2. THE OPERA MODEL

The OPERA model is an optimizing mathematical program used for finding the best energy retrofit strategy for a multi-family building. This strategy is characterized by the the lowest possible remaining LCC which is the sum of the building costs, the maintenance costs and the running costs for the building during its project life.

Below a very simplified flow chart is presented, showing the principle method of the OPERA model.

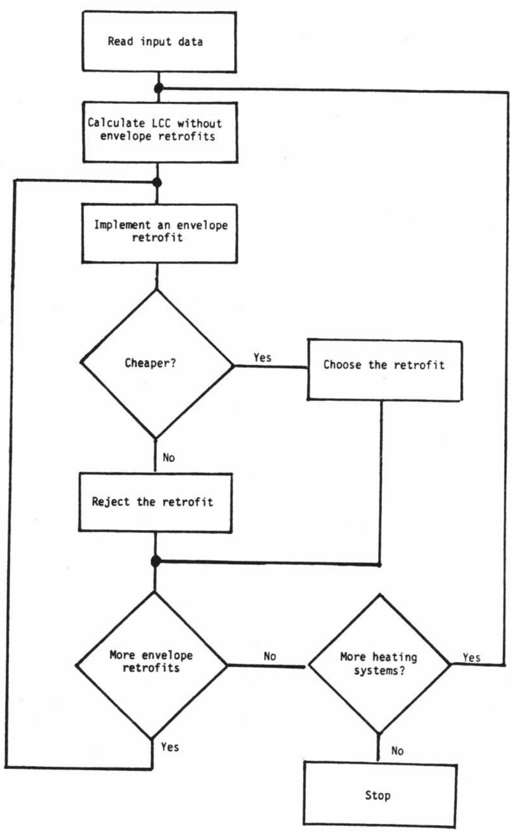

Figure 1. Principle flow chart. OPERA model.

For every building there are costs for necessary renovation, heating and maintenance. In this model only energy related costs are dealt with and thus the LCC here only contains costs that in one way or another are related to energy retrofits. The basic concept of the model is that every energy retrofit will influence the LCC of the building. If a wall is insulated there are costs for building, implementation of insulation etc. On the other hand, the future running costs for heating the building are expected to be decreased.

All the costs are transferred to one base year, using the present value method, see appendix III, page 143, and thus LCCs for any different alternative can be compared. The model thus starts reading the input data, e g the building geometry, the thermal status of the building etc, and proceeds with calulating the existing building LCC. This value shows the cost for implementing only the inevitable retrofits to the building. Such a retrofit can be to change the windows if the old ones are rot. The new ones are then of the same type as the old ones concerning their energy performance.

When this existing LCC is calculated, a retrofit is implemented and a new LCC for the retrofitted building is elaborated. If this later LCC is lower then the previous one, the retrofit is profitable and selected by the model, otherwise not. The procedure is repeated for another retrofit and also this LCC is compared to the existing building LCC.

When all the envelope retrofits have been tested there are some candidates for the optimal solution, i e if only the existing heating system is to be considered. The decrease in the LCC for each retrofit is calculated and thus the resulting LCC can be calculated. However, the retrofits cannot be added to each other without consideration, which shall be dealt with in due course. Only strong candidates are to be found by this procedure.

The heating system is now changed and the procedure starts almost from the beginning. A new LCC with no building envelope measures is calculated, and after this the retrofits are implemented. The procedure continues and finally all possibilities are tested and the solution with the lowest estimated LCC is selected. In order to find the real best solution, within an accepted accuracy, a more thorough study must be elaborated. This procedure is presented below, page 55.

[3] describes how different retrofits can be optimized due to the lowest possible LCC. In that work there is also information about the evaluation of building- and installation costs, and references to authors dealing with that subject. The model, or the FORTRAN code, is not presented, and it nor is fruitful to do so here. Still, it is necessary to describe the model in detail because it must be possibile to scrutinize. This is done in the following chapters and also in appendix III, page 142, where some of the subroutines are presented.

2.1 CALCULATION OF THE EXISTING BUILDING LCC

The aim of the retrofits is to make the remaining LCC for the building as low as possible. However, implementing a retrofit can also make the LCC higher, which of course must be avoided. The savings from a decreased energy use might be lower than the building- or installation cost for an improvement of e g an external wall insulation. In order to examine this, the existing LCC for the building must be calculated initially. All the considered retrofits shall later be compared to this existing LCC. If the LCC is lower after the retrofit is implemented the retrofit shall be chosen, otherwise not, see figure 1.

Subroutines are commonly used for frequent calculation procedures and the OPERA model has several subroutines following the main program. For calculating the existing building LCC, five subroutines are used:

- The number of degree hours
- The inevitable retrofit cost
- The present values
- The proper energy prices
- The energy balance for the building

The presentation of these subroutines can be found in appendix III.

The main program starts with reading the total input file for the building, see figure 2. In this file the geometry, thermal status, climate, building costs etc, concerning the building, are described. In a separate chapter, page 31, the input data are discussed and a complete input data list is presented in appendix II at page 123.

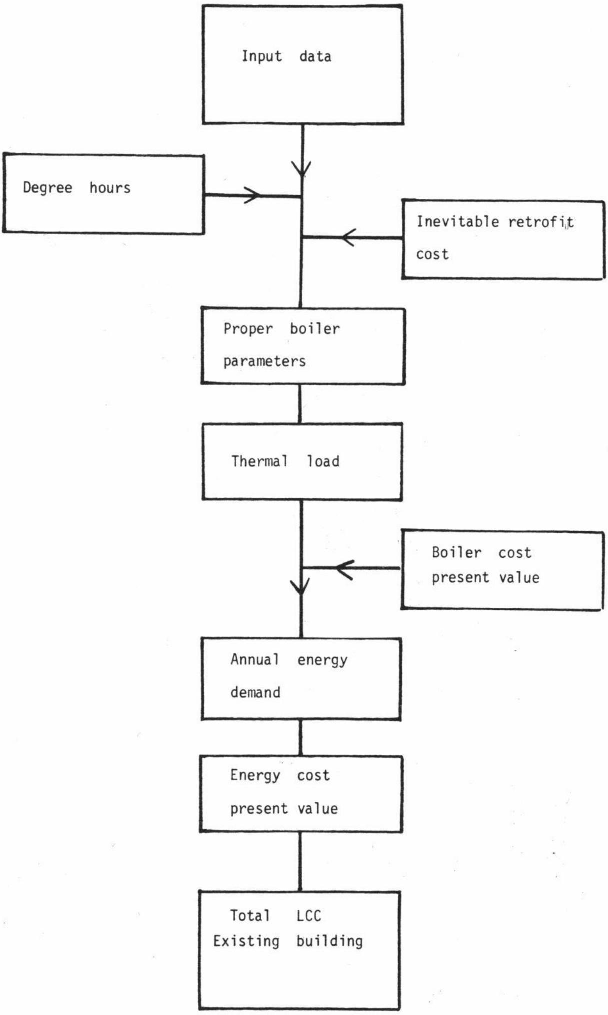

Figure 2. MAIN program, flow chart, part 1.

The program proceeds, after some minor calculations, by calling the subroutines for degree hours and inevitable retrofit cost calculations. The first routine presents the number of degree hours, assuming that one unit is generated if the monthly mean outside temperature is lower than the desired inside temperature during one hour. The second routine presents the inevitable retrofit cost, as a present value, for the existing building. See appendix III, page 142, for more details.

The total power demand and the inevitable retrofit cost for the existent boiler are then calculated. The proper parameters are assigned to the boiler variables and the boiler cost is calculated by calling the present value subroutine.

The energy demand for the building is calculated using the energy balance subroutine, another subroutine provides the program with the proper energy price and by use of formula (AIII 3), page 144 in appendix III, the total energy cost is elaborated for the chosen optimization period.

Remaining now, is only to sum the values and the LCC for the existing building is found.

2.2 CALCULATION OF THE OPTIMAL RETROFIT STRATEGY WHILE KEEPING THE EXISTING HEATING SYSTEM

The building and ventilation retrofits in the OPERA model are:

- Attic floor insulation
- Floor insulation
- External wall insulation at the outside
- External wall insulation at the inside
- Three different fenestration retrofits
- Weatherstripping
- Exhaust air heat pump

The retrofits are presented in the order they appear in the model. The program starts with the optimization of the attic floor insulation. The optimal extra amount of insulation is calculated and the new LCC for the building is elaborated. If this is lower than the LCC for the existing building the retrofit is selected, otherwise not. The procedure continues with the floor and the external wall. The external wall can be insulated both at the outside as well as the inside. However, OPERA selects the most desireable solution from the two alternatives, and thus the wall cannot be insulated both at the inside and at the outside at the same time.

For the windows a number of different constructions are evaluated. This because of the immence difficulties of optimizing a window due to solar gains, number of panes, the distance between them and so forth. Here it is beyond the scope to optimize such a construction and it is questionable if this is possible at all. Some of the difficulties are discussed further in detail in [3 p. 65-]. The problem is also dealt with in [24].

The procedure continues with the weatherstripping and the exhaust air heat pump and finally the candidates of the optimal strategy for the existing heating system are found.

In [3] it is shown in detail how the optimization procedure is elaborated for different retrofit measures.

It is important to note the fact that the candidates might fall out from the optimal solution. This might occur if the LCC is not a linear function due to the thermal losses in the building. A decrease in the energy demand must correspond to the same decrease in the LCC whether the retrofit is implemented in the beginning or the end of the graph in figure 3. If this is the fact, the order of the implementation does not matter, else there might be different optimal strategies for identical measures. In reality this problem might occur due to e g the habit of manufacturing heating equipment in discrete sizes, but the influence of this is neglected here. If the optimization problem, for some reason must deal with this, the optimal solution found by OPERA must be scrutinized in detail. However, the errors in the input parameters make such an analyzis very hazardous.

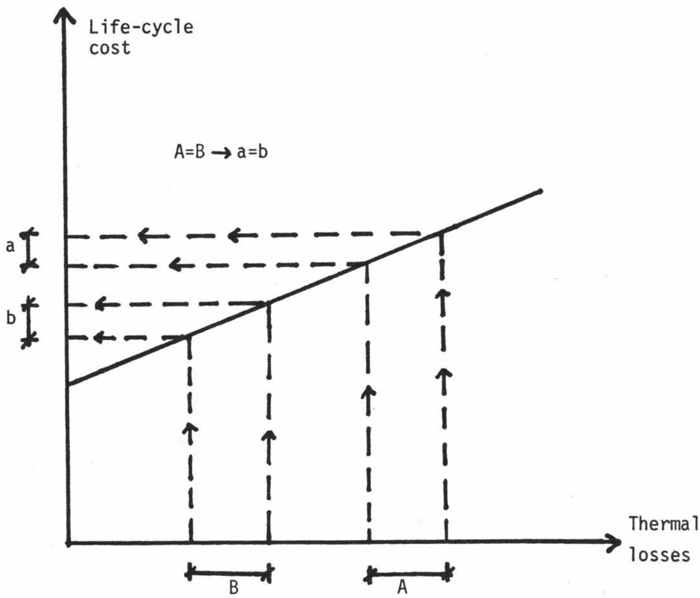

Figure 3. Optimization due to LCC function.

The same problem occurs when real energy tariffs are considered, or if the implementation of a retrofit leads to a longer turn off period for the heating system. The situation gets worse for strategies where a lot of envelope retrofits are considered or if the amount of free energy from solar gains and appliancies is large. The problem also increases due to the use of monthly mean temperatures in the energy balance calculations.

OPERA however, calculates the resulting LCC, implementing the combination of the envelope retrofit candidates for an optimal solution for all the heating systems considered. Fortunately the optimal strategy is mostly characterized by a low running cost heating system and very few envelope retrofits, and thus this problem will not influence the total retrofit strategy very much. For most cases it can be neglected. The error in the LCC might be about 5 % due to these considerations.

When the optimal retrofit strategy for the existing heating system has been found, the procedure continues with different types of heating systems, possible to install in the building. These are the oil-boiler, the electricity boiler, district heating, the heat pump, the bivalent heat pump - oil-boiler system and differential Time-Of-Use, T-O-U, rates for district heating and electricity.

The procedure stops when all the possibilities have been tested and after this the best solution is selected. This solution is presented in further detail by the program and a table is shown of the LCC for the different heating systems without the envelope retrofits, the amount of savings and the new LCC, if the optimal, or the almost optimal strategy is implemented. In table I at page 53 this is shown.

2.2.1 Envelope retrofits

In the insulation retrofit part of the main program subroutines are used for calculating:

- The inevitable retrofit cost
- The present values
- The energy rates
- The energy balances

These subroutines are presented in appendix III, page 142.

The program starts with the calculation of the inevitable retrofit cost. It is assumed that the new retrofit will be implemented at the base year, which might be a number of years before it is actually needed. The inevitable retrofit cost might thus be increased compared to the earlier calculated, concerning the existing building.

After this the insulation optimization starts. Using the energy balance subroutine, the thermal losses are calculated for the building, with the building part under consideration excluded. This is convenient because the LCC for the rest of the building can be considered as a constant. The energy balance will probably show that, due to solar gains and free energy from appliances, the heating equipment can be turned off during a part of the year. This part of the heat loss, is subtracted from the total heat loss in the building, and will provide the suitable number of degree hours for insulation optimization. During summer when the heating equipment is turned off there is no reason for saving energy. When the heating season starts the situation is different. Each unit of energy is now valuable, no matter how it is produced. It is worthwile to save energy even if it comes from e g solar gains. If there was no free energy the heat had to be produced by the heating system and thus also part of the amount of free energy is valuable. The situation is of course different when the heating system is to be optimized. The heating system does not work at all when the desireable inside temperature can be obtained from free energy. The number of degree hours is thus less for the heating equipment considerations. The subject is discussed in detail in [23]. See table V at page 59 for an example of the energy balance.

After that an expression is developed showing the life-cycle energy cost for the building part considered. However, there is also a contribution from the heating equipment cost, due to the insulation thickness, which must be added to the LCC expression. The situation can be depicted by the following expression:

$$LCC = C_1 + C_2 + C_3 \cdot t + \frac{C_4}{C_5 + C_6 \cdot t} \qquad (1)$$

where C_1 = The costs independent of the building part concerned

t = The insulation thickness

$C_2 + C_3 \cdot t$ = The insulation cost and

$\frac{C_4}{C_5 + C_6 \cdot t}$ = The energy and heating equipment cost.

Using the fact that the minimum LCC can be found by calculating the derivative to the expression (1) and setting it equal to zero, provides the following equation:

$$t_* = -\frac{C_5}{C_6} \pm \left(\frac{C_4}{C_3 \cdot C_6}\right)^{1/2} \qquad (2)$$

The subscript * on t shows that this is the optimal thickness of insulation for the retrofit concerned. The formula (2) is elaborated in [3 p. 46].

From expression (2) it is obvious that C_1 and C_2 do not influence on the optimal thickness of insulation. Implementing the optimal thickness in (1) will provide a LCC but this will not be correct due to the high amount of degree hours used for the optimization. Thus a new energy balance is calculated and this time the heat produced by the heating equipment is used for calculating proper energy- and heating equipment costs, using the situation for the retrofitted building as a whole.

The procedure and the evaluation of these expressions are described in detail in [3], although slightly changed according to the theories in [23].

In figure (4) the process is shown schematicly.

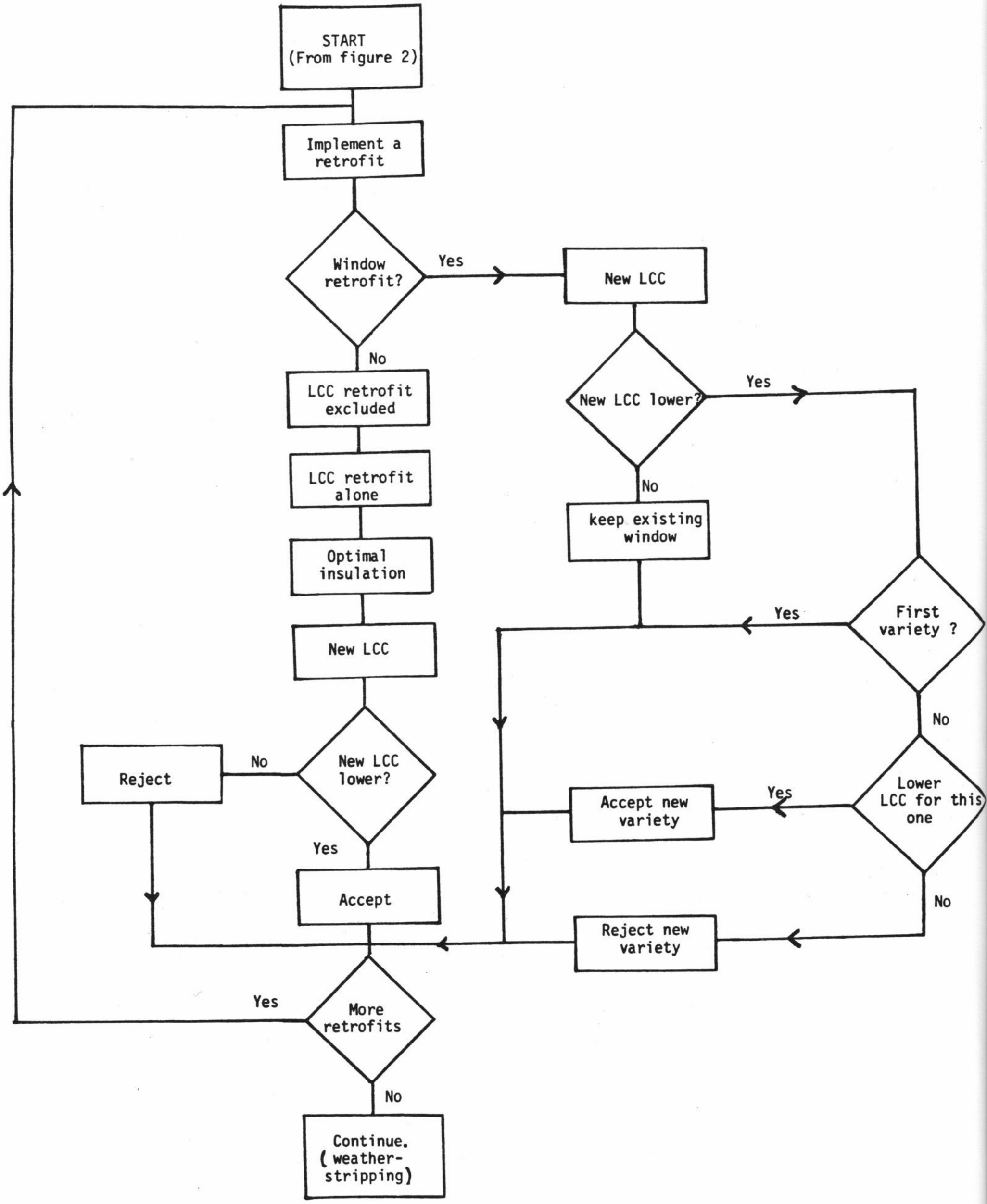

Figure 4. Simplified main program flow chart. Part 2.

It shall be emphazised here that the energy balance subroutine is also used several times when the window retrofits are considered. Implementing a new window does not only affect the thermal status of the envelope but also the solar gains radiated through the window. This might have its importance and thus separate calculations are elaborated for different orientations of the window type concerned. The different window constructions also have to be compared to each other, a gas filled triple glazed window could result in a lower LCC than an ordinary ditto, however both result in a lower LCC than the existing windows.

2.2.2 Weatherstripping

One of the cheapest retrofits to implement is weatherstripping. By caulking windows and doors in the building it is possible to decrease the amount of cold air leaking through small passages in the building envelope. In many existing multi-family buildings the ventilation system works due to these leaks. The only driving force for the ventilation is the buoyancy force, which forms a natural ventilation system. By caulking the building, the ventilation flow will decrease and less heat is transferred out from the building with the exhaust air. Of course it is not preferable to stop the ventilation totally in a building due to hygienic reasons, even if money is saved by lower energy bills. In [3 p. 84-] all details about the calculations can be found.

The money saved by caulking measures can be calculated by using equation (AIII 5), page 148, in appendix III, the value of VENT will get lower. However, weatherstripping costs money and only if the amount of money saved is higher than the money spent the measure is profitable. In most cases this is the fact because caulking is rather cheap and the influence on the ventilation flow can be considerable. The OPERA model compares the LCC after the weatherstripping has been implemented with the earlier calculated LCC for the existing building.

2.2.3 Exhaust air heat pump

Using an exhaust air heat pump makes it possible to take care of the heat in the ventilation air and recirculate it. Earlier it was common to heat only domestic hot water with this kind of facility but nowadays the device is also connected to the ordinary heating system used for space heating. Naturally this will provide a better profitability because the heat pump will be working almost always, at least during the heating season.

The OPERA model evaluates the profitability of the heat pump, i e if the LCC gets lower, assuming the weatherstripping was profitable. This means that the ventilation flow will be lower than the existing flow and thus less heat can be taken care of in the exhaust air. However, the model also tests if it is more profitable to reject the weatherstripping and spend the money on a slightly bigger exhaust air heat pump. In [3 p. 135] such cases can be found. The energy balance subroutine is used to evaluate the proper amount of heat recirculated through the building. In [3] all the input data are discussed and more details can be found in the case study starting at page 43 in this thesis.

2.2.4 Exhaust air heat exchangers

Another way to take care of the heat in the exhaust air is to use a heat exchanger. However, this system must have a way to deliver the warm fresh air in the different apartments. Mostly, such systems are very expensive to install in existing buildings and subsequentely they will seldom be profitable. The problem is discussed further in [3 p. 91]. Because of the high retrofit cost this measure is not included in the OPERA model but it can be implemented in the program quite easily.

2.3 OTHER HEATING SYSTEMS

In previous chapters it is shown how the OPERA model works in order to find the optimal retrofit strategy. However, up to now it is assumed that no changes are considered in the existing heating equipment.

Most multi-family buildings in Sweden, now concerned for retrofit measures, were originally equipped with a central oil-boiler heating system, but lately this system has been changed to e g district heating in many areas. Sometimes a more complicated system, like a heat pump is installed which provides the heat at a very low running cost. This running cost is approximately 0.25 SEK/kWh for the oil-boiler and 0.30 SEK/kWh for electricity. Heat pumps have a coefficient of performance, COP, of approximately 3 which means that they deliver heat 3 times the electricity input. Subsequentely the running cost for the heat pump is about 0.1 SEK/kWh. District heating systems and bivalent oil-boiler - heat pump systems have a running cost which is between that of the single oil-boiler and the heat pump systems. In appendix I, page 107, this is discussed in detail.

The difference in running cost, that appears when the heating system is changed, has to be considered when optimizing the envelope retrofit strategy. A high running cost will of course generate more envelope retrofits. The money saved in a lower energy use can pay for a more extensive retrofit strategy. On the contrary a low running cost system will generate only the cheapest retrofits.

For the simple systems this is evaluated simply by changing efficiencies, energy prices, installation costs etc valid for the new type of system and start the process almost from the beginning. This will provide a new retrofit strategy showing the situation for the new heating equipment. The new LCC might be higher than the existing one and the strategy has to be rejected. This is mostly the case when a lower running cost heating system is exchanged for a higher running cost ditto, e g from oil to electricity. The installation cost is almost the same for the two systems, [3 p. 99, 106], and the running cost will thus be very important.

However, some of the heating systems provide lower running costs but at higher installation costs. A heat pump system, with the lowest running cost, is very expensive and thus the high installation cost cannot compensate for the low running cost. It is important to note that the actual heat pump design is not optimized by OPERA, but the model calculates the best thermal size of it. Authors that have treated the design problem are e g [58 and 59].

Another rather low running cost system at present, is the district heating system, at least if the energy cost for the consumer reflects the cost for producing the heat. The installation cost for the consumer will also be acceptable and thus this heating system often is the best choice.

Bivalent oil-boiler - heat pump systems also combine a very low running cost with an acceptable installation cost and therefore these kinds of systems are very interesting.

In [25] the influence of the installation cost and the running cost, on the envelope strategy, is shown for different systems, and here will only be discussed thorougly two of the heating systems above, viz heating systems with differential rates and bivalent heating systems. Ordinary heating systems are treated in [3].

2.3.1 Heating systems with differential rates

When producing heat or electricity in a public utility there are several ways to do it. In the district heating plant it is nowadays common to use garbage, wood chops, coal and oil as fuels. It is obvious that the Short Range Marginal Cost, SRMC, cannot be the same independently of the fuel. (The SRMC is the cost for producing one extra unit of energy or the money saved not to produce one.) When refuse is the only fuel in the plant the SRMC is very low, approximately 0.003 SEK/MJ, (0.01 SEK/kWh). This is because the utility must either get rid of the garbage or they have to put it in a refuse dump. The garbage is used as a base fuel, i e it is used all through the year. However, in the winter there is not enough refuse to burn and the utility has to use the other fuels as well. Oil, which normally is the most expensive fuel, is used for peak load conditions and the SRMC is of the magnitude 0.06 SEK/MJ (0.20 SEK/kWh).

The same discussion can be elaborated for producing electricity, the base load is produced by hydro electrical plants and the peak load by gas turbines. In [26, 27 and 61] this is treated in detail.

It is obvious that an ordinary rate, with a constant energy price throughout the year will encourage the energy consumer to save energy regardless of the season. One MJ saved during the summer equals one MJ saved during the winter. This is not true for the heating utility, one MJ saved during the winter can be worth 20 times more than the same amount of energy produced in the summer. Thus it is of great importance to encourage energy savings during the winter, and one way is to implement differential rates.

In [28] it is shown that it is not very easy to design a rate that will advantage top peak saving and at the same time disadvantage competing energy producing facilities such as solar panels or exhaust air heat pumps. The rate also has to be normalized which means that the utility cannot increase the total level of the rate. The income of the plant thus will be the same no matter what type of rate is used for an identical thermal load. Because of this, the differential rates used in Malmö, and in this thesis, will only slightly encourage top peak saving but will give considerable disadvantage to competing energy production at the consumer during the summer.

The OPERA model uses the differential rates elaborated by the municipality of Malmö for the calculations. This is done in a subroutine, page 147. By some programming work it is easy to implement other rates than the default ones, and the differential rates can be compared to the fixed rates. If the new rates in their design are similar to the Malmö cases it is possible to implement the rates in the input file concerning the subroutine. In [28 and in 3 p 109-] the calculations are described. See also page 86 in this thesis.

2.3.2 Bivalent heating systems

As mentioned above a bivalent heating system can often be a very good solution for minimizing the LCC. The systems treated in the OPERA model are oil-boiler - heat pump systems where the oil-boiler takes care of the thermal peak loads and the heat pump the base load. The difference between the systems depends on the heat source. The first alternative uses a fixed COP, while the other system is evaluated using a varying COP due to the outside temperature. There are also some differences concerning the installation cost calculations. In [29] it is shown how the first system is optimized for the existing building thermal load and furthermore when insulation measures or other retrofits are implemented. The second system is described in appendix I, page 107.

In the OPERA model the procedure is elaborated using mainly two subroutines, the first one finding a mathematical expression for the duration graph concerning the existent building and the other one for the optimization. In the references it is shown that a mathematical expression showing the LCC for the bivalent system and one insulation measure can be depicted as:

$$LCC = C_1 + \frac{C_2}{C_3 + C_4 \cdot t} + C_5 \cdot P + \frac{C_6 \cdot P^2}{C_7 + C_8 \cdot t} + \frac{C_9 \cdot P^2 \cdot t}{C_7 + C_8 \cdot t} + C_{10} \cdot t \qquad (3)$$

C_1 to C_{10} shows different constants, however not the same as in the earlier expressions, P shows the thermal power of the heat pump and t shows the extra insulation thickness.

The expression (3) above shall be minimized and in the OPERA model this is done by a derivative method. However, it is not very easy to calculate the minimum point and thus the sign of one of the derivatives is examined and the minimized LCC is found by an iterative process. Also in this case it is important to use the proper amount of degree hours for the optimization. The insulation thickness is subsequentely optimized for more degree hours than the heat pump - oil-boiler system. The model is also provided by a maximum number of iterations, 500, because the shape of the expression might be very flat at the bottom. A small change in t might change the derivative less than the significance in the computer memories. This is so even if double precision is used for some sensitive parameters.

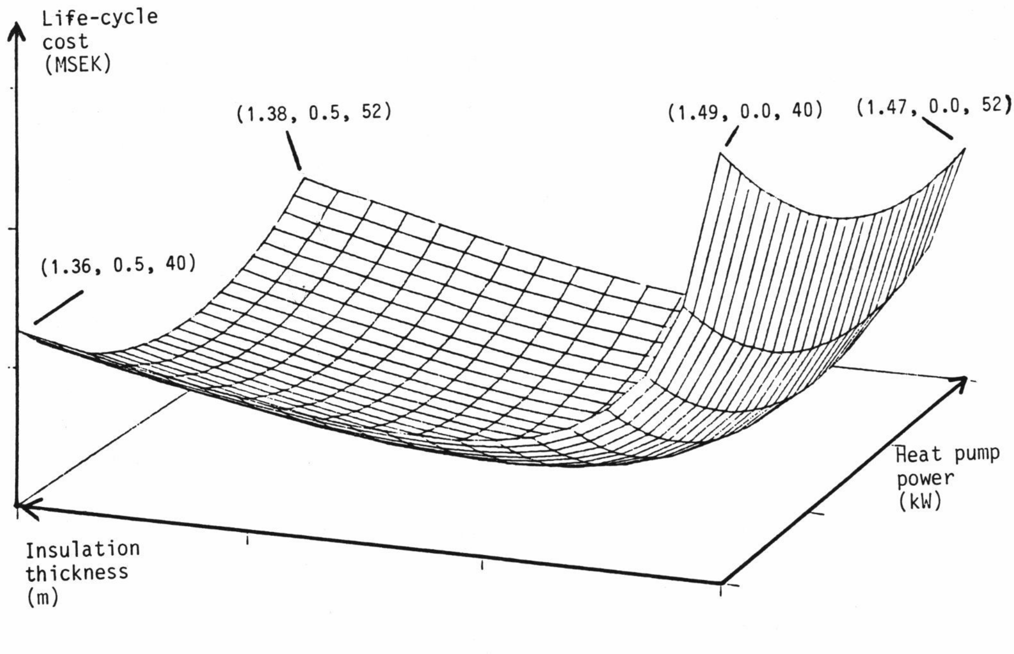

Figure 5. LCC field for bivalent system and insulation.

Figure 5 shows, using the situation found in [29], how the LCC varies due to the insulation thickness and the thermal power of the heat pump. With no extra insulation at all, the minimum point of the LCC is located to 52 kW thermal power of the heat pump while the other extreme is located, for a very large amount of extra insulation, to 40 kW.

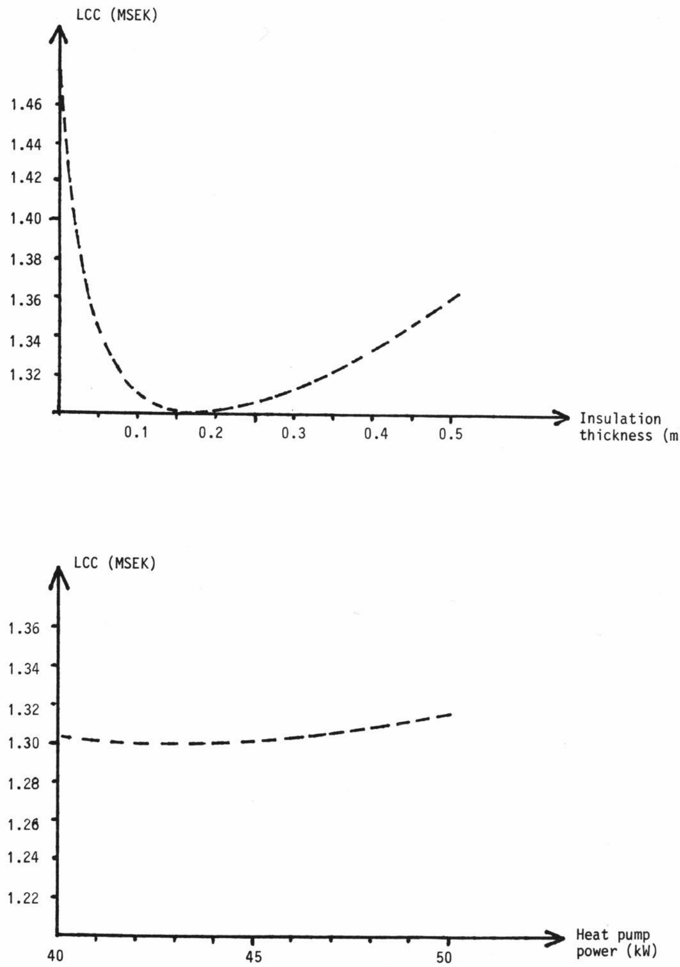

Figure 6. LCC due to insulation and heat pump size.

This represents a situation when no heat at all transfers through the building part considered. However, the minimum LCC thus can be found somewhere between these extremes and with the optimization procedure discussed above this point is found for 0.16 m extra insulation and 42 kW thermal power of the heat pump. In figure 5 the first coordinate shows the LCC in MSEK, the second the insulation thickness in meter and the last one shows the thermal output of the heat pump.

From figure 6 it is obvious that it is more important to choose the proper thickness of the insulation than to choose the proper size of the heat pump. It is also shown that it is better to insulate a little too much than the opposite.

The optimization procedure is much easier for the other envelope and ventilation retrofits, when a number of alternatives are to be evaluated. The situation is shown in [29] and here will only be emphazised that those problems are handled by common derivative methods for one variable.

However, the situation above shows the case when the heat pump has a COP which is constant over the year. This is the approximate situation for e g ground coupled heat pumps with a heat source whose temperature is constant. Outside air heat pumps cannot be dealt with exactely in the same way because of the outside temperature dependent COP. This is dealt with in appendix I, page 114.

An expression showing the influence on the COP due to the temperature is:

$$COP = \frac{-\Delta T + 66.43}{20.53} \qquad (4)$$

where ΔT shows the difference between the desired inside temperature of 20 °C and the outside temperatures. The expression (4) has been elaborated using information from a heat pump manufacturer [79].

Using the energy balance subroutine the duration of the heating season is calculated and a mean value of the COP is calculated for the suitable temperatures. However, the heating of domestic hot water is carried out throughout the whole year and thus a second mean value COP has to be used.

A minor change also has to be done because the oil-boiler has to provide the total thermal load during the worst climatic conditions, and during that time the heat pump will be turned off.

There are also some difficulties with heat pumps not dealt with in the OPERA model. One of those is the fact that during the coldest winter days a very high water temperature might have to be maintained in the water radiators else they cannot provide the desired inside temperature. This means that the returning water to the heat pump is rather hot, maybe higher than 60 °C which means that the heat pump cannot work properly and will turn off earlier than expected. The profit subsequentely is jeopardized. It is very important to do some monitoring and scrutinize each system concerning conditions specific for the building.

Such difficulties and others depending on the single components in the installed equipment are not dealt with in the OPERA model.

In subsequent chapters other difficulties will be discussed when bivalent systems are optimized due to the free energy provided by e g solar gains and appliances. See figure 15 at page 91 or appendix I at page 107.