7. DISCRETE OPTIMIZATION OF BIVALENT SYSTEMS

The theories behind the OPERA model have been presented in several papers published in journals and at conferences dealing with energy conservation. Some of the papers explicitly treat the optimization of bivalent, or dual fuel, heating systems, i.e. a system where an oil-boiler and a heat pump are used for producing the necessary heating in a building.

The concept in such a system is that the heat pump is used for the base load in the building, while the oil-boiler only is used at peak conditions. It is not a profitable strategy to use solely the oil-boiler because of the high operating costs. Neither is it desirable to use solely the heat pump. This because of the high acquisition cost for a heat pump large enough to deliver the necessary heat for very cold periods over the year.

In the OPERA model such bivalent systems, where also insulation and other measures are of concern, are traditionally optimized by derivative methods. A mathematical function must then be developed, containing the two unknown variables, i.e. the size of the heat pump and the thickness of the insulation. The theories for developing this expression and how to find the optimal point are described in [1 and 44].

The method used, however, will unfortunately lead to an approximation of the energy prices, e.g. when a T-O-U rate for electricity is utilized. Another approximation is the use of a straight line for describing the thermal losses in the building, see Figure 23.

These facts made it necessary to examine how discrete optimization was to be elaborated, where steps in the mathematical function could be dealt with, as in the original model of the building and its surroundings.

Up to now three papers have been published [45, 46 and 47]. The first one only deals with the heating system optimization, the second considers also insulation optimization while the third paper compares the derivative and the discrete methods. The last paper emphasizes that some misoptimization might occur if the discrete optimization is not taken into account. This misoptimization does not lead to a total change in retrofit strategy, and further not to a severe change in the LCC, but the optimal sizes of the oil-boiler and the heat pump are miscalculated.

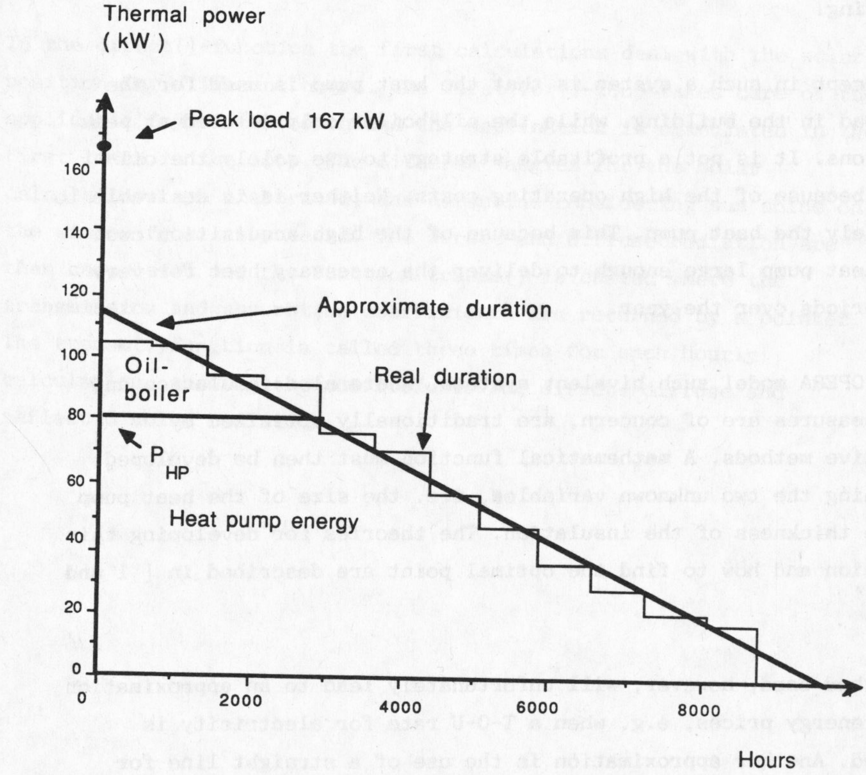

Figure 23. Derivative and discrete model for optimizing. [46]

In order to examine this possible misoptimization, a new programming routine, written in FORTRAN, was elaborated, see appendix E. The reason for chosing FORTRAN here was the fact that the program during the development, was run as a subroutine to the OPERA model.

However, some extra programming lines in the original model were necessary to include. These extra FORTRAN statements will produce a separate output file, "BIV.DAT", read by the new program. The output data file is produced during the ordinary OPERA running, and the operator only has to type the name "BIVAL" at the DOS prompt. The program will start the calculations and after some seconds the optimal distribution between the oil-boiler, the heat pump and insulation is revealed. It has not been possible to include all the different strategies that the OPERA model can present, and thus only one insulation measure is dealt with. The new program does not check whether it is better to reject the retrofits or implement them. It is therefore necessary to consider the solution found optimal in some detail. Note that the program must reside in the current directory if it is not in the PATH documentation.

Below a case, resulting from the input data file in Figure 3, is examined to enlighten the use of the program.

7.1 Case study

As mentioned above the input data file, "BIV.DAT" is produced during ordinary OPERA operations, but it must be emphasized that it is only the basic case that generates a new "BIV.DAT" file. The OPERA run will mostly find a very close approximation of the real optimal solution, and thus the discrete optimization starts from this almost optimal point. In the input data file this optimal point is described by the applicable values for the heat pump size, 17.18 kW, and insulation thickness, 0.075 m. The LCC is then calculated for this point by use of the real electricity tariff, as can be found under 3.2.16.3.1 in this manual. The process is repeated but with a somewhat larger heat pump, 1 kW is added. If this new LCC is lower than the original one, the process is repeated with a still larger heat pump. This goes on until a higher LCC is calculated. The step in the heat pump size is now changed to 1/10 of the earlier size and further the sign is changed, which means that the next iteration is made for a smaller heat pump. The process terminates when a the difference is smaller than a certain value, i.e. 100 SEK, in the original program.

When the heat pump size has been optimized in this way, a small value is added to the insulation thickness, here 0.01 meter. The iterations start again and a new optimal heat pump size is discovered. If the new LCC is higher than the earlier one the insulation level is decreased and so on. The program terminates when the difference between two consecutive LCC is lower than 100 SEK.

7.1.1 The thermal view of the case

The input data file must describe the optimization problem in detail. The program starts by resetting the thermal conditions valid for the almost optimal building. The transmission and ventilation coefficients, called NTRA and NVEN in the program, are therefore calculated due to the measures OPERA found optimal. In this case the external wall insulation, an extra 0.075 meter, and two window retrofits must be dealt with. The original transmission coefficient is 1 602 W/°C, see Figure 6. An extra 0.075 meter of insulation will decrease the coefficient to:

$$1\,602 - 616 \cdot 1.2 + \frac{616 \cdot 0.04 \cdot 1.2}{0.04 + 1.2 \cdot 0.0754} = 1\,089.6 \text{ W/°C}$$

where 616 is the area of the external wall, 1.2 is the existing U-value of the wall, and 0.04 the thermal conductivity of the new insulation, see Figure 3 and [2] for a closer explanation.

The window retrofits will decrease the transmission coefficient as:

$$1\,089.6 - 2.8 \cdot 27 \cdot 1.5 - 2.4 \cdot 29 \cdot 1.5 = 871.8 \text{ W/°C}$$

where 2.8 and 2.4 are the areas of the windows, 27 and 29 the number of the windows and 1.5 is the difference in U-value between them. If the ventilation coefficient is added, 454 W/°C, a total thermal loss of 1.326 kW/°C is obtained. This value must subsequently be multiplied with the number of degree hours for the applicable month, in order to find the amount of heat transferred through the building envelope, see Figure 6. In January this value is 21 207, in February 19 506 kWh. The number of hours in January is 744, while February has 678 hours. The demand of heat will thus be 28.5 and 28.8 kW respectively. In such a way all the months will yield a specific thermal load shown in Figure 24. Note that the peak load is calculated to 46.4 kW according to the Swedish Building Code.

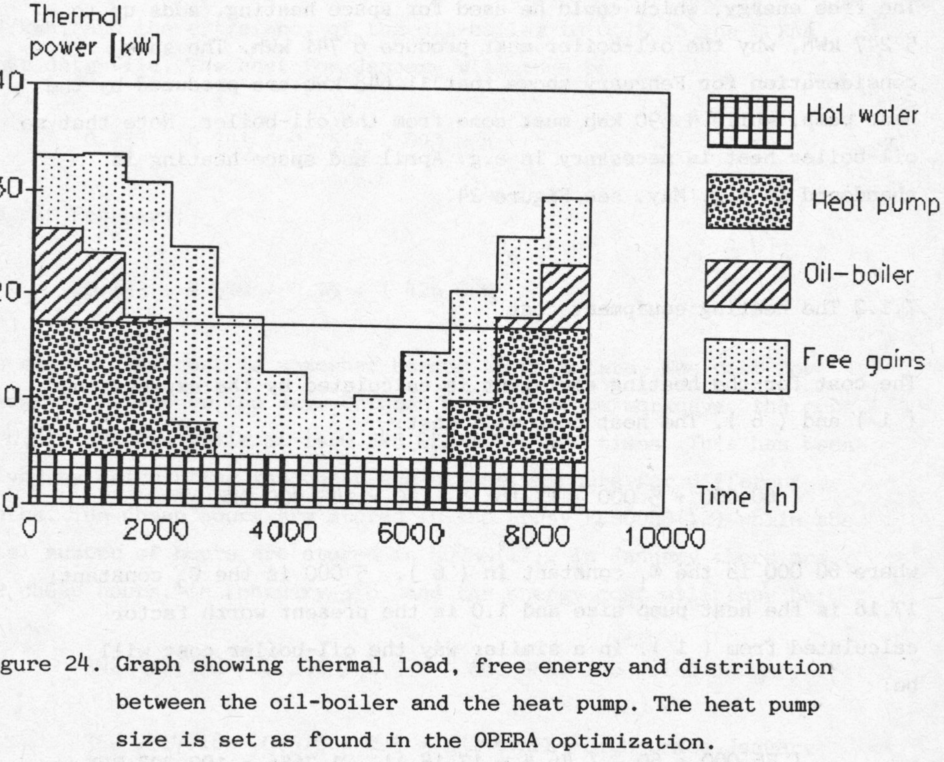

Figure 24. Graph showing thermal load, free energy and distribution between the oil-boiler and the heat pump. The heat pump size is set as found in the OPERA optimization.

Naturally, the heat needed for heating hot water must also be added, and 42 000 kWh will yield a load of 4.79 kW if a year is 8 766 hours. There is also free energy to consider. These values are provided by use of the OPERA model and transferred to the input data file. In January the solar gains are calculated to 1 080 kWh while the free energy from appliances and persons are set to 4 167 kWh. For February the value for solar gains is 2 348 kWh. Note that the solar gains must be calculated due to the optimal retrofit strategy because different windows can be implemented. The solar gains are stored in an array called SUNNY(12), while the free energy from appliances resides in FREEA(12).

In January there are 744 hours and subsequently the heat pump, with a thermal load of 17.18 kW, which was found optimal by OPERA, is able to produce 12 782 kWh. The need for heat exceeds this value. Space heating requires 21 207 kWh while hot water heating uses 3 563 kWh. The free energy, which could be used for space heating, adds up to 5 247 kWh, why the oil-boiler must produce 6 741 kWh. The same consideration for February shows that 11 648 kWh are produced by the heat pump, while 4 590 kWh must come from the oil-boiler. Note that no oil-boiler heat is necessary in e.g. April and space heating is abandoned in e.g. May, see Figure 24.

7.1.2 The heating equipment cost

The cost for the heating equipment is calculated by the expressions (1) and (6). The heat pump will cost:

$$(60\,000 + 5\,000 \cdot 17.18) \cdot 1.0 = 145\,900 \text{ SEK}$$

where 60 000 is the C_1 constant in (6), 5 000 is the C_2 constant, 17.18 is the heat pump size and 1.0 is the present worth factor calculated from (1). In a similar way the oil-boiler cost will be:

$$(55\,000 + 60 \cdot (46.4 - 17.18)) \cdot 1.7656 = 100\,203 \text{ SEK}$$

where 46.4 is the peak load of the system. There are also costs for piping and the cost for the heat pump which is calculated as:

$$1\,500 \cdot 17.18 \cdot 2.3642 = 60\,925 \text{ SEK}$$

while the piping cost for the oil-boiler is calculated as:

$$200 \cdot (46.4 - 17.18) \cdot 1.0 = 5\,844 \text{ SEK}$$

The total cost, as a present worth, for the heating equipment will thus be 312 872 SEK.

7.1.3 The energy cost

The cost for oil is easy to calculate. The oil price is set to 0.233 SEK/kWh, and the efficiency of the oil-boiler to 0.75 in the OPERA input data file. The cost for January will thus be:

$$0.233 \cdot 6\,741 / 0.75 = 2\,093 \text{ SEK}$$

and for February:

$$0.233 \cdot 4\,590 / 0.75 = 1\,426 \text{ SEK}$$

The electricity cost is somewhat harder to calculate. The cost for energy differs over the day. Between 6 am to 10 pm workdays, the cost is 0.515 SEK/kWh while it is 0.245 SEK/kWh other times. This has been solved by calculating the cheap and expensive hours for different months. The cheap hours are stored in the array ELHOURS(12) while the total number of hours are stored in HOURS(12). In January there are 392 cheap hours, in February 358, and the energy cost will thus be:

$392 \cdot 17.18 \cdot 0.245 / 2.5 = 660$ SEK, low price January

$352 \cdot 17.18 \cdot 0.515 / 2.5 = 1\,245$ SEK, high price January

$358 \cdot 17.18 \cdot 0.245 / 2.5 = 602$ SEK, low price February

$320 \cdot 17.18 \cdot 0.515 / 2.5 = 1\,132$ SEK, high price February

There is also an annual subscription fee. In this case the electric current to the heat pump will be:

$$17.18 \cdot 1000 \;/\; (380 \cdot 3^{0.5}) = 26.1 \text{ A}$$

where 380 is the voltage between the three conduction phases. The electric tariff implies that 830 SEK must be paid each year.

The procedure shown above is utilized for all the months of the year and the result is:

Table 7. Energy costs for different months

Month	Oil cost	Electricity cost	
		High	Low
January	2 093	1 245	660
February	1 426	1 132	602
March	146	1 304	634
April	-	-	539
May	-	-	349
June	-	-	338
July	-	-	349
August	-	-	349
September	-	-	339
October	-	-	750
November	271	1 248	622
December	1 444	1 192	682
Sum	5 381	6 121	6 213

The costs above must be multiplied with the present worth factor calculated with the expression (2), which in this case equals 18.26. The total energy cost will thus be:

$$(830 + 5\,381 + 6\,121 + 6\,213) \cdot 18.26 = 338\,595 \text{ SEK}$$

7.1.4 The retrofit costs, miscellaneous costs and total LCC

When the building is retrofitted there are also retrofit costs. For insulation measures the expression (4) is used. The cost resulting from C_1 is dealt with in the inevitable retrofit cost and so the insulation cost in this case can be calculated as:

$$616 \cdot 200 + 616 \cdot 2\,000 \cdot 0.0754 = 216\,092 \text{ SEK}$$

where 616 is the area of the external wall, 200 is the C_2 constant, 2 000 is the C_3 constant and 0.0754 is the thickness of extra insulation. There are also two window retrofits dealt with, as shown in expression (5). In this case, one of the constants equals zero and then the cost for the two retrofits will be:

$$27 \cdot 2.8 \cdot 1300 + 29 \cdot 2.4 \cdot 1300 = 188\,760 \text{ SEK}$$

where 27 and 29 is the number of windows, 2.8 and 2.4 are the area of the windows and 1 300 is the retrofit cost for one m^2 of one window.

The inevitable, or unavoidable, retrofit cost shows the cost for retrofits made for other than energy conservation reasons, and it also shows the inluence of retrofitting before it is actually needed. The cost is calculated in the OPERA model and is thus tranferred to the input data file. Another cost that is transferred from the OPERA model is the salvage cost of the existing boiler. The reader is referred to [2] for all the details of how these costs are actually calculated . The total LCC for the system will be:

Table 8. The contents of the LCC for the OPERA optimal point, calculated with a discrete method

Heating equipment cost = 312 872
Energy cost = 338 595
Insulation cost = 404 946
Inevitable cost = 253 788
Salvage value = 20 533

Sum = 1 330 734 SEK

The value of the total LCC found by OPERA, i.e. 1 328 695 SEK, differs very little from the LCC in Table 8, where the optimal point from OPERA is the base for a discrete calculation.

7.1.5 The optimization procedure

Above, the optimal point found by OPERA was used as a start for the LCC calculations. The question is then if some other distribution between the oil-boiler and the heat pump size, or some other thickness of extra insulation, will provide a still lower LCC. In the program the heat pump size is thus increased by 1 kW, to 18.18 kW, and the above process is repeated. This time the total LCC became 1 329 083 SEK which was lower than before. One more kW is thus added to the heat pump size producing a LCC of 1 330 460 SEK which is an increase compared to the last calculation. The step in the increment of the heat pump size is now divided by 10.0, and the sign is changed, and the new calculation is made for a heat pump of 18.08 kW. After 13 such iterations the minimum LCC was found to be 1 329 168 SEK for a heat pump size of 17.98 kW. This value is slightly larger than the one found for a 18.18 kW heat pump but the program iterations terminated because of the small difference between two consecutive LCC.

The extra insulation thickness is now increased with 0.01 meter, and the above procedure is repeated. In this case, the optimal heat pump size, 17.58 kW, for 0.085 m of extra insulation was calculated to 1 333 824 SEK which is higher than the optimal LCC for 0.075 m of insulation. Thus a thicker insulation will not be the best solution why a thinner is tested instead. After some iterations, i.e. several hundreds, the best solution found by the program is a 18.98 kW heat pump and 0.055 m of extra insulation. The lowest LCC is calculated as:

Table 9. Optimal LCC. Discrete optimization

Heating equipment cost	=	328 351
Energy cost	=	343 329
Insulation cost	=	379 074
Inevitable cost	=	253 788
Salvage cost	=	20 533
Sum	=	1 325 075

This result confirms that OPERA provides an acceptable optimization for the case studied here, the uncertainties in the input data will probably yield larger errors than of the influence of chosen optimization procedure.

7.2 OPERA optimization failure

In the case studied above, the oil energy price was 0.233 while the high electricity price was 0.515 SEK/kWh. Using a COP of 2.5 for the heat pump results in a heat price of about 0.21 SEK/kWh and it is obvious that the heat pump should produce heat also under high electricity price conditions. If the oil heat price is lower than the electricity heat price the heat pump of course shall be turned off. In [47] such a case is considered, where a bivalent system with a natural gas boiler and a heat pump is dealt with. The situation is depicted in Figure 25.

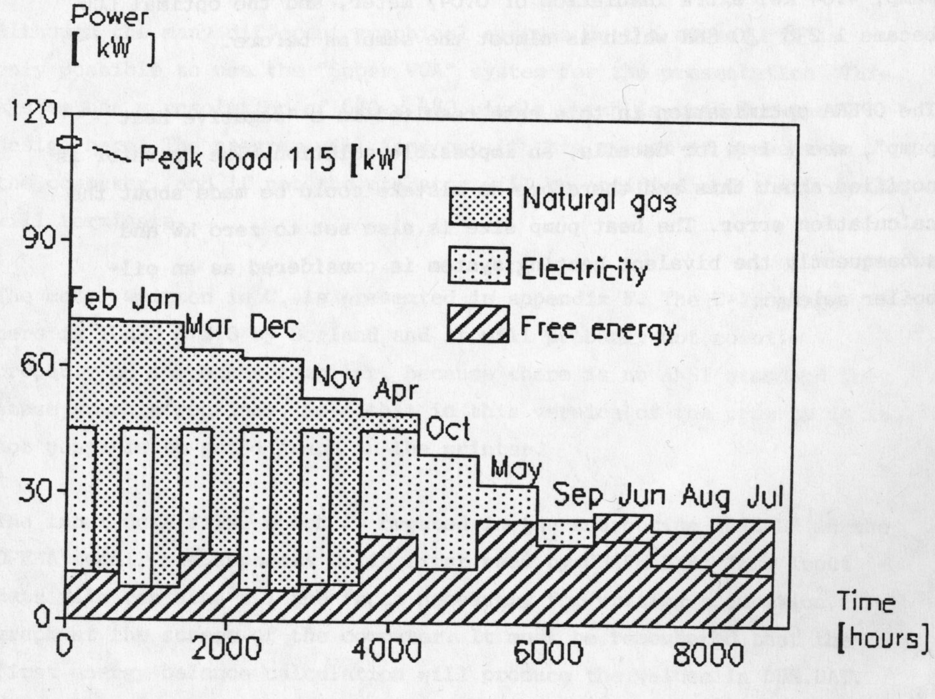

Figure 25. Graph showing the thermal load, free energy and distribution between an oil-boiler and a heat pump. Oil heat is cheaper than heat from the heat pump under high electricity price conditions. [47]

The LCC for the system was almost the same if OPERA or discrete optimization were used but the size of the natural gas boiler and the heat pump changed significantly. The FORTRAN program must thus be able to deal with a similar situation. If an oil price of 0.15 SEK/kWh is used the heat price from oil will be 0.2 SEK/kWh if an efficiency of 0.75 is utilized. The heat price for the oil is thus slightly lower than the price of heat for the heat pump. In January during high electricity price conditions the heat pump will only work for 392 hours instead of 744. The oil heat will thus be substantially increased from 6 739 to 12 716 kWh. The cost for oil will also increase, from 2 093 to 2 557 SEK although of it is much cheaper per kWh. The discrete optimization now resulted in a much smaller heat pump, 4.84 kW, extra insulation of 0.047 meter, and the optimal LCC became 1 238 130 SEK which is almost the same as before.

The OPERA optimization in this case resulted in a "negative heat pump", see [1] for details, an impossible solution. The operator is notified about this and therefore no mistake could be made about the calculation error. The heat pump size is also set to zero kW and subsequently the bivalent heating system is considered as an oil-boiler solely.

8 GRAPHICAL ROUTINES

The OPERA model does not contain graphical output routines, because of the difficulties to transport the code between different computers. Instead OPERA uses the text mode which is standard by use of the ASCII character system. Nevertheless, a graphical interpretation is sometimes useful and then the program GRAPH.EXE is used. With it is possible to depict duration graphs from the energy balances made by OPERA. The program uses the file DUR.DAT for the writing, but when OPERA is run this file is produced automatically. After this when the OPERA program has stopped just type the name of the program, i.e. GRAPH, on the DOS line.

Although the many different graphical systems on the market, it is only possible to use the "Super VGA" system for the presentation. This system has a resolution of 640 x 480 pixels which is used for the design here. The program will find out if this system is present in the computer, and if not the operator will be notified and the program will terminate.

The code, written in C, is presented in appendix F. The C-language here is TURBO C 2.0 by Borland and it will probably not compile properly on any other compiler, because there is no ANSI standard for these graphic routines. Note that in this version of the program it is not possible to get a graph on the printer.

The input data file, which is created in the subroutine TABELL2 in the OPERA model, see appendix B, is first read by GRAPH.EXE. This input data file contains all the facts necessary for writing a duration graph at the screen of the computer. It must be remembered that the first energy balance calculation will produce the values in DUR.DAT. If any other energy balance is of greater interest the TABELL2 subroutine must be called from OPERA after the energy balance of interest is produced. There is also a variable called DUR which must equal 1 if the file will be produced. See the first lines in the TABELL2 subroutine in appendix B. The DUR variable must subsequently be changed in the programming code of OPERA.

The duration graph shows the mean thermal load for each month. The number of the month is written in red and it could be found that it is the month number 2, i.e. February, that has the highest average load. The second highest load has January because the number shown is 1. The free energy is shown in a light green colour, which in this case has the same magnitude for every month during the year, see Figure 3. The solar energy is depicted in a dark green colour and it can be found that the magnitude differs a lot with the month. In a light blue colour the necessary space heating is shown. It can also be found that the heating season terminates at approximately hour number 5 000, when only hot water heating, dark blue, is utilized. Note that the average load for hot water production differs over the year, because the applicable number of hours differs each month, while the use of hot water is set as a value in kWh, see Figure 3.

The graph program sets the scale automatically on the axis showing the thermal load. If the load exceeds 1 000 kW, which is unlikely the program terminates. A message is then printed out on the screen and changes must be made in the C-code if larger values are to be considered.

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