A computer model for optimal energy retrofits in multi-family buildings. The Opera model

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PREFACE

This document shows the design of the OPERA model which is used for optimization of energy retrofits in multi-family buildings. It is developed at the Institute of Technology, division of Energy Systems, in Linköping, Sweden.

The work with the model, elaborated as part of a PhD in Energy Systems, was funded by the Swedish Council for Building Research and the municipality of Malmö, Sweden. Up till now, it has been implemented in a NORD 570 computer. Thank you Gunnar Andersson who helped me with all the FORTRAN programming. This type of machine, however, is not very common with the assumed users of the program, why there was an interest in implementing the model in smaller computers as well. Therefore, the Council also funded this work, and the model can now be run on an IBM-PC or other compatible computers. Recent work, October 1993, with the model has made it possible to run the program as a Windows application.

In order to enlighten the influence of the Swedish subsidy system, the National Energy Administration has funded part of this document, as well as the computer program that transfers the original OPERA input data file to a new one, with recalculated prices for building costs etc.

The municipality of Malmö, Egon Lange and Claes Alfredsson, must also be acknowledged for testing the model. They have used several buildings of different types and put in much work on finding proper input data to the model. They have also evaluated the results from the OPERA runnings and suggested enhancements. Without their efforts the model would not be what it is today.

The foundations of Elna Bengtsson and Helgo Zettervall has also funded some of this work. The first fund has contributed to the elaboration of a solar radiation program used for finding input data to the model, while the other has funded work with bivalent heating system optimization. The author also wants to thank his mentor, and the supervisor of this project, professor Björn G Karlsson, for his support and for invaluable advice about the performance and the mathematical design of the model.

Much work has been sacrificed to find bugs in the programming code. Experience shows, however, that there sometimes is something that does not work as expected. The author will thus be very grateful to those readers of this document and the users of the model, who send comments and suggest further enhancements. The author also hopes that the model will be a useful tool in the everyday work with designing optimal building retrofits in common engineering practice.

This text was published by The Swedish Council for Building Research as Document D21:1990. New versions of the program made it necessary to add text to the original publication. This document therefore shows how to use the model in its 1996 state of performance.

ABSTRACT

This document deals with the OPERA model designed for finding optimal energy retrofits in existing multi-family buildings.

The model can be implemented in IBM PC:s or compatible computers. The main program with its subroutines, however, is written in FORTRAN 77 and there will only be minor problems if other computers are used.

The program is designed for solving an optimization problem, i.e. to find the cheapest combination of all the possible retrofits that could be put into a building. Building retrofits, ventilation retrofits and heating equipment retrofits are dealt with simultaneously and the combination with the lowest Life-Cycle Cost, LCC, is elaborated. The LCC shows the totality of the building costs, the maintenance costs and the operating costs for the building.

Ten different heating systems are dealt with, e.g. simple ones like oil-boilers and more complex ones like bivalent oil-boiler heat pump systems and systems dealing with differential rates. Insulation measures on the building envelope are optimized as well as fenestration retrofits. The program also deals with the ventilation system and calculates if weatherstripping and/or exhaust air heat pumps are part of the optimal solution.

There is also one program, written in C, which is used for transferring original OPERA files to files that emulate the influence of the Swedish subsidy system of 1990. The original OPERA model had therefore to be changed on several points in order to handle this file.

Further, one program has been developed for a graphic presentation of the building energy system. However, this program also written in C, is closer confined to the IBM PC environment and thus it cannot be used in other computers without a lot of reprogramming. This program must be used under DOS only, not in Windows sessions.

Much work has also been sacrificed in order to develop a program for optimizing the use and sizes of bivalent heating systems. The program, which uses discrete optimization opposed to OPERA, is written in FORTRAN and was originally run as a subroutine to the OPERA model. In the present version, the discrete optimization program is run separately from OPERA and only one input file is elaborated in the OPERA session.

KEYWORDS

Retrofits, Buildings, Optimization, Installation, Heat pumps, Insulation, Windows,Weatherstripping, Heating systems.

NOMENCLATURE

A	Constant for irradiation	(1)
A_{loan}	The total loan	(SEK)
A_m	Mean absorption factor	(1)
A_n	Area of building part number n	(m)
A_w	Area of one window	(m)
A_α	Complete absorption factor	(1)
$A_=$	Parallel absorption factor	(1)
$A_\sharp$	Perpendicular absorption factor	(1)
a	Number of years	(Years)
af	Absorbed fraction of radiation	(1)
az	Solar azimuth	(rad)
B	The cost for a retrofit measure	(SEK)
BA	Dwelling area	(m^2)
BB	Constant for irradiation	(1)
b	Project life	(Years)
C	Annual recurring cost	(SEK)
$C_{1,2,...}$	Constants	(1)
COP	Coefficient of performance	(1)
COP_{mv}	Coefficient of performance, mean value	(1)
cv	Coefficient for solar calculations	(1)
cp	Heat capacity for air	(J/kg·°C)
D	Dimensioning load, district heating	(W)
DA	The number of the day during a year	(1)
DH	Degree hours	(K·h)
E_{hp}	Heat pump energy	(J/year)
E_{loss}	Energy loss	(J/year)
E_{ob}	Oil-boiler energy	(J/year)
EC_{hp}	Heat pump energy cost, present value	(SEK)
EC_{ob}	Oil-boiler energy cost, present value	(SEK)
FIP	Fixed instalment payment	(SEK)
f	Threlkeld factor	(1)
H	Distance between the floor and the ceiling in an apartment	(m)
h	Solar elevation angle	(rad)
ha	Horizontal shadowing angle	(rad)
I_{dH}	Diffuse radiation at horiz. surface	(W/m^2)
I_{DN}	Solar irradiation	(W/m^2)
I_{DN}	Solar irradiation on tilted surface	(W/m^2)
$I_{d\beta}$	Diffuse radiation from the sky	(W/m^2)
$I_{d\beta r}$	Diffuse radiation from the ground	(W/m^2)
$I_{T\beta}$	Total radiation at a surface	(W/m^2)
I_r	The reflected part of radiation	(W/m^2)
i_{es}	Incidence angle from the sky	(rad)
i_{eg}	Incidence angle from the ground	(rad)
i_β	Incidence angle	(rad)

(Nomenclature continuing)

k	Thermal conductivity	(W/m·K)
k_{new}	Thermal conductivity, new insulation	(W/m·K)
LCC	Life-cycle cost	(SEK)
m	Number of building parts	(1)
m_i	Convection heat coefficient, inside	(K·m/W)
m_o	Convection heat coefficient, outside	(K·m/W)
n	The number of the month, value etc	(1)
nf	Refraction index	(1)
nm	Convection heat coefficient	(1)
OPERA	Optimal energy retrofit advisory	
P	Power for e g a heat pump	(W)
P_{dim}	Maximum power demand during one hour	(W)
P_{ehp}	Power for an exhaust air heat pump	(W)
P_{fhs}	Free power gain to thermal load during the heating season	(W)
P_{som}	Free power gain to thermal load during the summer	(W)
P_1	Thermal load in bivalent system optimization	(W)
PV	Present value	(SEK)
p	Payback time	(years)
q	Annual energy price escalation	(%)
R	Reduction factor	(1)
RN	Number of air renewals	(1/h)
R_m	Mean reflection factor	(1)
R_r	Complete reflection factor	(1)
R_π	Parallel reflection factor	(1)
$R_\#$	Perpendicular reflection factor	(1)
r	Discount rate, inflation excluded	(%)
rd	Coefficient for the distance to the sun	(1)
re	Reduction factor	(1)
r_j	Discount rate, justified	(%)
rm	Reflection factor for the ground	(1)
rt	Total reflection factor	(1)
r_π	Parallel reflection coefficient	(1)
$r_\sharp$	Perpendicular reflection coefficient	(1)
s	Thickness of glass pane	(m)
SPV	Subsidized Present Value	(SEK)
T	Transmission value for windows	(1)
T_π	Parallel part of transmission	(1)
T_m	Mean transmission factor	(1)
$T_\sharp$	Perpendicular part of transmission	(1)
t	Thickness of insulation	(m)
t_{af}	Thickness of attic floor insulation	(m)
t_{ew}	Thickness of external wall insulation at the outside	(m)
t_{fl}	Thickness of floor insulation	(m)
t_{in}	Thickness of external wall insulation at the inside	(m)
t^*	Optimal thickness of insulation	(m)
TOD	Total energy demand	(J/year)
T-O-U	Time-of-use rates	
$TRANS$	The transmission coefficient	(W/K)
T_i	The desired inside temperature	(°C)
$T_{s,n}$	The monthly mean outside temperature	(°C)
t	The hour angle of the sun	(rad)

(Nomenclature continuing)

U_{eq}	Equivalent U-value	(W/K·m^2)
U_{ex}	Existing U-value, insulation measures	(W/K·m^2)
U_n	U-value for part number n	(W/K·m^2)
U_{new}	New U-value, insulation measures	(W/K·m^2)
U_0	Existing U-value	(W/K·m^2)
$VENT$	The heat loss from ventilation	(W/K)
v	Surface azimuth	(rad)
W	Heat transferred through windows	(W/m^2)

Greek

α	Absorption factor	(1)
α_π	Parallel absorption factor	(1)
$\alpha_\sharp$	Perpendicular absorption factor	(1)
β	Surface to horizontal plane angle	(rad)
γ	Solar - surface azimuth	(rad)
ΔT	Temperature difference	(K)
δ	Solar declination	(rad)
ρ	The density of air	(kg/m^3)
τ	Duration	(h)
τ_n	The number of hours in month n	(h)
τ_1	Duration, free energy	(h)
τ_2	Oil-boiler duration	(h)
φ	The latitude angle	(rad)

Contents

Chapter 1

INTRODUCTION

The OPERA model, (OPERA = OPtimal Energy Retrofit Advisory), enables the user to find the optimal combination of building, installation and heating equipment retrofits which are possible to implement in a building. It is assumed that a multi-family building is of concern but the model will, of course, work also for single family houses and all other types of buildings.

This document emphasizes the design of the model, or the computer program, and the proper handling of it while the theories that led to the design, are described elsewhere, e.g. in Refs. [1] and [2]. References to literature, covering the theoretic background will be given when needed for the understanding of the context, but no closer explanations are given if they can be found in the specified reference.

It must also be noted that it is assumed that the operator is familiar with how to use and run programs in the IBM PC environment. Nothing, or very little, is mentioned here about how to use e.g. MS DOS or different editors, in order to change data in the input files. The OPERA model is very easy to use when the input data file , see Chapter 2, has been completed. Under DOS, when the program and the input data file are copied to the hard disc of the system, type OPERA and press RETURN, and the program will start by asking for the name of the data file. Under Windows, choose the applicable menu and start as you do with other programs, See Chapter 4 for closer details about how to use the model. There is an input file on the shipping disc, called HOUSE.DAT, which can be used for testing the program.

If the influence of the Swedish subsidy system is to be examined, this first input data file must be recalculated by using a program called SUB. The program will provide the operator with a new input data file called SUB.DAT. Use this file when OPERA asks for the input data file name. The program will then continue as if the original file was used. The subsidy system is often changed by the authorities why it was convenient to put these values necessary for calculations in an input data file too, called LOAN.DAT. The program SUB will read this file automatically and no typing is needed. See Chapter 5 for more information.

Also included in this package is a program called SORAD. Together with the applicable input data file SUN.DAT, it provides values for the solar radiation through double-glazed windows in kW/m . The program is described in detail in Chapter 6 .

On certain conditions the optimization of bivalent systems may be miscalculated when the derivative method provided by OPERA is used. This prompted the design of a new program, called BIVAL, where these occational errors could be deleted. The input file to this program is created every time OPERA is run and the operator only has to start the program BIVAL. All details can be found in Chapter 7.

The final program included in this package is used for a graphic presentation of the duration graph for the retrofitted building. The graphics in computers are closely related to the system used for the presentation. It has thus only been possible to design the program for VGA systems with a resolution of 640 x 480 pixels. If other graphic systems are to be used the programming code must be changed. Thus, do not use this program under Windows. All information is found in Chapter 8.

It is recommended that the program is run, with a floating point coprocessor, but the program can be used with an emulating library as well. This library is present all the time but is not used if a coprocessor is installed. Using a co-processor means that the process proceeds significantly faster.

A system with a hard disc is not compulsory, but recommended because of faster reading and writing operations. Further it is recommended to use a printer to which OPERA can send its output. In the input data file, certain parameters can be set, in order to provide redirection of the chosen output. It is thus possible to reveal much of the calculations not normally printed out. DOS can of course also be used for the redirection and subsequently disc files can easily be used for the printing of the result. In the following, the overall design of the model is shown and the input data files, with all the details about the elaboration, are presented. Redirection et. c. is only possible under DOS. Use the Windows clip board and paste the output to a word processing program for printing the output, when in a Windows session. When printing from e. g. Windows 95 you must restart the computer in MS-DOS mode and connect the printer to LPT1 in order to print correctly. Do not use a PostScript printer under DOS. A more detailed presentation of how to run the program, and some possible problems are also shown in Chapter 4. In that part of the document it is also shown how to interpret the output of the program. The programming code is presented in a separate document, see the beginning of this information.

Chapter 2

THE OPERA MODEL IN BRIEF

When a building is to be renovated it is important to find the optimal way because, if the wrong strategy is used it might be hard to rechange the building with any profitability. The first thing to examine, is how to characterize the optimal solution. In the OPERA model it is assumed that this solution occurs when the remaining LifeCycle Cost, LCC, is as at its lowest. The LCC for the building includes the cost for building, ventilation and heating equipment retrofits as well as maintenance and operating costs. It seems plausible that if the LCC is minimized, the best solution has been found.

The costs included in in the LCC, however, do not occur at the same time. The costs for heating the building exist as long as the building is used. Thus the different costs cannot be added without properly considering the aspect of time. In the OPERA model, this is done by use of the present worth, or present value, method, recommended by many economists today, see Ref. [3]. An economic event, that will emerge in say, twenty years from now, can and must be transferred to a base year, which in the model is assumed to be at present. More about the LCC and the present worth method can be found in e.g Ref. [4], and only the basic expressions will be shown here.

For a future non-recurring cost, B, the present value, PV, can be calculated as:

$$PV = B \cdot (1+r)^{-a} \tag{2.1}$$

and for annually recurring costs, C, as:

$$PV = C \cdot \frac{1-(1+r)^{-b}}{r} \tag{2.2}$$

where: r is the real discount rate, a is the number of years until event B will occur and b is the number of years event C occurs.

The values for a , b, and r cannot be chosen with absolute accuracy. The solution to this problem is to run the program several times and change the values a little for each run. This is called a sensitivity analysis, and in fact, OPERA has a built in routine for this procedure. One disadvantage with the LCC concept is that all the consequences from a retrofit must be described in monetary terms. The program will find the cheapest solution, but this one possibly has to

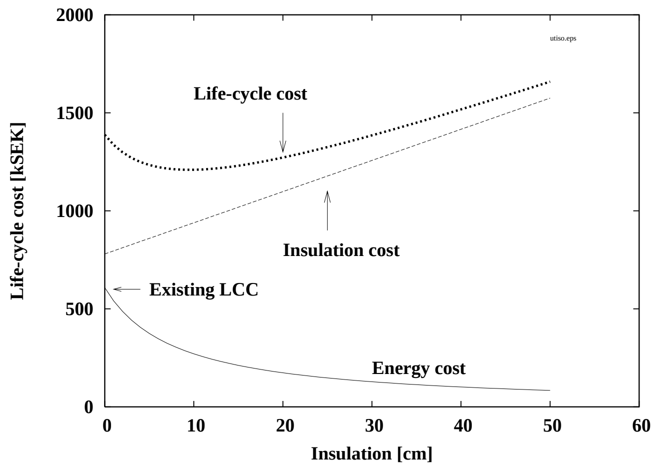

Figure 2.1: Insulation optimization in the OPERA model

be rejected for other than LCC reasons. Two different optimization methods are involved in the procedure. One that uses the derivative of a continuous function and sets it equal to zero, and one that uses a trial and error method for finding the minimum point. The first method is used e.g. for insulation optimization and is described in Figure 2.1.

The cost for insulation is assumed to be reflected by a straight line showing how the cost for insulation increases with the insulation thickness.

The energy cost, however, follows a curved line which will decrease if the insulation thickness increase. Note that both lines show the present values of the costs and thus the sum shows the total LCC for the asset. At some point on this total LCC line, the cost has its minimum value, which is calculated by the program.

The second method is to implement a measure, say a window retrofit, and then calculate if the LCC gets lower. The window itself is not optimized because of the difficulties in doing so, and thus the retrofit is introduced as a whole. Double-glazed windows are thus compared with e.g. triple-glazed ones.

The program starts by reading the input data, see Figure 2.2.

It calculates the existing LCC of the building if no, but the inevitable, retrofit is introduced in the building. An inevitable retrofit, which also can be called an unavoidable retrofit, is one that has to be made from other than energy conservation reasons, like if the window frames are affected by rot and have to be exchanged for new ones. When the inevitable retrofit cost is calculated it is assumed that the same type of windows etc. are introduced if the change is unavoidable.

This existing LCC is now to be compared to the one from the retrofitted building. An envelope retrofit is introduced, the first one is attic floor insulation, and the optimal amount of insulation is calculated with the method in Figure 2.1. The retrofit is implemented on the building and the new LCC is elaborated. If this new LCC is lower than the original one, the retrofit is considered as a candidate in the total optimal solution. If the opposite occurs the retrofit is rejected. The procedure continues with another envelope retrofit,

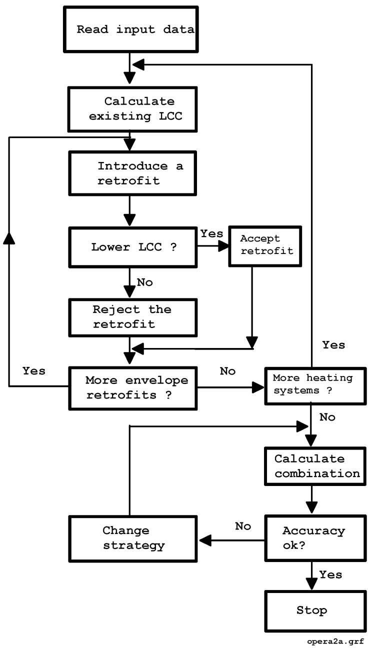

Figure 2.2: Schematic view of the OPERA model

i.e. floor insulation, and the situation is repeated. Note that the retrofit LCC always is compared to the original LCC, not to the former calculated retrofit LCC. When the envelope and the ventilation retrofits have been examined a strategy has been found for the existing heating equipment. This equipment is is now changed to new one and the process starts almost from the beginning. When all the heating systems are tested, the program, mostly, has found the best solution, i.e. the one with the lowest LCC.

However, if two or more envelope or ventilation retrofits are selected in the solution, they might interact. It has been shown, see Ref. [1], that this interaction almost always might be neglected but nonetheless, OPERA is provided with a routine for examining this. It is also possible to choose one of the interacting retrofits and change it a little in order to examine if the LCC gets lower. Thus the optimal solution can be revealed with any wished accuracy.

The result from the OPERA running is presented in some tables, which show the strategies found best for all the heating systems under consideration, and the optimal LCC is presented in more detail. It is thus easy to find the resulting energy and power demand for the retrofitted building, the present values for inevitable retrofits, heating equipment costs and so forth. The strategy can be scrutinized in order to provide the operator with more details from the calculations. Parameters which affect the amount of output data from the program can also be changed.

Further, the program automatically provides the operator with tables suitable for a sensitivity analysis. The calculations are iterated for a number of discount rates, project lives and annual energy cost escalation rates. In the following chapter, the input data are examined in detail and references given to relevant literature.

Chapter 3

THE INPUT DATA FILE

The first thing to do in order to elaborate an OPERA runnning is to gather all the necessary input data about the building and the possible retrofit measures. This is tedious, but very important for finding the "true" optimal solution. Fortunately, the experience from a number of earlier OPERA runnings can be used, and this means that less effort may be used on systems which rarely affect the optimal solution. Such a system could be the electrically heated boiler. Due to the high energy price, this facility will seldom be the most profitable solution. On the contrary this system seems to have the highest LCC of all the examined heating systems, at least for older multi-family buildings. Small changes in the installation cost of the electrical boiler will not change the total situation, and therefore it is not worthwhile to examine this installation cost in detail. Such a situation is described in Ref. [5].

Other equipment or retrofits are often selected by the model, and thus the efforts ought to be concentrated on those systems. Starting from scratch with a unique building, it can be hard to consider the plausible result from the OPERA running. Therefore, it is preferable to implement very approximate data in the first session, and after evaluation, continue with further examining of the more interesting parts.

In a following section of this manual all the input data that have to be implemented, are described. In that chapter most of the information is from Refs. [1] and [2], but new information is of course also treated. In Figure 3.1, a print of the input data file is shown.

The file consists of some 200 values which must be presented to OPERA. The program is written in FORTRAN 77 and thus there are certain rules for typing the values.

It is important to note that some of the values are floating point, i.e. they have a decimal point, some are integers, i.e. they cannot have decimal points and further some values consist of characters, i.e. they have to be enclosed between quotation marks, ' '. The program is very sensitive for these different types of values and if, for example an integer is presented, where the program wants a floating point, the session is terminated and an error message is written on the screen.

Each value must be separated by a comma, or start on a new line.

If an error is encountered when the program is started there is, however, some help for finding it. Figures, ranging from 1 to 7 are written on the screen

```
0
273.,273.,616.,819.
1.,0,2.8,27,1.,0,2.4,29
0.8,.5,1.2
3.5
0.,50.,0.,0.,0.
.6
'OIL-BOILER',110.,.75,5.
3501.,3502.,3503.,3504.,3505.,3506.,3507.,3508.,3509.,3510.,3511.,3512.
.04,.05,.04,.05
2.
1.5
1.2
50.,50.,50.,50.,30.
50.,.05,.0
0.,260.,530.
0.,380.,500.
300.,200.,2000.
50.,390.,300.,2.8,450.
0.,1100.
0.,1300.
0.,1500.
100000.,100000.
55000.,60.,.75,15.,200.,50.
20000.,100.,.95,25.,1.,50.
40000.,60.,.95,25.,300.,50.
60000.,4000.,2.5,50.,1500.,10.
55000.,60.,.8,20.,200.,50.
40000.,6000.,66.43,20.54,15.,200.,40.,.1,7.
-.5,-.7,1.4,6.,11.,15.,17.2,16.7,13.5,8.9,4.9,2.
-2.9,-3.0,-.1,5.3,11.,15.4,17.7,16.4,12.2,7.1,2.7,.0
-12.2,-12.4,-8.9,-3.5,2.7,9.2,12.9,10.5,5.1,-1.5,-6.8,-10.1
56,250.,.1,10.
14,20.,21.,-14.
10000.,50.
10000.,4500.,10.,2.,10.
'UPPLAND 5'
1
1,0,0,0,0,0,0,1,1
4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.
4.3,8.94,18.57,28.82,44.5,53.48,50.54,36.63,23.12,13.54,5.82,3.08
8.27,17.97,41.86,61.97,87.58,90.91,89.07,75.07,53.11,28.3,10.75,5.36
29.66,43.69,73.68,75.29,82.59,76.28,78.5,79.81,79.37,61.57,32.7,21.22
8.27,17.97,41.86,61.97,87.58,90.91,89.07,75.07,53.11,28.3,10.75,5.36
.1,.6,.7
.233
.3658357,0.515,0.245
.175,120.
.2763422,300.,700.,2400.,600.,.64
.195,.195,.195,.145,.145,.145,.145,.145,.145,.145,.195,.195
830.,1030.,1230.,1640.,2060.,2380.,2900.,3520.,4300.,5420.,6760.,8400.
16.,20.,25.,35.,50.,63.,80.,100.,125.,160.,200.,250.
352,320,368,320,368,352,336,368,336,352,352,336
392,352,376,400,376,368,408,376,384,392,368,408
6000.,55.,245.
.405,.256,.218,.202,.179
```

Figure 3.1: The input data file to the OPERA model

when the input file is read. If the error emerges after the figure "1" has been written, but before figure "2" shows up, the error is in the beginning of the file. If everything works fine until number "6" is written, the error is located in the end of the file, and so forth. Exactely where the numbers are printed out, can be found in the beginning of the FORTRAN code in appendix A.

3.1 How to write it

When values are to be changed in the input data file some kind of editor or word processing program must be used. Almost any editor will be suitable but it is important to save the file as an ASCII-file, i.e. only the text you want to change in the input file, shall be affected.

Many word processing programs put other text or figures in the file in order to encounter format specifications etc. When an ordinary editor is used, the file almost always is saved as an ASCII-file and consequently it is simple to save input data files. Do not forget to save the original files or other accurate files before you change them.

3.2 How to present input data

The input data file describes the building under consideration. The geometry, the thermal conditions as well as building costs etc. are presented as certain values. As mentioned before, the model is the result of a research project and has lead to about fifteen publications in the field of building retrofits. During this work a major effort has been put on finding proper input data which reflect the building, its retrofits etc. as correct as possible. The design of the input file is a result of this research, and it is necessary to use the same method for other buildings.

It is recommended to put the geometry of the building into the original data file as a start but to leave the building costs etc. as they are. The program can then be run and the operator will be able to consider the output from the program. If the total input file is changed at the same time, reasons for errors or peculiarities that might occur will be harder to find.

The following pages show in detail how the input data are elaborated. Further details can be found in Refs. [1] or [2] but the facts presented here are supposed sufficient for an unexperienced OPERA operator. The input file presented in Figure 3.1 is used as a numerical example.

3.3 Type of file and building geometry

The first value in the input data file shows OPERA which type of file to be read. If a 0 is encountered, the file is an ordinary OPERA file while if a 1, or a 2, are found the file has been transferred to emulate the Swedish subsidy system, see chapter 5. The variable in OPERA, an integer, is called LAN. The value of LAN is checked at several places in the code, see appendices A and B.

The area of the attic floor, the external wall, the floor and the windows and their orientation have to be implemented as well as the number of apartments and the total apartment area. Some of these values are used for the thermal calculations while others are only used for the cost functions.

Today it is not possible to implement values for the basement directly in the input file. Instead, the basement has to be simulated using other U-values or other geometry for the lowest floor in the building. See Equation (9) and the discussion at page 82 in Ref. [1]. The basement is after this dealt with as an ordinary floor. This is so because it is hard to calculate the proper U-values, or thermal resistance, for the ground, outside the basement wall. Furthermore, it is not common to use a fixed desired inside temperature in the basement. Experience from a number of OPERA runnings also implies that retrofits made in the basement are seldom profitable due to the low inside temperature, the rather high outside temperature and the rather low equivalent U-values for the basement walls and the soil outside [6]. In Ref. [2] this is also emphasized.

The situation is similar for a crawl space instead of a basement. This building part must also be simulated with a slightly different floor in the OPERA calculations. Crawl spaces are treated in Ref. [7], where the complexity of the problem is described in detail.

Of course also more complex situations can be implemented in the model but it is questionable whether it is worthwhile, due to the earlier experience.

In the following the input data is described. The parameter names, which can be found in the FORTRAN code in appendix A and B, are presented to make it easier for those of the readers who are heavy hackers and want to enhance the program code.

The four values, note the floating point, in the file show the areas for the:

Attic floor	=	273	m^2	AT
Floor	=	273	m^2	AG
External walls, windows excluded	=	616	m^2	AY
Total apartment	=	819	m^2	BA

There is also a variable named AI in the code, showing the area of the inside of the external walls. Setting a different value from the external wall area here, will lead to peculiar results. In the program code, the values thus are set equal.

The following line in the data file shows values for the window geometry. Four different orientations are dealt with. The real orientation is of no interest as long as the values are coupled to the solar gains, also shown in the input file. For simplicity, the orientations are said to be to the north, east, south and west. The values show:

Area of one north window	=	1	m^2	AN
Number of north windows	=	0	pcs	ANN
Area of one east window	=	2.8	m^2	AO
Number of east windows	=	27	pcs	ANO
Area of one south window	=	1	m^2	AS
Number of south windows	=	0	pcs	ANS
Area of one west window	=	2.4	m^2	AV
Number of west windows	=	29	pcs	ANV

The fact that an area value has been used although there is no window, is due to the fact that unpredictable results might occur when a number is devided with a very small value. It is possible, however, to use the integer 0 for the number of windows, because of facilities in the programming code. The area values are floating point and the number of windows are integers. The window area include the frames of the windows or otherwise the program expects that the frames are of the same material as the external walls.

3.4 Existing thermal status

The existing U-values of the building parts also have to be provided to the model. Usually these values can be calculated with traditional methods similar to those in Refs. [8] or [9]. The U-values in Figure 3.1 are:

Attic floor	=	0.8	$W/m^2{\cdot}K$	BKT
Floor	=	0.5		BKG
External wall	=	1.2		BKY

This is not the fact for the windows, which are very complex in their thermal performance and thus it is very hard to calculate proper U-values during darkness and the difficulties are still greater during the day. The situation is dealt with in Ref. [2].

However, it is not within the scope of OPERA to find an optimal window design and thus some different constructions are tested against each other. See [10] for information about the optimization of windows. Input to the model are the U-value during darkness. The solar gains are treated in an energy balance subroutine, see appendix III, in Ref. [10], and they are given as monthly mean values further down in the input file. In Figure 3.1 the existing U-value for the windows during darkness is 3.5 $W/m^2{\cdot}K$. The value is supposed to reflect the situation for a double-glazed window and the variable is named MK2.

3.5 Remaining life of the envelope

In Refs. [1] or [11] the importance of the remaining life of the existing building parts is shown. An external wall has a very high initial cost for extra insulation. Scaffolding and demolition of the outer part of the facade etc. are expensive and thus it will probably never be profitable to put more insulation to an external wall if the facade is in a good shape. In such cases an inside insulation might be profitable and OPERA will examine this case too. However, the loss of apartment area can be a major drawback and the cost for this loss might make the insulation unprofitable.

The situation is different if the facade needs renovation. The extra cost for insulation in such cases will nearly always be profitable, the energy savings only have to pay for the extra insulation. However, it is very hard to predict the remaining life, with an absolute accuracy. The lack of information about the durability of building assets is considerable. Nevertheless, the shape of the envelope has to be considered, and mostly it is possible to make qualified guesses about the remaining life of the envelope parts. Recently there has been an increasing interest in predicting the remaining life of building envelope details and some authors could be found in Ref. [1].

The input values to the model must show the number of years from now, to the year when the retrofit is inevitable, i.e. the remaining life. These values are used together with the retrofit cost functions in order to calculate the inevitable retrofit cost. In line 6 in the data file the values, used in this example, are shown:

Attic floor	=	0	years	LT
Floor	=	50		LG
External wall, out.	=	0		LY
External wall, ins.	=	0		LI
Windows	=	0		LF

The abbreviations out. and ins. mean outside and inside respectively. It is important to note that these values are coupled to the present value calculations, see expression 2.1. They are used for calculating the so called inevitable retrofit cost, i.e. renovation for other than energy conservation reasons. Setting the remaining life to 0, (zero), for a building asset means that the retrofit has to be done immediately.

3.6 Ventilation system

The existing ventilation system is assumed to be of the natural ventilation type and it works only because warm air is lighter than cold air. The number of renewals of the air has to be implemented in the input file and the value is used for the thermal calculations of the building. Also in this case the reality is much more complex. The number of renewals are not the same in different apartments and the situation will also change due to the outside temperature. Some references for finding this number are mentioned in Ref. [1]. In the example 0.6 renewals per hour is used and the variable name in the code is OMS.

The remaining life of the ventilation system is assumed to be very long and thus, no inevitable retrofits are considered at present in the OPERA model.

If some extra FORTRAN lines are added the use of air heat exchangers can be simulated by providing the program with a factor showing the efficiency of the equipment. This situation is described in Ref. [2].

Of course, in the same way, some small changes can be made in the programming code in order to evaluate mechanically ventilated systems, with exhaust air heat exchangers. However, such buildings are rarely subject for renovation, due to age and thermal envelopes.

3.7 Heating equipment

Input data concerning the existing heating system are:

- Type of equipment
- The thermal power of the equipment
- The efficiency

- The remaining life

Several types of equipment can be dealt with by the model. The alternatives are, with the abbreviations for the OPERA recognition and for the code:

Oil-boiler	OIL-BOILER
Electricity, fixed rate	ELFIX
District heating, fixed rate	DISFIX
Heat pump, ground water coupled	HPGROUND
Natural gas	NATGAS
District heating, differential rate	DISDIFF
Electricity, differential rate	ELDIFF
Bivalent oil-boiler - heat pump, ground w.	
Bivalent oil-boiler - heat pump, outside air	

The first eight systems can be considered as existing heating systems. The other two have not been implemented because they are not in common use in the existing building stock, but the program, of course, considers them as plausible retrofits. The input text, e.g. ELDIFF, must be identical to the ones stored in OPERA, otherwise the model cannot recognize the system.

The first value is used for comparing the existing power installed, with the calculated need, provided by the OPERA model. OPERA tells the user if the system is too big or too small according to ordinary design routines, common in Sweden. The model uses the calculated power in continuing calculations.

The efficiency of the heating system is given as less, equal or higher than 1.0. The efficiency for ordinary oil-boilers is approximately 0.7 while heat pump systems can have "efficiencies", or Coefficients Of Performances, COP, of the magnitude 3. There are of course, difficulties in choosing the values, because no absolute accuracy can be given. In Ref. [1] some of the problems are discussed and references are given mostly to Swedish literature.

Also here, in the heating equipment case, it is important to consider the remaining life of the existing system. There are difficulties to provide an accurate value, but nevertheless a qualified guess must be made.

The values found in line 8 in the input data file are:

Type of existing equipment	=	'OIL-BOILER'		VATYP
Existing thermal power	=	110	kW	EF
Efficiency	=	0.75	(1)	VGVAR
Remaining life	=	5	years	LVA

Note the quotation marks around the text input. The number of characters is limitid to 30.

3.8 Domestic hot water use

OPERA also has to consider the hot water consumption in the building and the model requires information about the annual consumption in kWh. The calculations are made, assuming that no extra power is needed for this, because of the short duration of the top peak load during the coldest winter days. However, this is not the fact for the bivalent system calculations. See [1] for more details.

The value used in the example is 42 000 kWh/year and the variable name is TV. The latest versions of OPERA use one value for each month. Instead of one value the operator must provide twelve values separated by ",". The values must be written on the same line. Twelve values of 3500. kWh are therefore present in the submitted input data file.

3.9 Thermal properties of new envelope measures

The model has to be informed of the new thermal conductivities in the insulation material. Values have to be provided for the attic floor, the floor and the external wall insulation. These values must correspond to the building cost functions below. The thermal performance of different types of windows are presented as U-values during darkness. The values must correspond to the cost functions for the windows. The figures presented in the next lines in the data file are:

Attic floor	=	0.04	$W/m^2 \cdot K$	NLAT
Floor	=	0.05		NLAG
External wall, out.	=	0.04		NLAY
External wall, ins.	=	0.05		NLAI

New U-values for triple-glazed windows:

Normal	=	2.0	$W/m^2 \cdot K$	MK3
Low-emissivity	=	1.5		MK4
Low-emissivity + gas	=	1.2		MK5

Note that the type of windows is unimportant to OPERA. However, the U-value is important and the building cost for changing windows presented below.

It has been found that the thermally best type of windows are rarely chosen by OPERA. If, nevertheless, such windows are selected the program terminates. The way of solving this is to replace the MK4 value with the MK5 value and the corresponding building costs below in the input data file.

3.10 New life-cycles for the envelope retrofits

The retrofits on the envelope will change the periodicity when the retrofits are inevitable. The new life span in years must thus be provided for the attic floor, the floor, the external wall and the windows. The situation is discussed in detail in Ref. [1]. The values in Figure 3.1 are:

New life-cycle,	attic floor	50	years	NLT
	floor	50		NLG
	external wall, out.	50		NLY
	external wall, ins.	50		NLI
	windows	30		NLF

3.11 Economic factors

One of the most important value in the LCC calculations is the discount rate. The item is discussed in e.g. Refs. [1], [12] and [13] where more information can be found. The discussion can be summed up just by saying that there is no ultimate discount rate, but the references advise us to use a rate between 4 and 11 %. The rate used in OPERA is the real discount rate, i.e. inflation excluded. A recent paper shows that a rate between 0.2 and 4.0 % has been used in the reallity for high quality dept instruments such as domestic corporate utility bonds, see Ref[14].

Neither can an ultimate optimization time or project life be found. In Sweden there are special subsidies for buildings older than 30 years or if more than 30 years have passed since it was last renovated with subsidies. In this case there must be a qualified guess to provide the model with a suitable value.

This is also the case for future escalating, or falling, energy prices. OPERA requires a value for the annual increase in % or zero. The problem is also dealt with in [1]. The influence from escalating energy prices is calculated in OPERA with the help of a justified discount rate. The expression is:

$$r_j = \frac{r - q}{1 + q} \tag{3.1}$$

where r_j equals the justified rate and q the annual increase in energy prices.

Note that expression 3.1 yields an approximate value. If q equals r the rate will be 0 and if q is greater than r, the justified rate will be negative. Negative values will work fine but if the result is 0 or close to it a proper value is set in the code, see appendix A. If q and r are equal the present value factor will equal the project life of the building. It must also be remembered that running the program until it automatically terminates, will yield calculations for a number of different annual energy price escalations. This if a special variable equals 0, see below.

The values used in the example are found in line 15 in Figure 3.1. They are:

The project life	50	years	OPTA
The real discount rate	0.05	(1)	R
The annual escalation	0.00	(1)	Q

3.12 Building cost functions

OPERA must be given the building costs for different retrofit measures. As mentioned earlier, there is also a need for the inevitable retrofit cost if related to energy conservation measures. First, OPERA must calculate the present value for e.g. an external wall, without any energy retrofits. Sooner or later, the facade has to be renovated, e.g. because it is affected by rot. Earlier in the input data file, this instant is specified and the cost function will tell OPERA the expense.

However, the cost function must also provide the model with the specific insulation cost. In Ref. [2] and in Ref. [15] it is shown that an expression for the building cost can be written as:

$$C_1 + (C_2 + C_3 \cdot t_{in}) \tag{3.2}$$

where C_1, C_2 and C_3 are different constants and t_{in} equals the extra insulation thickness.

C_1 shows the value for the inevitable cost while C_2 and C_3 are connected to the direct insulation cost. In [15] there is an example which enlightens the elaboration of the three constants. However, see also Table 3.1.

Type of cost	Price
Scaffolding	29.70
Demolition of boarding	8.70
New boarding	104.40
Mineral wool of thickness t	$6.96 + 230 \cdot t$
New studs	$19.72 + 260 \cdot t$
Indirect costs, non-insulation	144.87
Indirect costs, insulation	48.29
Taxation for non-insulation	37.02
Taxation for insulation	$9.64 + 63.06 \cdot t$
Sum of non-insulation costs	324.69
Sum of insulation costs	$84.61 + 553.06 \cdot t$

Table 3.1: Building costs for retrofitting an external wall with extra insulation. Prices in SEK/m^2. See Ref. [15]

In Table 3.1 the direct insulation costs are separated from the costs not coupled to the insulation material. Figure 3.2 gives a graphic presentation of the C - values.

The inevitable retrofit cost only consists of the noninsulation cost, C_1 , i.e. 324.69 SEK/m^2. When extra insulation is added the cost will increase with $(84.61 + 553.06 \cdot t)$ SEK/m^2 , $C_2 + C_3 \cdot t$. The C_1 - value is thus coupled to the remaining life for the building asset and to the new life for the same asset, while the C_2 and C_3 values are coupled only if the asset is extra insulated.

Figure 3.3 gives a graphic representation of the present value calculations.

The C_1 values are supposed to occur each 20 years and are also subjects of salvage value calculations. The C_2 and C_3 values only occur once, viz. when the wall is actually retrofitted with extra wall insulation. Note that this is only an example and the values in Figure 3.3 not part of the submitted input data file.

OPERA deals with four different expressions like 3.2, representing the attic floor, the floor and the external wall insulation measures. The author of [16] uses a similar concept, however, with no inevitable cost. The values used in Figure 3.1 are:

Asset	C_1		C_2		C_3	
Attic floor	0	INT	260	KOT	530	AKT
Floor	0	ING	380	KOG	500	AKG
External wall outside insul.	300	INY	200	KOY	2000	AKY
External wall inside insul.	50	INI	390	KOI	300	AKI

When inside insulation is considered it is necessary to include the loss of rent from the tenants. Information about the height and the rent of the apartment is needed. In the example the following values are present:

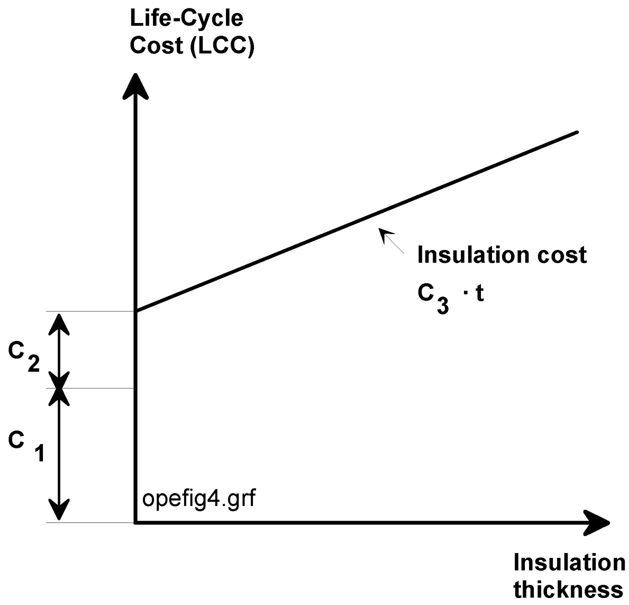

Figure 3.2: The retrofit cost for insulation measures

Apartment height	2.8	m	HOJD
Apartment rent	450	SEK/m^2· year	HYRA

The retrofit cost for the windows is described with only two constants as can be found in the following expression:

$$C_1 + C_2 \cdot A_w \tag{3.3}$$

C_1 and C_2 are constants and A_w is the area for one window. In Ref. [2] the retrofit costs for a number of different windows are shown. By applying a line through the mapped dots in the graph an expression like 3.3 was evaluated. The method of least squares can also be used to provide the function of the retrofit cost.

OPERA can handle four different types of windows, and expressions have to be presented for each type. Dummy values can be presented for OPERA, if only a few alternatives shall be considered. The procedure is described in detail in Ref. [2]. The values used in the example are:

Asset	C_1		C_2	
Double-glazed	0	INTV	1100	AKTV
Triple-glazed	0	INTR	1300	AKTR
Triple-glased, low-e.	0	INFY	1500	AKFY
Triple-gl., low-e., gas-f.	10000	INFE	10000	AKFE

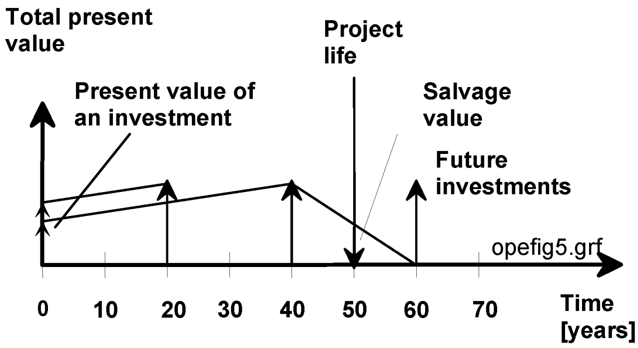

Figure 3.3: The present value calculation

The values for triple-glazed, low-emissivity, gas-filled windows are dummy values, chosen so that the alternative will never be selected by the model.

Expressions like 3.2 or 3.3 cannot show the exact building cost, but they will give an approximate view of the real cost.

3.13 Heating equipment cost functions

The cost for acquisition and installation of new heating facilities must also be known to OPERA, e.g. by using expressions like:

$$C_1 + C_2 \cdot P + C_3 \cdot P \tag{3.4}$$

where C_1, C_2 and C_3 are constants and P equals the thermal demand of the system.

One expression must be used for each system. However, the bivalent systems use the expressions given for the first heat pump or the outside air heat pump and the oil-boiler. The expressions, like 3.4, are evaluated in the same way as the window retrofit costs, i.e. a number of alternatives are mapped in a graph and a "best line" is applied, supposed to reflect the costs. In Ref. [2] all the details are shown.

Naturally the efficiency, COP, and the new life span, L_1 , for the equipment must also be presented. The program can also deal with installations like chimneys for oil-boilers or drilling holes for ground water coupled heat pumps, namely the cost C_3. All these items have a much longer life-cycle, L_2 , than the precise heating facility itself, why they have to be treated separately. A chimney can have a life span of 50 years, while the oil-boiler has a life-cycle of 15 years.

The input data found in the lines 24 - 29 are the following:

Asset	C_1	C_2	COP	L_1	C_3	L_2
Oil-boiler	55000	60	0.75	15	200	50
Electricity boiler	20000	100	0.95	25	1	50
District heating	40000	60	0.95	25	300	50
Ground w. heat pump	60000	5000	2.5	50	1500	10
Natural gas boiler	55000	50	0.8	20	200	50
Outside air heat p.	60000	6000	see below	15	200	40

The corresponding variable names found in the code are:

Asset	C_1	C_2	COP	L_1	C_3	L_2
Oil-boiler	INPO	AKPO	VGVNO	NLPO	SLANGO	LSLANGO
Electricity boiler	INPE	AKPE	VGVNE	NLPE	SLANGE	LSLANGE
District heating	INPF	AKPF	VGVNF	NLPF	SLANGF	LSLANGF
Ground w. heat pump	INPV	AKPV	VGVNP	NLPV	SLANGV	LSLANGV
Natural gas boiler	INPY	AKPY	VGVNY	NLPY	SLANGY	LSLANGY
Outside air heat p.	INPU	AKPU	VGVNU	NLPU	SLANGU	LSLANGU

When the outside air heat pump is considered the COP of the pump cannot be reflected with only one constant, as the COP varies due to the outside temperature. In Ref. [1] an expression shows this influence:

$$COP = \frac{-\Delta T + 66.44}{20.53} \tag{3.5}$$

The two constants can be found in Figure 3.1, and in the code they are named UTE1 and UTE2 respectively. ΔT shows the difference between the inside and outside temperature.

There are however, also other differences. The outside air heat pump is supposed to be renovated after some years. The cost for this is assumed to be reflected in a certain percentage of the total installation cost. In the input data file this share, named PROC, is 0.1 and the renovation appears every 7 years, named LPROC. In Ref. [17] LCC and different types of heating equipment are discussed.

3.14 Climate conditions

In the OPERA model the climate conditions are described by monthly mean values of the outside temperature in °C. Three different climates can be put into the data file. OPERA picks the applicable one after reading a variable in the file, named ORT. If ORT equals 1 the first line is chosen and if ORT equals 2 the next one and so on. The values, showing the temperatures, are put into an array KLIM(3,12) and the figures in the example show the climates in Malmö, Linköping and Kiruna, Sweden. The values are:

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Malmö	-.5	-0.7	1.4	6.0	11.0	15.0	17.2	16.7	13.5	8.9	4.9	2.0
Linkö.	-2.9	-3.0	-0.1	5.3	11.0	15.4	17.7	16.4	12.2	7.1	2.7	0.0
Kiruna	-12.2	-12.4	-8.9	-3.5	2.7	9.2	12.9	10.5	5.1	-1.5	-6.8	-10.1

Note that the designing outside temperature is set below.

3.15 Costs for ventilation measures

Weatherstripping will be profitable in most of the OPERA runnings. The program assumes that the cost can be predicted by showing the cost for caulking one window or door and furthermore, the number of doors etc. to be dealt with. Important is also to present the decrease in the ventilation flow after weatherstripping is completed, see Ref. [18]. The life span of the caulking measures must be known to the model.

Exhaust air heat pumps are dealt with by presenting the cost for the heat pump due to its thermal power. The expression is similar to expression number 3.4.

The temperature of the in- and outflowing air must be given, and OPERA will calculate the proper thermal power of the heat pump and proceed with the heat pump cost, the life-cycle of the pump and its COP. Similar to oil-boilers and chimneys, the heat pump needs installations with another life-cycle then the pump itself. Those costs are presented due to the number of apartments in the building and the life span of the installations.

In Sweden the power of the heating equipment is designed due to the Lowest Outside Temperature. This temperature can be found in the Swedish building code and in Malmö it is set to -14 °C or -16 °C due to the type of building. Heavy building material corresponds to the higher of the temperatures. This method makes it possible to take into account the influence of the thermal mass in the building. The problem is discussed more in detail in Ref. [2]. The values, found in Figure 3.1 are:

Number of items to seal	56	Pcs	AOP
Cost for sealing one item	250	SEK	KPO
Decrease in ventilation flow	0.1	Ren./hour	OMDIFF
New life for weatherstripping	10	Years	LITA
Number of apartments	14	Pcs	ALGH
Inlet temp. in exh. air heat pump	20	°C	TFIN
Desired inside room temperature	21	°C	TIN
Designing outside temperature	-14	°C	DUT1
Cost for piping, exh. air hp.	10000	SEK/apart.	ROR
New life of this piping	50	Years	LROR
Exh. air heat pump cost, C_1	10000	SEK	INFL
Exh. air heat pump cost, C_2	4500	SEK/kW	AKFL
New life of the heat pump	10	Years	LFL
COP of the heat pump	2.0	(1)	VGFLVP
Outlet temperature, exh. air hp.	10	AC	TFUT

Note that the number of items and the number of apartments above are integers.

3.16 Project name, site and output parameters

In the next line of the input data file it is possible to write the project name, in this case UPPLAND 5. The name must be shorter than 30 characters, note the quotation marks in Figure 3.1. The variable in the code is OBJECT.

The next value shows OPERA which site is of concern. The variable is called ORT and the number for it selects the applicable climate. The value can be 1, 2 or 3.

In the input file values for the output presentation of OPERA can be assigned. Part of the calculations can be presented at the terminal or on the line printer etc. This means that it is possible to scrutinize each step of the calculations. Further, by small changes in the code part of the calculations, e g one of the subroutines or the exhaust air heat pump, can be considered in detail.

By assigning other values to the programming loops it is possible to control how many cases of discount rates etc. that shall be presented by the model. This provides the operator with a very good means for sensitivity analysis, i.e. how much the optimal solution changes if the input data are changed.

There are eight different parameters, all of them integers. If a parameter equals 1 the output is written on the screen, if it equals 0 it is written to a dummy file, called NUL by DOS, and if it equals 3 it is written on the printer. See the OPEN statements in the FORTRAN code, appendix A. The variables are:

Outputs	Value in Fig. 3.1	Variable name
Basic result	1	U
Insulation optimization	0	U1
Detailes from main program	0	U2
Bivalent optimization	0	U3
Diff. rates, district heat.	0	UT7
Diff. rates, electricity	0	UT8
Miscellaneous	0	UT10
Input data	1	U11

Note however, that using the extra information mostly demands expert knowledge of the program code. It is not meant for the novice users of the model.

There is also one parameter for terminating the program after the base case has been studied. This parameter an integer is named ST1. If another value than 1 is set, the program continues as usual.

3.17 Solar gains and free heat from appliances and persons

The values for solar gains, stored in an array called SOL(4,12), and free heat, stored in an array called GRATIS(12), must be given to OPERA as monthly mean values in the input data file. The solar gains are assumed to be presented as the heat in kWh/m^2, transferred through a double glazed window for the considered orientation. Four orientations can be dealt with without extra programming work. Note that the values must correspond to the other data concerning the windows above. These values can be calculated using the SORAD program shipped with OPERA, see Chapter 6.

Also necessary to provide are the shading coefficients concerning the types of windows, stored in an array called SHADE(3). The values show how much of the solar radiation lost, when a window with a better thermal performance is introduced. The values shown in the example are:

Free gains from appliances and persons	4167	kWh/month	GRATIS

There are 12 values, one for each month, but in this example they are all identical. The solar gains presented in the example are:

Month	North	East	South	West
January	4.3	8.27	29.66	8.27
February	8.94	17.97	43.69	17.97
March	18.57	41.86	69.73	41.86
April	28.82	61.97	75.29	61.97
May	44.50	87.58	82.59	87.58
June	53.48	90.91	76.28	90.91
July	50.54	89.07	78.50	89.07
August	36.63	75.07	79.81	75.07
September	23.12	53.11	79.37	53.11
October	13.54	28.30	61.57	28.30
November	5.82	10.75	32.70	10.75
December	3.08	5.36	21.22	5.36

The shading coefficients shown in the input data file are:

Triple-glazed	0.1
Triple-glazed, low-emissivity	0.2
Triple-glazed, low-emissivity, gas-filled	0.3

Note that the coefficient shows the sun shade compared to a ordinary double-glazed window. If triple-glazed windows are introduced 10 % less sun is transferred through the window panes. If very high shading coefficients are used it might give strange results. The problem is dealt with in Ref [19]. It is thus recommended to use shading factors lower than 0.5.

3.18 Energy prices and rates

Information about the energy cost is essential for the result of an OPERA running. For the oil-boiler or the electricity case the energy cost must be presented, as a price in SEK/kWh, while for district heating and natural gas, information also is needed about the connection fee. The heat pump cases use the electricity price, and if applicable the, oil price.

Also implemented in this example are real tariffs for energy used by the utilities in Malmö, i. e. the differential rates. The tariff elements are stored in the input file and new values can easily be implemented. If a completely new tariff, with a different design, will be used it is necessary to make small changings in the FORTRAN code, see the subroutine TAXOR in the code, appendix B. The design of the tariffs is dealt with in [1] and thus only a brief presentation is given here.

3.18.1 Prices for oil,electricity and natural gas, fixed rates

The first three lines dealing with the energy prices show:

Price of oil	0.233	SEK/kWh	EOL
Price of electricity	0.3658357	SEK/kWh	EEL
Price for natural gas	0.175	SEK/kWh	EGAS
Connection fee, natural gas	120	SEK/kW	ANSGAS

It might seem peculiar to use seven decimals in the electricity price, but is because OPERA also calculates the optimal retrofit strategy when differential rates are considered. If the design of the rates are to be examined, it is important that a fixed rate, with a static price for electricity over the year and time of day, can be compared to a differential one, where the price varies with the time of use. The level of the two rates must then be identical which means that they are normalized. OPERA calculates this normalized price during execution of the subroutine TAXOR. If another building is considered, i.e. the load changes, this will lead to a new normalized fixed price. See Ref. [20] for a more detailed discussion about normalization of rates.

3.18.2 District heating rates

The same discussion is applicable also when district heating is considered. First a fixed price is presented in the data file, and then some values which present the real rate.

Energy price fixed rate	0.2763422	SEK/kWh	EFJ
Connection fee	300	SEK/kW	ANSL
Fixed fee, $D \leq 800$ kW	700	SEK/Year	FAST
Fixed fee, $D > 800$ kW	2400	SEK/Year	FAST
Power fee	600	SEK/kW · Year	FAST
Reduction factor	0.64	(1)	RV

The value for D above is calculated as the energy demand during January and February, divided by the number of hours during that period. The connection fee is multiplied with the maximum load during one hour, while the power fee is multiplied by the value D above. The reduction factor is multiplied with the power fee which makes the fee lower in this case. The variable FAST above, is an array with three elements. The energy prices differs due to the season and they are:

November - March	0.195	SEK/kWh	EP
April - October	0.145	SEK/kWh	EP

EP is an array with 12 elements.

The use of the OPERA model in other parts of Sweden made it necessary to implement other tariff structures as well and from version 1.09 there is a way to do this without reprogramming. The tariff structure implemented deals with so called category values. Adding a reduction factor above higher than 1 tells the model to use this later method. A line with the following content:

```
.26,300.,4000.,2200.,260.,10.
```

shows the model that category values should be dealt with, this because the last value is greater than 1.0. The value "4000." shows that a fixed fee of 4000 SEK must be paid each year while the value "2200." is the so called category value which equals 2200 hours in this case. The added energy need during January and February is divided by the category value resulting in a so called dimensioning load. This load in turn is multiplied with the value 260 SEK/kW which results in an annual fee.

3.18.3 Electricity rates

OPERA deals with energy calculations for monthly mean values. This means that it is necessary to present the energy prices in monthly mean values. When district heating was concerned, no difficulties emerged but this is not the fact when electricity rates are considered. There are two different rates that might be applicable in Malmö, Sweden.

3.18.4 Fuse tariff

The fuse tariff is applicable when the necessary fuse size is lower than 250 A. The demand charges are presented first in the input data file and they are:

Fuse smaller than	Demand charge
16 A	830 SEK/Year
20	1 030
25	1 230
35	1 640
50	2 060
63	2 380
80	2 900
100	3 520
125	4 300
160	5 420
200	6 760
250	8 400

The charges and the fuse sizes are stored in an two arrays, ABONA(12) and SAK(12).

The energy cost depends on the season and the time of use during the day. The following tariff is used, stored in two variables HELP and LELP.

Nov - March, Monday - Friday, 0600 - 2200	0.515 SEK/kWh
Otherwise	0.245 SEK/kWh

Taxation of 0.072 SEK/kWh is included in the price. Note that the taxation will be changed from 1990 03 01. Due to the monthly mean values used in OPERA, it is necessary to transform the rate above to one that reflects a monthly mean price. This is made by the program, in subroutine TARIFF, but OPERA must know how many working hours and free hours there are each month, and the hours with low and high price. The high and low price hours are stored in two arrays called HHOURS(12) and LHOURS(12). The values in the input data file are:

Month	High price hours	Low price hours	Month	High price hours	Low price hours
January	352	392	July	336	408
February	320	352	August	368	376
March	368	376	September	336	384
April	320	400	October	352	392
May	368	376	November	352	368
June	352	368	December	336	408

Note that the high price hours are considered as those from 0600 and to 2200 during working days also in the summer. This is so because of the demand tariff below. The applicable price is implemented in the subroutine.

From version 1.10 of the OPERA model it is possible to add other tariff structures as well. A new line has been added in the input data file. If the value in this line equals 1 the old structure is used. If a value 2 is present OPERA expects three prices. The first two prices show the high and low price from November to March while the third price shows the electricity cost per kWh during the summer.

3.18.5 Demand tariff

If the fuse size is higher than 250 A the demand tariff is applicable. The tariff is designed as follows:

Fixed fee	6000	SEK/Year	FASTAVG
Subscription fee	55	SEK/kW · Year	ABONAVG
Power fee	245	SEK/kW · Year	EFFAVG

The energy tariff is more complicated than the earlier one, price in SEK/kWh:

November - March, Monday - Friday, 0600 - 2200	0.333
Otherwise	0.184
April, September, October, Mon. - Fri. 0600 - 2200	0.184
Otherwise	0.146
May - August, Monday - Friday, 0600 - 2200	0.130
Otherwise	0.107

Taxation is not included in these prices, but for residential space heating purposes it is 0.072 SEK/kWh. Note that taxes are included in Figure 3.1.

As shown above there are 5 price levels. These levels are stored in an array called ENEDEM(5) and implemented in the input data file with the high price first, taxation included. The electricity tariffs end the input data file.

As can be found, there are a lot of values to be presented to OPERA. It is thus again recommended to copy and rename the file when a new building is considered, and then to change the values in the file one by one, if needed. An extra comma or point, or an integer when OPERA expects a floating point, will terminate the program. Remember also the figures written out by OPERA which will make it easier to locate errors in the data file.

Chapter 4

USING THE OPERA MODEL

When a computer program is to be used it is important that the operator is familiar with it, both in order to use it properly and also how to interpret the result. Here, it is explained how to run the program and how to understand the output on the screen or on the printer. The input file shown in Figure 3.1 is used as an example, and the tables presented look the same in this manual, as on the screen. If the figures in the tables differ from the ones presented in the manual there is something wrong, or the input data file has been changed.

4.1 How to start

The OPERA model in this version is elaborated for use in the IBM PC or close compatibles. It is assumed that a printer is connected to the computer, using the port PRN, see the OPEN statement in the beginning of the FORTRAN code. Mostly this port is the same as LPT1 and normally no changes are needed. However, in the text below, the screen is supposed to be the output device.

The program disk shall be put in the computer, normally in drive A, and the programs and data be copied to the hard disk of the system. There is no installation program and it is assumed that all the programs and the data files are put into the same directory. Further it is assumed that a floating point co-processor is present. If not, it is not necessary to use special versions of the program files, but the program will operate much slower.

The following program and data files shall be present in a full OPERA implementation:

- OPERA.EXE, the main program for floating point processors
- HOUSE.DAT, the data file in Figure 3
- OPERA.TXT, the first text output from OPERA
- SUB.EXE, for simulating the Swedish subsidy system
- SUB.C, - ” -

- SYS.C, for simulating the Swedish subsidy system
- LEAST.C, - ” -
- LOAN.DAT, shows the subsidy system
- SUB.DAT, a converted input data file for subsidies
- OPERA.FOR, source code in FORTRAN, main program
- OPSUB.FOR, source code in FORTRAN, subroutines
- SORAD.EXE, for solar calculations
- SUN.DAT, for solar calculations
- SORAD.C, source code in C, solar radiation program
- BIVAL.EXE, for discrete optimization of bivalent heating systems and time-of-use tariffs
- BIV.DAT, discrete optimization input file. (Created by OPERA.)
- BIVAL.FOR, source code in FORTRAN, bivalent system optimization
- GRAPH.EXE, for the graphic presentation
- DUR.DAT, data file for the duration graph
- GRAPH.C, source code in C, graphic presentation
- E2.TXT, Shows the text when OPERA starts.

Note that the source code is not shipped for all versions. The normal installation shows the following files:

- OPERA.EXE
- HOUSE.DAT
- E2.TXT
- BIVAL.EXE
- SORAD.EXE
- SUN.DAT

When the files have been stored on the hard disk, type OPERA and press the RETURN key and the program will start. If everything has worked fine a question on the screen asks for the applicable input data file. Here the file is called HOUSE.DAT. After typing this, press the RETURN key, and the program will start calculating the optimal strategy of the building. The program can be halted by a control-S, for a closer look at the output.

There are also versions for running OPERA and the other programs in the Windows environment. At this moment these programs are not shown in this manual.

MONTH NO	DEG.- HOURS	ENERGY- TRANSM	HOT - WATER	FREE ENERGY	SOLAR HEAT	UTILIZ. FREE	FROM BOILER	INSUL. OPTIM.
1	15996.	32893.	3501.	4167.	1201.	5368.	31027.	32893.
2	14713.	30254.	3502.	4167.	2609.	6776.	26980.	30254.
3	14582.	29987.	3503.	4167.	6078.	10245.	23245.	29987.
4	10800.	22209.	3504.	4167.	8998.	13165.	12548.	22209.
5	7440.	15299.	3505.	4167.	12717.	15299.	3505.	0.
6	4320.	8883.	3506.	4167.	13200.	8883.	3506.	0.
7	2827.	5814.	3507.	4167.	12933.	5814.	3507.	0.
8	3199.	6579.	3508.	4167.	10900.	6579.	3508.	0.
9	5400.	11104.	3509.	4167.	7712.	11104.	3509.	0.
10	9002.	18512.	3510.	4167.	4109.	8276.	13746.	18512.
11	11592.	23837.	3511.	4167.	1561.	5728.	21620.	23837.
12	14136.	29069.	3512.	4167.	778.	4945.	27635.	29069.
TOTAL	114008.	234440.	42078.	50004.	82796.	102183.	174335.	186761.

Figure 4.1: Energy balance calculation in OPERA

4.2 Basic output and how to interpret it

After the initial text presenting the program, and some figures, 1 to 8, shown on the computer screen, the program output starts with the input data. The figures are shown just for help if some input is not read properly. The output is followed by an energy balance which has been calculated from the outdoor climate data, the thermal status of the building, and the desired inside temperature, se Figure 4.1.

In the case studied here, the total number of degree hours is 114 008. This value is calculated, using expression 4.1, with the assumption that one degree hour is generated for each hour the desired inside temperature exceeds the outdoor temperature.

The equation used for the degree hour calculations is:

$$DH = \sum_{n=1}^{12} (T_i - T_{s,n}) \cdot \tau_n \tag{4.1}$$

where DH is the number of degree hours for one year, n is the number of the month, T_i the desired inside temperature, $T_{s,n}$ the mean outside temperature at month n, site s and t_n is the number of hours in month n.

The process of calculation is described in detail in [2] p. 43, while a more scientific discussion about the degree hour concept can be found in [21].

In this case study, the monthly mean temperature in January is - 0.5 °C and the desired inside temperature is 21 °C, see Figure 3.1. The difference is 21.5 °C, and the number of hours in January is 744. Subsequently the degree hour number is:

$$744 \cdot 21.5 = 15996$$

The degree hour calculations are elaborated in a subroutine called GRADTIM, see appendix B, and the numbers of degree hours for each month are stored in an array, called GRAD(12), for later calculations on e g differential rates or tariffs.

It is common to use an indoor base temperature, which is set lower than the desired, for calculating the number of degree hours. In Sweden, this temperature is often set to 17 °C, assuming that free energy from appliances etc shall meet the demand up to 20 °C. In OPERA the energy balance subroutine takes care of the free energy considerations.

OPERA also calculates the total transmission and ventilation coefficients for the building. The coefficiants are called TRANS and VENT, see the code in appendix A, and they are calculated as:

$$TRANS = \sum_{n=1}^{m} (U_n \cdot A_n) \tag{4.2}$$

where n is the building part indices, m the number of building parts, U_n the thermal transmittance and A_n is the area for the building parts.

$$VENT = H \cdot BA \cdot RN \cdot \rho \cdot cp \tag{4.3}$$

where H is the distance between the floor and ceiling in an apartment, BA is the net dwelling area, RN the number of air renewals in the apartments, ρ the density of air and cp is the heat capacity.

A more detailed discussion about formula 4.2 and 4.3 can be found in Ref. [2].

After this, the energy losses in the building are calculated by multiplying the total transmission and ventilation factor, TRANS + VENT, by the number of degree hours. In this case the result will be:

$$15996 \cdot (1602 + 454) = 32893000\,\text{Wh}$$

Note that the coefficients, TRANS and VENT, are presented by OPERA in the energy balance table on the screen, and that the coefficients in the code sometimes have slightly different names such as TRANSEF, TRANSEN etc.

The need for heating domestic hot water and the above value are added while the free gains are subtracted. The demand in January will thus be:

$$32887 + 3500 - 4167 - 1201 = 31026\,\text{kWh}$$

Note that the values above have been truncated for simpler reading.

The total gains are subtracted from the total losses and the result is tested whether negative or not. If negative, the gains are bigger than the losses and the heating equipment can be turned off during the whole month, i.e. for space heating purposes. As shown in Ref. [1] this is important to consider, when deciding the proper optimization values for both the heating system and the envelope retrofits. The heating system shall only be optimized for the heat actually produced in the facility, and the free energy over the year has to be excluded from the total energy losses in the building.

The envelope retrofits, however, shall not be optimized for the same amount of energy. Most of the year the free energy is valuable. If there is no free energy, the heating system must produce the heat. Only during the months when the heating system does not work with space heating, the free energy is unimportant. It only raises the temperature inside the building to an uncomfortable level and then the free gains are of course useless.

Because of this, it is necessary to recalculate the energy balance every time a new retrofit is implemented in the model. OPERA, however, does only present one of the balances on the screen or printer when basic output is selected. There is also a value, showing the used part of the free gains. During the summer, see Figure 4.1, there is a surplus of free heat and thus more free gains are utilized during May than during June.

The program continues by calculating the retrofit strategies for each heating equipment, see Figure 2.2. If something happens that the operator should be notified about, there will be an extra line of text on the screen. In our case, weatherstripping was not found profitable when heating system # 6, i.e. the natural gas boiler, was considered. If the operator finds this peculiar there might be a need for examining this fact in detail.

There are also other values presented during the operation. Normalized energy prices for district heating and electricity are shown. These prices have to be used if the design of e.g. a differential district heating tariff shall be compared with a fixed rate. See also chapter 3.18.1 and 3.18.2.

OPERA continues with calculating the different retrofit strategies and after this is done, selects the optimal one, or at least the almost optimal. This strategy is presented in further detail. OPERA tells the operator which building retrofits are selected and the heating system they shall be combined with. If insulation measures are chosen the thickness of the extra insulation is presented. For each implemented retrofit the total design load, the total transmission and ventilation coefficient, the energy need for one year, the inevitable retrofit cost and the building and/or ventilation retrofit cost can be found.

Also the resulting LCC is of course presented and the sum is split up. If the example in Figure 3 is run, the output is presented as follows:

The optimal LCC	=	1,197,530 SEK
Salvage value, existing heating system	=	20,533 SEK
Inevitable retrofit cost	=	253,788 SEK
New heating system cost, pipes excluded	=	86,840 SEK
Cost for pipes	=	12,870 SEK
Energy cost	=	627,017 SEK
Insulation cost	=	188,760 SEK
Connection fee	=	7,721 SEK

OPERA also calculates the LCC for the building when all the retrofits found optimal are introduced. The difference between this sum and the earlier assumed LCC is shown and in this case it is zero. The optimal building retrofits, i.e. triple-glazing the east and west windows, did not interact.

There is also a table presented by OPERA, showing the different building retrofit strategies, and the LCC for each heating system. The table is presented in Figure 4.2.

On the horisontal axis the heating systems under consideration are presented. The vertical axis first shows the LCC for the building with no envelope retrofits and then the savings that are assumed for each retrofit. In Figure 4.2 the first value, i.e. 1.48, shows the LCC for the existing heating system if no building or ventilation retrofit at all is introduced. The next value below 1.48 is .00 showing that attic floor insulation was not profitable and thus not implemented. The same happens for floor insulation, but external wall insulation gives 0.05. This means that the insulation is assumed to save 0.05 MSEK for the period in consideration. One more building retrofit is selected, viz. tripleglazed windows,

*** LCC TABLE FOR BASE CASE 1.00 ***
VALUES IN MSEK

	EXIS. SYST.	NEW OIL	ELE. HEAT	DIST. HEAT	GR.W HEAT	NAT. GAS	TOU DIST	TOU ELEC.	BIV. GR.HP	BIV.O. AIRHP
NO BUILD. RETR.	1.48	1.54	1.69	1.45	1.50	1.23	1.45	1.69	1.35	1.48
SAVINGS:										
ATTIC FL. INS	.00	.00	.01	.00	.00	.00	.00	01	.00	.00
FLOOR INS.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
EXT. WALL INS.	.05	.05	.11	.04	.04	.00	.04	.11	.00	.03
INS. WALL INS.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TRIPLE-GLAZING	.06	.07	.09	.06	.07	.04	.06	.08	.04	.06
TRIPLE-GL. L.E.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TR.-GL. L.E. G.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
WEATHERSTRIP.	.01	.01	.02	.01	.01	.00	.01	.01	.00	.00
EXH. AIR H. P.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
SUM. OF RETRO.	1.36	1.41	1.46	1.34	1.38	1.20	1.34	1.48	1.30	1.39
SUM. OF COMB.	1.36	1.41	1.46	1.34	1.38	1.20	1.34	1.46	1.30	1.39
DISTRIBUTION:										
SAL. OLD BOILER	.00	.02	.02	.02	.02	.02	.02	.02	.02	.02
NEW BOIL. COST	.08	.10	.03	.06	.24	.09	.06	.03	.27	.31
PIPING COST	.00	.01	.00	.01	.16	.01	.01	.00	.10	.01
ENERGY COST	.60	.59	.62	.56	.28	.63	.56	.61	.46	.35
CONNECTION FEE	.00	.00	.00	.01	.00	.01	.01	.00	.00	.00
BUIL. RETROF. C	.43	.43	.54	.43	.43	.19	.43	.54	.19	.44
INEVITABLE COST	.25	.25	.25	.25	.25	.25	.25	.25	.25	.25

Figure 4.2: LCC table presented by OPERA

which is assumed to save 60 000 SEK for the optimization period. When the existing heating system is dealt with the resulting LCC is will become 1.36 MSEK. The lowest LCC, however, is achieved when a natural gas system is introduced. If that is the case, the external wall retrofit is unprofitable and triple-glazing is the only building retrofit selected by the model. The total new LCC is assumed to be 1.20 MSEK or 160 000 SEK cheaper than the earlier discussed strategy.

The table in Figure 4.2 is used by the operator in order to compare the different strategies to each other. It is also possible to see the distribution between the different costs for all the heating systems under consideration, but in less detail than the table for the optimal strategy.

4.2.1 Sensitivity analysis

The optimal strategy calculated by OPERA is only valid as long as the input data do not change. Some of the input data however, cannot be chosen with an absolute accuracy, and thus it might be valuable to compare the result from a number of OPERA runnings. The fact is that, if the value on ST1, see Figure 3.1, is set to 0, the model generates more tables, and automatically, optimization periods from 10 to 50 years, interest rates from 3 to 11 % and annual energy escalation prices up to 3 % are presented. It is, however easy to change the code if more or less tables are wanted, see the last part, near the END statement in the main program code, appendix A.

By examining these tables some basic facts about the optimization can be found. If one of the input data is increased, say by 10 %, the resulting LCC might be:

- lower
- higher

- not affected at all

One example of lower LCC for an increased value is the interest rate. If the rate is increased the LCC gets lower, which could be found by studying expression 2.1 or 2.2 above. An example of the opposite can be found by increasing the optimization period. With a longer period the LCC will be higher. The third way of influence can be shown by increasing the electrical boiler cost. If this is increased, nothing happens to the optimal LCC because the electrical boiler was not optimal from the beginning.

Unfortunately it is not possible to say which of the data is of the greatest interest to examine. The answer to this depends on the problem under consideration. One example of this can be the price of the electrical boiler. If the price for electrical energy is high, the system will never be chosen by the model, and different cost functions for electrical boilers are not interesting. If, however, the energy cost is decreased, the electrical boiler might be of interest in some combinations of the input data. Fortunately, this combination, may be assumed to occur only in the academic world, and can thus be excluded from future considerations.

Other times the resulting LCC for different strategies might be very close. Looking at only one criterion it will be difficult to choose the optimal solution. If it is expected that one of these solutions will be very rare, because of its price etc., it is better to choose a more robust solution even the cost is somewhat higher. Such considerations, however, are very hard to build into the model where the problem must be solved in a mathematical way, and thus there is a need for a skilled operator as well.

One way to present the situation is a kind of LCC mapping, see Figure 4.3.

The LCC has been depicted for a number of values for the two variables and the optimal strategy is shown for each combination. Note that it is not the case presented in Figure 3.1 that is depicted. More about the sensitivity analysis subject can be found in e.g. Ref. [1].

4.3 Practical session

In order to illustrate the work with the OPERA model, the building presented in Figure 3.1 is now examined. When the table in Figur 4.2 is presented, consider the figures shown by OPERA. As can be found, the natural gas heating was the optimal solution combined with triple glazed windows. No other building retrofit was found profitable. The new windows were assumed to save 40 000 SEK for the optimization period, while changing the heating system from the existing oil-boiler to the natural gas system decreased the LCC from 1.48 to 1.23 MSEK.

It might also be important to consider the other strategies, especially if they get very close to the optimal one. In this case, the bivalent heating system combined with triple-glazed windows was the closest one, with a LCC of 1.33 MSEK. The bivalent system was in turn followed by district heating combined with external wall insulation and triple-glazed windows. It is obvious that it is the heating system retrofits that are important while building measures are less profitable. This is a very common result in OPERA runnings. At least in Sweden, the heating system should thus be much more emphasized than is the

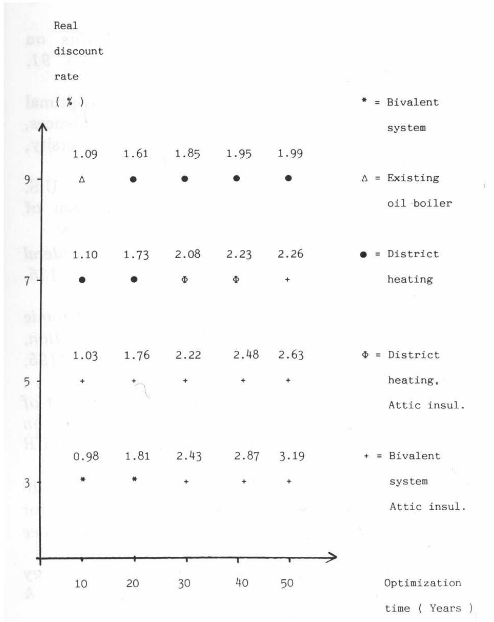

Figure 4.3: Bivariate sensitivity analysis, see Ref. [22]

case today. When the result is as clear as this, it is no point in making closer examinations of the other strategies. No interaction could be found between the building retrofits because only one was chosen and normally the program can be terminated which also is the default.

It could, however, be of interest to consider what will happen if the project life or the discount rate are changed. If the variable ST1 is set to 0 instead of 1, the program will produce more scenarios. First the project life is decreased by 10 years. When a project life of 40 years is considered the LCC is decreased to 1.14 MSEK for the optimal solution. The strategy, however, is the same as above, i.e. natural gas and triple-glazed windows. The savings from the better windows is decreased but the profitability of a change is still valid, and the fact is that this solution is optimal for a project life as low as 10 years. Note that the LCC changes very much but the strategy does not, a fact that is dealt with in [1] in more detail.

After this, the OPERA model changes the real discount rate to 3 %, while the project life is set back to 50 years as in Figure 3.1.

The optimal solution is now natural gas combined with external wall insulation and triple-glazed windows. It is thus obvious that external wall insulation might be of interest for special cases, but the asset is withdrawn again if a 3 % rate and e.g. 40 years project life is dealt with. Note that the resulting LCC is raised when the discount rate is decreased. This is also dealt with in [1]. When the discount rate is increased, less retrofits will be profitable, and this makes the triple-glazing disappear at high discount rates. However, at 9 % where OPERA stops changing the rate, the retrofit is still profitable.

Escalating energy prices are important to consider, and thus three cases are dealt with by OPERA, from 1 to 3 % annual increase in real terms. OPERA uses a justified real discount rate in these calculations and this justified rate is calculated as shown in expression (3). Note however, that for high escalation of the energy prices and low real discount rates the justified rate will become negative but this will nevertheless work fine. When 1 % annual energy price escalation occurs, external wall insulation will be a part of the optimal solution, while attic floor insulation and weatherstripping will be profitable if the energy prices increase faster than app. 3 % per year. It is also important to consider that as long as the optimal solution is encountered, the interaction between these four building and ventilation retrofits is very small, about 4 000 SEK for the 50 year period, and this interaction could therefore be neglected.

It could also be interesting to consider what amount of insulation should be implemented if the retrofit shall be included in the optimal strategy. The external wall insulation is to be of the magnitude 0.07 m, and it should be remembered that this measure is close to fall out of the optimal solution. This means that if an insulation measure is to be profitable it is important that it has some magnitude. About 0.2 m extra insulation on the attic and 0.1 to 0.15 m extra on the wall will often be the best. If the asset is to be extra insulated it is subsequently important to implement sufficient insulation from the beginning. It must also be emphasized, that if too little insulation is implemented, it is impossible to make a profitable new insulation retrofit later.

The existing U-value on the wall does not affect the LCC much as long as the asset is insulated in an optimal way, but the profit will vanish if the U-value is low from the beginning. Also note that the existing U-value has no influence on the optimal insulation level, a fact that is dealt with in Refs. [1] and [23].

From the above discussion it is apparent that if the real values are close to the values given in Figure 3.1, the optimal retrofit solution is to change the heating system to a natural gas boiler, and change windows to triple-glazed ones. It is very important that the operator examines the figures calculated by OPERA, and makes one or two extra runnings if the result is not as obvious as above. Sometimes, several different strategies give almost the same LCC and then other than LCC reasons have to determine the best retrofit strategy.

4.4 Understanding the FORTRAN code

In appendix A the main program FORTRAN code is presented. Here it is not possible to show the design of FORTRAN programs. The interested operator must find the knowledge elsewhere. However, it is shown how the OPERA program is designed in order to provide the necessary information for the operator to change the code and subsequently get the information which might be needed for some special cases not dealt with in the original model output. The program is split into two divisions, one for the main program and one for all the subroutines, shown in appendix B. The reason for this is that once the subroutines have been transferred, or compiled to the computer's machine language there is no need for compiling them again unless they have been changed. This is valid also for the main program. If one of the subroutines is changed, it might not be necessary to compile the main program once again. This will save time when changes are made in the code.

The program is developed with the FORTRAN 77 standard and almost no changes are necessary if different computers are used, but one or two exeptions must be mentioned. The code contains some variables with longer names than FORTRAN 77 approves. Many compilers have special commands for solving such problems and in e.g. MICROSOFT FORTRAN 4.0 so called metacommands can be used. The default in the version 5.0 is 31 significant characters.

There might also be some problems with the input/output expressions in the OPEN statements when external files are to be read or written to. The operator must consult the manual of the specific compiler for such problems. Some compilers are not very sensitive for the way characters or figures are written in the input data file. Integer values might thus be interpreted as such even if a floating point is actually written. As mentioned earlier the compiler used here must find the correct form.

The code is originally developed in a NORD 570 computer, but the code shipped on the disk is changed so it will compile without any problems when MICROSOFT FORTRAN 5.0 for PC is used. (Note that the code not always is present on the disk.) It must be emphasized that programming mistakes are easily made if the code is changed by novice programmers. Sometimes the errors are easy to discover but other times the errors will only occur at very special occasions and are therefore very hard to find. It is recommended not to change the original programming code but instead to use a copy of it given a new name. A debug program will then be very useful for comparing the two versions. Setting the output parameters in clever combinations might also be a fine alternative.

Further it must be noticed that some of the comments in the code still are in Swedish. It has not been possible to change all of them into English but the mostly used parts are translated. All the default output is in English and further, all the new subroutines.

4.4.1 The main program

The main program code, which contains about 3 000 lines, starts like all FORTRAN programs by declaring all variables, dimensioning statements and so forth. After the OPEN statements, the program starts reading the input data file and proceeds by writing all the input data on the screen or at the printer depending on the variable U. If U equals 0, no text at all is shown, if it is 1 the screen takes care of the output and if it equals 3 the printer starts working. If the Windows versions are used the lines above might not apply because of possible redirection.

The calculations start at about line 450 and what happens first happens is that the LCC for the existing building is elaborated. This part of the program ends at about line 760 and the LCC is stored in a variable called TOTNUVB(Y) where Y shows the number of heating system. When the existing heating system is of concern, Y will equal 1.

The program will now implement a retrofit and the first one is attic floor insulation. There are four different insulation retrofits, four window retrofits, from double to triple-glazed windows for each orientation, weatherstripping and exhaust air heat pumps. The program will then check if still better windows, like triple-glazed windows with low-emmisivity coatings, are profitable.

The insulation and window retrofits are mixed in the code but weatherstripping starts at about line 1,300 and exhaust air heat pumps at about line 1,430.

The first heating system is evaluated approximately about line 1,720 and the new heating system calculations start at label 700 again. When all the heating systems are dealt with the cheapest strategy is found by a routine at about line 1,900. All the candidates for the optimal strategy are then implemented and the combined retrofit LCC is evaluated. This is accomplished at approximately line 2,770.

The remaining programming lines deal with the number of tables that OPERA provides for different real discount rates, project periods and escalating energy prices. Note the lines in the vicinity of 2,780 where it is possible to evaluate if the LCC will decrease if more or less insulation is implemented because of the interaction between the retrofits.

4.4.2 Subroutines

The second part of the program contains the subroutines called from the main program, see appendix B. There are 10 different routines:

NUVARDE	Present value calculations
SKALROT	Inevitable retrofit calculations
TABELL1	Writes the retrofit strategy tables
TAXOR	Calculates normalized rates etc.
GRADTIM	Degree hour calculations
VARAKT	Duration graph calculations
BIOPTIM	Bivalent system optimization
ENEBAL	Energy balance calculations
TABELL2	Writes energy balance table
TARIFF	Transfers real tariffs to montly mean values

In all of these tables it is possible to set the U variable to e.g. 1 and get out the necessary calculation results for scrutinizing the optimization process. Note that some of the subroutines are called several hundred times, and because of this it might be hard to select only these values of interest. It might often be better to include an IF statement in the main program, set the U variable there, and let the subroutine CALL transfer the value. In later versions a few new subroutines have been added. Another way is to use a debugger program.

Chapter 5

THE SWEDISH SUBSIDY SYSTEM

This part of the program is obsolete, 1996. The government has introduced a variety of subsidies for encouraging proprietors to implement energy conservation measures. The system can be divided into three categories:

- Renovation loans
- Interest rate subsidies
- Energy retrofit subsidies

The most advantageous of the means is the renovation loan, which is provided with an interest rate warranty, but also the other types reduce the cost for introducing energy conservation retrofits in the building. Note that the energy retrofit subsidies at present have been withdrawn until 1990-06-30, see Ref. [24].

The subsidy system is not part of the original OPERA model and for using the system, the original input data file as the one in Figure 3.1, must be transferred to a new file where the retrofit costs etc. are changed in order to reflect the system. Unfortunately, it has not been possible to design a program that is totally independent of OPERA for the simulation of the subsidized costs. OPERA has been changed to some extent for taking care of the new input data file and also to find out if the subsidy system is to be examined.

The result from some OPERA runnings, with the subsidy simulation file in effect, showed only a minute influence from the subsidy system on the optimal retrofit strategy. Therefore, only the most advantageous of the systems has been dealt with here in closer detail, i.e. the renovation loans.

There are also other subsidies, not applicable for energy retrofit considerations and therefore not dealt with here, e.g. for:

- Installing elevators in existing multi-floor buildings
- Decreasing radon radiation inside the building
- Adapting existing flats for physically handicapped

A brief review can be found in Ref. [25].

Further, there is one more subsidy for energy measures, viz.:

- Direct monetary contributions to solar plants

Normally this type of subsidy is not applicable and thus it will not be dealt with here at all.

In the Swedish Building Code see Refs. [8] and [26] there are certain limits to force the proprietor to make a building use less energy. However, Ref. [8] shows that there are possibilities to avoid the rules when retrofitting is of concern, if the costs are too high for e.g. an insulation measure. It is also said that the costs can be considered as too high if the existing U-value is so low, that an extra insulation will not entitle to energy retrofit subsidies. The new code Ref. [26] is not valid for old buildings and thus there are no mandatory limits for insulation measures in the existing housing stock.

5.1 Renovation loans

The renovation loans are the most advantageous form of subsidies. If the proprietor is entitled to loans, the government sets the highest intrest rate to 5.1 %, and 5.25 % for municipality ownership, for the first year [27]. Earlier, this rate was only 2.35 %.

The interest however, is increased with 0.25 % per year and further, the rate is based upon the original amount of borrowed money. The installments will not influence the money cost as long as the subsidy system is in effect. When the interest rate has increased to a level where it is cheaper to pay the ordinary interest, the subsidies are abolished. However, there are a lot of restrictions for this type of loan. The most important are:

- The building must be older than 30 years
- The result from the retrofits must be a substantially better building
- Only residential buildings are of concern
- No maintenance measures are entitled to renovation loans
- Energy retrofits are normally not entitled to loans, but may be included if they must be implemented when the rest of the building is retrofitted
- The residence must come up to a lowest acceptable standard - Energy retrofits must not be too expensive, relative to the other measures made on the building
- Loans for heating equipment, not desired by the municipality, are mostly not entitled to be included
- The residence must be permanent
- The total renovation cost cannot be higher than the cost for a new building
- The standard must be normal, no luxury renovation
- The building must be sold by the municipality
- Et c.

From most of these restrictions the municipality can make exeptions and the last mentioned above is rarely used nowadays. The restrictions discussed above are presented in detail in Ref. [28].

At present the government wants to encourage the construction of new buildings, instead of retrofitting old ones. A certain limitation has thus been set in the areas of Stockholm, Gothenburg and Malmö, and the annual amount of buildings to be retrofitted must not exceed 30 % of the amount retrofitted in 1986.

In the application for renovation loans, the assumed renovation cost, including costs for energy retrofits is calculated. If the proprietor is entitled to the loan, the total cost is devided in three parts:

- The base part, or first mortgage loan, 70 % of the renovation cost
- The residence loan, 25 - 30 % of the renovation cost
- 0 - 5 %, covered by the proprietor

The base part loan is a loan from a credit institution, like a mortgage bank, the second part is covered by the government and the third part is paid by the proprietor. If the proprietor is a municipality 0 % has to be covered this way, and if the landlord is a private person 5 %, see Ref. [29].

The interest rate for the base loan is not fixed by the government, but the same level is mandatory for five consecutive years. There are also some other rules for the credit, but of minor importance in this study.

The residence loan is covered by the government and the interest rate is set to what is valid for the moment. It is therefore not possible to know the exact level but at present it is about 12 %. The rate is set by the Governments Residence Financing Co, and also here the rate is fixed for five consecutive years.

There must also be a security for the loan and this is set by mortgages in the real estate and in the building. More details about the location etc of the mortgage bonds can be found in Ref. [28].

The government also sets a maximum interest rate for the first mortgage loan, and above this rate, no subsidies are paid.

The residence loan has a payoff time of up to 30 years while it is possible to get a longer payoff on the base part loan. The interest and amortizations are calculated as a fixed-yearly-instalment loan and the rate of interest is set to 8 %. The interest is calculated as:

$$FIP = A_{loan} \cdot \frac{r}{1-(1+r)^{-p}} \tag{5.1}$$

where FIP is the fixed instalment, A_{loan} the total loan, r the discount rate and p the payoff time. The base loan has a amortization plan that does not exactly follow the method with fixed-yearly-installments. The plan is determined for each case.

The society subsidizes the interest rate and the first year the rate is guaranteed to be 5.1 % for private owners and 5.25 % if the municipality owns the building. The rate is then increased with 0.25 % each year. Further, the interest is calculated on the total loan in spite of annual instalments. The subsidies therefore will be abandoned after some years. An example will show the situation:

Assume that A_{loan} above is 1000,000 SEK, the discount rate is 8 % and the payoff time 30 years. FIP in expression 5.1 will thus become 88,827 SEK. The interest cost is 80,000 SEK while the amortization is 8,827 SEK. Assume that the government now says that the interest is limited to 5.25 % and thus 52,500 SEK has to be paid. If the amortization is added the cost will be 61,327 SEK. If there was no guaranteed rate the interest would be some 12 % or 120,000 SEK, and the repayment about 4,143 SEK.

Next year, the real loan has decreased with 8,827 SEK, but the due interest has increased. This is because the rate increases with 0.25 % and has now become 5.5 %. The interest is still calculated on the 1000,000 SEK and the amount will become 55,000 SEK. The FIP above is also still 88,827 SEK but the interest part has decreased to 79,293 SEK calculated as:

$$(1000,000 - 8,827) \cdot 0.08 = 79,293$$

The amortization will thus be:

$$88,827 - 79,293 = 9,534 SEK$$

Adding the interest will yield 64,534 SEK, which has to be paid year number two. In Table 2 the situation is shown for a number of years in running prices. Note that the subsidy is abandoned between the years 16 and 17 where the real interest exceeds the warranted. In [1] a case is considered with a warranted rate of 2.6 %, which was the case some years ago. In that case the subsidy was abandoned between the years number 20 and 21.

Year	FIP	Interest cost 8 %	Amortization	Warranted int. 5.25 % + 0.25 %	To pay	Next year loan	Real interest rate 12 %
1	88,827	80,000	8,827	52,500	61,327	991,173	120,000
2	88,827	79,293	9,534	55,000	64,534	981,639	118,940
3	88,827	78,531	10,295	57,500	67,795	971,344	117,796
16	88,827	60,825	28,002	90,000	118,002	732,314	91 238
17	88,827	58,585	30,242	92,499	118,120	702,072	87,878
29	88,827	12,672	76,155	122,499	95,163	82,247	19,008
30	88,827	6,580	82,247	125,000	92,117	——	9 870

Table 5.1: Swedish subsidy system, running prices

It is, however, also necessary to calculate the present worth of the cash flow in Table 5.1. If the inflation is assumed to be 7 % annually, and the real discount rate is supposed to be 5 %, the situation can be depicted as in Table 5.2.

The cash flow is first calculated in fixed prices and then transferred to a base year at present. It is found that the originally 1000,000 SEK by use of the subsidy system has been changed to 654,112 SEK. The case where 2.6 % was used resulted in 466 600 SEK and it is thus obvious that the system is now less profitable to use. In the tables above it is shown how the subsidy system influences the total cost of the building. There are however, also other facts

Year	Running prices	Fixed prices 7 % inflation	Present worth 5 % real rate
1	61,327	57,315	54,586
2	54,534	56,366	51,125
3	67,795	55,341	47,806
4	71,120	54,257	44,637
29	95,163	13,376	3,250
30	92,117	12,101	2,800
Sum			654,112

Table 5.2: The Swedish subsidy system, fixed prices

that must be considered. Above it was assumed that the cost for the retrofits only was paid once, i.e. at the base year. If e.g. a heat pump is installed in the building, only the first cost for the pump can be included in the total loan. This is of course important to consider because the pump must be renovated after about 10 years and that cost is not subsidized. If an attic floor insulation is dealt with, the situation is different. This cost will probably emerge only once, and for such cases the method above will work well.

In the regulations of the renovation loans, there are also other constraints. Some energy retrofits have limitations for the cost included in the loan, and the cost for an attic floor insulation cannot exceed this cost even if found profitable. At least it cannot be included in the total loan over this limited cost. If the proprietor, nevertheless, finds it profitable to implement the insulation, it could be done but to a higher interest cost.

In order to enlighten the subsidy system, an example dealing with a heat pumpis shown below. The costs for the heat pump are taken from Figure3. The pump is supposed to cost 60,000 + 5,000 · P SEK where P equals the thermal power of the device. If it is assumed that the heat pump power will be of the magnitude 20 kW, the cost for the pump will be 160,000 SEK. The heat pump itself is supposed to last for 50 years, but there is also the installation and further, maintenance every 10 years, to a cost of 1,500 SEK per kW. This extra cost thus amounts to 30,000 SEK. The situation is depicted in Figure 5.1.

The subsidy system will only affect on the initial cost i.e. the 160,000 SEK that are to be invested first. The 30,000 SEK for the extra costs are only affected the first time they are invested, but not at later payments.

The residence loan is now assumed to be 25 %, the first mortgage loan 70 % and the down payment 5 %. The interest rates for the different loans are assumed to be 12, 11 and 15 % respectively, while the amortization periods are supposed to be 30, 40 and 25 years. The residence loan part, of the heat pump cost will be:

$$0.25 \cdot (160,000 + 30,000) = 47,500 \quad \text{SEK}$$

In Figure 10 the costs for the loan are presented as they are calculated in the program.

The fixed installment is calculated to 4,219 SEK by use of the expression 5.1. The amortization rate is set to 8 % and the warranted rate to 5.1 % with

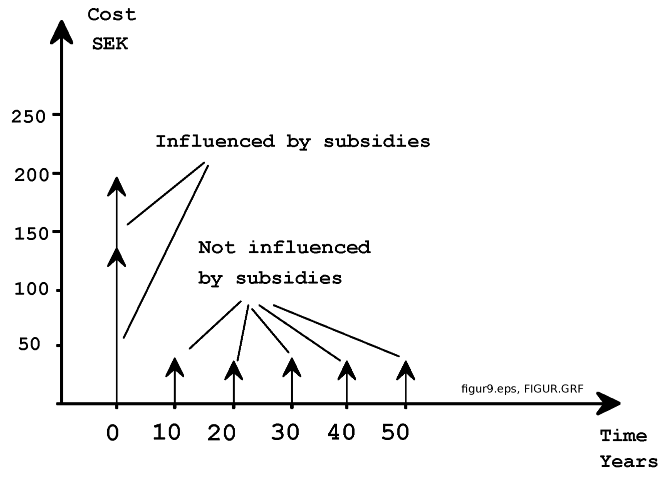

Figure 5.1: Cash flow from the heat pump installation.

an increase of 0.25 % per year. Note that the subsidies are abandonned year no 17. The payments in Figure 5.2 must also first be transferred to fixed prices due to inflation, which is set to 7 %, and secondly, due to the fact that the costs appear in the future. The expression 2.1 is used for both of the calculations and the real discount rate is estimated to 5 %. The result is presented in Figure 5.3.

As shown in the figure the total payments for the residence loan is 136 938 SEK, but if fixed prices are considered the cost will be 51,810 SEK. The present worth of all the payments, however, will only be 30,583 SEK, a reduction by about 35 %.

The first mortgage loan, or base loan, has been dealt with in the same way. In Figure 5.4 the cash flow is presented and the transfer calculation is depicted in Figure 5.5.

Note that the amortization period now is 40 years, the interest rate is 11 %, and the loan is 70 % of 190,000 SEK. From Figure 5.4 it is obvious that the subsidy is abandonned year number 19 where the real interest cost is 12,515 SEK and the warranted interest cost is 12,768 SEK.

Figure 5.5 shows that the present worth of the loan has decreased from 133 000 SEK to 80 164 SEK, a reduction by about 40 %.

In the example shown here, 5 % of the cost, i.e. 9,500 SEK, must be covered in some other way, e.g. by use of an ordinary bank loan, to an interest rate of 15 %. The rate of the ordinary loan is higher than the inflation and the real discount rate could motivate. The values imply an interest rate of about 12 %, and the extra 3 % could thus be considered as a profit for the bank. The total cost for the loan as a present worth will therefore be:

The residence loan	27,342
The first mortgage loan	81,580
The ordinary loan	11,252
Sum	121,999

THE RESIDENCE LOAN

Year Numb	FIP	Interest cost	Amorti- zation	Warr cost	To pay	Next year	Real int.
1	4219	3800	419	2422	2842	47081	5700
2	4219	3766	453	2541	2994	46628	5650
3	4219	3730	489	2660	3149	46139	5595
4	4219	3691	528	2779	3307	45611	5537
5	4219	3649	570	2898	3468	45040	5473
6	4219	3603	616	3016	3632	44424	5405
7	4219	3554	665	3135	3800	43759	5331
8	4219	3501	719	3254	3972	43040	5251
9	4219	3443	776	3372	4149	42264	5165
10	4219	3381	838	3491	4329	41426	5072
11	4219	3314	905	3610	4515	40520	4971
12	4219	3242	978	3729	4706	39543	4862
13	4219	3163	1056	3847	4903	38487	4745
14	4219	3079	1140	3966	5107	37347	4618
15	4219	2988	1232	4085	5317	36115	4482
16	4219	2889	1330	4204	5534	34785	4334
17	4219	2783	1437	4322	5611	33348	4174
18	4219	2668	1551	4441	5553	31797	4002
19	4219	2544	1676	4560	5491	30121	3816
20	4219	2410	1810	4679	5424	28312	3615
21	4219	2265	1954	4797	5352	26357	3397
22	4219	2109	2111	4916	5274	24247	3163
23	4219	1940	2280	5035	5189	21967	2910
24	4219	1757	2462	5154	5098	19505	2636
25	4219	1560	2659	5272	5000	16846	2341
26	4219	1348	2872	5391	4893	13975	2022
27	4219	1118	3101	5510	4778	10874	1677
28	4219	870	3349	5629	4654	7524	1305
29	4219	602	3617	5747	4520	3907	903
30	4219	313	3907	5866	4376	-0	469

Figure 5.2: Cash flow emerging from residence loan of 47,500 SEK

This is a reduction with about 36 %, from 190,000 to 122,000 SEK. The calculation procedures can be found in appendix C and the program, written in C, is called SYS.C. Note that SYS.C is linked with two other programs called SUB.C and LEAST.C. All output to SUB.DAT comes from SUB.C where there is a main program, while SYS.C and LEAST.C work as functions of the first program. There is also an input data file, LOAN.DAT, shown in Figure 5.6, that provides SYS.C with all the necessary input values.

By changing the input data in LOAN.DAT with an ordinary editor it is possible to study the influence of different interest rates, amortization periods etc. Note that the cost for the asset of consideration is set in SYS.C, i.e. the variable named "kost", see Appendix C. If different values are tested it is found that the rate of subsidy will not change, and thus the percentage value sent back to SUB.C from SYS.C, can be used for all measures that are subsidized at the base year. The values and the corresponding names in SUB.C, MINKVA.C and SYS.C are:

Year	To pay	Fixed prices	Present worth
1	2842	2656	2529
2	2994	2615	2372
3	3149	2571	2221
4	3307	2523	2076
5	3468	2473	1937
6	3632	2420	1806
7	3800	2367	1682
8	3972	2312	1565
9	4149	2257	1455
10	4329	2201	1351
11	4515	2145	1254
12	4706	2090	1164
13	4903	2035	1079
14	5107	1980	1000
15	5317	1927	927
16	5534	1875	859
17	5611	1776	775
18	5553	1643	683
19	5491	1518	601
20	5424	1402	528
21	5352	1293	464
22	5274	1190	407
23	5189	1095	356
24	5098	1005	312
25	5000	921	272
26	4893	843	237
27	4778	769	206
28	4654	700	179
29	4520	635	154
30	4376	575	133

Sum of payments is = 136,938
Sum of fixed prices is = 51,810
Sum of present worths is = 30,583

Figure 5.3: Transferring cash flow to fixed prices and present worths

Subject	Value	Name
The residence loan amortization period	30	bosam
The base loan amortization period	40	botam
The ordinary loan amortization	25	egtid
Residence loan as part of total loan	.25	boslan
Base loan part of total loan	.70	botlan
Ordinary loan as part of total loan	.05	eglan
Interest rate residence loan	.12	bosran
Interest rate base loan	.11	botran
Interest rate ordinary loan	15	egran
Warranted rate	.051	garran
Annual increase in warranted rate	.0025	okn
Interest rate in annuity calculations	.08	ambos
Annual inflation rate	.07	infl

THE BASE PART LOAN

Year Numb	FIP	Interest cost	Amorti- zation	Warr cost	To pay	Next year	Real int.
1	11153	10640	513	6783	7296	132487	14630
2	11153	10599	554	7116	7670	131932	14574
3	11153	10555	599	7448	8047	131333	14513
4	11153	10507	647	7781	8427	130687	14447
5	11153	10455	698	8113	8811	129988	14376
6	11153	10399	754	8446	9200	129234	14299
7	11153	10339	815	8778	9593	128419	14216
8	11153	10274	880	9110	9990	127539	14126
9	11153	10203	950	9443	10393	126589	14029
10	11153	10127	1026	9775	10802	125563	13925
11	11153	10045	1108	10108	11216	124454	13812
12	11153	9956	1197	10440	11638	123257	13690
13	11153	9861	1293	10773	12066	121964	13558
14	11153	9757	1396	11105	12502	120568	13416
15	11153	9645	1508	11438	12946	119060	13262
16	11153	9525	1629	11770	13399	117432	13097
17	11153	9395	1759	12103	13862	115673	12917
18	11153	9254	1900	12435	14335	113773	12724
19	11153	9102	2052	12768	14567	111721	12515
20	11153	8938	2216	13100	14505	109506	12289
21	11153	8760	2393	13433	14439	107113	12046
22	11153	8569	2584	13765	14367	104528	11782
23	11153	8362	2791	14098	14289	101737	11498
24	11153	8139	3014	14430	14206	98723	11191
25	11153	7898	3256	14763	14115	95467	10860
26	11153	7637	3516	15095	14017	91951	10501
27	11153	7356	3797	15428	13912	88154	10115
28	11153	7052	4101	15760	13798	84053	9697
29	11153	6724	4429	16093	13675	79624	9246
30	11153	6370	4783	16425	13542	74840	8759
31	11153	5987	5166	16758	13399	69674	8232
32	11153	5574	5579	17090	13244	64095	7664
33	11153	5128	6026	17423	13076	58069	7050
34	11153	4646	6508	17755	12895	51561	6388
35	11153	4125	7029	18088	12700	44532	5672
36	11153	3563	7591	18420	12489	36942	4899
37	11153	2955	8198	18753	12262	28744	4064
38	11153	2299	8854	19085	12016	19890	3162
39	11153	1591	9562	19418	11750	10327	2188
40	11153	826	10327	19750	11463	0	1136

Figure 5.4: Cash flow for the first mortgage loan, running prices

5.1.1 How to calculate the approved total loan

Above it is shown how the cost for the total loan changes when the subsidies are transferred to a base year, using the present worth method. When an existing building is to be retrofitted, the limit for the approved cost is that for a similar new building. This means that retrofits implemented in one part of the building might be very expensive as long as other retrofits are cheap. An extra amount, no matter how much, of attic floor insulation might therefore be approved but it may be hard to superinsulate all of the building because of the ”new building cost” limit.

When the approved cost for a new building is calculated there are certain values for e.g. the external wall cost that must not be exceeded. In Ref. [30] there are two values used for external walls, one for facades of bricks and one for wooden facades. The cost is limitid to 765 SEK/m^2 and 610 SEK/m^2 respectively. These values might also be multiplied by a time coefficient, at present 1.3, and the approved cost for the more expensive alternative will become 994 SEK/m^2. The approved cost can be increased by insulating the building more than a so called reference object, determined in the Swedish building code, see Ref. [26]. In this way the approved cost can be increased with 5 SEK for each kWh/year that falls below the energy demand for the reference building. The value shall be multiplied by the time coefficient. There is, however, a limit at 37 500 SEK per apartment in the building, see Ref. [31].

The reference building is supposed to have a mean average U-value of about 0.25 W/m^2·K, which means that the reference building is very thorougly insulated compared to the general building stock in Sweden today. The system with an average U-value which must not be exceeded, is unfortunately very hard to implement in the OPERA model, where each building asset is dealt with separately. It has subsequently been necessary to assume that the total cost for the retrofit will be approved as a loan by the authorities.

5.1.2 Simulation of the subsidies

When the building is to be retrofitted, and the loan is approved by the authorities, the subsidy is about 35 %. It must be observed that it is only the first cost that is subsidized. All future costs have to be paid whithout any subsidies, even if they originate from a subsidized retrofit.

When insulation measures are of concern, OPERA models the cost for them as found in expression 3.2. The C_2 and C_3 costs are assumed to occur only once during the life-cycle of the building. The C_1 cost may occur more often, and subsequently C_2 and C_3 will be subsidized to a full degree while C_1 only will be subsidized on first implementation.

The expression, given in Figure 3.1 for attic floor insulation, showed that C_1 equalled 0 SEK and thus there is no need for examining the influence of often occuring retrofits in this specific case. The C_2 and C_3 costs will be subsidized and the calculations are made in the INSUL function, see appendix C. The result from INSUL is that the C_2 and C_3 values are reduced by about 35 %, or the reduction factor calculated in SYS.C. If C1 differs from 0, it will influence the C_2 and C_3 values returned by the function INSUL. The costs for a number of insulation levels are calculated and then a straight line is elaborated using the method of least squares.

When OPERA was originally designed, the subsidy system was not included and therefore some changes had to be implemented in the OPERA code itself and the input data file changed. If the first parameter occuring in the input data file equals 2, it tells OPERA that the subsidy system is utilized and this will make the program calculate the inevitable retrofit cost in a slightly different way compared to the original situation. Setting the value to 1 makes OPERA believe that it is the old subsidy system that is to be simulated which will yield errors in the optimal solution of today, i.e. 1990. If a 0 is encountered, the program calculates as described in Refs. [1] and [2]. Note that the program SUB.EXE changes the OPERA data file automatically.

The output data file from this transferring program, will not affect the constant C_1 but will give it a somewhat different meaning. When OPERA encounters a value of 2 in the first parameter, the C_1 constant is used only for retrofitting at the base year, when it will be subsidized, due to the coefficient calculated above. This subsidy will be subtracted from the total inevitable cost, which is elaborated in OPERA.

The expression for the external wall insulation cost which in Figure 3.1 is:

$$300 + 200 + 2,000 \cdot t_{ew}$$

will be changed into:

$$300 + 321 + 1,284 \cdot t_{ew}$$

The cost function has been calculated by calculating the cost for a number of insulation levels and afterwards by the method of least squares. The first values will be:

t_{ew}	Cost	t_{ew}	Cost
0.00	321	0.15	513
0.05	385	0.20	577
0.10	453	0.25	648

The costs for the window retrofits are reduced in the same way by the subsidies when first implemented in the building. All of these calculations are made in the FORTRAN program and only the reduction coefficient is transferred from SUBV.C via the input file.

Some equipment has to be changed more often like boilers or compressors in heat pumps. The simulation of these retrofits is made in a function called BOILVAL in the SUB.EXE program, see appendix C. The present value coefficient, called "precoe" in the program, is first calculated. Then it is used with the reduction factor, "red" for elaborating a factor which will be multiplied with the applicable costs. Each call to BOILVAL provides SUB.EXE with coefficients for both the boiler itself and the piping cost. When the oil-boiler is of concern the equipment is to be changed every 15 years. With a project life of 50 years and a discount rate of 5 %, the present value coefficient will equal 1.7655. The subsidized present value "SPV" could be calculated as follows, if "PV" is the present value factor and "re" is the reduction coefficient:

$$SPV = OB_c \cdot PV - OB_c + OB_c \cdot (1 - re)$$

which gives:

$$SPV = OB_c \cdot (PV - re)$$

If re equals 0.35 as calculated above, the SPV will become:

$$SPV = OB_c \cdot 1.4075$$

which is a reduction of the original present value with about 20 %. The boiler cost function is thus multiplied with the factor:

$$\frac{1.4075}{1.7655} = 0.7972$$

and the subsidized oil boiler cost will subsequently be:

$$OB_c = 43,850 + 47.8 \cdot P \quad \text{SEK}$$

where P = the thermal load of the boiler.

Note that if the life of the component is changed, this will affect the present value coefficient and subsequently the subsidizing factor calculated above.

5.1.3 Influence on the optimal strategy

The new file, called SUB.DAT, is designed as shown in Figure 5.7, but the operators do not have to edit the file on their own.

Running the program SUB.EXE will automatically transfer the original HOUSE.DAT file to a SUB.DAT. However, the operators must edit the file LOAN.DAT which can be found in Figure 5.6. This file informs the program of the applicable interest rates etc. The first value in the file SUB.DAT equals 2, showing that the file is supposed to reflect the subsidy system. Some of the values from Figure 3.1, have not been affected at all while others have been changed in liason with the above discussion. There are also values added to the original input data file in order to inform OPERA of the new situation. In the FORTRAN and C codes, presented in appendix A, B and C, the precise way of how OPERA deals with the subsidies is shown. Look for statements like "IF(LAN.EQ.2)" where these lines occur.

In Figure 4.2 the optimal strategy from an OPERA running without subsidies is presented. A natural gas system combined with triple-glased windows should be chosen. When the subsidies are included the strategy will be slightly changed, see Figure 5.8, and the total LCC will have decreased from 1.20 to 1.07 MSEK.

The heating system should be changed, not from the oil-boiler to a natural gas system, but the oil-boiler should be combined with a heat pump yielding a bivalent equipment instead.

In this case the subsidy system affected the proprietor's actions for the most profitable result, and a slightly changed strategy should be chosen. The building retrofit, however, was the same, i.e. tripleglazed windows were to be installed. Note that the LCC for the two competing systems was almost the same and in this case it is not possible to be certain of the best strategy because of uncertainties in the input data. Note also that not very many building retrofits were profitable to install as long as the optimal solution was chosen. When the subsidy system is utilized there is an increased number of retrofits found profitable in the other heating system strategies but not in the optimal one.

5.2 Interest rate subsidies

Another means for retrofit subsidies is the interest rate subsidies. The subsidy is paid even if the proprietor does not borrow any money at all, but in that case he must get money from elsewhere. As is the situation, when the renovation loan is utilized, a total loan is calculated. The building measures are combined with certain amounts that will influence the total loan. One example is the cost for the painting of the external walls, which may be added to the total loan. The amount is set to 35 SEK/m^2 and this value is to be multiplied with the valid time coefficient, which at present is 1.3. Some of the measures are assumed to be of ten years duration while others are supposed to last for twenty years. The total loan must thus be divided in two parts, one for ten year measures and one for twenty year measures, and the total loan is supposed to be amortized as shown in Table 5.3.

After, say 5 years, the total loan for measures of 10 years duration is assumed to have decreased to 68.89 % of the original amount.

Year	Total loan		Year	Total loan
	10	20		20
1	100	100	11	68.34
2	93.1	97.81	12	63.62
3	85.64	95.45	13	58.53
4	77.59	92.9	14	53.03
5	68.89	90.15	15	47.09
6	59.5	87.18	16	40.67
7	49.36	83.97	17	33.74
8	38.41	80.5	18	26.25
9	26.58	76.75	19	18.16
10	13.8	72.71	20	9.43

Table 5.3: Applicable rest of total loan, interest rate subsidy system

The interest rate for long term state finances is used for the subsidy calculations. During 1990, 0.4 % is added to the rate, which at present equals about 11.8 %, and 40 % of this new rate is paid out as subsidies, or about 4.7 % of the total loan. This value is used if the proprietor is the municipality and the like. If the landlord is a private person this rate is decreased with a further 2 %. The private subsidies is thus about 2.7 % of the total applicable loan.

If the original loan is 100,000 SEK for 20 years' measures, and if the proprietor is a private person, the subsidy at year number 9, which is paid by the state, yields:

$$100,000 \cdot 0.7675 \cdot 0.027 = 2,072 \quad \text{SEK}$$

Some 200 values exist within the system which may be added to the total loan. Several values can be lumped together e.g. painting of windows and implementing extra glazing. Other walues are constrained, e.g. external wall insulation where the maximum amount of insulation is set to 10 cm or a new U-value of 0.25 $W/m^2 \cdot K$.

It is obvious that the interest rate subsidies yield less profit to the proprietor than the renovation loans, and calculations of the present worths of the subsidies result in 18.8 % and 26.4 % as contributions from the government for ten and twenty year measures respectively. It was then assumed that the inflation was 7 % and the real interest rate 5 %.

Above, it is shown that the influence on the optimal strategy is minute from the renovation loans, which yielded a subsidy of about 35 %, and thus the influence will be even less when interest rate subsidies are considered. This subsidy system is subsequently not included in the program package.

5.2.1 Energy retrofit subsidies

At present this form of subsidies does not exist. The government has decided that no energy retrofit subsidies shall be paid before 1990-06-30, see Ref. [24] . In the rules for the subsidy system it is said that the subsidy shall not exceed 20 % of the total approved cost for the item subsidized. This means, however, that the subsidy is of the same size as the interest rate system dealt with above.

The influence on the optimal retrofit strategy will thus be very small even if the system were in full use, and thus it is not implemented here at all.

Year	To pay	Fixed prices	Present worth
1	7296	6819	6494
2	7670	6699	6076
3	8047	6569	5674
4	8427	6429	5289
5	8811	6282	4922
6	9200	6130	4574
7	9593	5974	4246
8	9990	5814	3935
9	10393	5653	3644
10	10802	5491	3371
11	11216	5329	3116
12	11638	5167	2877
13	12066	5007	2655
14	12502	4848	2449
15	12946	4692	2257
16	13399	4539	2079
17	13862	4388	1915
18	14335	4241	1762
19	14567	4028	1594
20	14505	3748	1413
21	14439	3487	1252
22	14367	3243	1109
23	14289	3014	981
24	14206	2801	868
25	14115	2601	768
26	14017	2414	679
27	13912	2239	600
28	13798	2075	529
29	13675	1922	467
30	13542	1779	412
31	13399	1645	362
32	13244	1520	319
33	13076	1402	280
34	12895	1292	246
35	12700	1190	216
36	12489	1093	189
37	12262	1003	165
38	12016	919	144
39	11750	840	125
40	11463	766	109

Sum of payments is	=	486,919
Sum of fixed prices is	=	145,093
Sum of present worths is	=	80,164

Figure 5.5: Transfer calculations for the first mortgage loan

```
30,40,25
.25,.70,.05
.12,.11,.15,.051,.0025
.08,.07
1.24
530.,0.2
530.,0.3
378.,0.3
378.,0.3
40.,1.6
210.
75000.,2.
110.
```

Figure 5.6: Input data file LOAN.DAT for subsidy calculations

```
2
273.00,273.00,616.00,819.00,
1.,0,2.8,27,1.,0,2.4,29
0.80,0.50,1.20,
3.5
0.,50.,0.,0.,0.
.6
'OIL-BOILER',110.,.75,5.
3501.,3502.,3503.,3504.,3505.,3506.,3507.,3508.,3509.,3510.,3511.,3512.
0.04,0.05,0.04,0.05,
2.
1.5
1.2
50.,50.,50.,50.,30.
50.00,0.05,0.00,0.358
0.00,166.95,340.31
0.00,244.00,321.05
300.00,321.05,1284.20
50.00,282.52,192.63,2.8,450.
0.,1100.
0.,1300.
0.,1500.
100000.,100000.
 43850.8,   47.8,0.75,15.0,  128.4,50.0
 14473.9,   72.4,0.95,25.0,    0.6,50.0
 28947.7,   43.4,0.95,25.0,  192.6,50.0
 38526.0, 2568.4,2.50,50.0, 1272.9,10.0
 41657.6,   45.4,0.80,20.0,  128.4,50.0
 31891.5, 4783.7, 66.43, 20.54,15.0,  133.5,40.0,0.10, 7.0
-.5,-.7,1.4,6.,11.,15.,17.2,16.7,13.5,8.9,4.9,2.
-2.9,-3.0,-.1,5.3,11.,15.4,17.7,16.4,12.2,7.1,2.7,.0
-12.2,-12.4,-8.9,-3.5,2.7,9.2,12.9,10.5,5.1,-1.5,-6.8,-10.1
56,250.,.1,10.
14,20.,21.,-14.
10000.,50.
 8486.2, 3818.8,10.0, 2.0,10.0
'UPPLAND 5'
1
1,0,0,0,0,0,0,1,1
4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.,4167.
4.3,8.94,18.57,28.82,44.5,53.48,50.54,36.63,23.12,13.54,5.82,3.08
8.27,17.97,41.86,61.97,87.58,90.91,89.07,75.07,53.11,28.3,10.75,5.36
29.66,43.69,73.68,75.29,82.59,76.28,78.5,79.81,79.37,61.57,32.7,21.22
8.27,17.97,41.86,61.97,87.58,90.91,89.07,75.07,53.11,28.3,10.75,5.36
.1,.6,.7
.233
.3658357,0.515,0.245
.175,120.
.2763422,300.,700.,2400.,600.,.64
.195,.195,.195,.145,.145,.145,.145,.145,.145,.145,.195,.195
830.,1030.,1230.,1640.,2060.,2380.,2900.,3520.,4300.,5420.,6760.,8400.
16.,20.,25.,35.,50.,63.,80.,100.,125.,160.,200.,250.
352,320,368,320,368,352,336,368,336,352,352,336
392,352,376,400,376,368,408,376,384,392,368,408
6000.,55.,245.
.405,.256,.218,.202,.179
```

Figure 5.7: The file "SUB.DAT" which presents retrofit subsidies to OPERA

*** LCC TABLE FOR BASE CASE 1.00 ***
VALUES IN MSEK

	EXIS. SYST.	NEW OIL	ELE. HEAT	DIST. HEAT	GR.W HEAT	NAT. GAS	TOU DIST	TOU ELEC.	BIV. GR.HP	BIV.O. AIR HP
NO BUILD. RETR.	1.46	1.49	1.67	1.41	1.22	1.18	1.41	1.67	1.15	1.30
SAVINGS:										
ATTIC FL. INS	.03	.03	.05	.02	.00	.00	.02	.06	.00	.01
FLOOR INS.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
EXT. WALL INS.	.08	.08	.14	.07	.00	.00	.06	.15	.00	.02
INS. WALL INS.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TRIPLE-GLAZING	.13	.13	.15	.13	.11	.10	.13	.15	.10	.11
TRIPLE-GL. L.E.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TR.-GL. L.E. G.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
WEATHERSTRIP.	.01	.01	.02	.01	.00	.00	.01	.02	.00	.00
EXH. AIR H. P.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
SUM. OF RETRO.	1.22	1.24	1.30	1.18	1.10	1.08	1.18	1.29	1.06	1.16
SUM. OF COMB.	1.22	1.24	1.31	1.19	1.13	1.08	1.19	1.30	1.06	1.17
DISTRIBUTION:										
SAL. OLD BOILER	.00	.02	.02	.02	.02	.02	.02	.02	.02	.02
NEW BOIL. COST	.06	.06	.02	.03	.12	.05	.03	.02	.12	.20
PIPING COST	.00	.00	.00	.01	.17	.01	.01	.00	.10	.00
ENERGY COST	.49	.49	.59	.46	.36	.54	.45	.58	.45	.27
CONNECTION FEE	.00	.00	.00	.01	.00	.01	.01	.00	.00	.00
BUIL. RETROF. C	.55	.55	.57	.55	.28	.28	.55	.57	.19	.56
INEVITABLE COST	.12	.12	.12	.12	.19	.19	.12	.12	.19	.12

Figure 5.8: LCC table presented by OPERA, subsidies included

Chapter 6

SOLAR CALCULATIONS

It is mandatory to provide OPERA with values for the amount of solar radiation transferred through the windows of the building. The values, located in the input data file, see Figure 3.1, show how much heat, in kWh/m^2, that is transferred per month through one m^2 of a doubleglazed window, and for each of four different directions. The orientation of the windows must not necessarily be north, east, south and west but for the sake of simplicity this is assumed. Thus 48 values have to be implemented in the file.

However, experience showed that these values were not very easy to calculate, at least not from information found in literature easily available in Sweden. One method for energy balance calculations, called the BKL-method [32], provides solar radiation values but there are no algorithms for actually calculating this amount. Therefore, it is necessary to implement values taken from a number of tables presented. If the orientation and the location of the building site do not coincide with the ones presented, one must interpolate between the values written in Ref. [32]. The values are specially calculated for the BKL-method, where only radiation for a few days a month actually is calculated. Further, they use a FORTRAN program implemented in a big computer, UNIVAC, which is not in common practice. BKL, however, has a greate advantage because it can calculate the influence of shading obstacles.

Also in another method, described in Ref. [33], a big computer was used, and only one day per month was actually calculated.

A third program, see Ref. [34], is written in BASIC and calculates the energy balance for a building. There is, however, a solar radiation routine implemented, which calculates the radiation transferred through a window.

The programs above could of course be changed to be run in any computer, but the output is not suitable for direct implementation in OPERA. There was therefore a need for a PC-program which could provide applicable solar radiation values. The program also had to be fast, easy to use and portable between different computers without reediting the source code. It was also important that no manual calculations were necessary.

6.1 The SORAD program and how to use it

The source code, written in C for portability and fastness, is presented in appendix D. It is based on facts and theories found in Refs. [33], [35], [36], [37], [38], [39] and [40]. Reference [40] is recommended to readers interested in all the details of solar radiation calculations. The program SORAD is split in three parts, one called "main" and the other two, which work as functions to "main", called "direct" and "transm". The first part of the program opens the suitable input data file, called SUN.DAT, where all the necessary input data are stored, see Figure 6.1.

```
56. 90. 90. -2.0
3.1 3. 6.2 5.5 7.6 6.5 5.2 5.2 5.6 3.8 1.8 2.
19.2 16.4 13.4 11.6 8.1 8.4 8.8 9.6 9.1 14.4 18.8 21.1
```

Figure 6.1: Input data file SUN.DAT for solar calculations

The first value shows the latitude, called "lat" in the program. The value must be expressed in degrees, (360 degrees in a full circle), and 56 degrees is the latitude of Malmö, Sweden. The second value presents the azimuth, "azyta" in the program, of the window, i.e. the angle between the normal of the window and the south. A window with its frames directed to the east and west has the azimuth 0 or 180 degrees. In this case the azimuth is set to 90 degrees.

The angle between the normal of the surface and the horizon is called "b" in the program, see appendix D, but β in the text in accordance with the references, and β is set to 90 degrees showing that the window is vertical, see Figure 6.2.

Since April 1999 local time is calculated and presented for the times when the sun rises and sets. In order to calculate this the longitude is necessary as input data. For Malmö this is about 13 °E. The time meridian in Sweden is 15 °E and therefore a value of -2.0 is shown in the "sun.dat" file.

The next line in the input file shows the number of clear days for each month, while the third line presents the days overcast. The values are found in Ref. [33] and are applicable for Malmö in Sweden. Note that there is no "," between the values as is common in FORTRAN input data files, but instead a " " or a space. The values are stored in an array called "typer[2][12]", see appendix D. Note that the version of SORAD for Windows makes it easier to change these values.

The function called "direct" is used for the solar calculations while values for the total month are calculated in the main program. When the amount of radiation that hits the window surface has been calculated, a second function is called, calculating how much radiation is transferred through one window pane. The calculations in the first functions are mostly based on information in Ref. [36] while Ref. [35]is used as a reference for transfer calculations.

The program is started by typing "SORAD" after the program package has been copied into the hard disk of the PC or just click on the solar icon for the program. Just be sure that the program and the input data files are in the

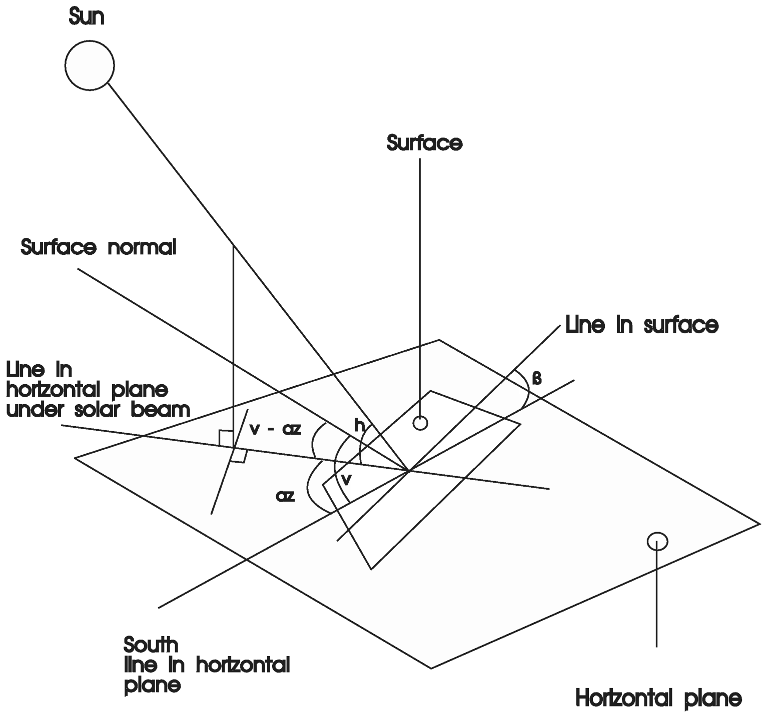

Figure 6.2: Names of the angles in solar calculations, see Ref. [37]

same directory. The calculations end when the three cases, clear, half clear and overcast days, have been elaborated for every day of the year. The output from the program is five tables shown in the following figures:

Note that the Windows version of this program does not work exactly like this, see section 6.3. The first table shows the solar radiation every hour for the chosen clear day, see Figure 6.3. The next two ones presents the same result but for half-clear and overcast days. The total radiation at the outside and inside of the window, for each month and for each of the day types, is presented in Figure 6.4.

The sums of the total transferred radiation through a double-pane window are shown in Figure 21.

Put the values in Figure 21 into the data file of OPERA, as shown in Figure 3.1. Note that the values in Figure 3.1 and Figure 6.5 are not identical, due to recent changings in the SORAD programmming code.

6.2 The details of solar calculations

Above is shown how to use the SORAD program for calculating the solar values which have to be part of an OPERA session. However, nor is the information sufficient for full understanding of the solar program, and neither has it been

CLEAR DAYS
CALCULATIONS FOR DAY NO 15

True solar time (h)	Eleva-tion angle (deg]	Solar azimuth angle (deg]	Solar radia. IDN (W/sq.m]	Beta angle (deg]	Solar radia. IDN1 (W/sq.m]	Diffuse radia. sky (W/sq.m]	Diffuse radia. ground (W/sq.m]	Total radia. outside (W/sq.m]	Total radia. inside (W/sq.m)
9	3.9	-41.3	0.0	131.2	0.0	5.9	2.8	8.6	7.0
10	8.7	-28.1	0.0	117.8	0.0	16.0	10.4	26.4	21.2
11	11.7	-14.3	0.0	104.0	0.0	22.1	15.5	37.5	30.2
12	12.8	0.0	608.5	90.0	0.0	27.9	17.2	45.1	36.3
13	11.7	14.3	586.8	76.0	141.6	31.0	15.5	188.1	116.7
14	8.7	28.1	502.5	62.2	234.2	27.8	10.4	272.4	214.2
15	3.9	41.3	240.8	48.8	158.7	12.0	2.8	173.4	146.7

The sum of the total outside radiation day no. 15 equals 751.5 Wh/sq.m.
The sum of the total inside radiation day no. 15 equals 572.2 Wh/sq.m.

Figure 6.3: Output from the solar radiation program SORAD.EXE day number 15, clear day

described elsewhere. The chapters below are written for those of the readers who want to make enhancements in the code. A thorough description is therefore made.

6.2.1 The position of the sun

This part of the program is dealt with in the function "direct", see appendix D, and the first thing to do is to calculate the solar declination, i.e. the angle between a line through the sun and the earth, and a plane through the equator at noon for the true solar time. This means that the sun exactly is facing the south. In order to convert solar time to local time two corrections have to be made. First, the longitude of the site must be considered and then, the equation of time which shows the influence of perturbations in the earth's rate of rotation, see Ref. [40]. The expression for calculating the declination has been, see Ref. [36]:

$$\delta = \arcsin(-0.3979 \cdot \sin C_1)$$

where:

$C_1 = C_2 + 0.0334 \cdot sinC_2 + 1.78128$, $C_2 = 0.017214 \cdot (DA - 2.8749)$ and DA = the number of the day during the year. The author to Ref. [36], however, refers to Heindel W. and Koch H.A. " Die Bereschung von Sonneneinstrahlungsintensitäten für Wärmetechnische Untersuchungen im Bauwesen", Gesundheits-Ingenier 97, 1976.

There are also other expressions that can be used and the authors to Refs. [32] and [41] seem to have used the same references viz. Spencer, J.W. "Fourier Series Representation of the Position of the Sun", Search, Vol. 2, No. 5, May 1971. Further information about different methods for finding the true solar position could be found in Ref. [42] where several methods are compared.

As is said above, day number 15 is shown explicitly when the program is run, and thus this day also is used as an example here. The values above will become:

$C_1 = 0.2087$, $C_2 = 1.9969$ and δ = - 0.3707

SOLAR RADIATION IN kWh/SQ.M. AT THE OUTSIDE AND THE INSIDE OF THE WINDOW						
Month	Clear days		Half-clear days		Overcast days	
nr	Outside	Inside	Outside	Inside	Outside	Inside
1	25.0	18.6	14.8	11.0	2.6	1.9
2	45.9	36.1	27.5	21.6	4.7	3.7
3	89.5	72.4	54.3	43.9	9.3	7.5
4	124.4	102.1	76.0	62.3	12.9	10.6
5	155.4	128.3	95.6	78.8	16.2	13.4
6	162.7	134.0	100.3	82.5	16.9	14.0
7	161.4	133.3	99.4	82.0	16.8	13.9
8	139.9	115.2	85.7	70.5	14.5	12.0
9	102.1	83.2	62.1	50.6	10.6	8.7
10	65.8	52.4	39.6	31.6	6.8	5.4
11	31.5	24.0	18.8	14.3	3.2	2.5
12	17.9	12.9	10.5	7.6	1.8	1.3

Figure 6.4: Total solar radiation at the outside and the inside of a one pane window for each month and type of day

Note that all the angles are calculated in radians.

The next thing to do is to elaborate the position of the sun due to the time of day. In Ref. [39] the following expressions occur:

$$sin\,h = sin\phi \cdot sin\delta + cos\phi \cdot cos\delta \cdot cos\,t \tag{6.1}$$

$$cos\,h = \frac{cos\delta \cdot sin\,t}{sin\,az} \tag{6.2}$$

$$cos\,h = \frac{-cos\phi \cdot sin\delta + sin\phi \cdot cos\delta \cdot cos\,t}{cos\,az}$$

where: h = the elevation angle, i.e. the solar height, az = the azimut angle, i.e. the horizontal angle, t = the hour angle of the sun and ϕ = the latitude angle on the earth surface.

When the sun passes the horizon the angle h equals zero and if this is inserted in the first of the three expressions 6.1 above, the result will be:

$$cos\,t = -\frac{sin\phi \cdot sin\delta}{cos\phi \cdot cos\delta}$$

It is thus possible to calculate the angle of time at sunrise or sunset. Inserting the values above for δ and ϕ, equalling - 0.3707 and 0.9773 which is 56 degrees in radians, results in a time angle of 0.9565 radians monitored from the true south direction. Each hour corresponds to 360/24 = 15 degrees = 0.2618 radians of the total circle and this means that the sun will rise 3.65 hours before, and set 3.65 hours after the true solar noon or at 8.35 and 15.65. Note that time

SOLAR ENERGY THROUGH A TWO PANE WINDOW The normal of the window directed 90.0 degrees clockwise from the south	
Month no	Energy kWh/sq.m
1	5.51
2	11.43
3	30.50
4	44.66
5	66.45
6	67.01
7	64.15
8	53.89
9	39.57
10	19.78
11	6.72
12	3.28

The program has now come to its end

Figure 6.5: Solar radiation transferred through a double pane window for each month

is written in the decimal format. Since April 1999, local time for sunrise and sunset are also calculated. Malmö is sited at 13 °E. Swedish local time is set after 15 °E and thus 2 ° differ. It takes $2 \cdot 24 \cdot 60/360 = 8$ minutes in order for the sun to rise compared to true solar time. The time equation used here was found in Ref. [40] page 11:

$$E = 229.2(7.5 \cdot 10^{-5} + 1.868 \cdot 10^{-3} \cdot \cos\ B - 3.2077 \cdot 10^{-2} \cdot sin\ B -$$

$$1.4615 \cdot 10^{-2} \cdot cos\ 2B - 4.089 \cdot 10^{-2}\ sin\ 2B)$$

where B = (n-1) · 360/365, and n = the number of the day of the year.

There is now an interval with possible sunshine on the earth and the program will calculate the solar radiation between 8.35 and 15.65 this day. However, at 8.35 the radiation is zero and thus the calculation starts at 9.00. At this hour the hour-angle equals - 0.7854 radians, i.e. 3 hours of 15 ° before the true solar noon. Using expression 6.1 once again for the new hour angle makes it possible to calculate the elevation angle at 9.00. Inserting this angle in expression 6.2 also yields the azimut angle. The angles become in radians:

h = 0.0682 and az = - 0.7216

6.2.2 The solar radiation flux

At the outer limit of atmosphere the irradiation from the sun is about 1400 W/m^2 see Refs. [9] or [43]. In fact the extra terrestrial radiation differs between 1300 - 1400 W/m due to the solar - earth distance see Ref. [40]. However, because of the angle of incidence, atmospheric conditions etc. this value must be decreased before the radiation hits the earth surface. There are a number of different suggestions for calculating this decrease, see e.g. Refs. [34] or [40]. Here a method found in Ref. [36] is used, and the author in his turn refers to

Rodhe B., "Calculated values on global radiation at clear days", The Swedish Hydrological and Metrological Institute, 1977. The expression is:

$$I_{DN} = rd \cdot A \cdot e^{-\frac{BB}{\sin h}}$$

where: I_{DN} = the solar irradiation on the earth surface perpendicular to the solar orientation, rd = a coefficient that depends on the distance between the earth and the sun, A, BB = constants showing the regression of measured irradiation, 991.64 and 0.09143 respectively and h = the hour angle of concern, in radians.

The coefficient rd above has been calculated for each month over a year and they vary slightly around 1.0, see Ref. [36] or the variable "rco[12]" in the programming code, appendix D.

The result from the solar irradiation calculations day number 15 can be found in Figure 6.3.

6.2.3 Calculations for a tilted surface

A window is not normally oriented in a way that the solar radiation hits the window at optimal conditions, i.e. the solar incidence and the normal of the surface do not coincide. The angle between the normal of the surface and the solar radiation must thus be calculated, and further it must be ascertained that the sun actually shines on the window front side, and not on the back where the building is.

In the case studied here, the surface azimute was set to 90 degrees which means that the normal of the window is oriented directely to the west. It is determined in the input data that the frame of the window is vertical as normal in an external wall. The azimut for the sun at 9.00 is - 0.7216 radians which equals - 41.34 degrees and thus the sun will shine on the back of the window, or on the other side of the building. Not until the solar azimut becomes greater than the surface azimut minus 90.0 degrees, the sun shine reaches the outside of the window. At 9.00 the radiation will thus become zero, see Figure 6.3.

At noon the sun has moved so far that it reaches the window, and at 13.00 the azimut angle for the sun will equal 14.26 degrees. In the program, see appendix D, there is a routine for different cases of azimut angles for the surface and the sun, the difference between them and further if the sun is shining on the front of the window or not.

In [36] the incidence angle towards a tilted surface is presented as:

$$cos\, i_{\beta} = sin\, h \cdot cos\, \beta + cos\, h \cdot sin\, \beta \cdot cos\, \gamma$$

where i_{β} = the incidence angle, β = the angle between the ground and the tilted surface, and, γ = the difference between the solar azimut and the surface azimut.

Inserting the applicable values for day number 15 and 13.00, i.e. h, β and γ equalling 0.2044, 1.5708 and -1.3219 respectively, will yield the angle, i_{β}, equalling 1.3272. All the values are in radians. The methods used in Refs. [34] and [41] are similar to the one used above.

The tilted surface will also decrease the solar radiation on the surface, and this must be noted according to the following expression:

$$I_{DN1} = C_1 \cdot I_{DN} \cdot cos\, i_{\beta}$$

With the values above, and C_1 which is a coefficient for clouds described below equalling 1.0, I_{DN1} will become 154 W/m^2.

6.2.4 Direct and diffuse solar radiation for different types of days

Up to now only the direct solar radiation has been taken into account. There is also a diffuse part, partly from the sky and partly from reflected direct radiation from the ground. In [36] the diffuse radiation is also considered to be influenced by the angle of direction. Very cloudy days this influence is minute but clearer days this has to be accounted for. The total solar radiation is thus calculated as:

$$I_{T\beta} = I_{DN1} + I_{d\beta} + I_{d\beta r}$$

where: $I_{d\beta}$ = the diffuse radiation from the sky and $I_{d\beta r}$ = the diffuse radiation reflected from the ground

In [36] it is also shown that use of so called Cloud Cover Factors makes it possible to model the irradiation also during cloudy and half clear days. The diffuse solar irradiation for one day, $I_{d\beta}$, is thus calculated as:

$$I_d\beta = I_{dH} \cdot (1 + C_1 \cdot (2f - 1) \cdot sin^2\beta) \cdot 0.5 \cdot (cos\ ha + cos\beta)$$

where: $I_{dH} = (C_3 + C_2 \cdot sin\,h) \cdot I_{DN}$, ha = the horizontal shadowing angle, from other buildings etc, $f = 0.55 + 0.437 \cdot cv + 0.313 \cdot cv^2$, $cv = cos\ h \cdot cos\gamma$ and C_1, C_2, C_3 = Cloud Cover coefficients.

The value of f above is called the Threlkeld factor, which must exceed 0.45, and thus a limit is set in the program. I_{dH} is the diffuse solar radiation on a horizontal surface.

The coefficients C_1 to C_3 are presented as found in Table 6.1:

	C1	C2	C3
Clear days:	0.9	0.2	0.04
Half clear days:	0.52	0.38	0.032
Overcast days:	0.1	0.35	0.016

Table 6.1: Cloud Cover coefficients see Ref. [33]

The reflected solar radiation from the ground is assumed to be totally diffuse and in Ref. [36] the following expression is presented:

$$I_{d\beta r} = rm \cdot (2 - cos\ ha - cos\beta) \cdot I_{TH}$$

where: rm = the reflection factor of the ground, $I_{TH} = I_{DH} + I_{dH}$, and $I_{DH} = C_1 \cdot I_{DN} \cdot sin\,h$, i.e. the irradiation on a horizontal surface.

In Figure 6.3 are shown values on some of the above parameters, and for 13.00 and rm = 0.2, they are in W/m^2 :

$I_{DN} = 586.8$ $\quad I_{DN1} = 141.6$ $\quad I_{d\beta} = 31.0$ $\quad I_{d\beta r} = 15.5$

6.2.5 Transmittance of solar radiation through windows

When calculating the solar radiation transfer through the window panes, differences if direct, diffuse or reflected radiation are of concern. The calculations are elaborated in a special function called "transm()", see appendix D, and the arguments sent to the function are the incidence angle and the absorbation coefficient for the glass type of the window. This coefficient is set to 0.07 in the first lines of the function direct() described above. The procedures of calculation follow the ones found in Ref. [35].

The transmittance of direct solar radiation through a window depends mainly on the incidence angle of the sunlight. Some of the light is instantly reflected, some is absorbed in the window pane and some is transferred through the pane.

When the solar radiation hits the window surface the light is polarized in two components, one parallel to the incidence and reflection plane and one perpendicular to it. In Ref. [35] it is shown that the reflection factors for the two types of radiation can be explained as:

$$r_\pi = (\frac{nf^2 \cdot cos\, i - (nf^2 - \sin^2\, i)^{0.5}}{nf^2 \cdot cos\, i + (nf^2 - \sin^2\, i)^{0.5}})^2$$

$$r_\sharp = (\frac{cos\, i - (nf^2 - \sin^2\, i)^{0.5}}{cos\, i - (nf^2 - \sin^2\, i)^{0.5}})^2$$

where: r_π = the parallel reflection coefficient, $r_\sharp$ = the perpendicular reflection coefficient and i_β = the angle between the incidence line and the normal of the window pane, see above, and nf = refraction index, = 1.52 for air to glass.

The two coefficients are closely related and:

$$rt = \frac{r_\pi + r_\sharp}{2}$$

where rt = the total reflection factor defined as:

$$rt = \frac{I_r}{I}$$

where: I_r = The reflected part of the solar radiation and I = The radiation through the window.

In the program, see appendix D, the coefficients are calulated in the beginning of the function named transm(). The function is only called upon for those hours when the sun is actually shining on the window. Some values are shown below, for 13.00 day number 15 i will equal 76.0 degrees, see Figure 6.3, nf equals 1.52 and thus:

$$r_\pi = \frac{-0.613}{1.727} = -0.355 \quad \text{and} \quad r_\sharp = \frac{-0.928}{1.411} = -0.658$$

When the solar radiation hits the window surface one part is reflected and one is transmitted. Some of the radiation is then absorbed in the glass and the window pane will thus get warmer. The absorbed part of the radiation is calculated as:

$$\alpha = (1 - rt) \cdot (1 - e^{\aleph})$$

where: $\aleph = \frac{af \cdot s \cdot nf}{nf^2 - sin^2\, i)^{0.5}}$, af = the absorbed fraction of transferred radiation, and s = the thickness of the glass pane in meter.

The coefficient α has different values for the two directions of polarization, and thus it is possible to calculate:

$$\alpha_\pi = 0.076 \quad \text{and} \quad \alpha_\sharp = 0.049$$

this when: $af \cdot s = 0.07$.

When the solar radiation hits the other surface of the window pane the radiation is reflected again and partly absorbed and so on. These reflections are decreasing as a geometrical series and the resulting coefficient will be:

$$R_r = r + \frac{r(1-r)^2 \cdot (1-\alpha)^2}{(1-r^2) \cdot (1-\alpha)^2}$$

In the same way coefficients for the absorbation and for the transmission are developed:

$$A_\alpha = \frac{\alpha \cdot (1-r) \cdot (1 + r(1-\alpha)}{1 - r^2 \cdot (1-\alpha)^2}$$

$$T = \frac{(1-r)^2 \cdot (1-\alpha)}{1 - (r^2 \cdot (1-\alpha)^2}$$

The calculations are to be utilized for the two cases of polarization and the mean value must then be calculated. The following values are calculated by the program:

$R_\pi = 0.209$	$A_\pi = 0.075$	$T_\pi = 0.716$
$R_\sharp = 0.585$	$A_\sharp = 0.047$	$T_\sharp = 0.368$
$R_m = 0.397$	$A_m = 0.061$	$T_m = 0.542$

where the indices m stands for mean value. Note that all the sums R+A+T equal 1.00, a fact that is examined in the program.

The diffuse radiation is dealt with in almost the same way but the angle of incidence is calculated somewhat differently. In Ref. [33] the following expressions are presented:

$$i_{es} = 59.68 - 0.1388 \cdot \beta + 0.001497 \cdot \beta^2$$

$$i_{eg} = 90 - 0.5788 \cdot \beta + 0.002693 \cdot \beta^2$$

where i_{es} and i_{eg} are the incidence angle from the sky and from the ground respectively and β the angle between the ground and the tilted surface. When β equals 90 degrees the two values above will become 59.31 and 59.72 degrees respectively.

The total amount of heat, finally transferred through the window, is then calculated as found in Ref. [33]:

$$W = I_{D\beta} \cdot (T_D + nm \cdot A_D) + I_{d\beta} \cdot (T_{d\beta} + nm \cdot A_{d\beta}) + I_{d\beta r} \cdot (T_{d\beta r} + nm \cdot A_{d\beta r})$$

where: $nm = m_o/(m_o + m_i)$.

m_o and m_i are the convection heat transfer coefficients on the outside and the inside respectively. Values from the example above are:

$$W = 141.6 \cdot (0.541 + 0.3 \cdot 0.061) + 31.0 \cdot (0.78 + 0.3 \cdot 0.07) +$$
$$+15.5 \cdot (0.78 + 0.3 \cdot 0.07) = 116.7 \quad W/m^2$$

6.2.6 Half-clear and overcast days

Under an earlier heading the solar radiation heat flux during halfclear and overcast days was discussed. The calculations above are thus repeated but now for these other types of days. In Figure 6.4 the resulting values are presented for a one pane window, and now only the number of different type days for each month during the year must be decided. In Table 6.2 some values are presented and the solar transfer for January is thus calculated as:

$$W_{Jan} = \frac{18.6 \cdot 3.1 + 11.0 \cdot 8.7 + 1.9 \cdot 19.2}{31.0} = 6.12 \quad W/m^2$$

Month	Clear	Overcast	Month	Clear	Overcast
January	3.1	19.2	July	5.9	8.8
February	3.0	16.4	August	5.2	9.6
March	4.3	13.4	September	5.6	9.1
April	5.6	11.6	October	3.8	14.4
May	7.6	8.1	November	1.8	18.8
June	6.5	8.4	December	2.0	21.1

Table 6.2: Number of clear and overcast days in Malmö, Sweden

The values in Figure 6.4 are valid for a one pane window and they must be reduced in order to show the solar radiation transfer for a two-pane ditto. In Ref. [33] it is shown that this can be done by a so called shading coefficient and it is found that about 10 % more of the solar radiation is reflected and absorbed for two-pane windows than for the first type. The value 6.12 above shall thus be multiplied by 0.9 and the resulting solar heat transfer during January will be 5.51 W/m^2 , see Figure 6.5.

6.3 Simplified flow chart of the SORAD program

In Figure 6.6 a simplified flow chart is shown over the SORAD program.

The calculations start in the main() program. After setting proper type definitions for the variables, the file SUN.DAT is opened. Values are read until the end of file, EOF, mark is encountered.The horizontal shadowing angle,ha, is set to 0.0 degrees and the reflection factor, rm, is set to 0.2. The program then runs into the for()-loop where constants are set for the different type days, see Table 6.1. The next for()-loop sets the applicable number of days in the month

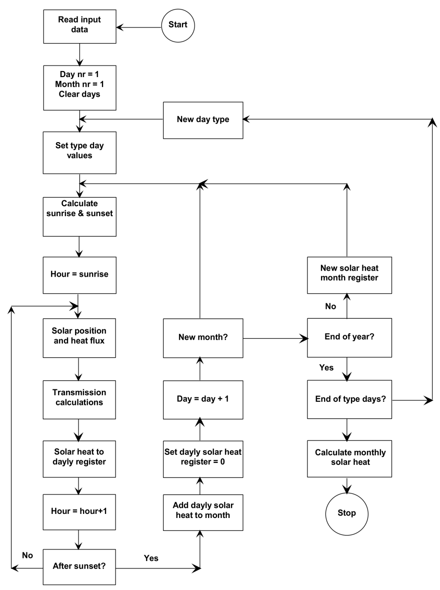

Figure 6.6: Simplified flow chart of the solar radiation program

of concern and the return value from the direct()-function is stored in the array mansum[ ][ ].

The rest of the main()-program mostly prints out the tables shown in Figures 6.3, 6.4 and 6.5.

In the direct()-function the first calculations deal with the solar position for different hours. The first for()-loop takes care of the applicable day of the month and the declination is calculated in the first lines in the loop. The different angles for the solar calculations are elaborated, and a routine considering sun shine on the window front is entered. The direct and diffuse radiation are then calculated and the function transm() is called where the transmission and absorbtion coefficients are returned by a pointer. The transm()-function is called three times for each hourly calculation, showing the coefficients for direct, diffuse and reflected solar radiation.

6.4 The Windows version of the SORAD program

In the Windows version you do not have to use the text editor at all. Instead of using e.g. Notepad it is possible to change the input data by use of dialog boxes. One dialog is used for the input angles and the number of the day which the operator wants to study in more detail. This number have been added as a fourth value of the first line in Sun.dat. Note that the value must be an integer. The other dialogs are used for the number of clear and overcast days. The full output from the program is redirected to a file Sunut.dat which may be studied in e.g. Notepad. Only the final table is presented on the screen.

Chapter 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 Refs. [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 7.1.

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, 1990, three papers have been published, see Refs. [46], [45] 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,

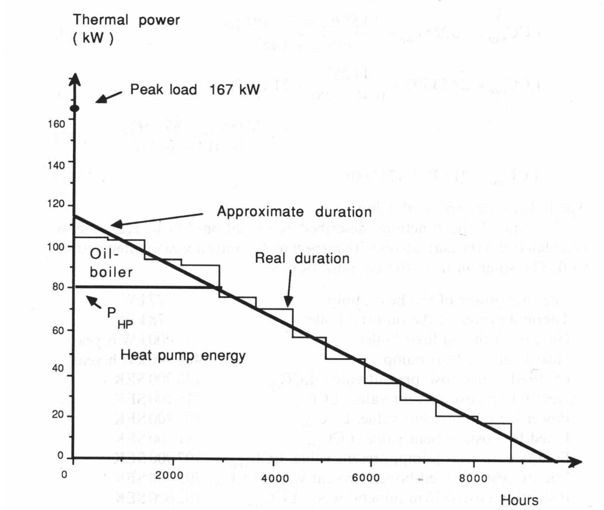

Figure 7.1: Derivative and discrete model for optimizing, see Ref. [45]

and further not to a severe change in the LCC, but the optimal sizes of the oil-boiler and the heat pump are miscalculated.

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 heading 3.18.4 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 4.1. An extra 0.075 meter of insulation will decrease the coefficient to:

$$1602 - 616 \cdot 1.2 + \frac{616 \cdot 0.04 \cdot 1.2}{0.04 + 1.2 \cdot 0.0754)} = 1089.6\,\frac{W}{{}^\circ C}$$

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 3.1 and [2] for a closer explanation.

The window retrofits will decrease the transmission coefficient as:

$$1089.6 - 2.8 \cdot 27 \cdot 1.5 - 2.4 \cdot 29 \cdot 1.5 = 871.8\,\frac{W}{{}^\circ C}$$

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 4.1. 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 7.2.

Note that the peak load is calculated to 46.4 kW according to the Swedish Building Code.

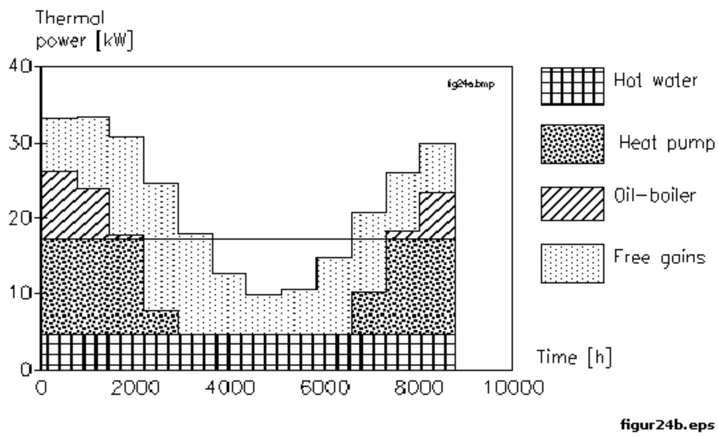

Figure 7.2: Graph showing thermal load, free energy and distribution between the oil-boiler and the heat pump. The heat pump size is set as found in the OPERA optimization

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 7.2.

7.1.2 The heating equipment cost

The cost for the heating equipment is calculated by the expressions 2.1 and 3.4. The heat pump will cost:

$$(60000 + 5000 \cdot 17.18) \cdot 1.0 = 145900\, SEK$$

where 60 000 is the C_1 constant in 3.4, 5 000 is the C_2 constant,17.18 is the heat pump size and 1.0 is the present worth factor calculated from 2.1.

In a similar way the oil-boiler cost will be:

$$(55000 + 60 \cdot (46.4 - 17.18)) \cdot 1.7656 = 100203\, SEK$$

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:

$$1500 \cdot 17.18 \cdot 2.3642 = 60925\,SEK$$

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

$$200 \cdot (46.4 - 17.18) \cdot 1.0 = 5844\,SEK$$

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:

$$\frac{0.233 \cdot 6741}{0.75} = 2093\,SEK$$

and for February:

$$\frac{0.233 \cdot 4590}{0.75} = 1426\,SEK$$

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:

$$\begin{aligned}
392 \cdot 17.18 \cdot 0.245/2.5 &= \text{660 SEK, low price January} \\
352 \cdot 17.18 \cdot 0.515/2.5 &= \text{1 245 SEK, high price January} \\
358 \cdot 17.18 \cdot 0.245/2.5 &= \text{602 SEK, low price February} \\
320 \cdot 17.18 \cdot 0.515/2.5 &= \text{1 132 SEK, high price February}
\end{aligned}$$

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

$$\frac{17.18 \cdot 1000}{380 \cdot 3^{0.5}} = 26.1A$$

where 380 is the voltage between the three conduction phases.

The electricity 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 found in Tab. 7.1:

The costs above must be multiplied with the present worth factor calculated with the expression 2.2, which in this case equals 18.26. The total energy cost will thus be:

$$(830 + 5381 + 6121 + 6213) \cdot 18.26 = 338595\,SEK$$

		Electricity cost	
Month	Oil 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

Table 7.1: Energy costs for different months

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 3.2 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:

$$616 \cdot 200 + 616 \cdot 2000 \cdot 0.0754 = 216092\, SEK$$

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 3.3. In this case, one of the constants equals zero and then the cost for the two retrofits will be:

$$27 \cdot 2.8 \cdot 1300 + 29 \cdot 2.4 \cdot 1300 = 188760\, SEK$$

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, see Tab. 7.2:

The value of the total LCC found by OPERA, i.e. 1 328 695 SEK, differs very little from the LCC in Table 7.2, where the optimal point from OPERA is the base for a discrete calculation.

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

Table 7.2: The contents of the LCC in SEK for the OPERA optimal point, calculated with a discrete method

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 found in 7.3:

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

Table 7.3: Optimal LCC in SEK. Discrete optimization

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.

7.1.6 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 Ref. [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 7.3.

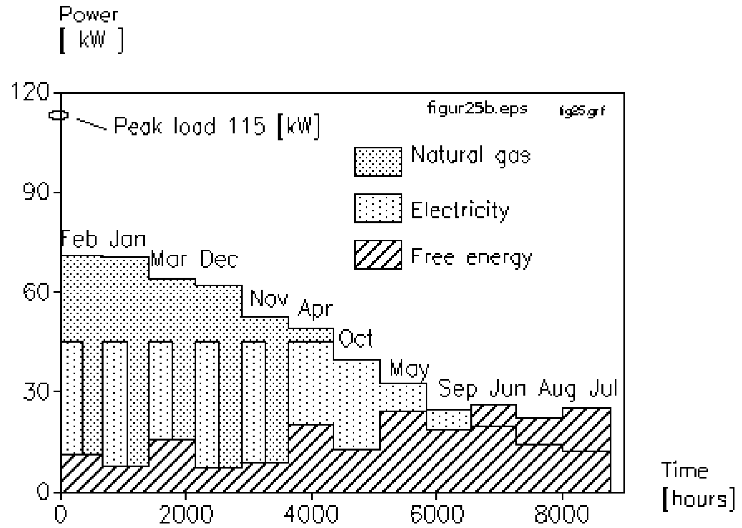

Figure 7.3: Graph showing the thermal load, free energy and distribution between an oil-boiler and a heat pump. Oil heat is cheaper than heat from the heat pump under high electricity price conditions, see Ref. [47]

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 Ref. [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 oilboiler solely.

Chapter 8

GRAPHIC ROUTINES

The OPERA model does not contain graphic 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, graphic interpretation is sometimes useful and then the program GRAPH.EXE is used. With it, 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 3.1. 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 one value in kWh, see Figure 3.1. (Note that new versions use twelve values)

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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