3.4 THE OPTIMAL STRATEGY, SENSITIVITY ANALYSIS

In earlier chapters it is shown how the different parts in the LCC change if some of the input parameters are changed. In this chapter and in appendix II, the total strategy is emphasized, i e how the optimal strategy changes if one or more of the input parameters are changed.

In [70] the importance of risk or sensitivity analysis in LCC is emphasized. If the total strategy in an optimal solution is changed for small changings in the input data this solution would be very hazardous to implement. One way to evaluate these LCC changings due to input changings is the spider diagram.

The authors to [70] suggest that the LCC is calculated for the best estimation found for the input data. After this is done, one of the input data is changed and the LCC is recalculated. The same method is used in the previous chapter but the presentation of the result is different. In [70] the percentage changings in the input data are emphasized, and thus several parameters can be shown in the same diagram. In figure 12 the same procedure is used to show the result from a number of OPERA calculations.

Three parameters in the input data file have been changed. Changings in the discount rate or the optimization time will influence very much on the LCC while a change in the external wall U-value will result in an almost constant LCC.

However, the new LCC is not very interesting as long as it is not compared to the existing LCC for the building. In the text accompanying table XIV, page 68, it was mentioned that as long as the wall was optimally insulated the LCC hardly changed at all, but for a certain U-value it is better to leave the wall as it is because the insulation is unprofitable.

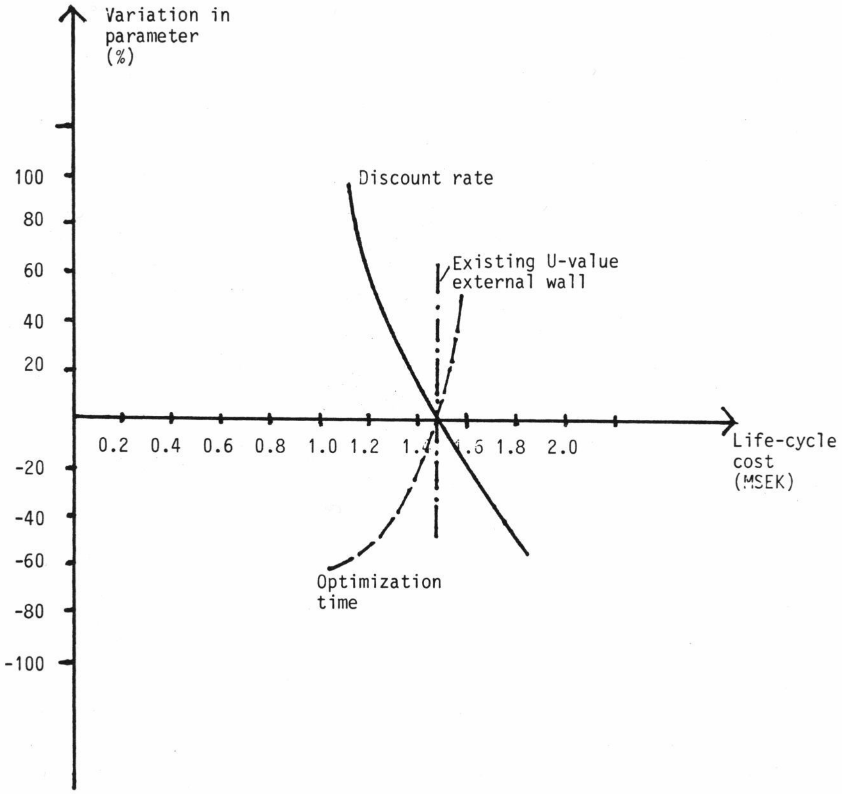

Figure 12. Spider diagram.

The curves in figure 12 show the LCC for the solution found optimal, the retrofit strategy is not the same for the different rates etc. Using the spider diagram, two or more identical strategies can be examined and in that case there will be two or more "spiders" in the diagram. However, such calculations are not very easy to perform in the OPERA model because you have to force the model not to optimize the situation. In this thesis other methods will be used to examine the sensitivity for input changements.

From table I, page 53, it is obvious that the envelope retrofits are mostly unprofitable no matter which of the heating systems used. In the case studied, only attic floor insulation, external wall insulation and weatherstripping were profitable for most of the heating systems examined. If the remaining life span for the external wall is longer than 0 years this retrofit also might be unprofitable.

A higher running cost, i e direct energy cost, works in the other direction and will also make exhaust air heat pumps profitable, as is the case for the electrically heated building.

Mentioned above are the possibilities in OPERA to examine what happens if one or more values in the input data file are changed. In fact, running the program to the end provides also tables for optimization times of 10, 20, 30 and 40 years, different discount rates from 3 to 13 % and escalating energy prices from 1 to 3 % annually. Of course it is very easy to change these limit values, if preferable. However, examining these tables makes it easy to examine what will happen to the optimal strategies.

In this case the district heating system with a differential rate was found the best one. This heating system should be combined with three envelope retrofits. From the OPERA tables mentioned above it can be found that this solution also is chosen for a number of other alternatives of the discount rate etc. In order to depict the situation a method found in [70] has been used which can be called LCC mapping. However, in this thesis, also the optimal solutions are shown. The values in the graph, figure 13, show the LCC in MSEK for different combinations of the discount rate and the optimization time.

The district heating system with a differential rate is the best system for long optimization periods and low discount rates. A 3 % discount rate implies that this solution is chosen for periods between 20 - 50 years. If the discount rate is higher, say 5 %, the solution is optimal for 30 - 50 years. It is obvious that high rates will imply less retrofits as well as shorter optimization periods. High rates and a short optimization time will reject all envelope retrofits except for weatherstripping, and keeping the existing heating system is the best solution.

However, in the vicinity of, e g a 10 % change, the best estimation, i e 5 % and 50 years, the first solution will not change. See also appendix II, page 123, where a 5 % change has been made for all the input data.

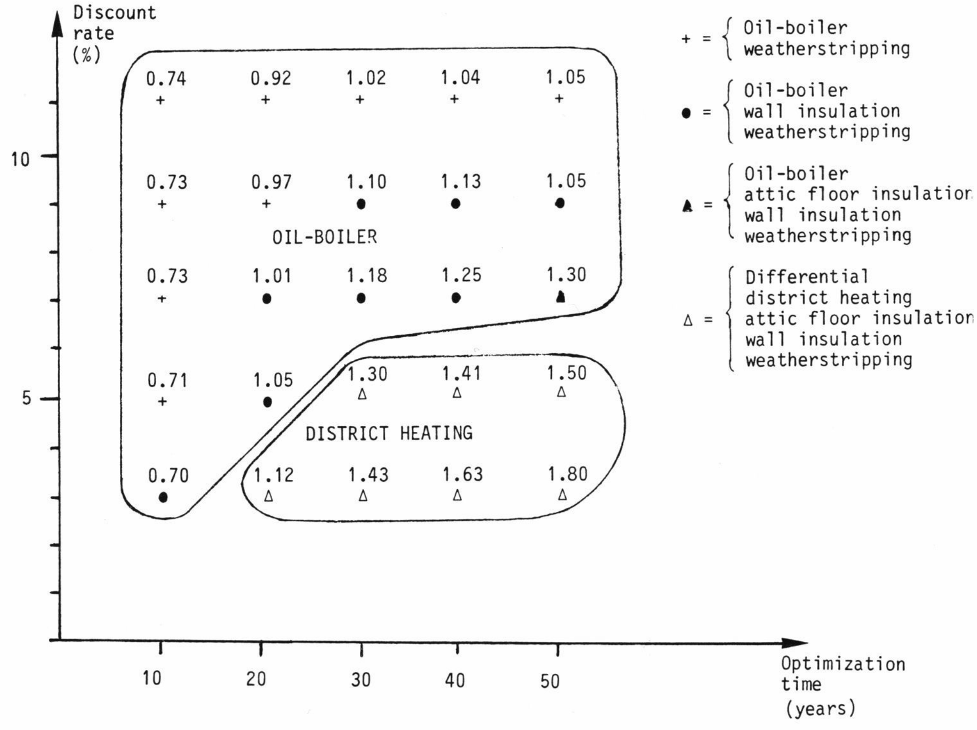

Figure 13. Bivariate sensitivity analysis. Discount rate versus optimization time. The values show the LCC in MSEK.

The same process can be elaborated for other combinations of input parameters. The situation is in the next figure depicted for annual increases in the energy prices and changes in the optimization time.

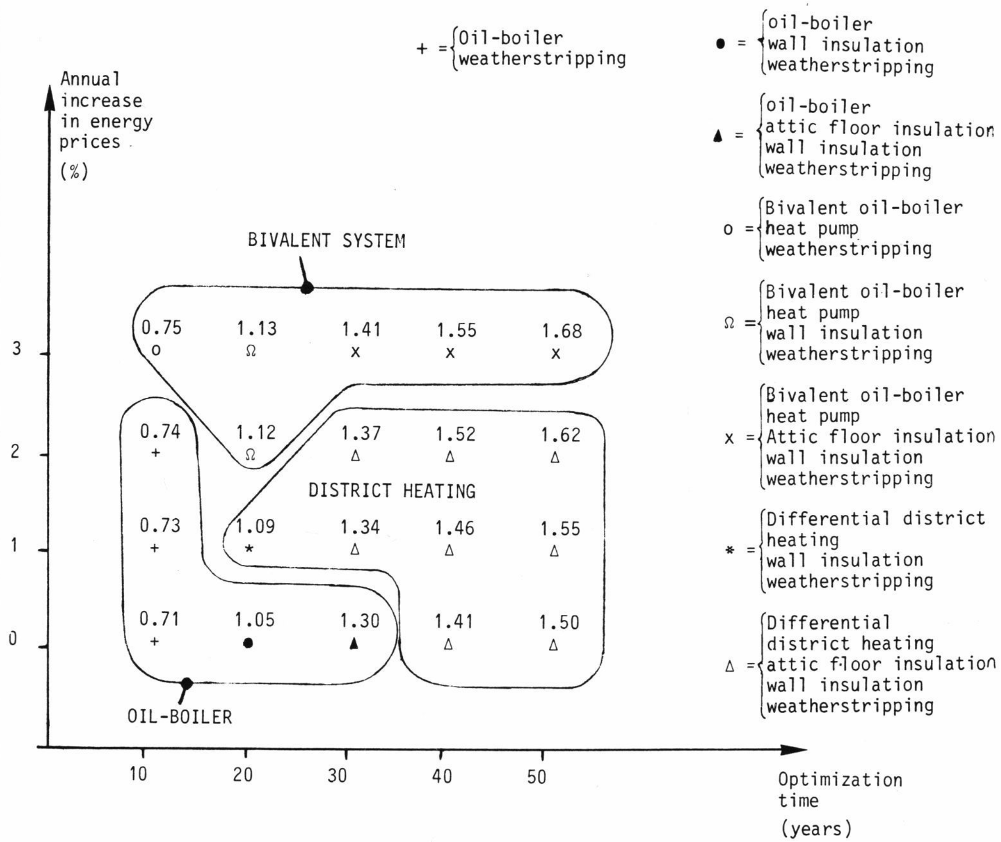

Figure 14. Bivariate sensitivity analysis. Annual increase in energy prices versus optimization time. The values show the LCC in MSEK.

In figure 14 it can be found that more complicated heating systems are chosen if the energy prices are escalating. Due to this heating system change, the same envelope retrofits will be considered as in figure 13. It could be expected that if the energy prices increase, an extensive envelope retrofit should be optimal. The best thing to do is however, not to save energy but to provide it at a lower price.

In figure 14 it is also shown that the system found profitable for the best estimation of input data, i e 50 years and 0 % increase, will be more robust due to changes in these parameters than was the case in figure 13.

It must be observed here that the insulation measures found profitable, and selected by the model, are not identical for the different sets of combinations. The attic floor insulation thickness varies from 0.13 to 0.24 meter, and the external wall insulation from 0.09 to 0.18 meter.

Weatherstripping was profitable in all the examined cases.

However, as is emphasized above there are also a lot of other variables that influence the optimal strategy, e g the existing thermal envelope. This is obvious from table XIV, page 68, low existing U-values will make the insulation retrofits unprofitable. Another example is that the weatherstripping measure of course will be influenced by the possibility to make the existing ventilation flow lower.

From the above discussion it is obvious that some of the input data values are more important than others. A high discount rate, e g higher than 10 % will make almost all of the possible retrofits unprofitable, which means that the total strategy is influenced. The same is valid for a short optimization time, say less than 10 years.

The opposite situation is valid for e g the COP for expensive heat pump systems. It will almost never be possible to find a system that is profitable for the building concerned in this case. This is also emphasized in appendix II. The situation is of course different for a much bigger building or a colder climate.

The best thing to do is thus to provide OPERA with values found by experience, run the program and see what happens. The retrofits that are selected in a number of cases will be the interesting ones to study in more detail.

3.4.1 Insulation measures

Changing the inevitable cost, C_1 in equation (5), page 38, will change the total LCC but it will not change the fact that insulation is profitable because of the 0 year remaining life span. However, changing also this makes the inevitable cost important, see table VIII and IX at page 62. The longer the remaining life span is, the smaller is the interval of the cost where insulation is profitable. Shortening e g also the optimization time will decrease the interval even more. Thus it is not very hard to construct cases where almost any situation can be found optimal.

However, the uncertainty is not total because it is possible to find intervals where all the values will probably be located. In [3] it is shown that e g the discount rate for national calculations has been recommended between 3 and 10 % but most of the authors suggest rates in a much smaller span, between 4 and 7 %. In [51] 5 % is recommended.

When retrofitting a building with a total new life span of more than 30 years, very short optimization periods are of no interest.

Uncertainties in the cost function (5) can be treated in the same way. A close study of the costs emerging from retrofitting walls etc will give us values that reflect the reality with errors less than say 20 %.

In the case studied above this means that attic floor and external wall insulation can be considered as profitable, and the insulation thickness shall be between 0.13 and 0.18 meter for attic floor insulation and between 0.10 and 0.15 meter for the external wall insulation.

Insulation of the external wall at the inside was never found profitable. This is because of the loss of apartment area. The loss of rent from this area is of the same magnitude as the insulation cost and thus the outside wall insulation cost must be approximately twice the inside insulation cost if the latter should be found profitable. If insulation at the outside is not preferable for other reasons, e g aesthetical, the situation will be different. By setting the outside insulation cost high OPERA can be forced to choose insulation at the inside.

The floor insulation was not found profitable by OPERA. This was because of the low U-value choosen for the floor, 0.6 $W/m^2 \cdot K$. The calculations for the floor are elaborated in the same way as the other insulation measures. This however, is not correct because the temperature in the basement is higher than in the outside air. The problem is solved by calculating an equivalent U-value for the floor. Assuming the existing U-value is 1.0 $W/m^2 \cdot K$ at the floor between the basement and the first apartment, and assuming that the inside temperature in the basement is 10 °C, this equivalent U-value will be approximately 0.6 $W/m^2 \cdot K$, which is used in this case.

The basement walls are surrounded by soil and it is not very easy to calculate an accurate value for the heat loss through them and through the ground. In [62] the author is dealing with the complexity of this problem but it is not worthwile to implement such procedures in OPERA. The following discussion enlightens the situation. In [45 p. 219] a simple expression is elaborated as follows:

$$U_{eq} = \frac{2 \cdot k}{\pi \cdot H} \cdot \ln \left(1 + \frac{\pi \cdot H}{2 \cdot k} \cdot U_0 \right) \qquad (9)$$

where: k is the thermal conductivity for the soil
H is the height of the wall
U_0 is the existing U-value of the wall

Using k = 1.0 $W/m \cdot K$, H = 2.5 m and U_0 = 1.0 $W/m^2 \cdot K$ will evaluate in an equivalent U-value of 0.4 $W/m^2 \cdot K$. For existing U - values of that magnitude an insulation retrofit will almost always be unprofitable. In [69] the subject of optimal insulation of the building foundation is treated for new residential housing. However, the authors use methods similar to those presented in [55], in this thesis dealt with in page 7, and no optimum can be found without a tedious trial and error procedure.

3.4.2 Window retrofits

In the case dealt with in this thesis window retrofits are only profitable with high energy prices. Note that high energy prices first will change the heating system and thus better windows are once again rejected by the model. This is so, even if the windows have to be changed anyway. The most profitable solution is to change windows to the ordinary double-glazed type, see also appendix II, remark number 1, page 136. The better thermal performance, in the other types of windows dealt with here, cannot justify the higher cost.

3.4.3 Weatherstripping

This is the retrofit that is almost always selected in an optimal strategy. The cost for caulking windows and doors is rather low compared to the amount of energy saved. However it is not easy to find proper values for the ventilation rate decrease. Here a value from [3] is used. The calculations are elaborated assuming a life span for the measure of 10 years, and the total cost is calculated as a present value. Lowering the ventilation rate decrease will of course make the retrofit less profitable regardless of the low cost. The influence of different discount rates etc are the same as for the insulation retrofits dealt with above. However, this measure was found profitable for all the tested variations and thus it can be considered as part of an optimal strategy. The exact calculation procedure is shown in [3].

3.4.4 Exhaust air heat pump

This is a rather expensive retrofit measure and thus only chosen if a high running cost heating system is optimal. This is almost never the situation and the retrofit will rarely be selected. Thus it seems a bad strategy to install an equipment like this. Small changes in the assumed input values might even aggravate the situation and thus it will not be part of the optimal strategy. The weatherstripping will decrease the ventilation flow through the building and thus OPERA tests if it is more profitable to reject the caulking and install a somewhat larger heat pump. However this was not the situation in the case shown. OPERA uses the energy balance subroutine to ensure that there is a need for the heat from the heat pump. During the summer the heat pump is only used for hot water production.

3.4.5 Changing the heating system

As mentioned above it was often optimal to change the heating system to district heating. In spite of its higher installation cost such a system will give advantages due to the lower running cost. However, in the case studied, there is very little difference in the total LCC, between the oil-boiler and the district heated system. Because of the uncertainties in the input data etc, it can be estimated it is best to keep the existing heating system. If the oil price will raise in the future it will also influence the district heating rate provided by the utility. However, if the utility uses a fuel mix to provide the heat, it is only the winter or peak load price that should be increased and thus, due to marginal cost pricing, only part of the heat price should be of the same magnitude as the oil price. This means that the normalized running cost from the district heating and the running cost from the oil-boiler will differ more than today.

3.4.6 The best strategy

From the analysis above the best strategy can be characterized by:

- Installing a district heating system
- Insulating the attic floor with 0.13 - 0.18 meter mineral wool
- Insulating the external wall with 0.10 - 0.15 meter mineral wool
- Caulking the windows and doors

Maybe the result above looks poor after all the analyses done. Not much was going to be done to the building in order to obtain the best profitability. However, this is the experience from a number of OPERA runnings. The envelope retrofits, as well as the exhaust air heat pump will seldom be profitable. The external wall insulation, found profitable above, is optimal only because of the 0 year life span.

On the contrary, the closeness of the existing heating system strategy might be a little surprising, see table II page 54. In many earlier OPERA cases it was more profitable to change the oil-boiler to a lower running cost system such as bivalent oil-boiler heat pump systems which provide a combination of a very low running cost and an acceptable acquisition cost. The reason for the competitive existing heating system is mostly due to the low energy demand in the case above. In the next chapter a more thorough study is elaborated in order to describe also these more complex heating systems.

3.5 DIFFERENT HEATING SYSTEMS

In the case studied, only two different heating systems were found to be candidates for the optimal solution. Due to different reasons one of those could be excluded, the existing oil-boiler. Below, the winning district heating system and the differential tariff is treated in further detail. However, it could also be interesting to examine the conditions necessary if other and more complex solutions were to be chosen.

In OPERA the first six heating systems are calculated in the same way. The differences between them are different prices for energy, different efficiency and acquisition costs etc. The energy price is a fixed value in SEK/kWh. The district heating system however, also considers a connection fee. For district heating and electricity these kinds of rates in recent years are the subjects for a change. Differential or time-of-use rates are introduced. The reason for this is that the cost for producing an extra unit of energy differs much due to the conditions when this extra unit is produced. During peak conditions, for Sweden in the winter, the cost can be five times higher or more than during base load. It is obvious that energy savings during base load conditions will be less profitable if a cost-reflecting rate is provided by the utilities. Energy should be saved when there is a need for it.

3.5.1 The differential district heating rate

When a building is coupled to the district heating system a connection fee has to be paid. In the case studied here, this is

$$300 \cdot P_{dim}$$

where P_{dim} is the maximum demand during one hour. There is also another fee, the demand fee, to be paid due to the demand which is calculated as:

Single-family houses:	$500 + 600 \cdot D \cdot R$
Multi-family houses,	
D = 0 - 800 kW,:	$700 + 600 \cdot D \cdot R$
D = 801 - kW :	$2400 + 600 \cdot D \cdot R$

D is calculated as the energy use during January and February devided by the number of hours during those two months. R is a reduction factor decided by the utility. In 1986 the factor equaled 0.25.

The energy price is 0.19 SEK/kWh, 0.053 SEK/MJ from November to March and 0.10 SEK/kWh, 0.028 SEK/MJ from April to October.

It is obvious that energy conservation during summertime is very difficult if it is going to be profitable.

In table V page 59, it is shown that OPERA calculates the energy demand month by month. Multiplying these figures with the applicable price provides the total running cost for energy during one year.

In our case this results in:

- Connection fee = 23 000 SEK
- Demand fee = 6 000 SEK
- Energy cost = 26 000 SEK

The direct energy cost as an annual mean value will become 0.047 SEK/MJ, 0.17 SEK/kWh. If the demand fee is included, the cost will be 0.057 SEK/MJ or 0.21 SEK/kWh.

In the OPERA running shown in table I page 53, this normalized price for district heating is also used in the ordinary district heating calculations. The total LCC for the existing building thus will be identical or 1.61 MSEK. Due to truncation errors the values are not exactly the same.

When a retrofit is introduced, OPERA calculates the total energy cost during one year, over again. The retrofit will lower the energy demand. Insulation measures, window retrofits etc, lower the cost mostly in the winter, while the energy demand during summer, as before, will equal the hot water production. This means that less of the more expensive energy is used. More money is thus saved if a differential rate is introduced. However, the influence is rather small because most of the heat is consumed during high price conditions, see table I.

The effect is enhanced for mineral wool insulation measures because the Energy 2 column in table V, page 59, is used for the insulation optimization. Almost no cheap energy at all is used and thus the optimization is elaborated for an energy price close to the high one in the tariff. The result is a thicker insulation compared to optimization with ordinary rates.

The exhaust air heat pump saves energy also during summer when the energy is cheap. The savings in money is therefore much lower if a differential rate is introduced. The subject is treated in detail in [28].

3.5.2 Differential rates for electricity

The electricity tariffs are slightly more complicated. For low voltage purposes, where the fuse size is lower then 250 A, the following rate is applicable:

- Energy cost, Nov-March, Monday to Friday, 06-22:	0.345 SEK/kWh	= 0.095 SEK/MJ
other times	0.16 SEK/kWh,	= 0.044 SEK/MJ
- Demand charges:	63 A	2380 SEK
	80 A	2900 SEK
	100 A	3520 SEK
	125 A	4300 SEK

To the energy cost a tax of 0.072 SEK/kWh shall be added, 0.02 SEK/MJ. There are more varieties for other sizes of the fuses but the information presented above is enough for the purpose in this thesis.

If a fuse bigger than 250 A is required another type of tariff is used, and OPERA will decide which tariff to use.

The high energy price will become 0.12 SEK/MJ, 0.417 SEK/kWh,and the low price 0.06 SEK/MJ, 0.232 SEK/kWh. Calculating on the rate for one week results in suitable monthly mean values used in this thesis:

$$\frac{5 \cdot 16 \cdot 0.417 + 5 \cdot 8 \cdot 0.232 + 2 \cdot 24 \cdot 0.232}{7 \cdot 24} = 0.3214$$

which is the high price from November to March (= 0.089 SEK/MJ). The low price is of course 0.232 SEK/kWh during all the other months. Considering the conditions for each month will result in small differences, see page 135. Using the same technique as above for district heating, the total cost during one year will become:

- Energy cost	47 200 SEK
- Demand charge	4 300 SEK

The normalized energy cost will be 0.08 SEK/MJ, 0.30 SEK/kWh, without the demand charge and 0.09 and 0.32 respectively with this included.

Implementing the optimal amount of attic floor insulation, 0.21 meter, will decrease the energy cost above mentioned to 40 500 SEK. The demand charge however will still be the same, or 4 300 SEK. The direct running cost for the energy, the demand charge excluded, will be lower for the retrofitted building. The cost changes from 0.2961 to 0.2949 SEK/kWh which means that more money would be saved if a differential rate was implemented.

However, the demand charge above is not changed and if this is included in the energy price, which surely is correct, the running cost is increased from 0.3231 to 0.3261 SEK/kWh. The savings with the differential rate will thus in this case be lower than if a fixed rate is used, see table I at page 53. The demand charge in this case will thus work in the opposite direction and make the differential rate a disadvantage .

The same thing concerns the caulking measure, the profitability is lower with the differential rate. It is obvious that the design of the rate is essential for the behaviour of the consumers.

The profitability of the exhaust air heat pump will be lowered very much. The fixed rate will generate approximately twice the savings compared to the differential rate. Extensive studies about the electricity differential rates can be found in [26] and [27].

3.5.3 The bivalent heat pump systems

Mentioned above are the advantages with a bivalent oil-boiler heat pump system. In the case studied here however, these systems were not found profitable, see table I page 53. The theories for the optimization are shown in [29] and in appendix I page 107. There are some differences in the calculation procedures between the two systems dealt with by OPERA, mostly concerning the elaboration of the equipment cost. In the first system the heat pump is assumed to work all year and thus the oil-boiler does not have to provide the thermal peak load. In the other case the heat pump is assumed to be turned off when the outside temperature is very low. The oil-boiler must provide all the heat under those conditions.

The present value for the equipment cost is elaborated in a more sophisticated way in the second case. During the life span of the system it is possible to implement a cost for reconditioning, which must be provided to OPERA as a share of the first time installation cost. It is also necessary to inform the program when the recondition takes place. In the first case these costs have to be included in the heating equipment cost.

The varying COP is also important in the second case which is assumed to be constant in the first one. In the case studied here this varying COP together with the system costs will make the outside air heat pump more expensive than the ground water coupled one.

If the amount of free energy, from solar gains and appliances is rather large, there is a risk that the optimization procedure will not work properly for the bivalent systems. This will happen if the optimization procedure results in heat pumps with less thermal power than the point " P summer " in figure 15 below. The true optimal situation will then be that the heat pump is to be abandonned, i e the oil-boiler system is better than the bivalent one. OPERA will tell the operator if this happens and the fact is that the outside air heat pump, in the case studied here, resulted in such conditions, see appendix I.

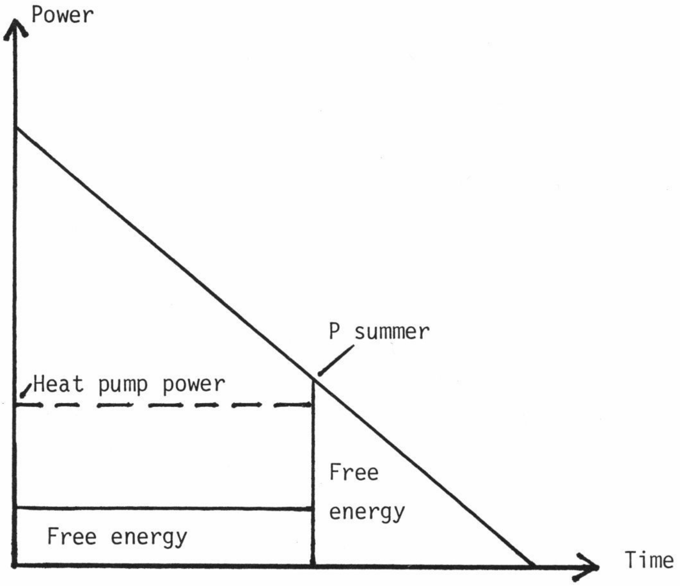

Figure 15. Duration curve with optimization failure.

The bivalent heating systems will be advantageous if the heat consumed in the building is increased. If the building is located in a colder climate or if the building is bigger than the one tested here, these systems seem to be the best solution. One case is discussed in [46].

If the amount of free energy is decreased the same thing will happen. In table XVIII this is emphasized. Abbreviations see page 52.

	Exist syst	New oil	Elec tric	Distr heat	Heat p. G	Heat p. E	Diff distr	Diff elec	Biv O-H	Biv O-O
No envelope retrofits	2.02	2.05	2.45	1.96	2.11	2.27	1.94	2.39	1.91	2.08
Savings:										
Attic ins	0.04	0.03	0.07	0.02	0.02	0.04	0.02	0.06	0.02	0.03
Floor ins			0.01							
Ext wall ins	0.12	0.12	0.21	0.09	0.12	0.16	0.09	0.19	0.08	0.12
Weatherstrip	0.06	0.06	0.09	0.05	0.07	0.08	0.05	0.08	0.04	0.06
Exhaust h.p.			0.04					0.02		
New LCC	1.81	1.83	2.02	1.79	1.89	1.98	1.78	2.04	1.77	1.86

TABLE XVIII. Retrofit strategy matrix. Free energy from appliancies = 0 kWh/month. Values in MSEK.

In the case studied one of the bivalent systems was the most profitable combined with three envelope measures. However the district heating system with a differential rate is very close and a more thorough study has to be made in order to find the real best solution. The important thing here, is that the amount of heat consumed in the building will influence the best strategy. If more heat is needed, the more complicated heating systems can compete. Compare with the result in table I.

The envelope retrofit strategy for the bivalent outside air heat pump is almost similar to the one for the oil-boiler. This is because the optimization resulted in a too small heat pump, see figure 15. OPERA thus calculates as if there were only the oil-boiler present. The hot water however, is still produced by the heat pump.