free energy from solar radiation and appliances is withdrawn and the result is depicted in Figure 2.

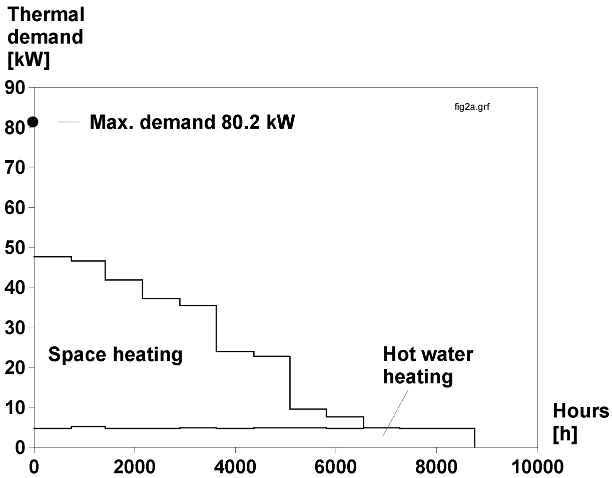

Figure 2: Thermal demand for the test building where free energy is withdrawn.

The total amount of heat in Figure 2 is 208 MWh, see Table 2. This amount must now be provided by a combination of the heat pump and the district heating system or some can even be saved by adding an optimal amount of extra insulation to the climate shield.

Say that the electric size of the heat pump is P_{hp}. In this study the cost for the heat pump is assumed to be reflected by the expression 60,000 + 5,000 $\times P_{hp}$. The life of the heat pump is assumed to be 50 years. There is, however, an additional cost of 1,500 $\times P_{hp}$ emerging each ten years.

Present value calculations show that the total cost for the heat pump, Chp, will become:

$$C_{hp} = 60,000 + 8,546 \times P_{hp} \quad SEK$$

The district heating system cost, C_{dh}, is assumed to be reflected by the expression 40,000 + 60 $\times P_{dh}$ with a life of 25 years. An additional cost is also here implemented, 300 $\times P_{dh}$ with a life of 50 years.

$$C_{dh} = 51,812 + 77.7 \times P_{dh} \quad SEK$$

The system must provide enough thermal power to meet the demand:

$$P_{hp} \times 2.5 + P_{dh} \times 0.95 = 80.2 - 39.0 \times \frac{U_{new} \times 273.}{1000.}$$

where 2.5 is the efficiency of the heat pump, 0.95 the efficiency of the district heating system, 80.2 the maximum demand for heat in the existing building, 39.0 the difference between the indoor and the dimensioning outdoor temperature, 273 the area of the building asset and 1000 the conversion factor for kW. Some calculations reveal that the district heating system cost now can be expressed as:

$$C_{dh} = 58,371 - 204.3 \times P_{hp} - \frac{27.2}{0.04 + 0.8 \times t}$$

The cost for the actual kWh are more difficult to express in continuous functions which are necessary if ordinary calculus is to be used. In Reference [8] this has been solved by using the method of least squares for approximating the thermal load in the form of a triangle. Another possibility is to use Linear Programming or the Mixed Integer Linear Programming, MILP, methods for this, see Reference [10] where such optimisation has been dealt with. In this case, however, a short C-program written for LINUX has been used instead. The program starts by using only a district heating system, i. e. $P_{hp} = 0.0$ and no extra insulation at all. This case is shown in Table 2 and the energy demand, 208 MWh, is used for calculating the applicable energy cost according to the tariff and after this the LCC. Electricity for the heat pump is of course not used here. After this the program increments P_{hp} with 2.0 kW. The heat pump yields cheaper energy than district heating so part of the hot water heating demand is now covered by the heat pump, see the lower part of Figure 2. The cheapest energy therefore covers the base. A new district heating cost now applies and further, the electricity tariff must be used. The LCC is calculated and the process starts all over again. When the heat pump size has reached a level of 20 kW no district heating is used and the size is set to 0. At the same time 0.02 m of extra insulation is added and the process starts all over again. The program stops when 0.2 m is reached. For a start the electricity prices valid for 1999 is used. The lowest resulting LCC is found for a heat pump of 20 kW and no extra insulation at all. This case is therefore studied in more detail. The heat pump of 20 kW will be able to deliver 50 kW heat because of the COP of 2.5 which is assumed to apply. The cost for the pump will be 231 kSEK. The district heating device must now cover the demand from 50 to 80.2 kW or 30.2 kW. The efficiency is 0.95 so the thermal size must be 32 kW. The cost for this apparatus will become 54 kSEK. All the kWh are now covered by use of the heat pump. By using the tariff shown above the applicable average electricity cost has been calculated to 0.482 SEK/kWh. The demand for energy is 208 MWh according to Table 2 and hence the present value of the energy cost will become 732 kSEK. Adding all costs result in the LCC equaling 1,444 kSEK which is significantly lower than before. The program calculates the LCC for a number of cases and the result is shown in Figure 3.

From Figure 3 it is obvious that the heat pump size in kW has a very large influence on the Resulting LCC. The insulation thickness is not that important. If insulation is applied about 0.12 m is optimal but the best is to leave the attic floor as it is. When a heat pump of 20 kW is implemented no energy at all comes from district heating. Only the peak is covered and in the model this does not result in any kWh. The shape of the surface area in Figure 3 is therefore not contiguous when going from 20 to 18 kW. The same is valid when insulation is considered. Adding the first 0.02 m of insulation, which is the smallest step in the model, result in a major leap in LCC.

The optimal way to heat the building was therefore to implement a large heat pump which will deliver all heat used for space and hot water heating. The

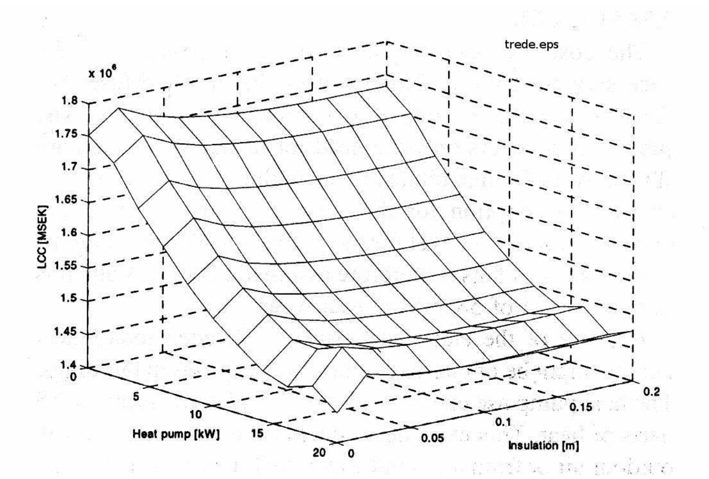

Figure 3: LCC for varying heat pump size and insulation thickness

result is achieved by use of the applicable district heating and electricity tariffs used during 1999. Nowadays, the electricity prices are still lower because of trade on the free electricity market. If district heating is to be competitive the prices must go down below approximately 0.20 SEK/kWh i. e. they must be halved compared to the prices of today. If the production apparatus of district heat is considered the warm water can be regarded as waste cooling water from a electricity generation process. See Reference [11] where optimal prices of that magnitude are calculated for summer conditions and still lower for winter. If this is so, the prices for district heat could be reduced significantly while at the same time keeping the customers. This might reduce the profit of the utility but not as much as if all customers was to act in an economic rational way i. e. to use the district heating system as a peak shaver.

CONCLUSIONS

This paper shows that Life Cycle Costing can be used for optimisation of the retrofit strategy of a building. Even if time-of-use tariffs for district heating and electricity are used, continuous functions could be used and because of these, ordinary calculus can be used for finding the minimum LCC. The optimal level of extra insulation depends on the optimal heating system and vice versa. This calls for optimisation of two variables at the same time and it is shown that this can readily be fulfilled by actually calculating the LCC for a number of cases and choosing the case where the LCC assumes its lowest value. With the prices found in the ordinary tariffs for electricity and district heat, heat pumps were competitive and the district heating system was only to be used as a peak heater. If the district heating utility wants to keep its subscribers the prices must be significantly reduced. If the process for how district heat is produced is considered this reduction can be achieved without hazardous effects on the utility. This because district heat many times emanates from cooling the condenser in the electricity generation plant.

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