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THE OPERA MODEL

Optimal Energy Retrofits in Multi-Family Residences

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Chapter 1

The OPERA MODEL

1.1 Akademisk avhandling

Akademisk avhandling som för avläggande av teknisk doktorsexamen vid Tekniska högskolan i Linköping kommer att offentligt försvaras i sal C3, Universitetet i Linköping, onsdagen den 1 juni l988, kl. 10.15. Fakultetsopponent är professor Gunnar Anderlind, Gullfiber AB, Helsingborg.

1.2 Abstract

A mathematical model, called OPERA (Optimal Energy Retrofit Advisory) has been developed in order to find the optimal energy retrofit strategy for each unique multi-family building. The optimal solution is characterized by the lowest possible life-cycle cost.

Input to the model are e. g. the geometry of the building, the building and maintenance costs for envelope as well as installation measures, climate conditions, economical parameters and the price of energy. Insulation measures, window retrofits, weatherstripping and exhaust air heat pumps are dealt with concerning the building envelope and the ventilation system. Ordinary heating equipment, such as oil-boilers, as well as more complicated systems e. g. district heating with time-of-use rates and bivalent heating systems, are treated. In these bivalent systems heat pumps provide the base load and oil-boilers the peak load.

The model is equipped with an energy balance routine which is used for the existing building, For each retrofit consideration and For the optimization procedure. Proper account is thus taken to the influence of solar gains and free energy From appliances et c. The energy balance procedure is also used for finding the proper amount of degree hours for insulation measures as well as the heating equipment. Two different values must be used which are influenced by the retrofits concerned.

A case study is also described and a sensitivity analysis is elaborated in order to find out if the found optimal solution will vary with small changes in input data.

From a number of cases some general conclusions can be drawn. A low running cost heating system is essential for a desirable result. District heating with rates that reflect the short range marginal cost are very competitive as well as bivalent heating systems. Heating systems, like these that combine a low running cost with an acceptable installation cost, make almost all of the envelope retrofits unprofitable. Only attic floor insulation and weatherstripping are thus common parts of the optimal solution. More expensive retrofits, like external wall insulation, can compete only if the remaining life of the asset is very short, i. e. if something has to be done to the wall for other reasons than energy conservation. Consequently it is very important to implement the op- timal solution when these situations occur. There is a severe risk that the suboptimized system will not be profitable to change again.

KEYWORDS: Retrofits, Buildings, Optimization, Installations, Heat pumps, Insulation, Windows, Weatherstripping, Heating systems.

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Chapter 2

PREFACE

During the first years of this decade the division of Energy systems at the University of Linköping, tried to find out how to build a single-family house in the best way. The best solution was to be characterized by the lowest possible cost for the owner, during the total life of the building.

This research lead to a thoroughly insulated building equipped with a very simple heating system. The heat in the building was distributed by air provided by the ventilation system. No radiators were needed because also the windows had sufficient thermal insulation level.

Since this concept was elaborated several thousands of houses have been built according to these ideas.

Encouraged by these results the interest was emphasized on how to retrofit extsting multi-family buildings. The aim was to find the best strategy in order to minimize the total cost for the building during its remaining lifetime.

In April 1985 a research project was initiated in order to find the best solution and the result is among other things, this thesis. The project has been funded by the Swedish Council for Building Research and the Municipality of Malmö, Sweden, who should be acknowledged for this.

I am very grateful for the support from the Seven Builders Group in Malmö, which has contributed substantially to the outline of the OPERA model here dealt with, (OPERA is an abbreviation of OPtimal Energy Retrofit Advisory). Among the members of the group I shall especially mention Lennart Strömvall, Egon Lange and Claes Alfredsson who took special interest in the moodel and have run it in spite of its shortcomings concerning manuals and so forth. Several buildings in Malmö have thus been the subject for OPERA runnings and much experience has been gained from this. I want to thank Gunnar Andersson, responsible for the NORD computer on which the computer program was developed. Without his help the project would have been severely delayed. I am also much indebted to my colleagues at the division of Energy Systems who have shared with me their wisdom. Finally I wish to thank my mentor Professor Björn Karlsson for his support and encouragement during these years. Without him this thesis never had come into existence.

Linköping in March 1988

Stig-Inge Gustafsson

Chapter 3

NOMENCLATURE

A_{loan}	The total loan	(SEK)
A_n	Area of building part number n	(m^2)
A_w	Area of one window	(m^2)
a	Number of years	(Years)
B	The cost for a retrofit measure	(SEK)
b	Project life	(Years)
BA	Dwelling area	(m^2)
C	Annual recurring cost	(SEK)
$C_{1,2,...}$	Constants	(1)
COP	Coefficient of performance	(1)
COP_{mv}	Coefficient of performance, mean value	(1)
cp	Heat capacity for air	(J/kg°C)
D	Dimensioning load, district heating	(W)
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)
H	Distance between the floor and the ceiling in an apartment, or basement	(m)
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)
n	The number of the month. value et. c.	(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)
R	Reduction factor	(1)
r	Discount rate, inflation excluded	(%)
RN	Number of air renewals	(1/h)
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_*	Optimial thickness of insulation	(m)
TOD	Total energy demand	(J/year)
T-O-U	Time-of-use rates	
TRANS	The transmission value	(W/K)
T_i	The desired inside temperature	(°C)
$T_{s,n}$	The monthly mean outside temperature	(°C)
U_{eq}	Equivalent U-value	(W/K$\times m^2$)
U_{ex}	Existing U-value insulation measures	(W/K$\times m^2$)
U_n	U-value for part number n	(W/K$\times m^2$)
U_{new}	New U-value insulation measures	(W/K$\times m^2$)
U_0	Existing U-value	(W/K$\times m^2$)
VENT	The heat loss from ventilation	(W/K)

Greek:

δT	Temperature difference	(K)
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)

Contents

Chapter 4

INTRODUCTION

In the beginning of this decade the division of Energy Systems at the University of Linköping was trying to find the best way to build new single-family houses. During this research some basic ideas about buildings emerged:

- Buildings constitute investment like any other subject with a high capital cost. Thus they can be dealt with in the same way as other investment and the profitability can be elaborated with commonly used economical theories.
- Buildings normally have a very long life and should be compared with other long life investment.
- It is the total cost of the investment that is of interest. This means that it is necessary to consider, not only the initial capital cost, but also the following maintenance and running costs.
- An almost perfect means to evaluate buildings is the so called Life-Cycle Cost, LCC. Future investment or annual recurring costs are transferred to a base year by the present va1ue method.
- The different alternatives can, if the LCC method is used, be compared with each other and the best one is the one with the lowest LCC.

The implementation of these aspects in the construction of new houses leads to a thoroughly insulated building, equipped with an air-to-air heat exchanger and a very simple electric heating systetm installed in the ordinary ventilation system.

However, some years ago the production of new buildings in Sweden decreased. The emphasis of the building activity was instead laid on retrofitting the existing housing stock, [1] p. 9. The society encouraged this and by use of the subsidiary system, for financing the building costs, it was possible to influence the retrofit strategy. The problem however, was to find the most desirable solution.

In Sweden energy conservation measures, e. g. attic floor insulation, are subsidized. The is will result in a lower energy demand in the retrofitted building. However, also complicated heating systems, e. g. a heat pump, are subsidized which will provide the heat required in the building to a very low cost. Due to the now heavily insulated building this new heating equipement will probably be turned off for long periods of time.

From the society's point of view, the heat puemap will not be profitable due to the low amount of energy it delivers. However, the insulation will probably also lose its profitability because the saved energy is so cheep. It is obvious that the subsidiary system, will lead to suboptimations in such cases. (The loans and grants for separated energy conservation measures, in single-family houses, were abolished in 1984 [2] p. 35.

In order to reach the best solution it is also very important that the producer of the heat or electricity informes the consumer of the real coast. This cost must also include environmental drawbacks.

However, up to now, there was no method or tool present that enabled finding and optimal solution without a very tedious itererative process.

The Swedish Council for Building Research and the municipality of Malmö in the south of Sweden, thus funded a research project in order to elaborate such a method. This thesis is one result of this project.

Due to the subsidiary systaem the energy aspect nowadays has to be considered when the building has to be renovated, at least if the most advantageous subsidies will be utilized. However, 30 years must pass between the subsidized renovations. Thus it is very important that the subsidiary rules and the building codes et c. are elaborated so, that they reflect the most profitable solution from the national point of view, i. e. the cheapest strategy should be implemented, considering all the resourses of the country.

In [3] it is shoown that the Life-Cycle Coast. LCC. i. e- the sum of the total remaining building-, maintenance- and running costs for the building, is a very good means for evaluating different retrofit strategies. The perfect strategy is distinguished by the lowest possible LCC. No other strategy or retrofit measure implemented to the building can lower the LCC. If this is the fact, both for private and national econoemic evaluation, the solution will be perfect.

In [3] it is also shown how the problem can be elaborated from a mathematical point of view, using the teminology from [4] or [5] The problem can be characterized as a nonlinear, mixed, integer program. Such problems, however, cannot be solved with ordinary programming methods in commercial use today. Methods used to piece- wise linearize the nonlinear parts of the problem, e. g. [4] p. 352 have only solved these difficulties to a part. This is so because integer problems have to be solved using e. g. the branch and bound method described in [4] p. 154-, which can not find the solution with and absolute accuracy.

However, the main work is to evaluate all the parameters in the mathematical problem. The optimization process can be elaborated rather easy and thus the ordinary programming methods have been rejected. Instead a FORTRAN program has been developed called the OPERA - model (OPtimal Energy Retrofit Advisory). This program is implemented in a NORD 570 machine which solves the base case problem in about 30 seconds. Derivative methods are combined with direct search procedures, which are described in detail in this thesis. Using this method the true minimum point always can be discovered.

It shall be noted here that the main work has been laid on elaborating the OPERA model. Of course also a big effort has been made in order to find proper input data to the model and a representative building for the analysis but it has to be remembered that it is the mathematical methods and programming that is the most important. The input parameters differ from building to building and each unique house will have a unique optimized retrofit strategy. Of course similar buildings will have most of the retrofits in common but the aiem of this thesis is not to find the optimal renovation procedure for all buildings, but instead to show that it is *possible* to find it.

It is also essential to remember that only energy related retrofit measures are dealt with. Aesthetical or other reasons for a retrofit are not discussed at all. It should also be possible to consider the measures and the consequences in monetary terms, which is to say they could affect the lCC.

4.1 HYPOTHESIS

It is possible to find the best combination of retrofit measures for each unique existing building. The best solution is assumed to be characterized by the lowest possible life-cycle cost for its remeaining life.

4.2 LITERATURE SURVEY

This thesis deals with a mix of three different, traditionally separated subjects:

- Retrofitting of buildings
- Life-cycle costing
- Optimization

The retrofit subject is often divided into one field related to the building envelope and one related to installation. In each of these different subjects there is a lot of literature but almost nothing treating the entirety. In [3] a survey is presented of the literature found at the end of 1986.

In fact no author had dealt with the mix of the three subjects above in the same work and none has been found since.

At the U.S. Department of Commerce/National Bureau of Standards in Washington D.C., NBS, a lot of work has been done, dealing with LCC and buildings. Mostly, however, new buildings are treated, but there are also reports about retrofitting. Unfortunately, these reports are not dealing with the optimization procedure at all.

In [6] several works about life-cycle costing are presented, all elaborated at the NBS. From the ones studied, [7], [8], [9], [10] and [11] give a very good view about the life-cycle costing subject and show why the LCC is a good means to evaluate different kinds of buildings.

There are also discussions in these studies about the impact of e. g. differences in the energy prices and the discount rate. A users guide to a computer program evaluating LCCs for different buildings is also included. However, no optimization process is involved and thus the LCC has to be calculated for a lot of building- and installation measures and the meost profitable solution has to be selected from, a number of alternatives. Further, the building is not considered as an energy system which probably will make us miss the aiem, i. e. to find the lowest possible LCC.

Other works about LCC can be found in the proceedings from some CIB conferences (Conseil International du Batiment pour la Récherche, l'Etude et la Documentation). In the 1984 conference there is one paper about LCC and retrofitting, [12], where the LCC for retrofits implemented to a single-family house are calculated. The retrofit strategy is decided due to minimized LCC but also here only a number of retrofits are tested, mainly for the building envelope. By a trial and error procedure some selected retrofits were choosen, if they were found profitable, and the LCC was calculated. However, no changes were considered on the heating system and the most profitable solution might have been to inastall a heat pump instead of using the original heating system. No real optimization has thus been made.

In [13] this was carried out, but for a new single-family building. A number of different constructions were tested, including envelope and installation measures, and after some calculations a solution was found. However, the paper dealt with a new building and not with retrofitting an old one.

The CIB 85 conference also dealt with LCC, but none of the presented papers treated retrofits or optimization [14].

At the CIB 1986 conference 11 papers about LCC were presented, but only one treated retreofitting of multi-family residences,[15].

The 1987 conference presented several papers on LCC. However, they discussed the subJect from a more principle point of view, e. g. [16] which treated the history and future of LCC. Other authors dealt with the risk analysis, [17], [18], comparisons with other economic evaulation methods, [19], and the importance of proper economical parameters, [20], [21]. One author dealt with optimization, [22], but for new governmeent office buildings.

In [23] the author treats insulation optimization, similar to how it is dealt with in this thesis, and he also elaborates the use of cost penalties due to misoptimization. However, only insulation measures are treated and the paper emphasizes the economic theories more than the optimal thickness of insulation.

One author deals with LCC from a more principle point of view and gives a brief review of problems and benefits with this method. He also emphasizes the difference between the life of a building material and the useful life of it. Mineral wool has a very long life but the building where it is implemented may have a very limited remaining life which has to be considered in the analysis [24].

There are also other papers written about LCC, some of them mentioned in [3], but no paper has been found dealing exactely with the subject in this thesis, though many are closely related to it.

There is very much written about optimization techniques and here [4], [5], [25] and [26] are used to find proper procedures in order to solve the problem. However, no perfect solution has been found examining the algoritms achievable on the market. It has been tried to implement the problem into the LAAMPS program, which solves linear and integer problems, using the linearization methods in [4] and also examined the OPTIVAR programming system [27] and [28]. Those systems are elaborated to solve mathematical problems and you have to start with ar very strict mathematichal expression. The major problem however, turned out to be not the optimization but to define the proper problem. Then the optimization could rather easily be implemented in the ”problem generation program”.

A considerable amount is also written about retrofit design, e. g. [29], but most authors deal only with part of the building, like how to find the best HVAC system, and they do not try to find the perfect solution for the total energy system of the building. In [30] a computer program called CIRA is described, dealing with energy retrofits. However, the authors rank the different retrofits in order to their saving-to-cost ratio. They also only deal with the thermal envelope and do not consider the importance of the proper heating equipment, The program works, for the envelope retrofits, in a similar way as OPERA, it tests the result for a number of different retrofits and calculates the energy balance for the building. However, the remaining life of the existing building parts are not taken into account which leads to suboptimizations. Due to these and other reasons, the program will not find the optimal solution for the building energy system.

A Swedish model that works almost in the same way is the MSA - model [31]. The model, which does not optimize the retrofit strategy, has however one big advantage, it can calculate the result of energy savings for the total Swedish building stock, and thus it was used in the so called Energy - 85 study for Sweden.

There are also other drawbacks with CIRA and MSA. They can not handle differential rates or bivalent systems. This is very unfortunate because these systems often seem to compete in the optimal solution. The models only deal with a constant energy price. Of course it is possible to run the programs many times but it is not easy to make correct presumptions about the applicable energy price from such heating systems. The amount of extra insulation will also influence the proper design of the heating system which aggravates the problem.

The fact is that this thesis shows that using the MSA or CIRA may lead to severe misoptimizations, even for ordinary heating systems as the oil-fired boiler, if they are used without expert knowledge about energy system optimization. This is due to the ranking of the retrofits in order to their saving-to-cost ratio. In MSA or CIRA weatherstripping will almost always be a proper retrofit because it is the cheapest one. They will not consider the fact that it could be cheaper to invest in an exhaust air heat pump, which takes care of the extra ventilation flow if the windows and doors are left as they are. The exhaust air heat pump has a higher saving-to-cost ratio. However also MSA or CIRA might choose the heat pump, but a smaller one than the optimal, due to the decreased ventilation flow.

One paper that deals with traditional optimizing methods and retrofits in buildings is [32]. However, only a few retrofits are dealt with and there is only one heating system taken into account. The optimization is worked out in order to find the lowest possible LCC but no energy balances are calculated and this might of course lead to misoptimization.

A lot of work has been done in order to find proper retrofit costs, energy prices, economic parameters et. c. and some of the 95 references in [3] concern such problems. In the following chapters it is referred to those and others. and thus they are not treated here. Several attempts have been made by the Swedish Institute of Building Documentation. BYGGDOK, to increase the amount of adequate information about this subject, but the result is rather poor. If this is due to weak searching procedures or to a lack of research and publications on the subject is not easy to tell but extensive work has undoubtedly been sacrificed to this.

The following data bases have been examined:

- BODIL
- BRIX
- BYGGFO
- DOE Energy
- NTIS
- COMPENDEX
- INSPEC
- IBSEDEX
- Conference papers index

Since 1987 monthly examinations have been elaborated by BYGGDOK, financed by the Swedish Council for Building Research.

In [33] the lack of information is mentioned and the author writes: "The technical barriers are due to the lack of information on the cost and performance of individual retrofits, as well as the more complex issues of how individual retrofits interact with each other and perform over time". The author presents a bibliography with some 150 references about retrofits but they only treat parts of the subject and thus some of them is referred to in subsequent chapters. This is also the case of the references in [34], where about 500 works about building equipment are presented.

Chapter 5

THE OPERA MODEL

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

Below a very simplified flow chart is presented, see Figure 5.1, showing the principle method of the OPERA model.

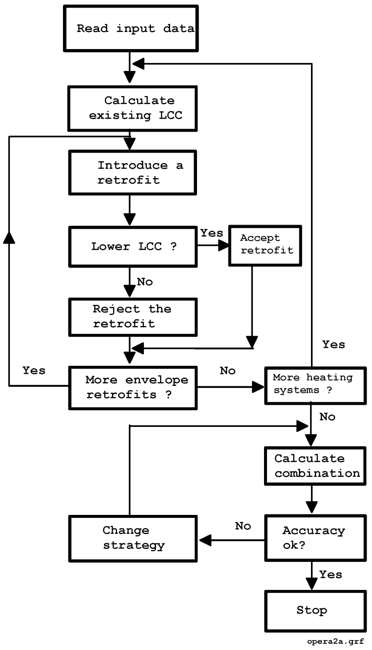

Figure 5.1: Principle flow chart. OPERA model.

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

All the costs are transferred to one base year, using the present value method, see Appendix 3, page 102, and thus LCCs for any different alternative can be compared. The model thus starts reading the input data, e. g. the building geometry, the thermal status of the building et c. and proceeds with calulating the existing building LCC. This value shows the cost for implementing only the inevitable retrofits to the building. Such a retrofit can be to change the windows if the old ones are rot. The new ones are then of the same type as the old ones concerning their energy performance.

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

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

The heating system is now changed and the procedure starts almost from the beginning. A new LCC with no building envelope measures is calculated, and after this the retrofits are implemented. The procedure continues and finally all possibilities are tested and the solution with the lowest estimated LCC is selected. In order to find the real best solution, within an accepted accuracy, a more thorough study must be elaborated. This procedure is presented below, page 44.

Reference [3] describes how different retrofits can be optimized due to the lowest possible LCC. In that work there is also information about the evaluation of building and installation costs, and references to authors dealing with that subject. The model, or the FORTRAN code, is not presented, and it nor is fruitful to do so here. Still, it is necessary to describe the model in detail because it must be possibile to scrutinize. This is done in the following chapters and also in Appendix 3, page 101, where some of the subroutines are presented.

5.1 CALCULATION OF THE EXISTING BUILDING LCC

The aim of the retrofits is to make the remaining LCC for the building as low as possible. However, implementing a retrofit can also make the LCC higher, which of course must be avoided. The savings from a decreased energy use might be lower than the building- or installation cost for an improvement of e. g. an external wall insulation. In order to examine this, the existing LCC for the building must be calculated initially. All the considered retrofits shall later be compared to this existing LCC. If the LCC is lower after the retrofit is implemented the retrofit shall be chosen, otherwise not, see Figure 5.1.

Subroutines are commonly used for frequent calculation procedures and the OPERA model has several subroutines following the main program.

For calculating the existing building LCC, five subroutines are used:

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

The presentation of these subroutines can be found in Appendix 3.

The main program starts with reading the total input file for the building, see Figure 5.2. In this file the geometry, thermal status, climate, building costs et c., concerning the building, are described. In a separate chapter, page 30. the input data are discussed and a complete input data list is presented in Appendix 2 at page 91.

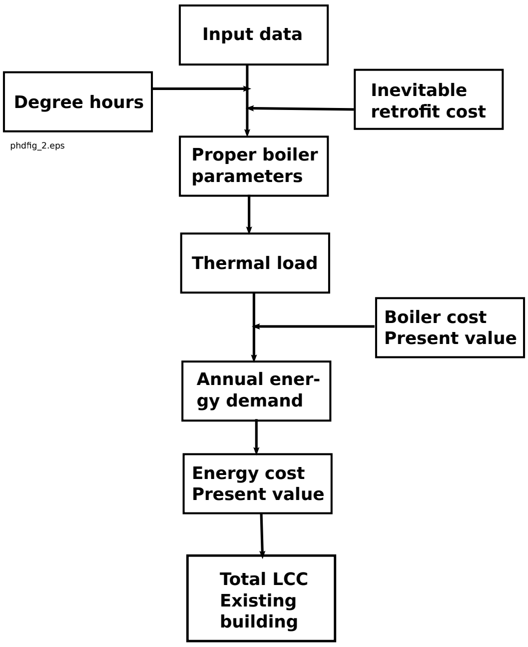

Figure 5.2: MAIN program, flow chart, part 1.

The program proceeds, after some minor calculations, by calling the subroutines for degree hours and inevitable retrofit cost calculations. The first routine presents the number of degree hours, assuming that one unit is generated if the monthly mean outside temperature is lower than the desired inside temperature during one hour. The second routine presents the inevitable retrofit cost, as a present value, for the existing building. See Appendix 3, page 101, for more details.

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

The energy demand for the building is calculated using the energy balance subruotine, another subroutine provides the program with the proper energy price and by use of formula (12.3), page 102 in Appendix 3, the total energy cost is elaborated for the chosen optimization period.

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

5.2 OPTIMAL STRATEGY, EXISTING HEATING SYSTEM

The building and ventilation retrofits in the OPERA model are:

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

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

For the windows a number of different constructions are evaluated. This because of the immence difficulties of optimizing a window due to solar gains, number of panes, the distance between them and so forth. Here it is beyond the scope to optimize such a construction and it is questionable if this is possible at all. Some of the difficulties are discussed further in detail in [3] p. 65-. The problem is also dealt with in [35].

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

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

It is important to note the fact that the candidates might fall out from the optimal solution. This might occur if the LCC is not a linear function due to the thermal losses in the building. A decrease in the energy demand must correspond to the same decrease in the LCC whether the retrofit is implemented in the beginning or the end of the graph in Figure 5.3.

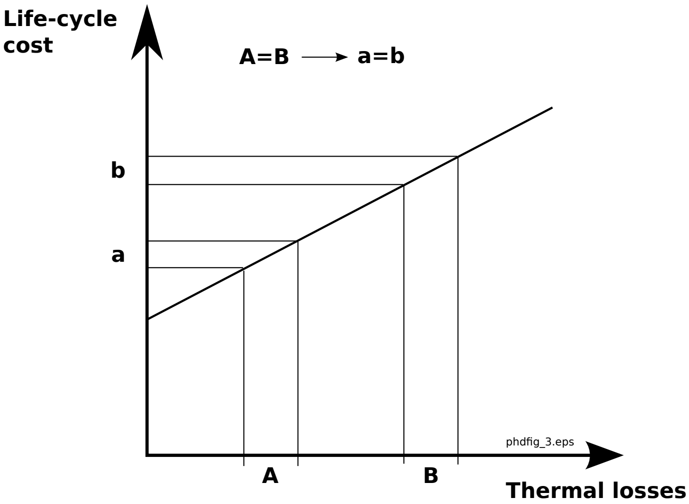

Figure 5.3: Optimization due to LCC function

If this is the fact, the order of the implementation does not matter, else there might be different optimal strategies for identical measures. In reality this problem might occur due to e. g. the habit of manufacturing heating equipment in discrete sizes, but the influence of this is neglected here. If the optimization problem, for some reason must deal with this, the optimal solution found by OPERA must be scrutinized in detail. However, the errors in the input parameters make such an analyzis very hazardous.

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

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

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

The procedure stops when all the possibilities have been tested and after this the best solution is selected. This solution is presented in further detail by the program and a table is shown of the LCC for the different heating systems without the envelope retrofits, the amount of savings and the new LCC, if the optimal, or the almost optimal strategy is implemented. In Table 6.2 at page 42 this is shown.

5.2.1 Envelope retrofits

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

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

These subroutines are presented in Appendix 3, page 101.

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

After this the insulation optimization starts. Using the energy balance subroutine, the thermal losses are calculated for the building, with the building part under consideration excluded. This is convenient because the LCC for the rest of the building can be considered as a constant. The energy balance will probably show that, due to solar gains and free energy from appliances, the heating equipment can be turned off during a part of the year. This part of the heat loss, is subtracted from the total heat loss in the building, and will provide the suitable number of degree hours for insulation optimization. During summer when the heating equipment is turned off there is no reason for saving energy. When the heating season starts the situation is different. Each unit of energy is now valuable, no matter how it is produced. It is worthwile to save energy even if it comes from e. g. solar gains. If there was no free energy the heat had to be produced by the heating system and thus also part of the amount of free energy is valuable. The situation is of course different when the heating system is to be optimized. The heating system does not work at all when the desireable inside temperature can be obtained from free energy. The number of degree hours is thus less for the heating equipment considerations. The subject is discussed in detail in [36]. See Table 6.6 at page 46 for an example of the energy balance.

After that, an expression is developed showing the life-cycle energy cost for the building part considered. However, there is also a contribution from the heating equipment cost, due to the insulation thickness, which must be added to the LCC expression. The situation can be depicted by the following expression, Equation (5.1):

$$LCC = C_1 + C_2 + C_3 \times t + \frac{C_4}{C_5 + C_6 \times t} \tag{5.1}$$

where:

C_1 = The costs independent of the building part concerned,
t = The insulation thickness,
$C_2 + C_3 \times t$ = The insulation cost and
$\frac{C_4}{C_5 + C_6 \times t}$ = The energy and heating equipment cost.

Using the fact that the minimum LCC can be found by calculating the derivative to the expression (5.1) and setting it equal to zero, provides the following equation:

$$t_* = -\frac{C_5}{C_6} \pm \left(\frac{C_4}{C_3 \times C_6}\right)^{\frac{1}{2}} \tag{5.2}$$

The subscript * on t shows that this is the optimal thickness of insulation for the retrofit concerned. The formula (5.2) is elaborated in Reference [3] p. 46.

From expression (5.2) it is obvious that C_1 and C_2 do not influence on the optimal thickness of insulation. Implementing the optimal thickness in (5.1) will provide a LCC but this will not be correct due to the high amount of degree hours used for the optimization. Thus a new energy balance is calculated and this time the heat produced by the heating equipment is used for calculating proper energy- and heating equipment costs. using the situation for the retrofitted building as a whole. The procedure and the evaluation of these expressions are described in detail in Reference [3], although slightly changed according to the theories in Reference [36].

In figure (5.4) the process is shown schematicly.

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

5.2.2 Weatherstripping

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

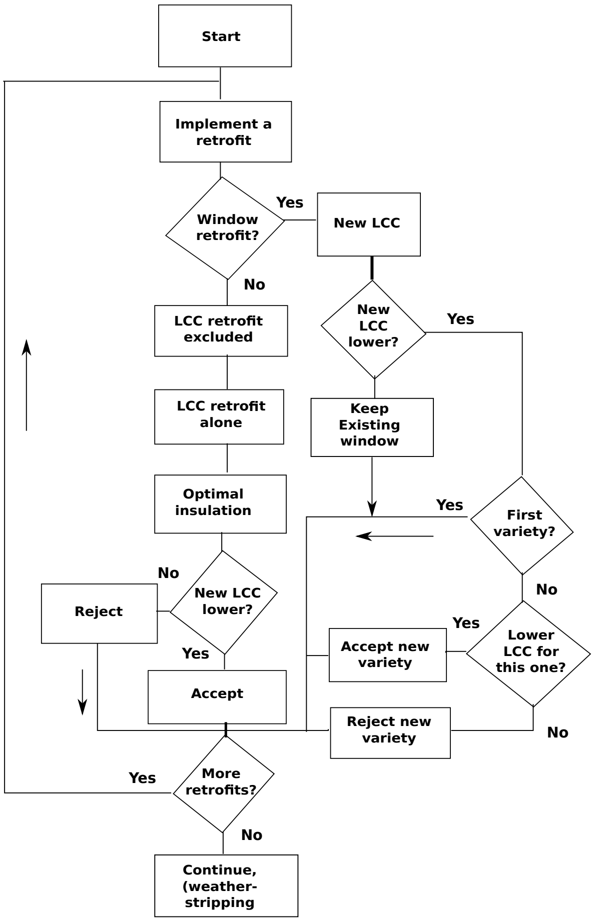

Figure 5.4: Simplified main program flow chart. Part 2.

The money saved by caulking measures can be calculated by using equation 12.5, page 101, in Appendix 3, the value of $VENT$ will get lower. However, weatherstripping costs money and only if the amount of money saved is higher than the money spent the measure is profitable. In most cases this is the fact because caulking is rather cheap and the influence on the ventilation flow can be considerable. The OPERA model compares the LCC after the weatherstripping has been implemented with the earlier calculated LCC for the existing building.

5.2.3 Exhaust air heat pump

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

The OPERA model evaluates the profitability of the heat pump, i. e. if the LCC gets lower, assuming the weatherstripping was profitable. This means that the ventilation flow will be lower than the existing flow and thus less heat can be taken care of in the exhaust air. However, the model also tests if it is more profitable to reject the weatherstripping and spend the money on a slightly bigger exhaust air heat pump. In Reference [3] p. 135, such cases can be found. The energy balance subroutine is used to evaluate the proper amount of heat recirculated through the building. In Reference [3] all the input data are discussed and more details can be found in the case study starting at page 37 in this thesis.

5.2.4 Exhaust air heat exchangers

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

5.3 OTHER HEATING SYSTEMS

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

Most multi-family buildings in Sweden, now concerned for retrofit measures, were originally equipped with a central oil-boiler heating system, but lately this system has been changed to e. g. district heating in many areas. Sometimes a more complicated system, like a heat pump is installed which provides the heat at a very low running cost. This running cost is approximately 0.25 SEK/kWh for the oil-boiler and 0.30 SEK/kWh for electricity. Heat pumps have a coefficient of performance, COP, of approximately 3 which means that they deliver heat 3 times the electricity input. Subsequentely the running cost for the heat pump is about 0.1 SEK/kWh. District heating systems and bivalent oil-boiler - heat pump systems have a running cost which is between that of the single oil-boiler and the heat pump systems. In Appendix 1, page 79, this is discussed in detail.

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

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

However, some of the heating systems provide lower running costs but at higher installation costs. A heat pump system, with the lowest running cost, is very expensive and thus the high installation cost cannot compensate for the low running cost. It is important to note that the actual heat pump design is not optimized by OPERA, but the model calculates the best thermal size of it. Authors that have treated the design problem are e. g. References [30] and [31].

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

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

In Reference [37] the influence of the installation cost and the running cost, on the envelope strategy, is shown for different systems, and here will only be discussed thorougly two of the heating systems above, viz. heating systems with differential rates and bivalent heating systems. Ordinary heating systems are treated in Reference [3].

5.3.1 Heating systems with differential rates

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

The same discussion can be elaborated for producing electricity, the base load is produced by hydro electrical plants and the peak load by gas turbines. In References [38], [39] and [40] this is treated in detail.

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

In Reference [41] it is shown that it is not very easy to design a rate that will advantage top peak saving and at the same time disadvantage competing energy producing facilities such as solar panels or exhaust air heat pumps. The rate also has to be normalized which means that the utility cannot increase the total level of the rate. The income of the plant thus will be the same no matter what type of rate is used for an identical thermal load. Because of this, the differential rates used in Malmö, and in this thesis, will only slightly encourage top peak saving but will give considerable disadvantage to competing energy production at the consumer during the summer.

The OPERA model uses the differential rates elaborated by the municipality of Malmö for the calculations. This is done in a subroutine, page 104. By some programming work it is easy to implement other rates than the default ones, and the differential rates can be compared to the fixed rates. If the new rates in their design are similar to the Malmö cases it is possible to implement the rates in the input file concerning the subroutine. In References [41] and in [3] p 109-, the calculations are described. See also page 63 in this thesis.

5.3.2 Bivalent heating systems

As mentioned above a bivalent heating system can often be a very good solution for minimizing the LCC. The systems treated in the OPERA model are oil-boiler - heat pump systems where the oil-boiler takes care of the thermal peak loads and the heat pump the base load. The difference between the systems depends on the heat source. The first alternative uses a fixed COP, while the other system is evaluated using a varying COP due to the outside temperature. There are also some differences concerning the installation cost calculations. In Reference [42] it is shown how the first system is optimized for the existing building thermal load and furthermore when insulation measures or other retrofits are implemented. The second system is described in Appendix 1, page 79.

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

$$LCC = C_1 + \frac{C_2}{C_3 + C_4 \times t} + C_5 \times P + \frac{C_6 \times P^2}{C_7 + C_8 \times t} + \frac{C_9 \times P^2 \times t}{C_7 + C_8 \times t} + C_{10} \times t \quad (5.3)$$

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

The expression 5.3 above shall be minimized and in the OPERA model this is done by a derivative method. However, it is not very easy to calculate the minimum point and thus the sign of one of the derivatives is examined and the minimized LCC is found by an iterative process. Also in this case it is important to use the proper amount of degree hours for the optimization. The insulation thickness is subsequentely optimized for more degree hours than the heat pump - oil-boiler system. The model is also provided by a maximum number of iterations, 500, because the shape of the expression might be very flat at the bottom. A small change in t might change the derivative less than the significance in the computer memories. This is so even if double precision is used for some sensitive parameters.

Figure 5.5 shows, using the situation found in Reference [42], how the LCC varies due to the insulation thickness and the thermal power of the heat pump. With no extra insulation at all, the minimum point of the LCC is located to

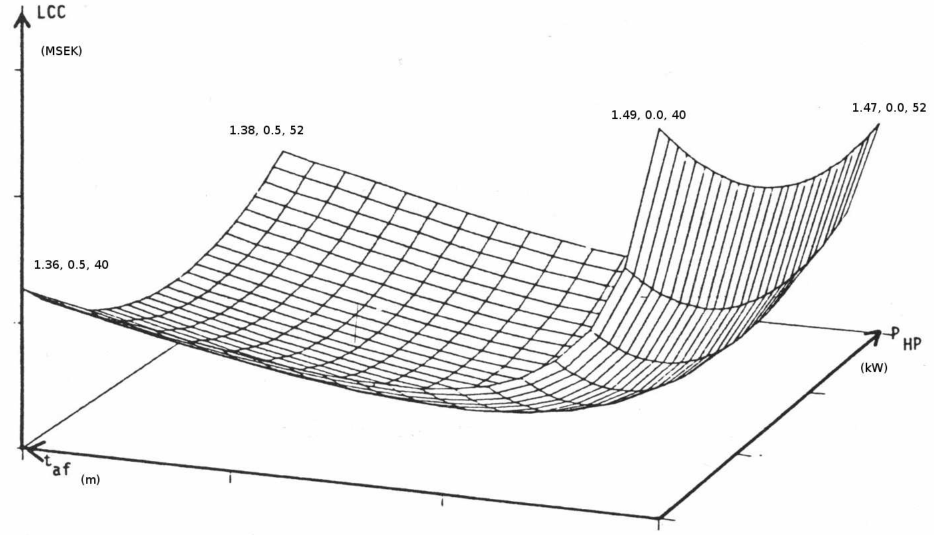

Figure 5.5: LCC field for bivalent system and insulation.

52 kW thermal power of the heat pump while the other extreme is located, for a very large amount of extra insulation, to 40 kW. This represents a situation when no heat at all transfers through the building part considered. However, the minimum LCC thus can be found somewhere between these extremes and with the optimization procedure discussed above this point is found for 0.16 m extra insulation and 42 kW thermal power of the heat pump. In figure 5.5 the first coordinate shows the LCC in MSEK, the second the insulation thickness in meter and the last one shows the thermal output of the heat pump. From Figure 5.6 it is obvious that it is more important to choose the proper thickness of the insulation than to choose the proper size of the heat pump. It is also shown that it is better to insulate a little too much than the opposite.

The optimization procedure is much easier for the other envelope and ventilation retrofits, when a number of alternatives are to be evaluated. The situation is shown in Reference [42] and here will only be emphazised that those problems are handled by common derivative methods for one variable.

However, the situation above shows the case when the heat pump has a COP which is constant over the year. This is the approximate situation for e. g. ground coupled heat pumps with a heat source whose temperature is constant. Outside air heat pumps cannot be dealt with exactely in the same way because of the outside temperature dependent COP. This is dealt with in Appendix 1, page 83.

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

$$COP = \frac{-\Delta T + 66.43}{20.53} \tag{5.4}$$

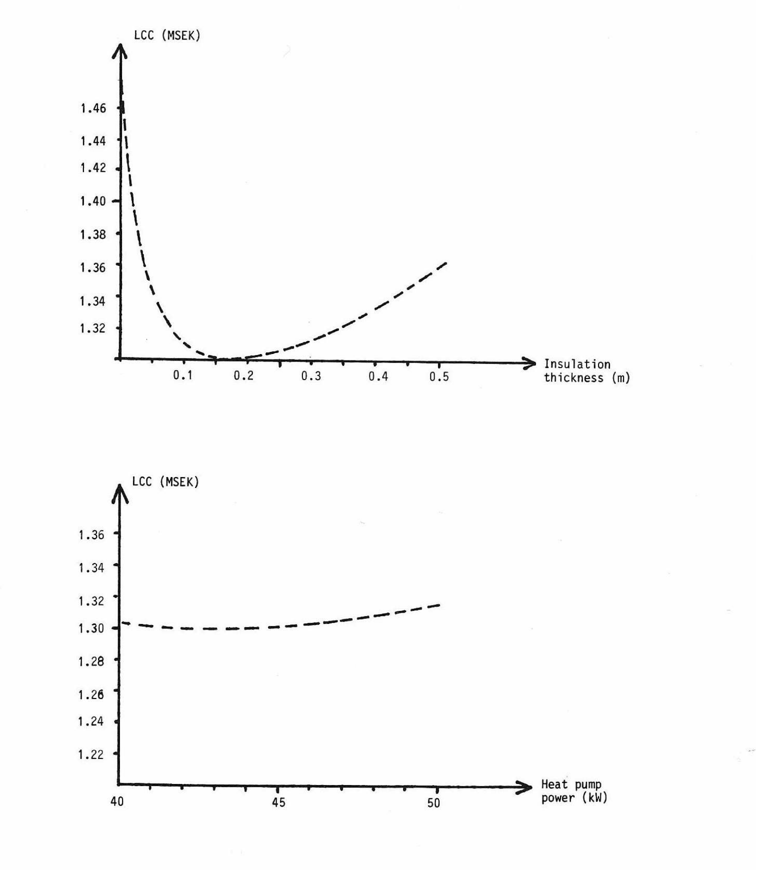

Figure 5.6: LCC due to insulation and heat pump size.

where ΔT shows the difference between the desired inside temperature of 20 °C and the outside temperatures. The expression 5.4 has been elaborated using information from a heat pump manufacturer Reference [43]. Using the energy balance subroutine the duration of the heating season is calculated and a mean value of the COP is calculated for the suitable temperatures. However, the heating of domestic hot water is carried out throughout the whole year and thus a second mean value COP has to be used.

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

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

Such difficulties and others depending on the single components in the installed equipment are not dealt with in the OPERA model. In subsequent chapters other difficulties will be discussed when bivalent systems are optimized due to the free energy provided by e. g. solar gains and appliances. See Figure 6.9 at page 67 or Appendix 1 at page 79.

5.4 INPUT DATA

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 a tedious work but very important for finding the true optimal solution. Fortunately, it is possible to use the experience from a number of earlier OPERA runnings, and this means that less effort can be used on such systems which almost never will be part of 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. Small changes in the installation cost for the electrical boiler will not change the total situation and therefore it will not be worthwhile to examine this installation cost in detail. The situation is described in Reference [37].

Other equipment or retrofits will be selected by the model very often and thus the efforts shall be concentrated on those systems. When starting from scratch with a unique building, it can be hard to consider the plausible result from the OPERA running. Thus it will be preferable to implement very approximate data in the first running and after this has been evaluated, continue with further examining of the interesting parts.

In the following section of this thesis the essential input data that have to be implemented, are described. The geometry is dealt with first and later the cost functions for different retrofit measures. In this chapter most of the information comes from Reference [3], but new information found will of course also be treated.

In Appendix 2 the total input file is presented, page 91.

5.4.1 Building geometry

The OPERA model is elaborated to find an optimal retrofit strategy for each unique building. It is thus important to describe the geometry of the building in the input data file.

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 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 (6.2) and the discussion at page 61.

This is because it is hard to calculate the proper U-values or thermal resistance in 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 done in the basement seldom will be 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, see Reference [15]. In Reference [3] this is also emphasized.

The situation is similar for a crawl space instead of a basement. The building part has to be simulated using a slightly different floor in the OPERA calculations. Crawl spaces have been treated in Reference [44], where the complexity of the problem is described in detail. Of course it is possible to implement also those more complex situations in the model but it is questionable whether it is worthwhile, due to the above experience.

5.4.2 Existing thermal status

The existing U-values for the building parts also have to be provided to the model. Usually these values can be calculated with traditional methods similar to those in Reference [3] p. 32.

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 day time. The situation is dealt with in References [3], [45], [46], [47], [48], [49] and [50].

However, it is not within the scope of OPERA to find an optimal window construction and thus some different constructions are tested against each other. Input to the model are the U-values during darkness. The solar gains are treated in the energy balance subroutine, see Appendix 3, page 101, where they are given as monthly mean values in the input file.

The existing ventilation system is expected to be of the type natural ventilation, and input is the number of renewals of air per hour. Also in this case the reality is much more complex. The number of renewals are not the same in the different apartments and the situation will also change due to the outside temperature. In Reference [51] the problem is examined.

Of course small changes can be made in the programming code in order to evaluate mechanically ventilated systems as well. However, those buildings are mostly not subject for renovation due to less age and better thermal envelopes.

5.4.3 Remaining life of the envelope

In Reference [52] 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 et c. 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 has to be renovated anyway. The extra cost for insulation in such cases will mostly always be profitable, the energy savings only have to pay for the extra insulation.

However, it is very hard to predict, with an absolute accuracy, how long the remaining life is. The lack of information about this subject is considerable, which is also emphasized in Reference [3] p. 26. 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. In recent years there has been an increasing interest in predicting the remaining life of building envelope details, see References [53], [54] [55] and [56].

The input values to the model must show the number of years from now to the year when the retrofit is inevitable. These values are used together with the retrofit cost functions in order to calculate the inevitable retrofit cost.

5.4.4 Ventilation system

The existing ventilation system is assumed to be of the natural ventilation type. 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. This problem has been dealt with in Reference [3], and in [57] some figures presented, show the situation in a multi-family house in Gavle. Sweden. 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. It is also possible to simulate the use of air heat exchangers by providing the program with a factor showing the efficiency of the equipment. The situation is described in [3], p. 84.

5.4.5 Heating equipment

Input data concerning the existing heating system is the:

- Thermal power of the equipment
- The type of equipment
- The efficiency
- The remaining life

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 also uses the calculated power in the continuing program.

Several types of equipment can be dealt with by the model. The alternatives are described in the chapter concerning the energy price subroutine, see Appendix 3, page 104. (The input text must be identical to the one stored in OPERA, otherwise the model cannot recognize the system.)

The efficiency of the heating system is given as being less. equal or higher then 1.0. The efficiency for ordinary oil-boilers are approximately 0.7 while heat pump systems can have "efficiencies". COP, of the magnitude 3. There are of course difficulties in choosing the values, because no absolute accuracy can be given. In Reference [3], p. 95, some of the problems are discussed and references are made to mostly Swedish literature.

In Reference [58] the performance of air-source heat pumps is discussed. However these pumps were installed in single-family houses and the COP was monitored for the total heating season. The values varied between 1.10 and 2.33.

Also here, in the heating equipment case, it is important to consider the remaining life of the existing equipment. There are difficulties if an accurate value is to be provided, but nevertheless a qualified guess must be made. References like [59] can be of importance if heat pumps are considered.

5.4.6 Domestic hot water production

OPERA also has to consider the hot water consumption in the building and the model requires information about the consumption in kWh. The calculations are made, assuming that no extra power is needed in the boiler for this. This is 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. In Reference [42] it is shown that it is optimal to provide all the heat for domestic hot water using the heat pump.

5.4.7 Thermal properties of new envelope measures

The model also 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. The values must correspond to the cost functions dealt with below. see page 34. The thermal performance of different types of windows must be presented as U-values during darkness. The values must correspond to the cost functions concerning the windows, see page 34.

5.4.8 New life-cycles for the envelope retrofits

The retrofits done to the envelope will change the periodicity whenthe retrofits are inevitable. It is thus necessary to inform the model of the new life span for the measures. The new life 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 Reference [3], p. 53.

5.4.9 Economical factors

One of the most important values in the LCC calculations is the discount rate. The item is discussed in Reference [3], p. 15, and in References [7] and [21] more information can be found about it. 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.

Neither can an ultimate optimization time or project life be found. In Sweden there is an opportunity to get special subsidies if the building is older than 30 years or if more than 30 years have passed since it was last renovated with subsidies. Also 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 X or zero. The problem is also dealt with in Reference [3].

5.4.10 Building cost functions

OPERA has to be informed of the building cost for different retrofit measures. As mentioned earlier there is also a need for the inevitable retrofit cost if it is related to energy conservation measures. First OPERA must calculate the present value for e. g. an external wall, without any energy retrofits at all. Some time, the facade has to be renovated, maybe because it is rot. Earlier in the input data file, this instant is specified and the cost function will tell OPERA how much money that has to be spent.

However, the cost function must also provide the model with the specific insulation cost. In Reference [3], p. 52 or in [60] it is shown that an expression for the building cost can be written as:

$$C_1 + C_2 + C_3 \times t \tag{5.5}$$

where C_1, C_2 and C_3 are different constants and t 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. OPERA deals with four different expression like (5.5) representing the attic floor, the floor and the external wall insulation measures. The author of Reference [32] uses a similar concept however with no inevitable cost.

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

$$C_1 + C_2 \times A_w \tag{5.6}$$

C_1 and C_2 are constants and A_w is the area for one window.

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 Reference [3], p. 77.

Expressions like (5.5) or (5.6) cannot show the building cost exactly but they will give an approximate view of the real cost good enough for the purpose of OPERA.

5.4.11 Heating equipment cost functions

The cost for acquisition and installation of new heating facilities must also be known to OPERA. This is provided by using expressions like:

$$C_1 + C_2 \times P \tag{5.7}$$

Where C_1 and C_2 are constants and P equals the demand of the system. Of course one expression has to be presented for each system under consideration. However, the bivalent systems use the expressions given for the first heat pump or the outside air heat pump and the oil-boiler. In Reference [3], p. 95, it is shown how to evaluate the expressions.

The efficiency and the new life span for the equipment must naturally be presented.

The program can deal with such installations as chimneys for oil- boilers or drilling holes for ground water coupled heat pumps as well. All of these items have a much longer life-cycle than the precise heating facility itself, and they have to be treated separately. A chimney can have a life span of 50 years while the oil-boiler itself has a life-cycle of 15 years.

5.4.12 Cost for ventilation measures

Weatherstripping is one measure that 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 to present the number of doors et c. to be dealt with. Important is also to present the decrease in the ventilation flow after the weatherstripping is completed. The caulking measures are also assumed to have a life span which 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 (5.7).

The temperatures of the air flowing in and out of the equipment must be presented and OPERA will calculate the proper thermal power of the heat pump and proceed with the heat pump cost. Also necessary to present is 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.

5.4.13 Energy prices and rates

In OPERA the energy prices are presented in a separate input file. For the oil-boiler or the electricity case the energy cost must be presented, while for district heating information also is needed about the connection fee. The heat pump cases use the electricity price.

Also implemented 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. The design of the tariffs is dealt with at page 63 - 66. If a completely new tariff, with a different design will be used it is necessary to make small changings in the FORTRAN code.

5.4.14 Climate conditions

As mentioned above OPERA uses the monthly mean outside temperatures to calculate the energy balances for the building. Values can be stored for a number of sites in the input data file. At present. OPERA assumes that three sites are stored, but with small changements in the code, the number can be enlarged.

In Sweden it is common to design the power of the heating equipment due to a so called 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 different types of buildings. A building made of heavy building material will be designed according to the higher of the temperatures. When using such a method it is possible to take into account the influence of the thermal mass in the building. The problem is discussed more in detail in Reference [3], p. 124.

5.4.15 Solar gains and free heat from appliancies and persons

The values for solar gains and free heat 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 any extra programming work.

Also necessary to provide are the shading coefficients concerning the types of windows described above. The subject is dealt with in Reference [3], p. 69.

5.4.16 Output information

In the input file it is also possible to assign values for the output presentation of OPERA. More or less of the calculations can be presented at the terminal or on the line printer et c. This means that it is possible to scrutinize each step of the calculations. By small changes in the code only parts 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 also possible to control how many cases of discount rates et c. 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, see page 54 and Appendix 2 at page 91.

Chapter 6

CASE STUDY

In order to show how the OPERA model is used. a case study is elaborated, emphasizing one special building. The building is totally fictional because of the freedom to choose suitable input data. This means that OPERA can consider all the types of different heating systems, heat pumps, oil-boilers, district heating et c. at each running, which is not possible for all real buildings. With this method it is possible to experiment with different life-cycles for windows, ventilation and heating systems et c. regardless of the conditions valid for just one real building. However, all the input data are located within the intervals of those applicable on real buildings and at least the cost functions are elaborated from information valid for real buildings.

Therefore there is a total freedom to choose retrofits in order to describe the OPERA model as close as required and examine which of the input data that are most important to consider. In a separate chapter. see page 54, and in Appendix 2 at page 91, this is dealt with in further detail.

The chosen building was built about 1950 and contains 18 apartments. It is a rather small three-storey multi-family building. The building envelope is in a very poor aesthetic and thermal shape and thus a renovation is inevitable. Three different U-values have been chosen, for the attic floor, the floor and the external wall, in order to enlighten the influence of the existing thermal status of the building envelope. The windows are double-glazed and in a poor shape and it is necessary to change them.

The ventilation system is a so called natural system and operates by the fact that warm air is lighter than cold. The heating system is an oil-boiler with some years left of its economical life.

Below the input data concerning the demonstration building is presented.

6.1 INPUT DATA

Geometry:
The bottom area of the building is 36 × 11 m = 396 m^2
External wall area, windows excluded = 720 m^2
Number of windows, area for each window
and total window area
North 30 × 1.69 = 51 m^2
East 3 × 1.69 = 5 m^2
South 30 *times* 2.23 = 67 m ^{2}
West 3 × 1.69 = 5 m^2
Number of apartments = 18
Total apartment area = 1000 m^2

Existing thermal status:
U-Values for the existing attic floor = 0.8 W/m^2 $\times K$
external wall = 1.0 W/m^2 $\times K$
floor = 0.6 W/m^2 $\times K$
windows, double-glazed, during darkness = 3.0 W/m^2 $\times K$

Ventilation:
Ventilation system type = natural
Air renewal rate, air changes/hour, see Reference
[3] and [57] = 0.8

Remaining life of the envelope and ventilation system:
In the base case it is assumed that the building
envelope is in a very poor condition and thus the
remaining life for all the building parts = 0 years
The ventilation system is assumed to have
a very long life span = 50 years

The existing heating equipment:
The building is assumed to be heated with an oil-boiler
with the power = 90 kW
the efficiency = 0.7
and with a remaining life = 5 years

Domestic hot water production:
The energy for production of hot water per year = 252 GJ
(70 000 kWh). The value corresponds to the
consumption in single-family houses and might be a
little too high see, Reference [61].

Thermal properties of new envelope measures:

It is assumed that for all the insulation measures,
mineral wool is used with a thermal conductivity = 0.04 W/m^2 × K
New windows, U- values
ordinary double-glazed = 3.0 W/m^2×K
ordinary triple-glazed = 1.8 W/m^2×K
low-emissivity, triple-glazed = 1.5 W/m^2× K
low-emissivity, gas-filled, triple-glazed = 1.4 W/m^2×K
The reason for choosing these types is due to the possibility of finding relevant prices. The U-values above comes from Reference [62].
Slightly different values are shown in Reference [63].

New life-cycles for the envelope retrofits:
The new life for the envelope retrofits = 20 years

Economical factors:
As mentioned above there are no ultimate discount rate, optimization time and escalating energy price rate. Thus a base case is chosen with the
Discount rate = 5 %
Optimization time = 50 years
Escalating energy prices = 0 %

Building cost functions:
In Reference [3] some cost functions are presented and here it is assumed that they are applicable also in this case. The following expressions are used
Attic floor insulation $0 + 125 + 300 \times t_{af}$
External wall insulation, outside $325 + 85 + 555 \times t_{ew}$
External wall insulation, inside $100 + 175 + 555 \times t_{in}$
Floor insulation $250 + 195 + 250 \times t_{fl}$
The values for the inside insulation above are calculated in the same way as in Reference [3] but must also be completed with the annual loss of rent due to less habitable area = 400 SEK/m^2
The cost for changing windows in [3] however, cannot be used because of the other types of windows concerned. The method for evaluating these new prices is exactely the same as earlier, i. e. a number of varieties are examined with a suitable price list Reference [64] and installation costs from [3]. A_w is the area of one window and the the costs are:
Double-glazed = 2,050 + 450 ×A_w
Triple-glazed = 2,700 + 700 ×A_w
Triple-glazed. low-emissivity = 2,700 + 1,000 ×A_w
Triple-glazed, low-emissivity, gas-filled = 2,700 + 1,100 ×A_w

There is very much written about building costs and cost effectiveness for retrofit measures. Unfortunately the authors do not present all the details about the retrofits and how the costs are calculated. Due to this it is difficult to use the figures presented in e. g. References [65], [66] and [67] in OPERA runnings.

Ventilation equipment retrofits:
As in Reference [3] the cost for caulking a window or a door = 200 SEK
If all the doors and windows in the building are dealt with, the renewals of air per hour in the building is decreased with = 0.3
The life span for the weatherstripping = 10 years
In recent years exhaust air heat pumps are used as a ventilation retrofit. The cost equals = 10,000 + 4,500 $\times P_{ehp}$
where P_{ehp} is the thermal power of the pump.
The life span for the device = 10 years
However there are many other costs for installing the pump, like a lot of pipes that have to be coupled to the device.
These costs have a longer life span = 30 years
Further, these costs are assumed to be represented by a cost per apartment = 5,000 SEK
The inlet temperature of the air flow = 20 °C
The outlet temperature = 5 °C
The COP of the pump is = 3.0

Heating equipment costs et c.:
The cost functions et c. from Reference [3] are used:

	Cost (SEK)	Efficiency	Life Span (years)
Oil-boiler	20,000 + 350 × P	0.8	15
Electricity boiler	20,000 + 100 × P	1.0	20
District heating	30,000 + 250 × P	1.0	30
Heat pump, ground water coupled	30,000 + 3,300 × P	3.0	10
Heat pump, earth coupled	30,000 + 4,300 × P	3.0	10
Heat pump, outside air, see Reference [43]	40,000 + 6,000 × P	Varying	15

Furthermore bivalent heating systems are examined, i. e. the oil-boiler - heat pump systems. The heat pump in the bivalent system can be of the type outside air or ground water/earth coupled. As mentioned above it is also possible to simulate the use of another life-cycle for e. g. chimneys or a brine system coupled to the heat pump. For a complete input data description, see Appendix 2, page 92.

In Reference [56] the cost for heat pump installations has been examined. However, the presentation of the result cannot be used as input data to OPERA without more details from the study. It seems that the prices presented above are too low, but maybe this is due to the fact that applications for the Swedish subsidiary system were used for the examination.

The COP of 182 heat pump systems has been examined in Reference [68] by laboratory tests. The values used in this thesis seem to coincide very well with those found there.

Energy prices:
The energy prices are stored in a separate input data file. The first cases evaluated by OPERA are assumed to have a fixed price/kWh:

Type	Cost in SEK/kWh	SEK/MJ
Oil	0.18	0.05
Electricity	0.32	0.09
District heating,	0.20	0.06
In the district heating case there is also a connection fee to be payed	=	300 SEK/kW

Furthermore two real tariffs are implemented in OPERA, both concerning Malmö, Sweden, one for electricity and one for district heating. All these energy prices and tariffs will be dealt with in due order, see pages 63, 93 and 104.

Climate conditions:
The lowest outside temperature, see page 35 and 51 = - 14 °C
The desired inside temperature = 20 °C
The monthly mean temperatures can be found in Reference [3] p. 43, or in Appendix 2 page 92.

Free energy and solar gains:
The free energy per month from appliances and persons
11.8 MWh/month, see Reference [36] = 42.5 GJ.

The figure above has been calculated from the assumption that examinations of free energy in single-family houses are applicable. The solar gains have been calculated as the amount of kWh transferred through an ordinary double-glazed window/m^2. The procedure follows the method used in Reference [3]p. 72-74 . The values used are shown in Table 6.1:

However, there is also a need for different shading coefficients for the type of windows concerned. The OPERA model assumes that the values above are presented with a proper shading coeffiicent for the double-glazed window. Constants for the other types of windows concerned in the running must be presented in the input data file. In this case the coefficients used are, see Reference [3] p. 75:

triple-glazed = 0.8
triple-glazed, low-emissivity = 0.7
triple-glazed, low-emissivity, gas-filled = 0.6

Above, nearly all the values that are used in this study are presented. The total input file is presented in Appendix II, page 91. It is very tedious work to find proper values for each unique building and it is hard to know if the prices et c. elaborated in a case study reflect the real situation.

Month	North	East/West	South
Jan	4.30	8.27	29.66
Feb	8.94	6 17.97	143.69
Mar	18.57	41.86	73.68
Apr	28.82	61.97	75.29
May	44.50	87.58	82.59
Jun	53.48	90.91	76.28
Jul	50.54	89.07	78.50
Aug	36.63	75.07	79.81
Sep	23.12	53.11	79.37
Oct	13.54	28.30	61.57
Nov	5.82	10.75	32.70
Dec	3.08	5.36	21.22

Table 6.1: Solar gains through windows

Once more it must be emphasized here that it is not within the scope of this thesis, to find proper input data to the model, but to show that it is possible to calculate the best combination of retrofit measures.

The reason for describing the input file at all, is the sensitivity analysis, see page 54 and Appendix 2. Changes, small or big ones, will of course influence the LCC, and the OPERA model can be used in order to quantify all these changes. However, there must be some situation to start with, and that situation is presented above.

6.2 THE OPERA PRESENTATION

In Table 6.2 an OPERA running is presented.

	Exist syst	New oil	Elec tric	Distr heat	Heat p. G	Heat p. E	Diff distr	Diff elec	Biv O-H	Biv 0-0
No env. retrofits	1.62	1.66	1.89	1.61	1.92	2.08	1.60	1.89	1.62	1.69
Savings:										
Att. ins	0.02	0.02	0.06	0.01	0.04	0.06	0.02	0.05	0.01	0.02
Flo. ins	—	—	—	—	—	—	—	—	—	—
Ext. ino	0.09	0.09	0.15	0.06	0.13	0.17	0.07	0.16	0.06	0.09
Ext. ini	—	—	—	—	—	—	—	—	—	—
3-glass	—	—	—	—	—	—	—	—	—	—
Low emi.	—	—	—	—	—	—	—	—	—	—
Gas fil.	—	—	—	—	—	—	—	—	—	—
Weathers.	0.05	0.05	0.08	0.04	0.06	0.08	0.04	0.07	0.04	0.05
Exhaust	—	—	0.04	—	—	—	—	0.02	—	—
New LCC	1.46	1.50	1.56	1.49	1.69	1.78	1.47	1.60	1.51	1.53

Table 6.2: Retrofit strategy matrix. Values in MSEK

The first value in Table 6.2, 1.62, shows the LCC for the existing building in MSEK. Under this value it is shown how much money is saved if the optimal amount of attic floor insulation is implemented to the building, i. e. 0.02 MSEK. If the measure was found unprofitable a —- is presented.

This is the precise situation for the floor insulation on the line below. Adding an optimal amount of insulation to the external wall saves 0.09 MSEK and so on. Finally the new LCC is presented if the optimal, or almost optimal, envelope solution is implemented, 1.46 MSEK.

The values in the first column are all valid for the existing heating system, the oil-boiler in this case. The next column shows the situation if a new oil-boiler is implemented now, i. e. at year 0. A new optimal strategy is presented, almost identical to the first one. In the table all values are truncated to two decimals and that is why they seem similar.

OPERA continues with the other heating systems under consideration and calculates the envelope strategy for each one.

The abbreviations in Table 6.2 denote in the heating system row: Existing system, new oil-boiler, electricity. district heating fixed rate, ground coupled heat pump, earth coupled heat pump, district heating differential rate, electric heating differential rate, bivalent oil-boiler ground coupled heat pump and bivalent oil-boiler outside air coupled heat pump.

The abbreviations in the column denote: life-cycle cost without any envelope or ventilation retrofits, attic floor insulation, floor insulation, external wall insulation at the outside, external wall insulation at the inside, triple-glazed windows, triple-glazed + low- emissivity windows, triple-glazed + low-emissivity + gas-filled windows, weatherstripping and exhaust air heat pump.

Eventually, all heating systems have been examined and OPERA now calculates the resulting LCC for the retrofit combination concerning the different heating systems and presents these more thoroughly.

From Table 6.2, the existing oil-boiler system seems most profitable combined with some envelope retrofits.

Table 6.3 shows one of the retrofit strategies in greater detail, such as the value of the thermal load in the existing building and the resulting new load if the retrofit is implemented.

	Thermal load [kW]	Thermal transm [kW/°C]	Annual energy [GJ]	Retrofit cost [MSEK]	Inevitable retrofit cost [MSEK]
Existing building	77.9	2.291	573.7	0.0	0.882
Attic floor ins. 0.18 m	69.5	2.045	497.7	0.070	0.882
Ext. wall ins., outs. 0.13 m	50.9	1.499	353.7	1.816	0.882
Weatherstripping	42.9	1.261	296.9	2.242	0.882

Table 6.3: Retrofit oil-boiler strategy in more detail

The load is thus 77.9 kW in the beginning and implementing 0.18 meter extra attic insulation decreases the load to 69.5 kW. After implementing the external wall insulation and the weatherstripping as well, the load in the building is 42.9 kW.

The total transmission factor, TRANS + VENT, from (12.4) and (12.5) in Appendix 3, see page 101, is presented and will decrease from 2.291 kW/°C to 1.261 kW/°C. The decrease in annual energy demand is shown, and so is the increase in the retrofit cost as well as the change in the inevitable cost. Note that it is the annual energy demand delivered from the heating system that is shown, calculated by the energy balance subroutine. In the case above, the inevitable costs are the same because the remaining life span for the envelope retrofits was 0 years.

OPERA now presents the combination LCC, considering the values from Table 6.3, for all the considered heating systems. If the combination of the envelope retrofits were independent of each other, this new LCC should be identical to the resulting LCC from table 6.2. However, this is not the case because of the facts discussed on page 21.

However, OPERA calculates the difference between the Table 6.2 and 6.3 LCC, and in the existing oil-boiler case it is 0.039 MSEK, or about 3 %.

Unfortunately this difference, however very small, may influence the best strategy presented by OPERA. If the LCC is 0.039 MSEK lower than the 1.46 MSEK found in Table 6.2 the district heating system with a differential rate is instead the best solution.

OPERA provides the lowest combination LCC as a preliminary result. It is now possible to force the model to choose the differential rate system as well as any other of the considered heating systems. The different solutions can be scrutinized very carefully.

The retrofits in Table 6.2 will be considered as very strong candidates for an optimal solution. The amounts of money saved in Table 6.2 however, are the maximum values, the real savings are slightly smaller. This means that when OPERA has calculated the LCC for the combination of retrofits, and found the best heating system the envelope retrofits must be reconsidered. This is done by implementing a slightly thinner insulation for e. g. the attic floor. If this new insulation results in a lower LCC the procedure is repeated, else the next insulation measure is tested, if found profitable in Table 6.2. In this way all the retrofits are examined once more.

In the case studied above the existing oil-boiler seemed to be the best solution, considering Table 6.2, combined with some envelope retrofits. This combination was estimated to result in a new LCC equaling 1.46 MSEK. The combination of the retrofits however, will result in a LCC of 1.50 MSEK. The differential district heating system, combined with another set of envelope retrofits was estimated to result in a LCC of 1.47 MSEK i. e. higher than the oil-boiler solution. However. the district heating system combined with the envelope retrofits provides a LCC of 1.49 MSEK, which is slightly lower than the oil-boiler case.

Considering the combination of the heating system and all the retrofits done to the envelope implies that the differential district heating system is the most profitable. Now OPERA examines this heating system with its candidates for optimal retrofits and calculates if the LCC gets lower, if less insulation is implemented to the attic floor.

In the first estimation it was found that 0.17 meter attic floor extra insulation was optimal. If this insulation is made 0.01 meter thinner, the LCC will decrease by approximately 250 SEK, from 1,496,870 to 1, 496,625 SEK. It is obvious that the LCC function is very flat in this region. However, the lowest LCC was found for 0.14 meter attic floor insulation and 0.10 meter external wall insulation, which differs 0.01 meter from the first estimated value. The LCC will equal 1,496,060 SEK.

Of course it is not possible to predict the future with such an accuracy that an analysis of the above type is worthwile, the uncertainty in the input data will overwhelm the possible misoptimization, due to the situation discussed above. Thus, if there are only minor differences between the strategies calculated by OPERA, other information than the lowest LCC must decide the most desireable strategy. However, using the OPERA model makes it possible to find the optimal solution.

It is also possible to provide the model with values in the input data file in order to bring out an extensive amount of information from the total calculation procedure if necessary. Such values may also be set in the program itself and there are possibilities to choose presentation from one of the subroutines as well as for parts of the main program.

6.3 SCRUTINIZING THE OPERA CALCULATIONS

Emphasized above are the great options in OPERA to evaluate all the calculations resulting in the most profitable retrofit strategy. This is also very important in order to elaborate a sensitivity analysis, i. e. how will the final result change if some of the input variables are changed. In this chapter the calculations of an OPERA running are shown in order to depict the principal situation. Only one retrofit and one heating system are dealt with at the same time, total system changings are dealt with at page 54. This is because it is easier to understand what happens if the heating system cannot change. The oil- boiler system has been chosen for the calculations due to the more difficult situation with differential district heating. Thus it is not the optimal solution for the total model but instead a subsystem that is scrutinized here. All information can easily be provided by OPERA by setting strategic output parameters in the input data file.

In Table 6.4, the first value in Table 6.2, 1.62, showing the existing LCC, is broken up into pieces.

Type of cost	Cost
Inevitable retrofit cost	0.882
Heating equipment cost	0.063
Energy cost	0.677
Total cost	1.622

Table 6.4: The existing LCC in MSEK

However, even these values can be split into parts, showing e. g. the inevitable retrofit cost in detail. See the Table 6.5.

Also interesting is to analyze the energy demand during one year. OPERA shows the energy balance for the building in monthly mean values. First the number of degree hours is presented using the equation (12.1), at page 101, then the energy loss is calculated using also the expressions (12.4) and (12.5), at page 101 in Appendix 3. Equation 6.1 shows the situation.

$$E_{loss} = DH \times (TRANS + VENT) \tag{6.1}$$

Building part	Cost
Attic floor	0.0
Floor	0.146
External wall, outside	0.345
External wall, inside	0.106
Windows, north	0.135
east	0.012
south	0.124
west	0.012
Total inevitable cost	0.882

Table 6.5: The inevitable retrofit cost in MSEK

However, also the solar gains and free energy from appliances are presented. The energy delivered from the heating system as well as the energy demand used for insulation optimization, see page 22, is calculated. The two values are called Energy 1 and Energy 2 in Table 6.6. (OPERA calculates the values in kWh instead of GJ and thus some truncation errors might occur in the Table.)

Table 6.6 shows that for five months during the summer the building does not need any space heating from the heating system. During that time no contributions are made to the insulation energy demand, Energy 2.

Month	Degree hours	Energy loss	Hot water consumption	Solar gains	Free energy	Resulting demand Energy 1	Energy 2
Jan	15,252	125.8	21.0 6.8	42.5	97.6	125.8	
Feb	14,035	115.8	21.0	10.8	42.5	83.5	115.8
Mar	13,838	114.1 21.0	19.5	42.5	73.2	114.1	
Apr	10,080	83.1	21.0	22.9	42.5	38.7	83.1
May	6,696	55.2	21.0	29.0	42.5	21.0	—
Jun	3,600	29.7	21.0	30.1	42.5	21.0	—
Jul	2,083	17.2	21.0	29.8	42.5	21.0	—
Aug	2,455	20.3	21.0	26.1	42.5	21.0	—
Sep	4,680	38.8	21.0	22.0	42.5	21.0	—
Oct	8,258	68.1	21.0	15.5	42.5	31.1	68.1
Nov	10,872	89.7	21.0	7.8	42.5	60.4	89.7
Dec	13,392	110.5	21.0	4.8	42.5	84.2	110.5
Sum	105,241	868.1	252.0	225.0	509.8	573.7	707.1

Table 6.6: Energy balance. Monthly mean values in GJ

From Table 6.4, at page 45, it is obvious that it is the energy cost that has to be reduced if the LCC will be considerably lower. The heating equipment cost is too small and the inevitable cost cannot be decreased.

OPERA starts trying to achieve this by examining attic floor insulation. The total inevitable retrofit cost in this case is identical to the first one. shown in Table 6.4, because of the zero attic floor inevitable cost. However, the remaining life is zero years and this will also mean that the inevitable cost will not change.

The next step is to calculate the optimal thickness of insulation. As mentioned above the Energy 2 value from Table 6.6 is used for this purpose and

OPERA calculates the minimum LCC using the formulas (5.1) and (5.2), at page 22 and 23. In this case the optimal extra thickness of insulation is calculated to 0.18 meter, see Table 6.3 at page 43. The new LCC is then calculated as presented in Table 6.7.

Type of cost	Cost
Inevitable retrofit cost	0.882
Heating equipment cost	0.059
Energy cost	0.587
Retrofit cost	0.070
Total new LCC	1.599

Table 6.7: LCC with attic floor insulation. Costs in MSEK

The new LCC is lower than the existing LCC and thus the retrofit is profitable.

This is not the case for floor insulation. The optimal amount is also in this case calculated to 0.18 meter. The constant C_3 in equation (5.5), see page 34, is identical for the two measures which would imply an identical insulation thickness, but this is not the case because the existing U-values differ. Further, the other insulation costs, C_1 and C_2 are higher, and the profitability will vanish. Table 6.8 shows the situation.

Type of cost	Cost
Inevitable retrofit cost	0.882
Heating equipment cost	0.061
Energy cost	0.614
Retrofit cost	0.095
Total new LCC	1.651

Table 6.8: LCC with floor insulation. Costs in MSEK

The same information is available for all the retrofits tested by OPERA and furthermore, the final result can be examined in the same way.

In the following, the four parts of the LCC, i. e.:

- the inevitable retrofit cost
- the heating equipment cost
- the energy cost
- the retrofit cost

are studied in detail and a number of OPERA runnings are elaborated in order to enlighten important parts dealing with LCC and the retrofitting of buildings.

6.3.1 Inevitable retrofit cost

In order to show the influence of changes in the input data on this cost, the external wall retrofit will be used. It is assumed that the remaining life of this building part is 20 years. The original situation, when the remaining life is 0 years, is not applicable. Neither the attic floor insulation can be used because the cost is O SEK due to the value of C_1 in equation (5.5), page 34. See also Table 6.5 at page 46. OPERA provides Table 6.9 and 6.10 as a starting situation.

The inevitable retrofit cost is calculated by the expression (12.2), page 102 in Appendix 3, and from equation (5.1) and (5.2) it is obvious that the optimal insulation thickness is independent of the remaining life of the considered building part. In Table 6.3 this is presented to be 0.13 meter. However, it is very important to note that a longer remaining life span makes it more expensive to make a retrofit in advance, i. e. at the base year. The profit might vanish, and then it is better to leave the external wall as it is.

In Table 6.4 the total existing LCC equals 1.622 MSEK. Setting the remaining life of the external wall to 20 years, instead of 0, makes the LCC 0.234 MSEK lower for the existing building, see Table 6.9.

Type of cost	Cost
Inevitable retrofit cost	0.647
Heating equipment cost	0.063
Energy cost	0.677
Total new LCC	1.388

Table 6.9: LCC existing building. Life span for external wall equals 20 years. Values in MSEK

Compare Table 6.9 and 6.10.

Type of cost	Cost
Inevitable retrofit cost	0.882
Heating equipment cost	0.055
Energy cost	0.488
Insulation cost	0.111
Total new LCC	1.536

Table 6.10: LCC with external wall insulation. Remaining life span equals 20 years. Values in MSEK.

The insulated building thus must have an energy- and heating equipment cost that is 0.234 + 0.111 MSEK lower then the not retrofitted building has, if the retrofit shall be profitable. This is not the case. This shows that the remaining life span for a retrofit can be very important.

Unfortunately it is not very easy to make accurate estimations about the remaining life span. The importance however, is increased if the remaining span is short. An error in the estimation of 10 years is much more important close to the base year than far away from it. If the span above was 10 years the inevitable cost would be 0.735 MSEK, i. e. the difference between the first 10 years is 0.147 MSEK but the second 10 years will only increase the cost with 0.087 MSEK. It shall be noted here that if the wall really is retrofitted at the base year, the influence of the remaining life is none on the resulting LCC, Table 6.10 will not change no matter if the span is changed.

Increasing the cost C_1 in the building cost function, equation (5.5) at page 34, will of course be of importance. Assuming the life span is 20 years, as earlier, but changing the cost from 325 to 500 SEK/m^2 will result in a 0.360 MSEK more expensive inevitable retrofit, compared to 0.234 MSEK above, see Tables 6.9 and 6.10. The problem with wrong estimations of the remaining life span, thus is greater if the cost is high. A higher cost will of course increase the probability that the insulation is unprofitable.

The inevitable retrofit cost will also change if the discount rate is changed. A higher rate will almost always make the inevitable retrofit cost lower but the rate will also influence the other parts of the total LCC. In the tables below the building LCC is presented with a discount rate of 3, 5 and 7 %.

Type of cost	3%	5%	7%
Inevitable retrofit cost	1.044	0.882	0.782
Heating equipment cost	0.084	0.063	0.050
Energy cost	0.946	0.677	0.516
Total cost	2.074	1.622	1.348

Table 6.11: Existing building LCC. Discount rate 3, 5 and 7 %. Costs in MSEK. Life span 0 years for the external wall

From Table 6.11 and 6.12 it is obvious that the inevitable retrofit cost will change if the discount rate is changed.

Tyne of cost	3%	5%	7%
Inevitable retrofit cost	1.044	0.882	0.782
Heating equipment cost	0.072	0.055	0.044
Energy cost	0.671	0.488	0.377
Insulation cost	0.123	0.111	0.103
(Insulation thickness in m.	0.155	0.125	0.105)
Total cost	1.910	1.536	1.306

Table 6.12: LCC with external wall insulation. Discount rate 3, 5 and 7%. Costs in MSEK.

A higher rate will make the the cost lower, in the case discussed. However, all the other costs are also changed and the important thing is that the difference between the existing LCC and the insulated building LCC gets smaller when the rate is increased. Note that these differences decrease if the rates concerned are high, a change in the discount rate from 3 to 5 % will not change the LCC difference as much as a change from 5 to 7 %. A further increase will sooner or later make the difference change sign and the retrofit will in that case be unprofitable. The situation is also depicted in Figure 6.1.

It can be confusing to find that the LCC gets lower if the discount rate is increased. The answer to this situation can be found in equation (12.2) at page 102. This may lead to the presumption that a high discount rate is very profitable, because the LCC gets lower. This is of course wrong, in reality a high discount rate implies higher costs for the retrofit and will decrease profitability

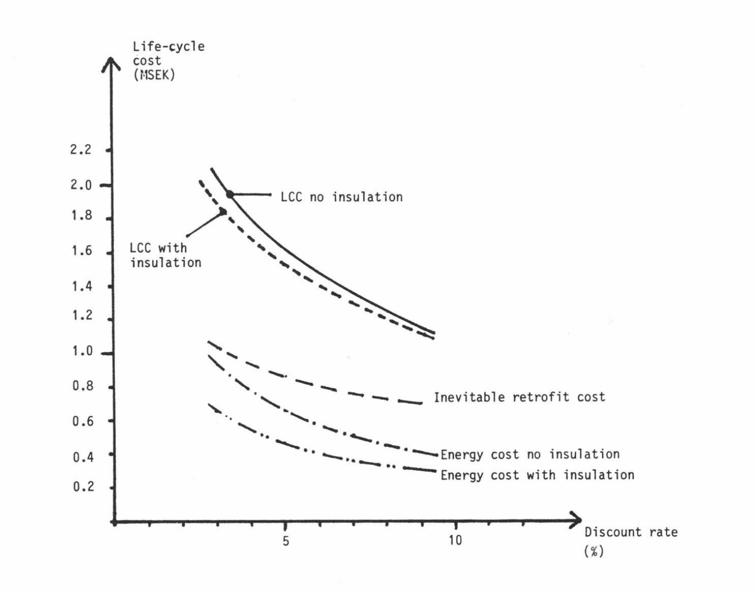

Figure 6.1: LCC changings due to discount rate.

exactly as is shown in Tables 6.11, 6.12 and in Figure 6.1. Also important is the total optimization time. See the following tables.

Type of cost	10 years	20 years	30 years
Inevitable retrofit cost	0.414	0.597	0.754
Heating equipment cost	0.018	0.037	0.051
Energy cost	0.299	0.469	0.573
Total cost 0.731 1.103 1.378			

Table 6.13: Existing building LCC. Optimization time 10, 20 and 30 years. Remaining life 0 years for the external wall. Costs in MSEK.

The inevitable retrofit cost will be lower with shorter time. However, the decrease is much higher considering short optimization periods. Changing the period from 50 to 40 years will not influence as much as changing it from 20 to 10 years. From the Tables it is obvious that the inevitable retrofit cost, as well as the other costs, will get lower if the optimization period is shortened. More important however, is the fact that for the short period, insulation is not profitable while the opposite is valid for longer periods. The situation is depicted in Figure 6.2.

Above is mentioned that an increase in the discount rate will decrease the inevitable retrofit cost. However, this is the situation only if the optimization period is longer than the remaining life of the building part. If the opposite is valid the inevitable retrofit cost will increase, and the fact is that if the optimization period is identical with the remaining life. the discount rate will not influence this cost at all.

Type of cost	10 years	20 years	30 years
Inevitable retrofit cost	0.414	0.598	0.754
Heating equipment cost	0.016	0.032	0.044
Energy cost	0.277	0.345	0.417
Insulation cost	0.089	0.100	0.106
(Ins.thickness in meter	0.07	0.10	0.11)
Total cost	0.746	1.075	1.321

Table 6.14: LCC with external wall insulation. Optimization time 10, 20 and 30 years. Costs in MSEK.

6.3.2 Heating equipment cost

From the Tables above it is obvious that the heating equipment cost in this case not considerably will influence the optimal total LCC. Note that only one heating system is dealt with here. The cost is calculated using equation (5.7), from page 34, and the total heating load for the building. This load however, is dependent of the total thermal loss in the existing or the retrofitted building.

Important is also the climate, which will influence on the size of the boiler. In OPERA this is dealt with using a lowest dimensioning outside temperature, provided by the Swedish building code. In Malmö this temperature is set to - 14 °C.

The retrofit cost for the boiler is dealt with in the same way as the retrofit cost for the building envelope, which is treated above. Thus the influence from a different rate, optimization time, retrofit cost et c. will follow the same rules presented there. The exact procedure for the calculations are presented in Reference [3].

The low influence on the total LCC in the case above, where the existing oil-boiler was dealt with, depends on the low cost for such boilers, which is of the magnitude 500 SEK/kW. The situation will be totally different for more expensive heating facilities such as heat pumps, which have costs of the magnitude 3000 SEK/kW or more. This more expensive heating equipment however, might be balanced by a much lower energy cost. (In Reference [37] it is shown that boiler costs lower than 1000 SEK/kW will hardly influence the optimal retrofit strategy.) In order to show this, the situation is stressed in some tables using the ground water coupled heat pump from Table 6.2 at page 42 as a demonstration subject.

From the upper part of Table 6.15, it is obvious that the heating equipment cost gets lower if there is a low U-value on the existing external wall.

However, more interesting is that if the wall is optimally insulated the existing U-value is of no importance at all, the heating equipment cost is not changed. The optimally insulated wall will have a total LCC that only slowly will increase if the existing wall is in a poor thermal shape. The total cost for the not insulated building has a steeper slope and for walls in a good thermal shape the insulation is unprofitable. This is also shown in Figure 6.3.

The influence from the climate, under this heading i. e. the dimensioning outside temperature. can be analysed in the same way. In Table 6.16 the situation is presented.

From the Table 6.16it is obvious that the heating equipment cost is increased

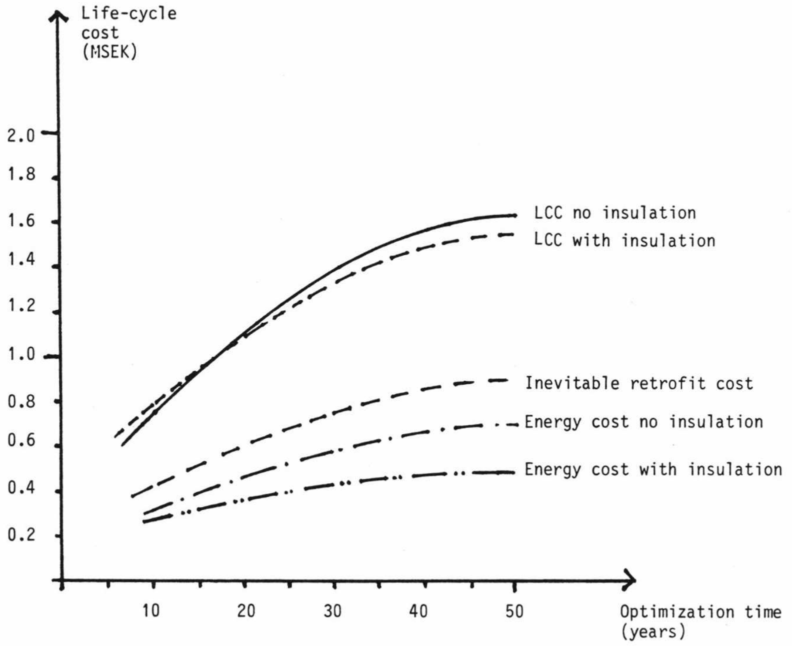

Figure 6.2: LCC changings due to different optimization time

for lower outside temperatures, and so is the total LCC. If the wall is optimally insulated the slope is getting less steep and for high outside temperatures the insulation retrofit will be unprofitable. This however, will be the situation only in a very mild climate.

The dimensioning outside temperature can be found in the Swedish building code. If the building is retrofitted in order to decrease its thermal losses, it takes a longer period of time before it gets cold if e. g. the heating equipment is not working properly. A short period with cold weather, when the outside temperature is lower than the dimensioning one, will not influence as much as if the building had not been extra insulated at all. Insulation et c. provides the building with a longer time constant. It is thus possible to use a higher dimensioning outside temperature in the retrofitted building. The problem is to find proper values for this influence. More details about this subject can be found in References [3] and [69].

6.3.3 Energy cost

The energy cost part of the total LCC will almost always be most important to decrease in order to minimize the LCC. This part is of course influenced by the direct energy cost, i. e. the cost for each MJ delivered from the heating equipment. A low running cost is thus essential for the result. Also the climate will naturally affect the cost and so does the thermal status of the building. Other important factors are the discount rate and the optimization time. In Table 6.17 the situation is shown for the oil-boiler equipment.

		U-value in W/m$^2\times$ K			
	Type of cost	0.4	0.6	0.8	1.0
No extra insulation	Inevitable retrofit	0.882	0.882	0.882	0.882
	Heating equipment	0.607	0.646	0.686	0.725
	Energy	0.242	0.265	0.289	0.313
	Total cost	1.731	1.793	1.857	1.921
Optimal insulation	Inevitable retrofit	0.882	0.882	0.882	0.882
	Heating equipment	0.573	0.572	0.572	0.572
	Energy	0.225	0.224	0.224	0.224
	Insulation	0.091	0.106	0.113	0.117
	(Thickness in meter	0.075	0.112	0.129	0.139)
	Total cost	1.792	1.805	1.812	1.816

Table 6.15: LCC for the building depending on thermal status for the external wall. Costs in MSEK

From the upper part of Table 6.17 it is obvious that the total energy cost is doubled if the direct cost for each MJ is doubled. The total LCC thus will increase with the same slope. If optimal insulation is implemented, more insulation is profitable if the direct energy price is increased. and thus the energy cost will not increase as much as could be expected, see Figure 6.4.

Changing into a colder climate, will of course raise the total energy cost and thus the LCC. In Kiruna, in the north of Sweden, the number of degree hours is approximately twice the number in Malmö. The total energy cost for the existing building will thus be doubled. Retrofitting the wall with 0.19 meter insulation, which was found optimal, will however decrease the energy cost in the same way as was found in Table 6.17.

From Tables 6.11 at page 49 and 6.12 at the same page 49, the influence of a changed discount rate is presented. A low rate implies a high LCC and vice versa. The energy cost for the existing building will decrease faster than the energy cost for the retrofitted building, and for a high rate the gap between the two energy costs is less than the insulation cost. The retrofit will be unprofitable.

In Tables 6.13 at page 50 and 6.14 at page 51, the situation for different optimization periods is shown. The energy cost will decrease faster for the existing building if the optimization period is shortened. and for some optimization time the gap is smaller than the insulation cost and the retrofit will be unprofitable.

The thermal losses in the building are naturally also important. This can be found in Table 6.15, page 53. The energy cost in the existing building will of course increase if the thermal shape is poor. The retrofitted building however will have a constant energy cost due to the optimal insulation, which is thicker for the poor envelopes. When the shape is good, the retrofit will be unprofitable.

6.4 Insulation cost

The direct insulation cost, C_2 and C_3 in equation (5.5), page 34, will of course influence on the total insulation cost. C_2 however, will only increase the level of the LCC and not the amount of insulation. It thus can be dealt with as an

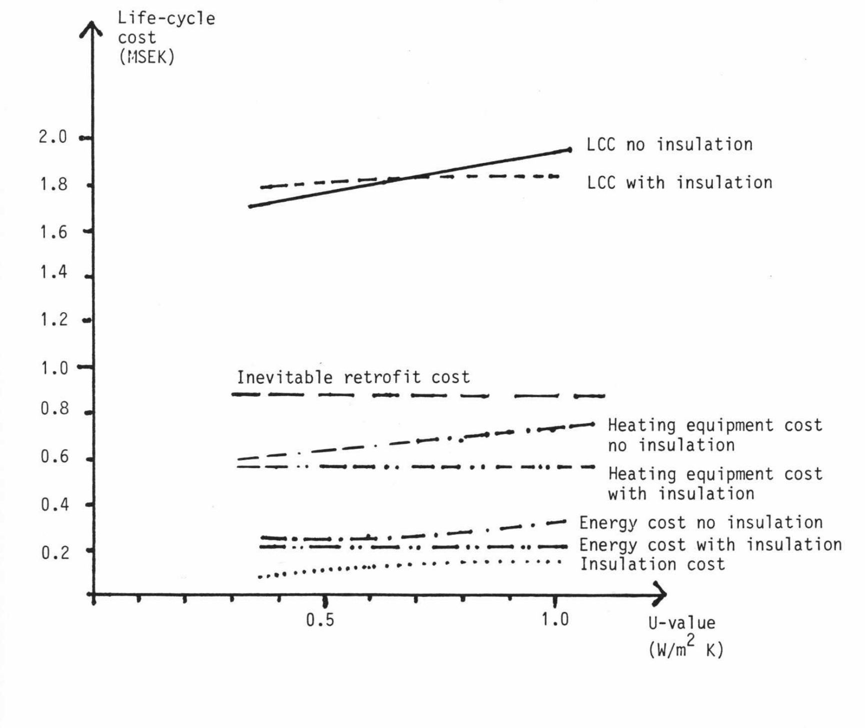

Figure 6.3: LCC changes due to thermal status, external wall

inevitable retrofit cost, only occurring once, i. e. at the base year. C_3 will influence the thickness of the insulation, and thus also the energy cost above.

From Table 6.18 it can be found that the total insulation cost will increase if the direct insulation cost is higher.

However, the optimal insulation thickness also decreases and the increase in cost is thus rather small. The LCC for the 200 SEK/m$\times$m^2 case is only marginally lower than the 800 alternative. The total cost will nevertheless increase and for very expensive insulations the retrofit will be unprofitable. This is also emphasized in Figure 6.5.

6.5 THE OPTIMAL STRATEGY, SENSITIVITY ANALYSIS

In earlier chapters it is shown how the different parts in the LCC change if some of the input parameters are changed. In this chapter and in Appendix 2, the total strategy is emphasized, i. e. how the optimal strategy changes if one or more of the input parameters are changed.

In Reference [18] the importance of risk or sensitivity analysis in LCC is emphasized. If the total strategy in an optimal solution is changed for small

		Dim. outside temp. in °C			
	Type of cost	-6	-10	-14	-18
No insulation	Inevitable retrofit	0.882	0.882	0.882	0.882
	Heating equipment	0.578	0.652	0.725	0.799
	Energy	0.313	0.313	0.313	0.313
	Total cost	1.773	1.847	1.921	1.995
Optimal insulation	Inevitable retrofit	0.882	0.882	0.882	0.882
	Heating equipment	0.463	0.518	0.572	0.626
	Energy	0.226	0.225	0.224	0.223
	Insulation	0.111	0.114	0.117	0.119
	(Thickness in meter	0.125	0.132	0.139	0.145)
	Total cost	1.698	1.757	1.816	1.874

Table 6.16: LCC for the building depending on the dimensioning outside temperature. Costs in MSEK.

changings in the input data this solution would be very hazardous to implement. One way to evaluate these LCC changings due to input changings is the spider diagram.

The authors to Reference [18] suggest that the LCC is calculated for the best estimation found for the input data. After this is done, one of the input data is changed and the LCC is recalculated. The same method is used in the previous chapter but the presentation of the result is different. In Reference [18] the percentage changings in the input data are emphasized, and thus several parameters can be shown in the same diagram. In Figure 6.6 the same procedure is used to show the result from a number of OPERA calculations.

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

However, the new LCC is not very interesting as long as it is not compared to the existing LCC for the building. In the text accompanying Table 6.15, page 53. it was mentioned that as long as the wall was optimally insulated the LCC hardly changed at all, but for a certain U-value it is better to leave the wall as it is because the insulation is unprofitable.

The curves in Figure 6.6 show the LCC for the solution found optimal. the retrofit strategy is not the same for the different rates et c. Using the spider diagram, two or more identical strategies can be examined and in that case there will be two or more ”spiders” in the diagram. However, such calculations are not very easy to perform in the OPERA model because you have to force the model not to optimize the situation. In this thesis other methods will be used to examine the sensitivity for input changements.

From Table 6.2, page 42, it is obvious that the envelope retrofits are mostly unprofitable no matter which of the heating systems used. In the case studied, only attic floor insulation, external wall insulation and weatherstripping were profitable for most of the heating systems examined. If the remaining life span for the external wall is longer than 0 years this retrofit also might be

		Price in SEK/MJ			
	Type of cost	0.03	0.06	0.09	0.12
No insulation	Inevitable retrofit	0.882	0.882	0.882	0.882
	Heating equipment	0.063	0.063	0.063	0.063
	Energy cost	0.417	0.835	1.252	1.669
	Total cost	1.363	1.780	2.197	2.615
Optimal insulation	Inevitable retrofit	0.882	0.882	0.882	0.882
	Heating equipment	0.055	0.054	0.054	0.054
	Energy cost	0.309	0.596	0.879	1.159
	Insulation cost	0.098	0.118	0.134	0.148
	(Thickness in meter	0.092	0.143	0.183	0.217
	Total cost	1.344	1.650	1.949	2.243

Table 6.17: LCC for the building depending on the energy price. Costs in MSEK. Existing heating system

	Insulation cost in SEK/m×m^2			
Type of cost	200	400	600	800
Inevitable retrofit	0.882	0.882	0.882	0.882
Heating equipment	0.054	0.054	0.055	0.055
Energy cost	0.468	0.480	0.490	0.498
Insulation cost	0.095	0.106	0.113	0.118
(Thickness in meter	0.236	0.155	0.119	0.098)
Total cost	1.498	1.522	1.540	1.552

Table 6.18: LCC due to different insulation costs. C3. Costs in MSEK

unprofitable.

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

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

In this case the district heating system with a differential rate was found the best one. This heating system should be combined with three envelope retrofits. From the OPERA tables mentioned above it can be found that this solution also is chosen for a number of other alternatives of the discount rate etc. In order to depict the situation a method found in Reference [18] has been used which can be called LCC mapping. However, in this thesis, also the optimal solutions are shown. The values in the graph, Figure 6.7, show the LCC in MSEK for different combinations of the discount rate and the optimization time.

The district heating system with a differential rate is the best system for long

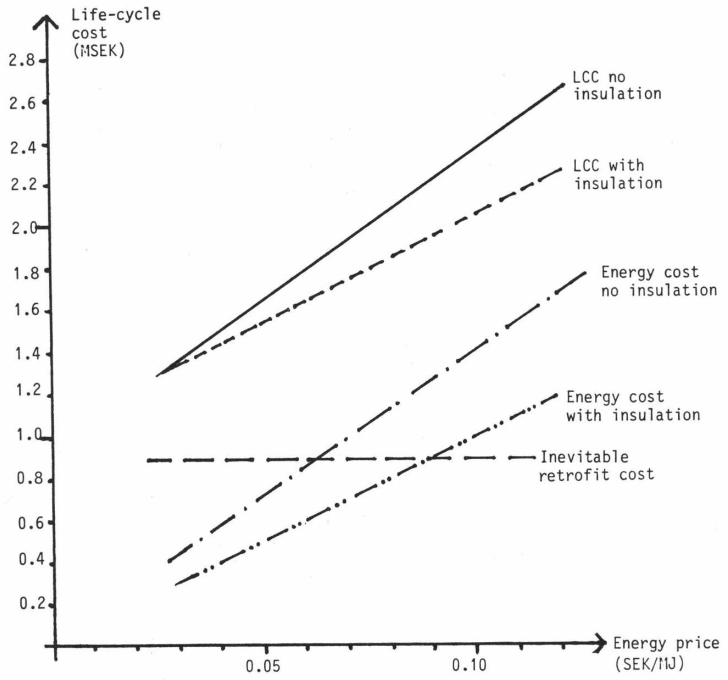

Figure 6.4: LCC changes due to energy prices.

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

However, in the vicinity of, e. g. a 10 % change, the best estimation, i. e. 5 % and 50 years, the first solution will not change. See also Appendix 2, page 91, where a 5 % change has been made for all the input data. The same process can be elaborated for other combinations of input parameters. The situation is in the next figure depicted for annual increases in the energy prices and changes in the optimization time.

In Figure 6.8 it can be found that more complicated heating systems are chosen if the energy prices are escalating.

Due to this heating system change, the same envelope retrofits will be considered as in Figure 6.7. It could be expected that if the energy prices increase, an extensive envelope retrofit should be optimal. The best thing to do is however, not to save energy but to provide it at a lower price.

In Figure 6.8 it is also shown that the system found profitable for the best estimation of input data, i. e. 50 years and 0 % increase, will be more robust due to changes in these parameters than was the case in Figure 6.7.

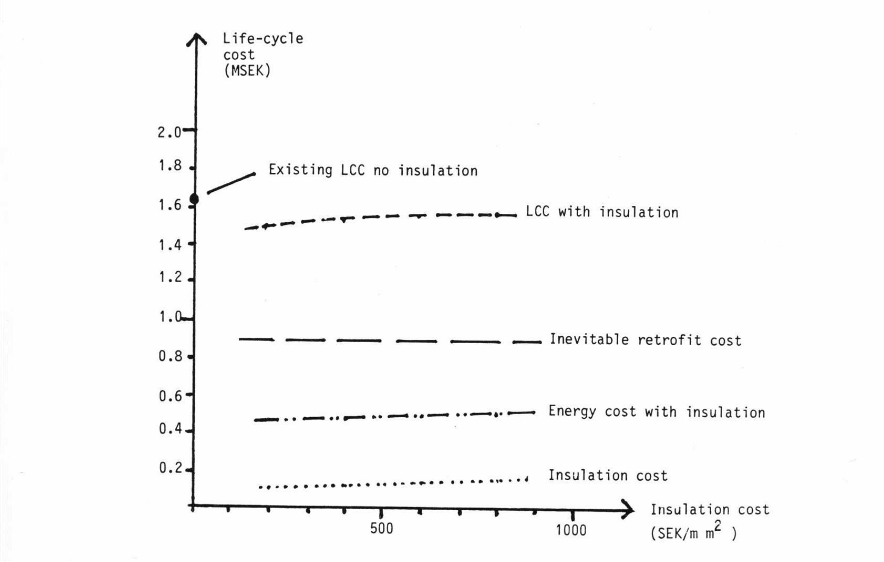

Figure 6.5: LCC changes due to insulation cost.

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

Weatherstripping was profitable in all the examined cases.

However, as is emphasized above there are also a lot of other variables that influence the optimal strategy, e. g. the existing thermal envelope. This is obvious from Table 6.15, page 53, low existing U-values will make the insulation retrofits unprofitable. Another example is that the weatherstripping measure of course will be influenced by the possibility to make the existing ventilation flow lower.

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

The opposite situation is valid for e. g. the COP for expensive heat pump systems. It will almost never be possible to find a system that is profitable for the building concerned in this case. This is also emphasized in Appendix 2. The situation is of course different for a much bigger building or a colder climate.

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

6.5.1 Insulation measures

Changing the inevitable cost, C_1 in Equation (5.5), page 34, will change the total LCC but it will not change the fact that insulation is profitable because of the

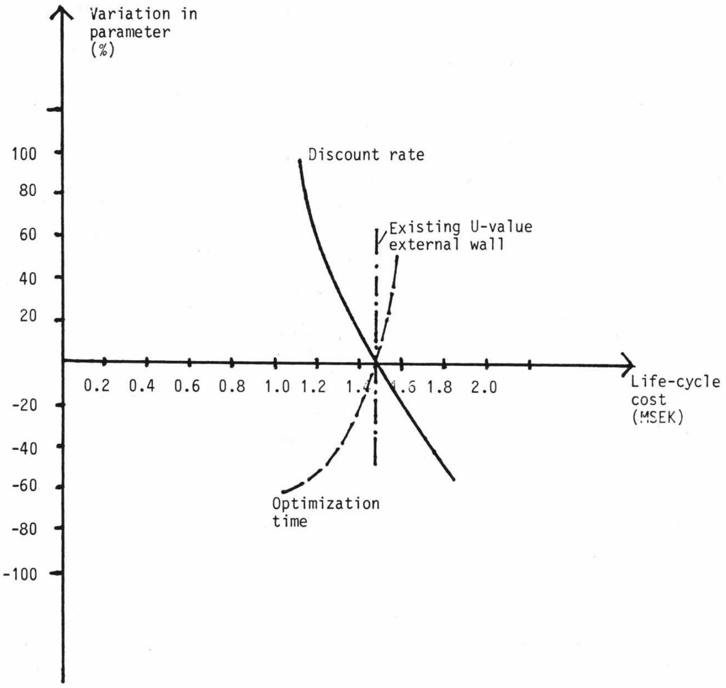

Figure 6.6: Spider diagram

0 year remaining life span. However, changing also this makes the inevitable cost important, see Tables 6.9 page 48 and 6.10 at page 49. The longer the remaining life span is, the smaller is the interval of the cost where insulation is profitable. Shortening e. g. also the optimization time will decrease the interval even more. Thus it is not very hard to construct cases where almost any situation can be found optimal.

However, the uncertainty is not total because it is possible to find intervals where all the values will probably be located. In Reference [3] it is shown that e. g. the discount rate for national calculations has been recommended between 3 and 10 % but most of the authors suggest rates in a much smaller span, between 4 and 7 %. In Reference [21] 5 % is recommended.

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

Uncertainties in the cost function (5.5) can be treated in the same way. A close study of the costs emerging from retrofitting walls et c. will give us values that reflect the reality with errors less than say 20 %.

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

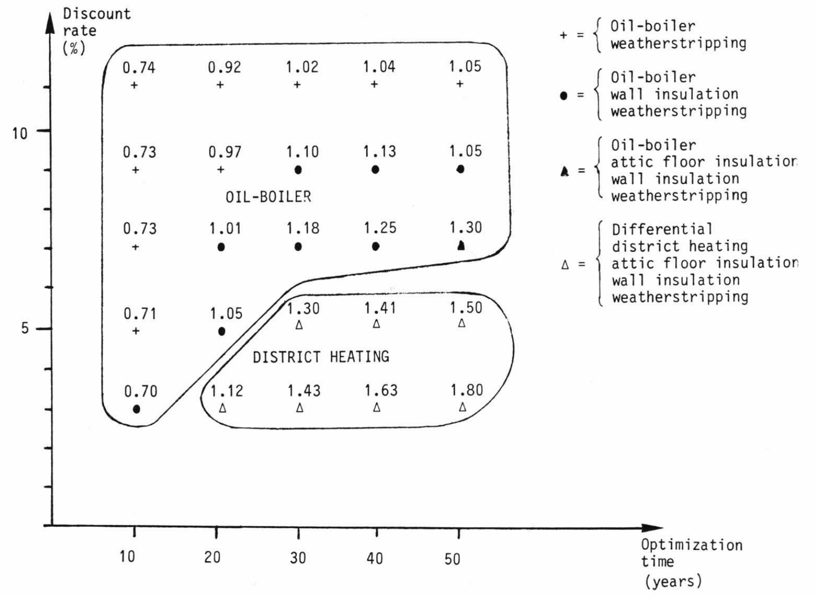

Figure 6.7: Bivariate sensitivity analysis. Discount rate versus optimization time. The values show the LCC in MSEK

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

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

The basement walls are surrounded by soil and it is not very easy to calculate an accurate value for the heat loss through them and through the ground. In Reference [44] the author is dealing with the complexity of this problem but it is not worthwile to implement such procedures in OPERA. The following discussion enlightens the situation. In Reference [70] p. 219 a simple expression is elaborated as follows:

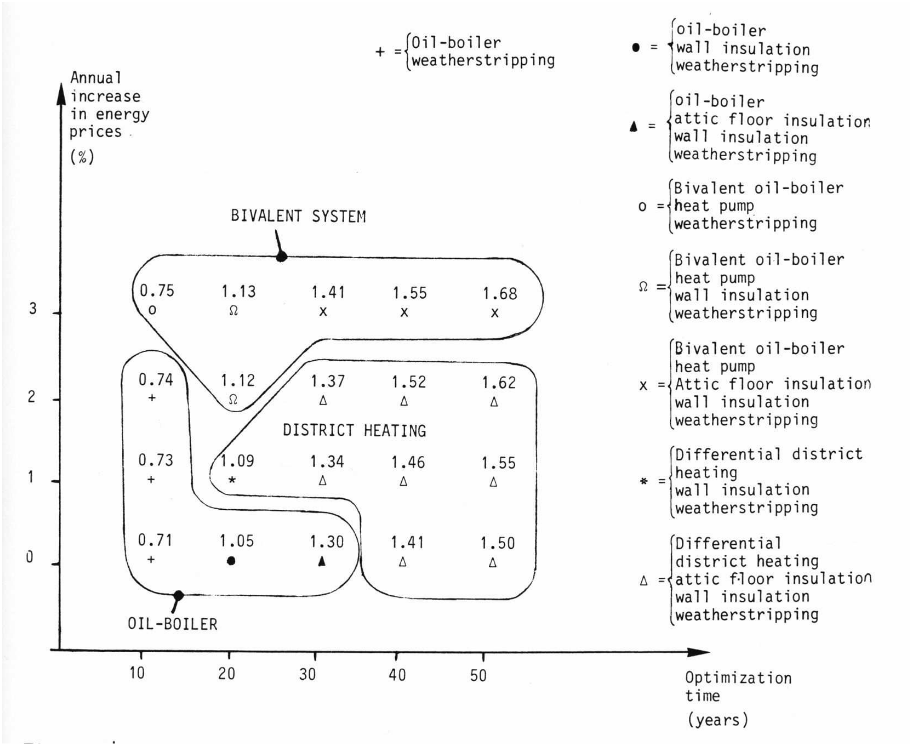

Figure 6.8: Bivariate sensitivity analysis. Annual increase in energy prices versus optimization time. The values show the LCC in MSEK

$$U_{eq} = \frac{2 \times k}{\pi \times H} \times \ln(1 + \frac{\pi \times H}{2 \times k} \times U_0) \tag{6.2}$$

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

Using $k = 1.0$ W/m^2×K, $H = 2.5$ m and $U_0 = 1.0$ W/m^2× will evaluate in an equivalent U-value of 0.4 W/m^2×K. For existing U - values of that magnitude an insulation retrofit will almost always be unprofitable. In Reference [71]the subject of optimal insulation of the building foundation is treated for new residential housing. However, the authors use methods similar to those presented in Reference [30], in this thesis dealt with in page 15, and no optimum can be found without a tedious trial and error procedure.

6.5.2 Window retrofits

In the case dealt with in this thesis window retrofits are only profitable with high energy prices. Note that high energy prices first will change the heating system and thus better windows are once again rejected by the model. This is so, even if the windows have to be changed anyway. The most profitable solution is to change windows to the ordinary double-glazed type, see also Appendix 2, remark number 1, page 97. The better thermal performance, in the other types of windows dealt with here. cannot justify the higher cost.

6.5.3 Weatherstripping

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

6.5.4 Exhaust air heat pump

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

6.5.5 Changing the heating system

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

6.5.6 The best strategy

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

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

- Caulking the windows and doors

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

On the contrary, the closeness of the existing heating system strategy might be a little surprising. see Table 6.3 page 43. In many earlier OPERA cases it was more profitable to change the oil-boiler to a lower running cost system such as bivalent oil-boiler heat pump systems which provide a combination of a very low running cost and an acceptable acquisition cost. The reason for the competitive existing heating system is mostly due to the low energy demand in the case above. In the next chapter a more thorough study is elaborated in order to describe also these more complex heating systems.

6.6 DIFFERENT HEATING SYSTEMS

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

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

6.6.1 The differential district heating rate

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

$$300 \times P_{dim}$$

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

Single-family houses: $500 + 600 \times D \times R$
Multi-family houses,
$D = 0$ - 800 kW,: $700 + 600 \times D \times R$
$D = 801 - \infty$ kW: $2{,}400 + 600 \times D \times R$

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

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

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

In Table 6.6 page 46, it is shown that OPERA calculates the energy demand month by month. Multiplying these figures with the applicable price provides the total running cost for energy during one year.

In our case this results in:

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

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

In the OPERA running shown in Table 6.2 page 42, this normalized price for district heating is also used in the ordinary district heating calculations. The total LCC for the existing building thus will be identical or 1.61 MSEK. Due to truncation errors the values are not exactly the same.

When a retrofit is introduced, OPERA calculates the total energy cost during one year, over again. The retrofit will lower the energy demand. Insulation measures, window retrofits et c., lower the cost mostly in the winter, while the energy demand during summer, as before, will equal the hot water production. This means that less of the more expensive energy is used. More money is thus saved if a differential rate is introduced. However, the influence is rather small because most of the heat is consumed during high price conditions, see Table 6.2.

The effect is enhanced for mineral wool insulation measures because the Energy 2 column in Table 6.6, page 46, is used for the insulation optimization. Almost no cheap energy at all is used and thus the optimization is elaborated for an energy price close to the high one in the tariff. The result is a thicker insulation compared to optimization with ordinary rates.

The exhaust air heat pump saves energy also during summer when the energy is cheap. The savings in money is therefore much lower if a differential rate is introduced. The subject is treated in detail in Reference [41].

6.6.2 Differential rates for electricity

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

Energy cost,
Nov-March,

Monday to Friday, 06-22:	0.345 SEK/kWh = 0.095 SEK/MJ
other times	0.16 SEK/kWh, = 0.044 SEK/MJ

Demand charges:

63 A	2,380 SEK
80 A	2,900 SEK
100 A	3,520 SEK
125 A	4,300 SEK

To the energy cost a tax of 0.072 SEK/kWh shall be added, 0.02 SEK/MJ. There are more varieties for other sizes of the fuses but the information presented above is enough for the purpose in this thesis. If a fuse bigger than 250 A is required another type of tariff is used, and OPERA will decide which tariff to use.

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

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

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

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

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

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

However. the demand charge above is not changed and if this is included in the energy price, which surely is correct, the running cost is increased from 0.3231 to 0.3261 SEK/kWh. The savings with the differential rate will thus in this case be lower than if a fixed rate is used. see Table 6.2 at page 42. The demand charge in this case will thus work in the opposite direction and make the differential rate a disadvantage.

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

The profitability of the exhaust air heat pump will be lowered very much. The fixed rate will generate approximately twice the savings compared to the differential rate. Extensive studies about the electricity differential rates can be found in References [38] and [39].

6.6.3 The bivalent heat pump systems

Mentioned above are the advantages with a bivalent oil-boiler heat pump system. In the case studied here however, these systems were not found profitable, see Table 6.2 page 42. The theories for the optimization are shown in Reference [42] and in Appendix 1 page 79. There are some differences in the calculation procedures between the two systems dealt with by OPERA, mostly concerning the elaboration of the equipment cost. In the first system the heat pump is assumed to work all year and thus the oil-boiler does not have to provide the thermal peak load. In the other case the heat pump is assumed to be turned off when the outside temperature is very low. The oil-boiler must provide all the heat under those conditions.

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

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

If the amount of free energy, from solar gains and appliances is rather large, there is a risk that the optimization procedure will not work properly for the bivalent systems. This will happen if the optimization procedure results in heat pumps with less thermal power than the point ”P summer” in Figure 6.9.

The true optimal situation will then be that the heat pump is to be abandonned, i. e. the oil-boiler system is better than the bivalent one. OPERA will tell the operator if this happens and the fact is that the outside air heat pump, in the case studied here, resulted in such conditions, see Appendix I. The bivalent heating systems will be advantageous if the heat consumed in the building is increased. If the building is located in a colder climate or if the building is bigger than the one tested here, these systems seem to be the best solution. One case is discussed in [72].

If the amount of free energy is decreased the same thing will happen.

In Table 6.19 this is emphasized. Abbreviations see page 43.

In the case studied one of the bivalent systems was the most profitable combined with three envelope measures. However, the district heating system with a differential rate is very close and a more thorough study has to be made in order to find the real best solution. The important thing here, is that the amount of heat consumed in the building will influence the best strategy. If more heat is needed, the more complicated heating systems can compete. Compare with the result in Table 6.2.

The envelope retrofit strategy for the bivalent outside air heat pump is almost similar to the one for the oil-boiler. This is because the optimization resulted in a too small heat pump, see Figure 6.9. OPERA thus calculates as if there were

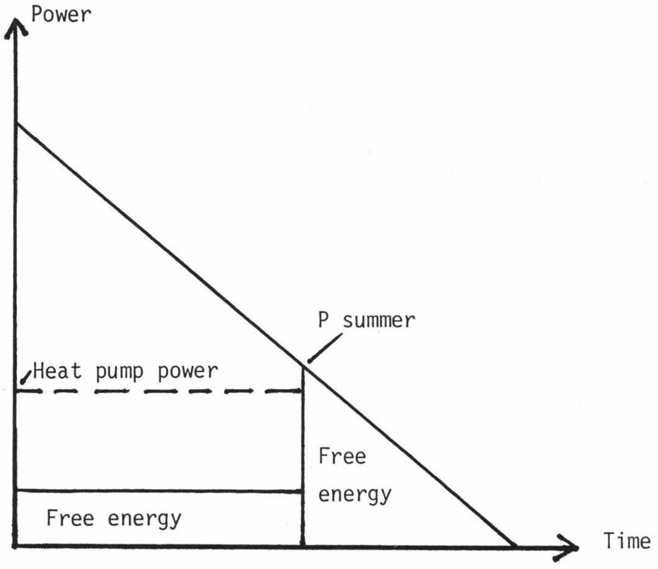

Figure 6.9: Duration curve with optimization failure

only the oil-boiler present. The hot water however, is still produced by the heat pump.

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

Table 6.19: Retrofit strategy matrix. Free energy from appliancies = 0 kWh/month. Values in MSEK

Chapter 7

INFLUENCE OF THE SWEDISH SUBSIDIARY SYSTEM

In previous chapters the optimal strategy has been studied for building costs, energy prices et c. found in literature dealing with these subjects. If these prices are adequate from the societal point of view is very hard to know. Wrong prices, of course, can lead to misoptimization.

Using the input data from the case study will regrettably lead to severe misoptimization considering the private economy for a landlord in Sweden. Here, as in many other countries, there is a subsidiary system in order to encourage the owner of a building to implement retrofit measures on the house. This system must be taken into proper consideration in private economy optimization.

In Sweden the subsidiaries can be split up in three types:

- Renovation loans
- Interest subsidiaries
- Energy retrofit subsidiaries.

The most advantageous part is the renovation loans and therefore these will be described in further detail. There are a number of restrictions for the loans.

- The measures must result in considerable improvement of the functional or technical performance of the building.
- The building must be older than 30 years.
- The owner of the building must be able to administer the building in a proper way.
- The building must, after the renovation, have the same standard as a new building.
- The building site or real estate must have been sold by the municipality.

- Et c., Et c.

The constraints above and other information about the subsidiary system, can be found in References [73] and [74].

The municipality accepts or rejects the application in the first consideration by the society. It is also authorized to reject some of the constraints, e. g. the constraint concerning the site.

If you are entitled to these renovation loans the society gives you a loan up to 30 % of the renovation cost. The remaining 70 %, must be covered by a credit institution, like a mortgage bank. The rate of interest of the 30 % loan was 11.75 % and for the second loan 11.20 %, in January 1986. Both loans are of the type fixed-yearly-instalment, i. e. the sum of the amortization and interest payments are the same every year. The amortization payment however, is calculated as if the rate of interest was 8 %. The first loan has a pay-off time of 30 years and the second 40 years or less, if decided by the mortgage institution. However, the second loan does not exactly follow the fixed-yearly-instalment method. A pay-off plan is decided for each case.

The society will subsidize the interest payments and the first year the rate is warranted to a value between 2.15 - 2.6 %. After this the rate is incremented by 0.25 % each year. The cost however is calculated on the total sum of the loan, as if no pay-off was made. This means that after some years the guaranteed interest payments will get higher than the real interest and by then the subsidiary will be abandoned.

When the influence of the subsidiary system is elaborated it is necessary to transfer all the future payments to the base year, using the present value method. First however. the cost must be evaluated in running prices. In order to simplify the calculations it is assumed that there only is one loan with an interest rate of 12 %. The annual amortization is calculated for an 8 % fixed-instalment loan with 30 years pay off time. The inflation is assumed to be 7 % and the real discount rate to 5 %. The total loan is estimated to be 100,000 SEK. and the guaranteed rate of interest in the beginning 2.6 %.

When the annual payment, i. e. the sum of the pay-offs and the interest cost, must be the same year by year, this can be calculated:

$$FIP = A_{loan} \times \frac{r}{1-(1+r)^{-p}} \tag{7.1}$$

where FIP = the fixed instalment payment, A = the total loan, r = the discount rate and p = the pay-off time. Using A_{loan} = 100,000, r = 0.08 and p = 30 the annual cost will be 8,883 SEK. The discount rate cost, 0.08 × 100,000, is 8,000 SEK and thus the amortization will be 883 SEK. The following year the loan has decreased to 99,117 SEK and the interest cost, 8 %, will become 7,929 SEK. The amortization will be 8,883 - 7,929 = 953 SEK.

From Table 7.1 it is obvious that the subsidiary system is abandoned at year 21, i. e. when the real cost of interest is lower than the guaranteed one.

However, Table 7.1 shows the running prices with an inflation estimated to 7 %. Using the net present value method, equation (12.2) at page 102, the annual payments can be transferred to fixed prices, and furthermore transferred to the base year using Expression (12.2) once more with a real discount rate of 5 %. Table 7.2 shows this.

Year	FIP	Int. cost 8 %	Amort-ization	Warr. int. cost 2.6 %+.25%	To pay	Next year loan	Real int. 12 %
1	8,883	8,000	883	2,600	3,483	99,117	12,000
2	8,883	7,929	953	2,850	3,803	98,164	11,894
3	8,883	7,853	1,029	3,100	4,129	97,135	11,759
20	8,883	5,073	3,809	7,349	11,159	59,603	7,609
21	8,883	4,768	4,114	7,599	11,266	55,489	7,152
29	8,883	1,267	7,615	—	9,517	8,225	1,901
30	8,883	657	8,225	—	9,211	—	986

Table 7.1: Swedish subsidiary system. Running prices

Year	Running prices	Fixed prices 7 % inflation	Present value 5 % real disc. rate
1	3,483	3,254	3,013
2	3,803	3,322	3,013
3	4,129	3,371	2,912
4	4,462	3,404	2,800
29	9,517	1,338	325
30	9,211	1,210	280
Present value at the base year			46,660

Table 7.2: Swedish subsidiary system. Present value calculation

In Table 7.2 the present value is calculated for the annual payment found in Table 7.1. The initial cost, 100,000 SEK, has decreased to approximately 50,000 SEK by the simplified subsidiary system. It is possible to calculate the precise situation in the same way as shown above but here the approximate situation is sufficient.

If the proprietor of the building is entitled to renovation loans all of the building and installation measures may be included in the loan as long as the total price for the retrofitted building does not exceed the price for a new building. The cost for the measures will thus be approximately half the real cost.

An OPERA running with these new cost functions implemented in the earlier presented case study, will result in a new bivalent heating system, the ground water coupled heat pump combined with an oil- boiler. The envelope retrofits combining this heating system are 0.26 meter attic floor insulation, 0.20 meter external wall insulation and weatherstripping. The total LCC is 0.86 MSEK.

It was thus optimal to change the existing heating system while the envelope measures were kept almost the same as before, although the optimal insulation thickness, was increased.

If the existing heating system, i. e. the oil-boiler, is not changed, an extensive envelope strategy should be implemented. This is of course natural because all the building costs have been divided by 2.

From the above discussion it is obvious that the subsidiary system has a very big influence on the optimal solution. The heating system is changed and the insulation thickness is increased by approximately one third. However, changing the heating system to a low running cost system, will still make e. g. exhaust air heat pumps unprofitable.

Chapter 8

CONCLUSIONS

The optimal retrofit strategy for a unique multi-family house can be calculated. The best strategy is then characterized by the lowest possible remaining life-cycle cost for the building.

This building is considered as an energy system and both envelope, ventilation and heating system retrofits are dealt with simultaneously.

Difficulties with uncertainties in input data can be solved by a sensitivity analysis. For a fixed set of input data there is an optimal solution and the OPERA model, described in this thesis, enables the finding of it.

The OPERA model is used for optimization of the retrofit strategy concerning a unique building. However, some general conclusions can be drawn from this thesis and a number of OPERA runnings:

1. The conventional method with retrofit ranking due to the saving-to-cost ratio is wrong. OPERA runnings show that essential for a low LCC is a low running cost. If the heating system provides this to an acceptable installation cost the first step is taken towards a low LCC. Such heating systems can be district heating with a rate that reflects the cost for producing the heat. or bivalent oil-boiler - heat pump systems. These kinds of heating systems shall be combined with a few cheap envelope retrofits. If the other method is used, where the retrofit with the highest saving-to-cost ratio is implemented first and after this the second highest. the demand of heat in the building might become too low. The profitability with a more complex heating system, which from the beginning was optimal, might vanish and misoptimization will occur.

2. Optimal energy retrofits shall be implemented when the building is subject for renovation from other reasons than energy conservation. If a low running cost heating system is implemented, very few envelope retrofits are profitable. Weatherstripping and attic floor insulation might emerge as plausible retrofits. However, more expensive retrofits can be profitable, i. e. when the remaining life of the considered building part is very short. Very poor windows might e. g. be changed to new ones with a better thermal standard. Most important is, that the best solution is implemented, if the envelope of the building is the subject for renovation measures. This means that the optimal solution, e. g. the optimal amount of insulation, must be applied. If a lower degree of insulation is chosen this will lead to

misoptimization and this cannot be changed with any profitability, until next time the building part has to be renovated for other reasons than energy conservation. This is the situation for many buildings in Sweden today, where 0.05 to 0.10 meter of insulation is applied on the external walls.

3. A combination of heating system, envelope and ventilation retrofits leads to the optimal solution. It is necessary to consider the building as an energy system. One example of this is that weatherstripping is not always part of the optimal retrofit strategy. It might be better to take care of the extra ventilation flow in an exhaust air heat pump. The marginal cost for the extra thermal power in the heat pump is lower than the cost for caulking the windows and doors.

4. The result of envelope retrofit combinations differs from calculations made for retrofits added one by one but the difference is minute and can mostly be neglected. OPERA calculates if a retrofit is profitable, i. e. if the LCC is decreased when the retrofit is introduced. If this is the situation, the retrofit is a candidate for the optimal solution. A number of retrofits are examined. The combination of the retrofits found profitable will not result in exactely the same life-cycle cost as if the savings for each retrofit were added to each other and then subtracted from the original cost. This difference is enhanced if a lot of retrofits are combined and if a lot of free energy, from e. g. appliances, is present in the building. In this thesis it is shown that the optimal solution is mostly characterized by a low running cost heating system with only a few retrofits implemented at the envelope, and thus the difference will be very small, about 5 % of the resulting LCC, and subsequently they mostly can be neglected. However, using OPERA it is possible to find the true optimal strategy with the significance required. In most cases the order of implementation can also be neglected. To insulate the attic floor first and after this implement extra insulation at the external wall will yield almost the same result as if the order was the opposite.

5. Bivalent heating systems and insulation measures can be optimized simultaneously. When a bivalent heating system is considered it is very important that the thermal power of the oil-boiler and the power of the heat pump as well as the amount of insulation are optimized. In this thesis it is shown how this can be elaborated. If the insulation is found profitable, up to 0.2 meter of extra insulation might be optimal. This is surprising because of the very low running cost for the bivalent system.

6. The ordinary degree hour concept must be abandoned. Energy balance calculations are necessary in order to find proper optimization parameters. The insulation measures shall be optimized for a higher amount of degree hours than the heating system. This is due to the influence of free gains from solar radiation, appliances et c.

7. District heating and electricity rates must reflect the real cost for producing an extra unit of energy. Marginal cost pricing might be essential for the optimization. It is important that the utility uses a tariff that reflects the real cost for producing the energy. The distribution between the firm

and the running part in the rate is essential. A high energy price per MJ, higher than it is in reality, will lead to more conservation measures in the buildings. This however also will lead to misuse of the utility investment, less energy will be produced than is optimal. Differential, or time-of-use rates might be of importance considering retrofit measures. If a differential rate is introduced it will slightly advantage insulation measures but will give severe disadvantage to competing energy production in the building.

8. Subsidiary systems might lead to misoptimization. Subsidiary systems that encourage energy saving measures are important for the strategy. Cheaper insulation will make it profitable to add more insulation to the building. However, also more efficient heating systems might be profitable, which will provide heat to a lower cost. This will influence the insulation level in the opposite direction and thus the optimal insulation level might have been higher if the subsidiary system had not existed. The subsidiary system might lead to suboptimizations from a societal point of view. Complex heating systems will be combined with an extensive envelope retrofit strategy. This will lead to a higher LCC than is necessary.

9. Optimization periods longer than 30 years exert very small influence on the retrofit strategy. Due to the present value calculations costs appearing in a distant future, have a very small influence on the solution. The retrofit strategy will be almost identical if 30 or 50 years are considered.

10. The LCC for different optimal solutions due to future changes of the input data differs less than could be expected. Future changes of energy prices et c. might considerly change the LCC for a building. The sensitivity analysis elaborated in an OPERA running shows that the LCC, for optimal solutions will not change as much as could be expected. Consider the influence of changes in the insulation cost. A low cost leads to a thick insulation while a high cost leads to the opposite or no insulation at all. In Figure 6.5 page 58, it is shown that the resulting LCC is almost constant, as long as the optimal amount of insulation is chosen. The influence of higher energy prices on the LCC follows a straight line when only one heating equipment is considered, see Figure 6.4 at page 57. If it is possible to change the heating system this is not the case and the LCC will increase slower after the heating system is changed. The LCC continues to follow a straight line but less blunt than the original one.

11. Changes in the time constant of the building will not influence the retrofit strategy very much. A high constant makes it possible to decrease the dimensioning outside temperature for the building site and subsequently smaller heating equipment can be chosen. However it is not very easy to calculate this temperature adequately but the influence can be simulated by testing a number of alternatives. The influence on the optimal solution is very small due to the rather low installation cost for the heating equipment.

12. The climate conditions at the building site are important. The climate of the building site is important for the optimal retrofit strategy. In a cold climate more heat is consumed in the building. The total life-cycle cost however will not be affected in the same way. This is due to changes

in the optimal strategy. The insulation levels are increased and a more sophisticated heating system is profitable to install. This will lead to a slower increase of the LCC than could be expected initially.

13. Electricity space heating is of no interest. Direct electricity for space heating seems to be of no interest because of the high running cost. For small buildings though, where the demand is very low, electricity might compete.

14. Exhaust air heat pumps will rarely be selected. Because of the low running cost heating system, almost always found optimal, exhaust air heat pumps, due to their high initial outlay, will seldom be part of the optimal retrofit strategy.

15. Costs for environmental pollution can be considered. Implementing higher energy prices or higher costs for insulation et c. makes it possible to include costs for environmental pollution. Note however the effect on the optimal heating equipment as well as on the thickness of extra insulation.

16. Implementing optimal retrofits can considerably decrease the remaining LCC for a building. If bigger buildings are retrofitted in an optimal way a decrease in the LCC with 40 % has been calculated. Implementing LCC optimization makes it possible. both for a private landlord and for the society, to save considerable amount of money.

Chapter 9

FUTURE WORK

In the now presented thesis, the superiority of life-cycle cost analysis and optimization is shown. The results from such considerations often differ from those achieved from other methods. However, these LCC methods are not in common use, mostly because of the tedious calculation work needed. Modern computers simplify this drudgery. The OPERA - model is run in about thirty seconds for the base case alternative, and thus it can be used extensively.

However, at present the model is implemented in a big computer, which is not in common use. No manual or tutorial exists to help the interested reader with implementing a building of his own.

A big effort will be made to implement the model in smaller computers, like IBM PC and others. If that is successful the LCC concept can be widely spread.

Enhancements will also be made on the model itself. The bivalent system which was found very competitive is at present using a fixed rate for electricity. Time-of-use, or differential rates will be more common in the future and thus it is important to optimize such a system as well. Maybe the model has to be equipped with a linear programming routine in order to solve this problem. This routine might also make it possible to optimize the retrofit combination situation without using the more complicated iterative process, necessary in OPERA today.

Other types of buildings can also be possible to examine by OPERA. For example industrial buildings which often have a much higher degree of ventilation than is common in residences. Then OPERA must be provided with heat exchanger retrofits which are excluded today.

It is also important to elaborate mathematical expressions for the LCC field, where heating system changes are included. Up to now only one heating system is considered in the LCC expressions. If this is possible the precise LCC field could be depicted and the breaking points in it can be revealed. Now this has to be examined from a number of OPERA runnings.

Another interesting issue is to examine how energy conservation measures will influence the running of district heating cogeneration plants. If the utility is used only for electricity production a marginal use of heat from the condensor will be very cheap, in fact at no cost at all, as the plant must get rid of the heat in some way as long as electricity production is utilized. District heating however, cannot use the low temperature of the cooling water from an ordinary electricity plant. The temperature in the condensor must be increased which leads to loss of electricity, and the price for the heat must reflect this. Optimal energy retrofits in buildings heated with district heating will subsequently be influenced by the needed electricity production at the utility.

The lack of proper input data is also emphasized in this thesis. There is thus a need for extensive research about retrofit costs et c. In the future, information from data bases might be used as default values in OPERA runnings. If the effort at finding suitable input data severely could be reduced, the method would come into common use.

A thorough study of the Swedish subsidiary system will also be elaborated. This is very important in order to encourage desireable behavior concerning energy conservation and retrofits, from the societal point of view. Using the subsidiary system must lead toward the optimal solution found by society. If this could be the situation the nation could use its limitid resources in a better way than today.

Chapter 10

APPENDIX 1

OPTIMIZATION OF BIVALENT OIL-BOILER - OUTSIDE AIR HEAT PUMP SYSTEMS WHILE ALSO CONSIDERING ENERGY CONSERVING RETROFITS

In this appendix it is shown how the optimization is elaborated for a bivalent heating system and energy conserving retrofits. The case study, see page 37. in the main thesis is used as an example. The total data file is shown in Appendix 2, page 91. The optimization procedure is shown here in detail and thus it might be somewhat tedious to read. That is the reason for presenting it as an appendix.

10.1 DURATION GRAPH

The calculations start with the construction of a duration graph for the existing building, considering the climate for the building site. In the OPERA model the climate is depicted by monthly mean temperatures. These are used for calculating the heat consumption in the building during one year. However, the heating system must also be able to provide enough heat during very cold winter nights and a lowest dimensioning outside temperature is used to ensure that the installed heating equipment power is sufficient. Unfortunately it is not very easy to construct a mathematical expression, suitable for optimization calculations, using these monthly mean values, and thus they are approximated with a straight line function, elaborated with the method of least squares. This function can be shown as:

$$\Delta T = -0.0025089 \times \tau + 22.991 \tag{10.1}$$

where ΔT = the difference between the desireable inside temperature (20 °C) and the monthly mean outside temperature, and τ = the duration in hours.

Setting ΔT to 0.0 implies that τ = 9,164 hours, and setting τ to 0.0 will make ΔT equal to 22.99 °C. The total amount of degree hours during one year will then become:

$$DH = \frac{9,164 \times 22.99}{2} = 105,340$$

This figure should be compared to the ”real one”, i. e. 105,241 and, as can be seen, the expression (10.1) is a very good approximation.

The situation is depicted in Figure 10.1, which also can be found in [42].

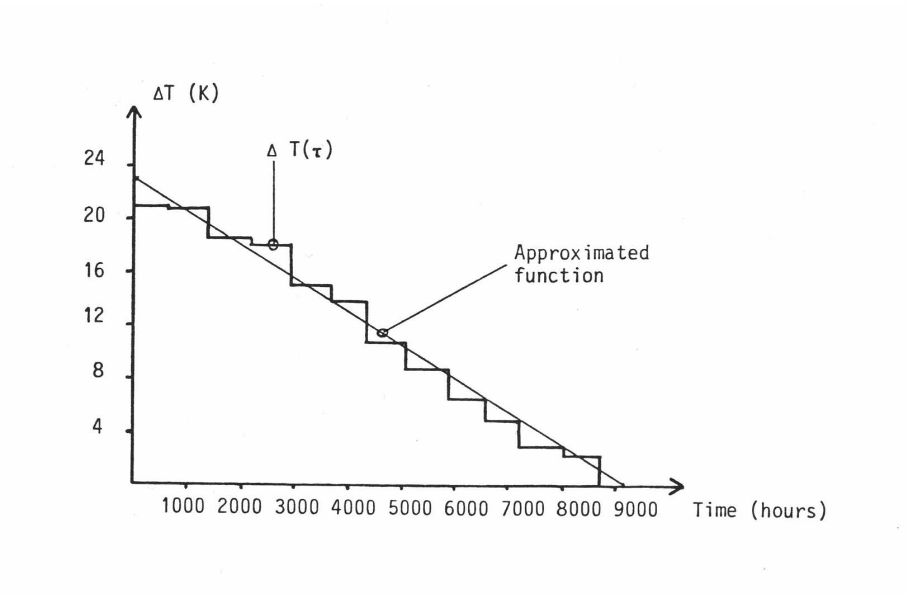

Figure 10.1: Duration graph. Monthly mean temperatures.

In this case study the existing building can thermally be described by an expression showing the thermal losses, i. e. TRANS + VENT from the equations (12.4) and (12.5) at page 148. This expression is evaluated to 2.291 kW/K, see Table 6.3, page 43, in the main part of the thesis. When multiplying this figure with the maximum temperature difference it is found that the thermal load in the duration graph for energy calculations equals 52.67 kw. The total energy demand during one year will then be:

$$TOD = \frac{52.67 \times 9,164}{2} = 241,334 \quad \text{kWh}$$

However, there is also free energy from solar gains and appliances that has to be considered. In Table 6.6 in the main part, page 46, the figures are presented. In Table 6.6 the monthly thermal losses are shown as well.

During the summer, i. e. when the heating equipment is turned off, this valuable free energy equals:

$$55.2 + 29.7 + 17.2 + 20.3 + 38.8 = 161.2 \quad \text{MJ}$$

or 44,711 kWh. This "summer energy" must be depicted in the duration diagram and the duration is calculated as:

$$\tau_1 = \frac{44,711 \times 2}{P_{som}}$$

$$\tau_1 = \frac{9,164 \times P_{som}}{52.67}$$

and thus $\tau_1 = 3{,}944$ hours and $P_{som} = 22.67$ kW.

The free energy during the rest of the year is also calculated by use of Table 6.6. The heat delivered from the heating system is 573.7 MJ. Excluding the domestic hot water part, will result in 321.7 MJ. The total energy loss in the building is 868.1 MJ and the free energy during the heating season can be calculated as:

$$868.1 - 321.7 - 161.2 = 385.2 \quad \text{MJ},$$

or 107,257 kWh. This free heat must answer to some thermal load in the duration graph and therefore it is spread out during the heating season:

$$P_{fhs} = \frac{107,257}{9,164 - 3,944} = 20.54 \quad \text{kW}$$

Of course this is an approximation but it makes the calculation much easier than calculating on monthly mean values. The situation is depicted in Figure 10.2.

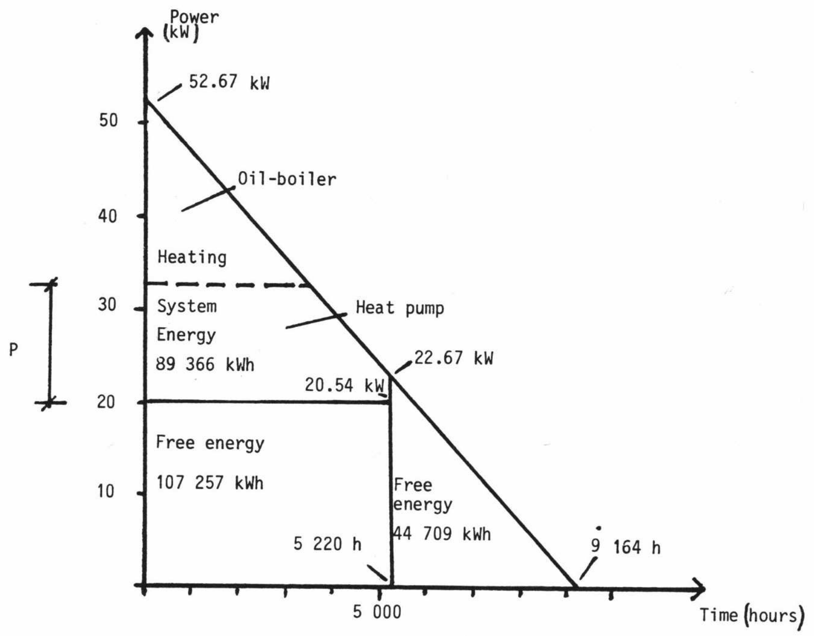

Figure 10.2: Approximated duration graph

This approximated duration graph is used for the optimization calculations. It is obvious that much of the heat consumed in the building comes from appliances et c. and these values may be too high. However, in Sweden it is common to turn off the heating system during the four summer months and from the energy balance calculations in Table 6.6, page 46, the free heat could provide the building with the desireable climate during five months. This implies that the magnitude is approximately right.

Later in this appendix there are also calculations where the free gains have been reduced in order to show the influence on the optimization, see page 115.

10.2 THE HEATING EQUIPMENT COST

Some of the heat, produced by the bivalent heating system, comes from the oil-boiler and the rest from the heat pump. In this case the oil- boiler has to provide the total thermal load during very cold winter periods, i. e. 77.9 kW.

In the input data chapter, page 40, it is found that oil-boilers cost:

$$20,000 + 350 \times P$$

where P is the power for the heating system concerned. Outside air heat pumps cost:

$$40,000 + 6,000 \times P$$

The oil-boiler as well as the heat pump have a life span of 15 years. The heat pump must also be renovated to a cost of 10 % of the initial cost each 7.5 years. It is also assumed here that other costs when installing the oil-boiler, such as piping costs et c., cost:

$$150 \times P$$

with a life span of 30 years. Such costs for the heat pump are assumed to be:

$$200 \times P$$

with a life span of 40 years. See Appendix 2 for the total input file.

The total cost for the oil-boiler can be calculated as:

$$(20,000 + 350 \times 77.9) \times (1 + 1.05^{-15} + 1.05^{-30} + 1.05^{-45} - \frac{2}{3} \times 1.05^{-50}) +$$

$$+150 \times 77.9 \times (1 + 1.05^{-30} + 1.05^{-50}) = 97,498 \quad \text{SEK}$$

The total cost for the heat pump with the power P is calculated in the same way i. e.:

$$(40,000 + 6,000 \times P) \times (1 + 0.1 \times 1.05^{-7.5} + 1.05^{-15} + 0.1 \times 1.05^{-22.5} + 1.05^{-30} +$$

$$+ \ldots = 75,440 + 11,575 \times P$$

The costs above show the present value for the heating equipment, formula (12.2) in Appendix 3, page 102.

10.3 THE ENERGY COST

The energy cost is a little more complicated to elaborate. The first thing to do is to find an expression for the oil-boiler duration time, τ_2. From equation (10.1) it is found that:

$$\tau_2 = \frac{-\Delta T + 22.991}{0.0025089} = -398.58 \times \Delta T + 9,164$$

However,

$$P_1 = \Delta T \times (TRANS + VENT) = 2.291 \times \Delta T$$

and thus

$$\tau_2 = -398.58 \times \frac{P_1}{2.291} + 9,164 = -173.97 \times P_1 + 9,164$$

$$P_1 = P + 20.54$$

and thus:

$$\tau_2 = -173.97 \times P + 5,590$$

The situation is depicted in Figure 10.3.

Now it is suitable to evaluate the heat pump energy:

$$E_{hp} = 5,220 \times P - \frac{(5,220 - \tau_2) \times (P - (22.67 - 20.54))}{2} =$$

$$= 2,610 \times P + 5,559 + \frac{P}{2} \times \tau_2 - 1.065 \times \tau_2$$

Inserting the expression above for τ_2 gives:

$$E_{hp} = -86.98 \times P^2 + 5,590 \times P - 394.$$

The oil-boiler energy is calculated as:

$$E_{ob} = \frac{(52.67 - P - 20.54) \times \tau_2}{2} = -0.5 \times \tau_2 \times P + 16.07 \times \tau_2$$

and thus:

$$E_{ob} = 86.98 \times P^2 - 5,590 \times P + 89,803$$

Now the energy cost must be calculated. The heat pump has a varying COP and accordingly a mean value during the heating season is used. Equation (5.4), page 28 in the main part shows the situation. For $\Delta T = 22.991$ the COP equals 2.12 and for $\Delta T = 0$ it will become 3.24. These two values answer to 0 and 9,164 hours in the duration graph. A new COP function can be calculated i. e.:

$$COP = 2.11 + 0.000122 - \tau$$

Implementing $\tau = 5{,}220$ hours i. e. the end of the heating season, see Figure 10.2, evaluates the COP to 2.75. The mean value will be:

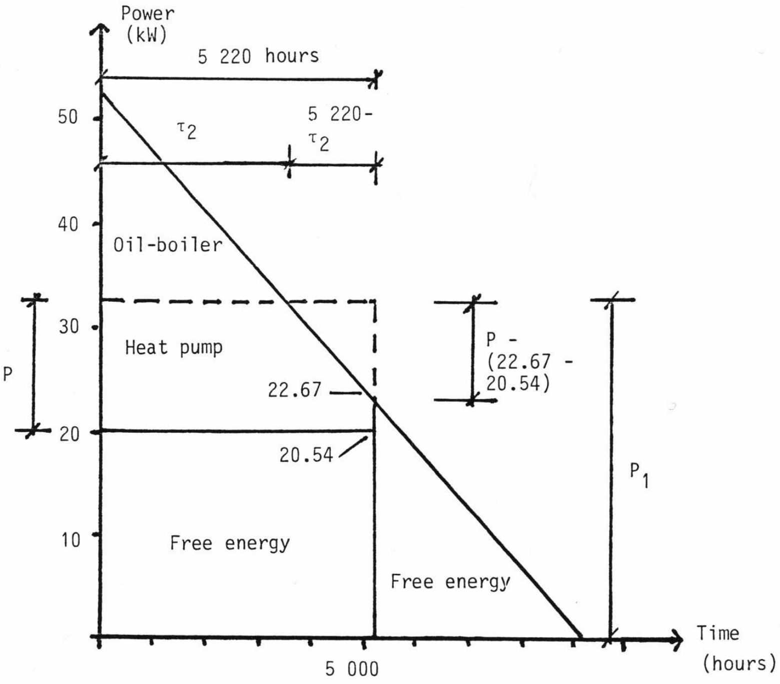

Figure 10.3: Energy evaluation graph

$$COP_{mv} = \frac{2.11 + 2.75}{2} = 2.43$$

The electricity price is assumed to be 0.089 SEK/MJ, 0.32 SEK/kWh, and the net present value factor for annually recurring costs can be evaluated to 18.26, see Expression (12.3) in Appendix 3 page 102. The heat pump energy cost thus can be calculated as:

$$EC_{hp} = (-86.98 \times P^2 + 5,590 \times P - 394) \times \frac{0.32 \times 18.26}{2.43} =$$

$$= -209.15 \times P^2 + 13,441 \times P - 947 \quad \text{SEK}$$

The oil-boiler energy cost will be:

$$EC_{ob} = (86.98 \times P^2 - 5,590 \times P + 89,803) \times \frac{0.18 \times 18.26}{0.8} =$$

$$357.36 \times P^2 - 22,966 \times P + 368,956 \quad \text{SEK}$$

10.4 TOTAL COST AND OPTIMIZATION

Adding the cost functions, i. e. the oil-boiler cost. the heat pump cost and the energy cost, result in:

$$LCC = 148.21 \times P^2 + 2,050 \times P + 540,947 \quad \text{SEK}$$

The minimum point for this function will emerge when:

$$P = \frac{-2,050}{2 \times 148.21} = -6.92 \quad \text{kW}$$

which of course is very disappointing as negative heat pumps do not exist. However this result means that the best thing to do is to reject the outside air heat pump. It is better to heat the building using only an oil-boiler. OPERA thus sets the heat pump power to 0 kW.

In the case above only space heating has been considered. Adding also the hot water production to the heating load, which has a duration all over the year will enhance the profitability for the heat pump. In Reference [42] it is shown that it is optimal to let the heat pump produce all the hot water due to its 100 % duration.

OPERA calculates the total LCC for this new system, setting the heat pump thermal load equal to the hot water production thermal load. The operator however, will be informed that this situation has emerged in order to avoid mistakes.

10.5 CHANGING THE AMOUNT OF FREE ENERGY

In the example presented above the optimization leads to an impossible result, a negative heat pump. This is because of the low thermal demand and a high heating equipment cost. Above was also mentioned that the free energy from appliances et c. might be overestimated. It could be interesting to show what will happen if the free energy is decreased. This has been done below, estimating that the monthly free gains is 0 kWh. The only free energy in the building comes from the solar radiation. A new duration graph has to be presented, see Figure 10.4.

This new situation leads to a more encouraging result. The heat pump size ought to be 9.3 kW if only space heating is considered and 17 kW if the hot water thermal load is added. It shall be emphasized here that the COP for the hot water production is calculated for the 100 % duration.

10.6 ADDING INSULATION TO THE ENVELOPE

If extra insulation is implemented on e. g. the attic floor, it may be possible to get a lower LCC due to a lower energy bill or cheaper heating equipment. The case with a low amount of free energy led to a successful optimization and that example is used for showing how the optimization is elaborated, considering

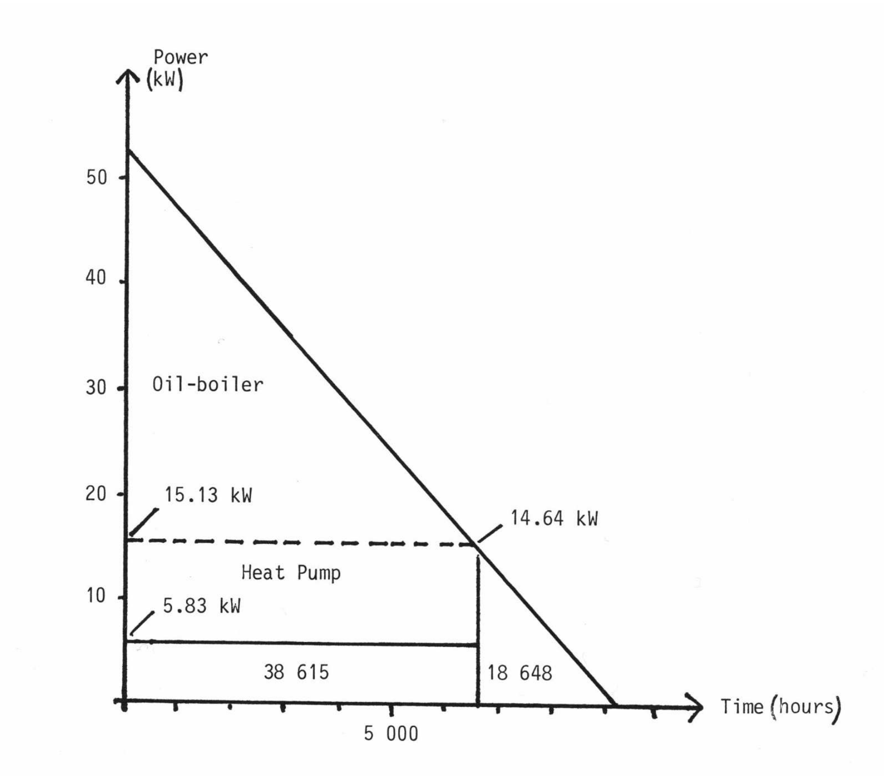

Figure 10.4: Duration graph. Free energy equals solar gains.

also an insulation measure i. e. the attic floor. The basic ideas are identical to the ones used in Reference [42], but here the complexity is larger due to energy balance calculations and free energy considerations. As earlier, the procedure starts with the heating equipment costs.

Adding more insulation to the attic floor will decrease the thermal load for the building and subsequently a smaller oil-boiler can be used. In Reference [3] it is shown that the new U-value can be expressed as:

$$U_{new} = \frac{k_{new} \times U_{ex}}{k_{new} + U_{ex} \times t}$$

where U_{new} = the new U-value, k_{new} = the conductivity of the new insulation, U_{ex} the existing U-value and t = the thickness of the extra insulation.

The new thermal loss for the building now has to be recalculated and this is done by subtracting the loss through the original attic floor and adding the new loss using the expression above. Mentioned above in the input data chapter, page 38, are the original U-value, i. e. 0.8 W/m$^2\times$ K and the attic floor area equalling 396 m^2.

The total TRANS +VENT factor in the building has been calculated to 2.291 kW/K and the new situation will result in:

$$2,291 - 0.8 \times 396 + \frac{0.04 \times 0.8 \times 396}{0.04 + 0.8 \times t} =$$

$$= 1,974 + \frac{12.67}{0.04 + 0.8 \times t}$$

The oil-boiler cost will be:

$$(20,000 + 350 \times (1.974 \times 34 + \frac{0.01267 \times 34}{0.04 + 0.8 \times t})) \times 1.7655+$$

$$+150 \times (1.974 \times 34 + \frac{0.01267 \times 34}{0.04 + 0.8 \times t}) \times 1.201 =$$

$$= 88,873 + \frac{343.8}{0.04 + 0.8 \times t} \quad \text{SEK}$$

The heat pump cost will be the same as before or:

$$75,440 + 11,575 \times P$$

In order to evaluate the heat pump energy the duration for the oil-boiler must be expressed. Above it is shown, page 83, that:

$$P_1 = \Delta T \times (TRANS + VENT)$$

In this case $(TRANS + VENT)$ is not a constant but a function of t, i. e. the insulation thickness. The expression is shown above and thus:

$$P_1 = \Delta T \times (1.974 + \frac{0.01267}{0.04 + 0.8 \times t})$$

and

$$\tau_2 = -398.58 \times \frac{P_1}{1.974 + \frac{0.01267}{0.04+0.8\times t}} + 9,164 \quad \text{hours}$$

In this case where the insulation optimization is emphasized $P_1 = P$, see page 22, and this expression can be simplified to:

$$\tau_2 = -\frac{15.94 \times P - 839.69 + 318.86 \times P \times t - 14,471 \times t}{0.09163 + 1.5792 \times t}$$

In the first case studied above, page 80, the heating season period could actually be calculated by the energy balance subroutine. Here however, the heating season is a function of t. Fortunately the heating season will not change very much for a single retrofit why an approximation can be used. In Reference [15] it is shown that rather thick insulations, i. e. about 0.2 meter, often can be found optimal, and such an insulation will result in a very low thermal flow through the attic floor. OPERA thus calculates the heating season for the building as if no heat at all was transferred through this asset. In this case the heating season is calculated to 6,616 hours. The energy produced by the heat pump now can be approximated as:

$$E_{hp} = 6,616 \times P - \frac{(6,616 - \tau_2) \times (P - 12.61)}{2} =$$

$$3,308 \times P + 41,713 + 0.5 \times P \times \tau_2 - 6.31 \times \tau_2$$

Implementing the expression for τ_2 gives:

$$E_{hp} = 3,308 \times P + 41,713 -$$

$$-\frac{7.97 \times P^2 + 159.43 \times P^2 \times t - 9,245 \times P \times t - 520.34 \times P + 91,239 \times t + 5,294.5}{0.09163 + 1.5792 \times t}$$

The oil-boiler energy will become:

$$E_{ob} = \frac{(22.991 \times (1.974 + \frac{0.01267}{0.04+0.8\times t}) \times 9,164}{2} - 16,068 - E_{hp} =$$

$$= 191,882 + \frac{1,334}{0.04 + 0.8 \times t} - E_{hp}$$

The constant 16,068 shows the amount of free energy during the summer if no heat at all is transferred through the attic floor. This is an approximation because the real value is a function depending on the thickness of the extra insulation.

The same approximations must be made for the COP of the heat pump, the real COP is approximated with the one calculated for the building with no thermal transport through the attic floor. The situation leads to the following expression:

$$Cost_{ob} + Cost_{hp} + Energy\ cost_{ob} + Energy\ cost_{hp} + Cost_{ins} = \text{Total cost}$$

From the expressions above it is achieved:

$$\text{Total cost} = 878,958 + 5,731 \times P + \frac{5,824.5}{0.04 + 0.8 \times t} +$$

$$+\frac{14.08 \times P^2 + 281.7 \times P^2 \times t - 16,335 \times P \times t - 919.4 \times P + 161,210 \times t + 9,354.8}{0.09163 + 1.5792 \times t} +$$

$$+49,500 + 118,800 \times t$$

Now this cost function must be derivated in order to find the minimum point.

$$f'_P(t,P) = 5,73 + + \frac{563.4 \times P \times t + 28.16 \times P - 919.5 - 16,336 \times t}{0.09163 + 1.5792 \times t}$$

$$f'_t(t,P) = -\frac{4,659.6}{0.04 + 0.8 \times t} + \frac{3.57 \times P^2 - 43.7 \times P - 3}{(0.09163 + 1.5792 \times t)^2} + 118,800$$

These two derivatives shall equal 0 simultaneously for the minimum point. However, it is not very easy to actually calculate this point. OPERA has thus been provided with an iterative process that tests the result for a number of

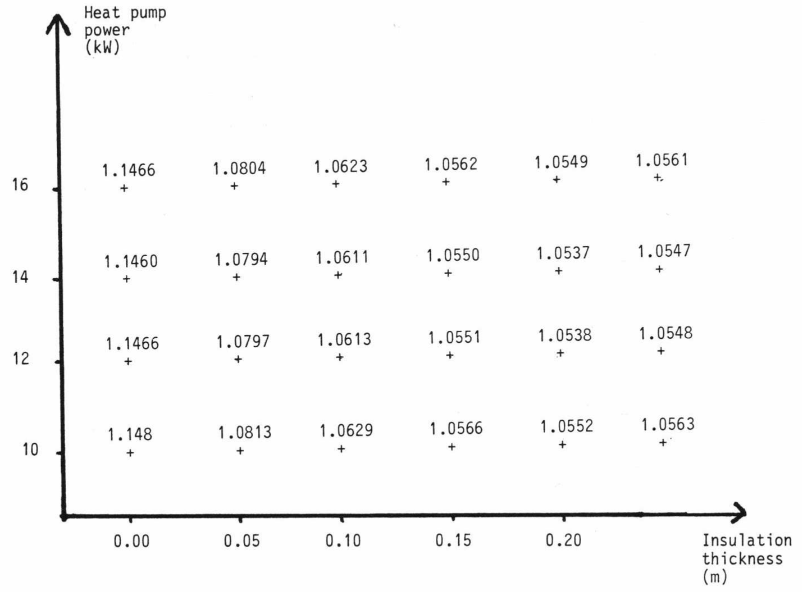

Figure 10.5: LCC field for insulation and heating system optimization

alternatives for *t* and *P*. This process results in a heat pump power equalling 13.26 kW and an extra insulation of 0.197 meter. The LCC field is shown in Figure 10.5.

See also Figure 5.5, at page 28, for a graphic presentation. Note however, that Figure 5.5 is elaborated from a slightly different mathematical expression.

It must be observed that it is not correct to implement the values for *P* and *t* above and calculate the total LCC. This is due to the free energy consideration see page 87. Thus the insulation thickness value is implemented in the (TRANS + VENT) equation and the optimization starts once again now for the building including its insulated attic floor. The process is shown in the beginning of this appendix and is not repeated here. However it results in a heat pump power equalling 7.63 kw if the hot water load is excluded.

10.7 EXHAUST AIR HEAT PUMPS

An exhaust air heat pump can be used to take care of the heat in the ventilation air. In this case when there already is a heat pump in the heating system it is most important to consider the duration graph when calculating the new LCC, see Figure 10.6.

In OPERA the space heating is default and the exhaust air heat pump delivers heat for the hot water production only when there is a heat surplus from the space heating. However, the hot water is produced with the ordinary heating system and thus the profitability of an exhaust air heat pump will mostly vanish. OPERA tests if the device is profitable or not using the process described in the beginning of this appendix and thus only the duration graph

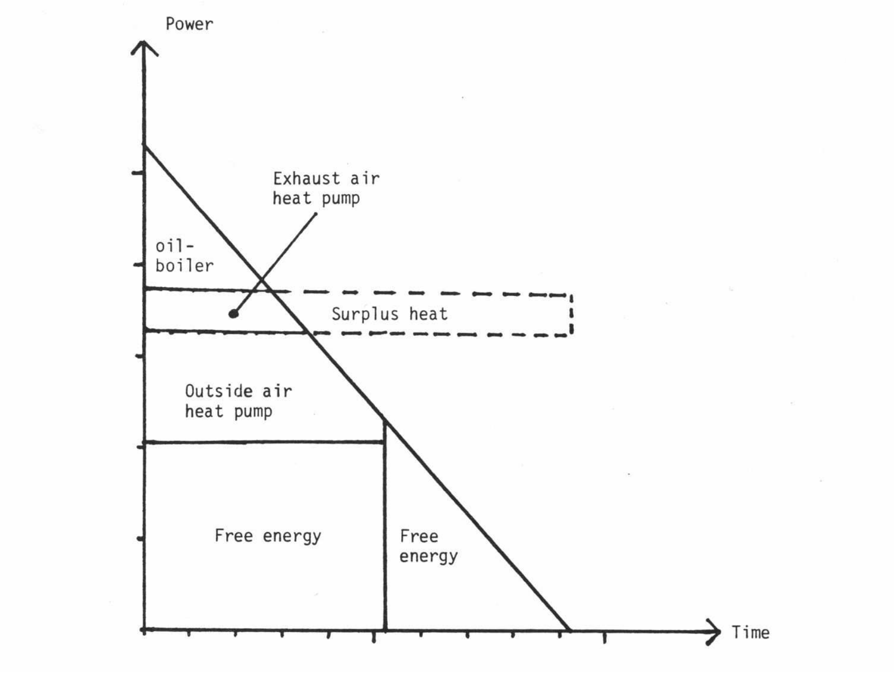

Figure 10.6: Exhaust air heat pump and heating system duration graph

will be presented here.

Chapter 11

APPENDIX 2

Sensitivity analyzis, influence on the optimal solution due to changes in the input data. As mentioned in the main part of the thesis, it is possible to use the OPERA model in order to elaborate a sensitivity analysis, i. e. how does the optimal solution change if small changes would appear in the input parameters. In the main part, the subject has been dealt with from a more principal point of View, and with considerable changings in the data. Here, a more thorough study will be elaborated and all input parameters will be scrutinized one by one.

It must be remembered that it is the optimal solution found for the basic case alternative that is examined due to small changings in the basic case input data. One of the parameters is increased or decreased with 5 % and the optimal LCC change is calculated. Note that there is no ultimate value to choose and thus 5 % is not better or worse than any other value. The result is presented in a table and, when considerable changings in the strategy emerge they will of course be examined in greater detail.

The OPERA input data files consist of some two hundred values, most of these discussed in the main part of the thesis. Some of the values describe the geometry of the building, e. g. the number of windows. Those will not be dealt with in this appendix, as part of the sensitivity analysis. Other values might be coupled to each other, e. g. the areas of the attic and the floor, which means that not only one of the parameters can be changed, while the other is constant. Such values are marked NPC below, i. e. Not Possible to Change. In the following Table 11.1 the total input files are described, the base case alternative is presented and a 5 % increase or decrease of applicable parameters is implemented. The percentage change in the new optimal LCC is calculated and shown. Note remarks in the end of the appendix!

Input data	Value	Quantity	LCC change in % for		Remarks
			- 5 %	+ 5 %	
Attic floor area	396	m^2	—	—	NPC
Floor area	396	m^2	—	—	NPC
External outside wall area windows excluded,	720	m^2	—	—	NPC
External inside wall area windows excluded	720	m^2	—	—	NPC
Total apartment area	1000	m^2	—	—	NPC
Area of one north window	2.23	m^2	—	—	NPC
Number of north windows	30		—	—	NPC
Area of one east window	1.69	m^2	—	—	NPC
Number of east windows	3		—	—	NPC
Area of one south window	1.69	m^2	—	—	NPC
Number of south windows	30		—	—	NPC
Area of one west window	1.69	m^2	—	—	NPC
Number of west windows	3		—	—	NPC
Existing thermal attic insulation	0.8	$W/m^2 \times K$	-0.021	0.019	
Existing thermal floor insulation	0.6	$W/m^2 \times K$	-0.211	0.211	
Existing thermal external wall insulation	1.0	$W/m^2 \times K$	-0.046	0.051	
U-value double-glazed window	3.0	$W/m^2 \times K$	-0.016	0.457	1
Remaining life attic floor	0	years	—	0	2
Remaining life floor	0	years	—	-2.333	2
Remaining life external wall at the outside	0	years	—	-1.939	2
Remaining life external wall at the inside	0	years	—	-1.697	2
Remaining life windows	0	years	—	-4.543	2
Type of ventilation	Natural		—	—	NPC
Number of air renewals	0.8	1/hour	-0.517	0.597	
Type of heating system	Oil-boiler		—	—	NPC
Existing power in the heating equipment	170	kW	-0.067	0.067	
Existing heating equipment efficiency	0.7	—	0	0	
Remaining life of existing boiler	5	years	-0.089	0.089	
Hot water energy demand	70,000	kWh/year	-0.666	0.666	
New thermal conductivity attic floor insulation	0.04	$W/m \times K$	-0.057	0.055	
New thermal conductivity floor	0.04	$W/m \times K$	0	0	
New thermal conductivity external wall outside 0.04	$W/m \times K$	-0.137	0.133		
New thermal conductivity external wall inside	0.04	$W/m \times K$	0	0	
U-value new triple-glazed window	1.8	$W/m^2 \times K$	0	0	
U-value new triple-glazed window with low-emissivity	1.5	$W/m^2 \times K$	0	0	
U-Value new triple-glazed window with low-emissivity gas-filled	1.4	$W/m^2 \times K$	0	0	
New duration of attic floor	20	years	0	0	
New duration of floor	20	years	0.299	-0.276	
New duration of external wall, outside	20	years	0.706	-0.653	
New duration of external wall, inside	20	years	0.217	-0.201	
New duration of windows	20	years	0.581	-0.538	

Input data	Value	Quantity	LCC change in % for		Remarks
			- 5 %	+ 5 %	
Optimization time	50	years	-1.037	0.873	
Discount rate	5	%	1.981	-1.865	
Annually escalating					
energy prices	0	%		3.488	3
Attic floor, building costs,					
part 1	0	SEK/m^2	—	0.785	4
part 2	125	SEK/m^2	-0.166	0.166	
part 3	300	SEK/m$^2\times$ m	-0.057	0.055	
Floor building costs,					
part 1	250	SEK/m^2	-0.491	0.491	
part 2	195	SEK/m^2	—	—	
part 3	250	SEK/m$^2\times$m	—	—	
External wall building cost, outside,					
part 1	325	SEK/m^2	-1.160	1.160	
part 2	85	SEK/m^2	-0.206	0.206	
part 3	555	SEK/m$^2\times$ m	-0.137	0.133	
External wall building cost, inside,					
part 1,	100	SEK/m^2	-0.357	0.357	
part 2,	175	SEK/m^2	0	0	
part 3,	555	SEK/m$^2\times$ m	0	0	
Apartment height	2.4	m	-0.342	0.356	
Annual rent	400	SEK/m$^2\times$ year	0	0	
Building cost, windows, double-glazed,					
part 1	2,050	SEK	-0.671	0.671	
part 2	450	SEK/m^2	-0.285	0.285	
triple-glazed, part 1	2,700	SEK	0	0	
part 2	700	SEK/m^2	0	0	
triple-glazed, low-emissivity,					
part 1	2,700	SEK	0	0	
part 2	1,000	SEK/m^2	0	0	
triple-glazed, low-emissivity,					
gas-filled, part 1	2,700	SEK	0	0	
part 2	1,100	SEK/m^2	0	0	
Oil-boiler cost, part 1	20,000	SEK	-0.022	0.022	
part 2	350	SEK/kW	-0.067	0.067	
efficiency	0.8		0	0	
New duration	15	years	0.094	-0.085	
Piping cost	150	SEK/kW	0	0	
Duration	30	years	0	0	
Electricity boiler cost,					
part 1	20,000	SEK	0	0	
part 2	100	SEK/kW	0	0	
efficiency	1.0		0	—	5
New duration	20	years	0	0	
Piping cost	0	SEK/kW	—	0	
Duration	40	years	0	0	6
District heating boiler cost,					
part 1	58,000	SEK	-0.234	0.234	
part 2	50	SEK/kW	-0.009	0.009	
Efficiency	1.0	+1.001	—	7	
New duration	30	years	0.102	-0.094	
Piping cost	0	SEK/kW	—	0.031	8
Duration	45	years	0	0	
Heat pump, ground water					
coupled, part 1	30,000	SEK	0	0	
part 2	3,300	SEK/kW	0	0	
COP	3.0		0	0	
New duration	10	years	0	0	
Piping cost	200	SEK/kW	0	0	
Duration	25	years	0	0	

Input data	Value	Quantity	LCC change in % for		Remarks
			- 5 %	+ 5 %	
Heat pump, earth coupled,					
part 1	30,000	SEK	0	0	
part 2	4,300	SEK/kW	0	0	
COP	3.0		0	0	
New duration	10	years	0	0	
Piping cost	0	SEK	—	0	
Duration	20	years	0	0	
Outside air heat pump cost,					
part 1	40,000	SEK	0	0	
part 2	6,000	SEK/kW	0	0	
COP part 1	66.43		0	0	9
COP part 2	20.54		0	0	9
New duration	15	years	0	0	
Piping cost	200	SEK/kW	0	0	
Duration	40	years	0	0	
Reinvestment	10	%	0	0	10
Period	7.5	years	0	0	10
Monthly mean temperatures:					
January	-0.5	°C	0.351	-0.351	11
February	-0.7	°C	0.320	-0.320	11
March	+1.4	°C	0.225	-0.080	11
April	+6.0	°C	0.006	-0.006	11
May	+11.0	°C	0	0	11
June	+15.0	°C	0	0	11
July	+17.2	°C	0	0	11
August	+16.2	°C	0	0	11
September	+13.5	°C	0	0	11
October	+8.9	°C	0.006	0.003	11, 12
November	+4.9	°C	0.169	-0.005	11
December	+2.0	°C	0.225	-0.225	11
Number of items for weather-stripping	90		0.159	-0.159	13
Cost for each	200	SEK	-0.143	0.143	
Decrease in ventilation flow if weather-stripping	0.3	renewals/hour	0.211	-0.211	
Duration weather-stripping	10	years	0.121	-0.100	
Number of apartments	18	—	—	NPC	
Inlet temperature to exhaust air heat pump	20	°C	0	0	14
Inside room temperature	20	°C	-1.034	1.315	15
Dimensioning outside temperature	-14 °C	0.031	-0.031	16	
Piping cost, exhaust air heat pump	4,500	SEK/apart.	0	0	
Duration	30	years	0	0	
Exhaust air heat pump cost,					
part 1	10,000	SEK	0	0	
part 2	4,500	SEK/kW	0	0	
Duration	15	years	0	0	
COP	3.0		0	0	
Outlet exhaust air temperature	5.0	°C	0	0	17
Free energy:					
January	11,800	kWh/month	0.214	-0.214	18
February	11,800	kWh/month	0.214	-0.214	18
March	11,800	kWh/month	0.138	-0.072	18
April	11,800	kWh/month	0	18	
May	11,800	kWh/month	0	0	18
June	11,800	kWh/month	0	0	18
July	11,800	kWh/month	0	0	18
August	11,800	kWh/month	0	0	18
September	11,800	kWh/month	0	0	18
October	11,800	kWh/month	0	0.010	18, 19
November	11,800	kWh/month	0.091	0	18, 19
December	11,800	kWh/month	0.119	-0.138	18

Input data	Value	Quantity	LCC change in % for		Remarks
			- 5 %	+ 5 %	
Solar gains north direction:					
January	4.3	kWh/m^2	0.005	-0.005	
February	8.94	kWh/m^2	0.011	-0.011	
March	18.57	kWh/m^2	0.015	-0.014	
April	28.82	kWh/m^2	0	0	
May	44.5	kWh/m^2	0	0	
June	53.48	kWh/m^2	0	0	
July	50.54	kWh/m^2	0	0	
August	36.63	kWh/m^2	0	0	
September	23.12	kWh/m^2	0	0	
October	13.54	kWh/m^2	0	0	
November	5.82	kWh/m^2	0	0	
December	3.08	kWh/m^2	0.002	-0.002	
Solar gains, east direction:					
January	8.27	kWh/m^2	0.001	-0.001	
February	17.97	kWh/m^2	0.002	-0.002	
March	41.86	kWh/m^2	0.002	-0.002	
April	61.97	kWh/m^2	0	0	
May	87.58	kWh/m^2	0	0	
June	90.91	kWh/m^2	0	0	
July	89.07	kWh/m^2	0	0	
August	75.07	kWh/m^2	0	0	
September	53.11	kWh/m^2	0	0	
October	28.30	kWh/m^2	0	0	
November	10.75	kWh/m^2	0	0	
December	5.36	kWh/m^2	0	+0.0003	20
Solar gains, south direction:					
January	29.66	kWh/m^2	0.027	-0.027	
February	43.69	kWh/m^2	0.040	-0.040	
March	73.68	kWh/m^2	0.044	-0.044	
April	75.29	kWh/m^2	0	0	
May	82.59	kWh/m^2	0	0	
June	76.28	kWh/m^2	0	0	
July	78.50	kWh/m^2	0	0	
August	79.81	kWh/m^2	0	0	
September	79.37	kWh/m^2	0	0	
October	61.57	kWh/m^2	0	0	
November	32.70	kWh/m^2	0	0	
December	21.22	kWh/m^2	0.013	-0.013	
Solar gains, west direction:					
January	8.27	kWh/m^2	0.001	-0.001	
February	17.97	kWh/m^2	0.002	-0.002	
March	41.86	kWh/m^2	0.002	-0.002	
April	61.97	kWh/m^2	0	0	
May	87.58	kWh/m^2	0	0	
June	90.91	kWh/m^2	0	0	
August	75.07	kWh/m^2	0	0	
September	53.11	kWh/m^2	0	0	
October	28.30	kWh/m^2	0	0	
November	10.75	kWh/m^2	0	0	
December	5.36	kWh/m^2	0.0003	-0.0003	
Shading coefficient,					
Triple-glazed	0.1		0	0	
Triple-glazed, low-emissivity	0.2		0	0	
Triple-glazed, low-emissivity gas-filled	0.3		0	0	
Oil price	0.18	SEK/kWh	-0.194	0	21
Elecricity price	0.32	SEK/kWh	0	0	
District heating price	0.20	SEK/kWh	0	0	
Connection fee, district heating	300	SEK/kW	-0.045	0.045	
Fixed fee no 1	700	SEK	-0.043	0.043	22
Fixed fee no 2	2,400	SEK	0	0	23

Input data	Value	Quantity	LCC change in % for		Remarks
			- 5 %	+ 5 %	
Power related fee	600	SEK/kW	-0.139	0.139	24
Reduction factor	0.25		-0.139	0.139	
Energy price differential district heating:					
January	0.19	SEK/kWh	-0.141	0.141	
February	0.19	SEK/kWh	-O.109	0.109	
March	0.19	SEK/kWh	-0.078	0.078	
April	0.10	SEK/kWh	-0.036	0.036	
May	0.10	SEK/kWh	-0.036	0.036	
June	0.10	SEK/kWh	-0.036	0.036	
July	0.10	SEK/kWh	-0.036	0.036	
August	0.10	SEK/kWh	-0.036	0.036	
September	0.10	SEK/kWh	-0.036	0.036	
October	0.10	SEK/kWh	-0.036	0.036	
November	0.19	SEK/kWh	-0.073	0.073	
December	0.19	SEK/kWh	-0.119	0.119	
Electricity rate, demand charges, Fuse less than,					
35 A	1,640	SEK/year	0	0	
50 A	2,060	SEK/year	0	0	
63 A	2,380	SEK/year	0	0	
80 A	2,900	SEK/year	0	0	
100 A	3,520	SEK/year	0	0	
125 A	4,300	SEK/year	0	0	
160 A	5,420	SEK/year	0	0	
200 A	6,760	SEK/year	0	0	
250 A	8,400	SEK/year	0	0	
Energy price, differential electricity heating:					
January	0.33	SEK/kWh	0	0	
February	0.32	SEK/kWh	0	0	
March	0.32	SEK/kWh	0	0	
April	0.23	SEK/kWh	0	0	
May	0.23	SEK/kWh	0	0	
June	0.23	SEK/kWh	0	0	
July	0.23	SEK/kWh	0	0	
August	0.23	SEK/kWh	0	0	
September	0.23	SEK/kWh	0	0	
October	0.23	SEK/kWh	0	0	
November	0.32	SEK/kWh	0	0	
December	0.33	SEK/kWh	0	0	
Demand tariff, electricity:					
Connection fee	4,500	SEK	0	0	
Demand tariff, electricity:					
Subscription fee	65	SEK/kW	0	0	
Demand charge	135	SEK/kW	0	0	
Energy price:					
January	0.31	SEK/kWh	0	0	
February	0.31	SEK/kWh	0	0	
March	0.31	SEK/kWh	0	0	
April	0.23	SEK/kWh	0	0	
June	0.19	SEK/kWh	0	0	
July	0.19	SEK/kWh	0	0	
August	0.19	SEK/kWh	0	0	
September	0.23	SEK/kWh	0	0	

Input data	Value	Quantity	LCC change in % for		Remarks
			- 5 %	+ 5 %	
October	0.23	SEK/kWh	0	0	
November	0.31	SEK/kWh	0	0	
December	0.31	SEK/kWh	0	0	

Table 11.1: OPERA input data values and sensitivity analysis

11.1 Remarks

1. When an increase of 5 % is implemented. triple-glazed windows in the east and west directions are considered as candidates of the optimal solution. In this case the LCC increased with 0.5 % for a 5 % increase in the U-value but decreased only by 0.02 % for a decrease in the U-value. A closer study may thus result in rejecting these window retrofits. See the discussion about the combination of different retrofits in page 21.
2. The original values of the remaining life of the assets are set to 0 years. Thus it is not possible to calculate a 5 % change in these parameters. An increase is instead implemented by 5 years.
3. The original value is 0 % increase in escalating energy prices. It is not possible to calculate a 5 % increase in this parameter and thus a 1 % escalation is evaluated.
4. The cost is 0 SEK/m^2 in the original input file. A 5 % change thus cannot be calculated. An increase from 0 to 20 SEK/m^2 is thus evaluated.
5. The electricity boiler efficiency cannot be higher than 1.0. A 5 % increase is thus not considered.
6. The duration of the piping measures is of no interest here because of the 0 cost for this measure.
7. The efficiency of the district heating equipment is set to 1.0. No higher value can be implemented.
8. The original value is 0 SEK/kW. This cannot be changed with 5 %. Instead 10 SEK/kw is evaluated.
9. This value is discussed in connection with formula 5.7 in the main part of the thesis.
10. In Chapter 10 this value is discussed in further detail.
11. The temperature values are not changed by 5 %. Instead an increase or decrease with 1 °C is made.
12. For an increase here of 1 °C the LCC is increased by 0.003 %, which is not logical. This value however is very small and may be the result of some truncation error.
13. This is an integer value and thus the change here is 5 items. No decimal values are accepted.

14. The temperature is increased or decreased with 1 °C, instead of 5 %.
15. The temperature is not changed with 5 %. Instead a 1 °C difference is implemented.
16. A 1 °C change is implemented instead of 5 %.
17. The outlet temperature is changed by 1 °C instead of 5 %.
18. The free energy here is considered as energy from appliancies. Solar gains are treated below.
19. When the free energy is increased by 5 % the LCC increases with 0.01 %. This is not logical and may be the result of some truncation error. The influence however, is very small and no closer investigation has been made.
20. For an increase of the free energy of 5 % the LCC raised by 0.003 % which is not logical. This may be the result of some truncation error.
21. In this case the best strategy is to keep the oil-boiler. The rest of the strategy is however almost the same.
22. The original value 700 is paid every year. See the applicable chapter in the main part of the thesis dealing with the differential district heating rate.
23. The value 2,400 shows the fixed fee for buildings with a higher thermal load than 800 kW. This is not the case here and thus the influence is 0.
24. This value shall by multiplied by the thermal load resulting from the energy demand during January and February, and divided by the number of hours in this period.

11.2 Some further notes

From the above Table 11.1 the change in the optimal, or almost optimal. LCC is presented for a 5 % change in the input value concerned. Sometimes it was not possible to change the value with 5 % and in those cases other input changings were calculated.The Table above shows the total input data files to the OPERA model except for outside temperature values for other sites than Malmo. Sweden.

It is possible to devide the resulting LCC changings in three parts:

- An increase in the input value results in an increase in the resulting LCC.
- A decrease in the input value results in an increased resulting LCC.
- A change in the input value does not influence the resulting LCC at all.

One example from the first group is the change in existing thermal insulation status. A change from 0.8 to 0.84 $W/m^2\times K$ for the attic floor results in a LCC increase from 1,487,950 SEK to 1,488,233 SEK or with 283 SEK. A change to 0.76 $W/m^2\times K$ will decrease the LCC with 313 SEK. Note that the LCC function is not linear. In this case a change in the input value with 5 % results in a change, however very small, in the resulting LCC with about 0.02 %. This is so because the attic floor insulation retrofit was found profitable. A high U-value results in a thicker insulation which means that the resulting LCC is changed much more slowly than if no insulation at all is implemented. See Table 6.15, at page 53, in the main part of the thesis.

An example where this is not the case can be found in the next value in the table, concerning floor insulation. This has a U-value of 0.6 W/m$^2\times$ K and a 5 % change will result in a change of the magnitude 0.2 % or ten times the change discussed above. The insulation measure here was found unprofitable and thus the increase in U-value must result in a higher energy demand. For some U-value however, the insulation retrofit will be profitable and thus the LCC slope will have a severe change in that point. It is essential to note that the change of 0.2 % is no more important to the result than the ten times smaller value. In the floor insulation case the optimal strategy is identical for better U-values, nothing ought to be done to the floor. The LCC however, will change but nothing profitable can be done to influence the LCC. When the breaking point is reached, however. the slope is ten times less blunt, but every small change in the original U-value will influence the optimal strategy, i. e. the insulation will be thicker or thinner.

The same situation can be found considering the optimization time or the so called project life. A 5 % change here results in a LCC change of about 1 %. This does not imply that there are severe changings in the optimal strategy. The competing strategy is changed in the same way and the new situation is almost the same from a relative point of view. Figure 6.2, page 52, shows the situation.

The input values discussed above will influence the total LCC for all possible changings. This is not the situation considering e. g. the district heating equipment cost. The cost is devided in two parts, one initial cost, 50,000 SEK. and one cost that depends of the thermal size, 50 SEK/kW. A 5 % change in the second part will result in a 0.009 % change in the resulting LCC. If the value is increased enough the district heating equipment will suddenly be defeated by another heating system, probably the existing oil-boiler, which ought to be combined with other envelope retrofits as well. Increasing the district heating equipment cost still more, will not change the new LCC at all. The equipment is not part of the optimal solution.

Using the OPERA model enables one to find the optimal retrofit solution for the studied building. If the model was perfect there would be smooth transitions from one solution to another. No blunt steps would appear in the LCC function. However, as can be found considering the U-value for double-glazed windows. such steps can appear if the strategy is changed. A decrease of 5 % in the input value results in a LCC change of 0.016 % while an increase of 5 % results in a change by 0.457 %. The reason for this is due to the way OPERA operates. The candidates for the envelope retrofits are selected if the new LCC is lower than the LCC for the existing building. The amounts of savings can sometimes be overestimated. In this specific case, where the strategy was completed with two window retrofits with a very low profitability, the optimal solution is probably to reject those retrofits. With some extra efforts this point can be revealed if the calculations are scrutinized.

There are also input values that, if they are increased, will decrease the resulting LCC. One example of this is the discount rate. A 5 % increase will result in about 1.8 % decrease in the new LCC. The change is severe but, as discussed above in connection with the project life, it will not necessarily change the optimal strategy very much. The competing strategies will change to the same degree. See Figure 6.1, page 49, and Figure 6.7, page 60, in the main part of the thesis.

The last category of values is the one which does not change the resulting LCC at all. One example is the electricity demand fee, i e 135 SEK/kW. This parameter can be changed infinitely. and still it will not affect the resulting LCC. There must be other changings in the input data for something to happen.

Another example is the cost for triple-glazed windows. If this cost is decreased enough the retrofit will suddenly be part of the optimal solution and further changes will of course result in another LCC.

In the Table 11.1 above a 5 % change is introduced into applicable input data. The resulting change in the new LCC is calculated, and the maximum change is found to be about 2 %, i. e. a change in the discount rate. However almost all values have a ten times smaller influence, or even smaller, on the resulting LCC. There are also many parameters that will not change the result at all.

From the above discussion it is obvious that it is not possible to classify or rank the parameters in rate of importance, in a general way. Each unique building will have a set of parameters that must be studied in detail. If another building is studied the set might be completely different. The experienced OPERA operator, will be able to find these important parameters and thus it will be possible to find the best solution with a high degree of accuracy.

Chapter 12

APPENDIX 3

The OPERA model has several subroutines following the main program. In this appendix five of those will be presented. The five subroutines are used for calculating:

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

12.1 THE NUMBER OF DEGREE HOURS

In Sweden it is common to use the degree hour concept in order to calculate the annual energy demand for a building. The degree hours are used in OPERA e. g. for the energy balance calculations and thus it is convenient to use monthly mean outside temperature values. The equation used for the calculations is:

$$DH = \sum_{n=1}^{12} (T_i - T_{s,n}) \times \tau_n \tag{12.1}$$

where DH = the number of degree hours, n = the number of the month, T_i = the desired inside temperature, $T_{s,n}$ = the mean outside temperature at month n and τ_n = the number of hours in month n. The process is described in detail in Reference [3] page 43.

The numbers of degree hours for each month are also stored in an array for later calculations on e. g. differential rates or tariffs.

In the subroutine the desired inside temperature is read as an input parameter. Traditionally this temperature has been used to simulate the contribution of free energy, e. g. solar gains in the building. This can be done by setting this value lower than the desired inside temperature.

In Sweden, 20 °C are normally considered as an adequate inside temperature, but 17 °C are used for the energy calculations. Due to this it is assumed that the free heat takes care of the remaining three degrees. A more detailed discussion about the degree hour concept can be found in Reference [75].

In Reference [3] 20 °C was used for the inside temperature and subsequentely the influence from the free energy was neglected. However the calculations were elaborated for a number of different climates and thus for a number of different amounts of degree hours.

Discussions with many interested readers of Reference [3], proposed the use of energy balance calculations instead of using the traditional degree hour concept. The method used in OPERA is presented in Reference [36], where the energy losses and heat production in the building are calculated with an extensive use of energy balances. This also means that it is possible to take solar gains and free energy from appliances into proper consideration.

12.2 THE PRESENT VALUE CALCULATIONS

When calculating the LCC it is important to compare the building costs, the energy cost et c. on one special occasion, the base year. It does not matter which year this is, but it is essential that the same year is considered for all the costs when adding them together. A method that transfer costs, occurring at different occasions, to one base year, is called the net present value method. The method is described in detail in Reference [3] and is well known from economic literature and will thus not be presented here once again. Only the formulas used in OPERA are shown. For a future non-recurring cost the Present Value can be calculated as:

$$PV = B \times (1 + r)^{-a} \tag{12.2}$$

and for annual recurring costs as:

$$PV = C \times \frac{1 - (1 + r)^{-b}}{r} \tag{12.3}$$

where B = The cost for one measure, r = The discount rate, a = The number of years from the base year to event B, C = The annual recurring cost and b = The number of years in the calculation period.

If the considered measure has a longer life than the total project. the remaining, so called salvage value, has to be subtracted from the net present value. This value is also calculated by use of expression (12.2). This equation is the only one used in the subroutine while the annual recurring costs are calculated in the main program. This is because there is no need to calculate this more than twice for one program cycle. The discount rate and the project life are constants during this calculation.

The input parameters in this subroutine are the cost for measure B and the discount rate r, in equation (12.2). but also the total optimization period, b, the number of years before event B happens, a. and how long it takes until it happens again.

The output parameter is the present value for the measure under consideration. In Appendix 1, page 82 an example is shown using equation (12.2).

12.3 THE INEVITABLE RETROFIT COST

When calculating the total LCC for the existing building it is necessary to find out how much the inevitable retrofits cost is. One example of such a measure is changing windows because of rot in the frames. The retrofit measure in this case, is implemented from other than energy conservation reasons and is thus considered as inevitable. Nevertheless, they have to be taken into proper account, because if an energy retrofit is implemented at the base year, the following inevitable retrofit periods will change, and the cost increases. The savings from the energy conservation thus have to be higher than the increased retrofit cost if the retrofit will be profitable. The subject is discussed in detail in Reference [3] page 53.

The subroutine serves the main program with the calculations concerning the building envelope, i. e. the attic floor, the external walls, the floor and the windows. The procedure is depicted in Figure 12.1.

In the subroutine the input parameters are:

- The area of the building part
- The initial cost, i. e. the inevitable cost, see C_1 in Equation (5.5), page 34, in the main part of the thesis
- The life-cycle for the new building part the remaining life-cycle for the existing building part.

Each building part has an assigned parameter which runs from 1 to 8.

Part number:

1. The attic floor
2. The floor or "basement equivalent"
3. The external wall. outside insulation
4. The external wall, inside insulation
5. Windows to the north
6. Windows to the east
7. Windows to the south
8. Windows to the west

The subroutine starts with calculations for the attic floor, and calculates the inevitable retrofit cost for one occasion i. e. "B" in Expression (12.2). After this is done the present value is calculated by calling the applicable subroutine. The process is repeated until all the building parts are treated. The total present value of the inevitable retrofit cost has then been found.

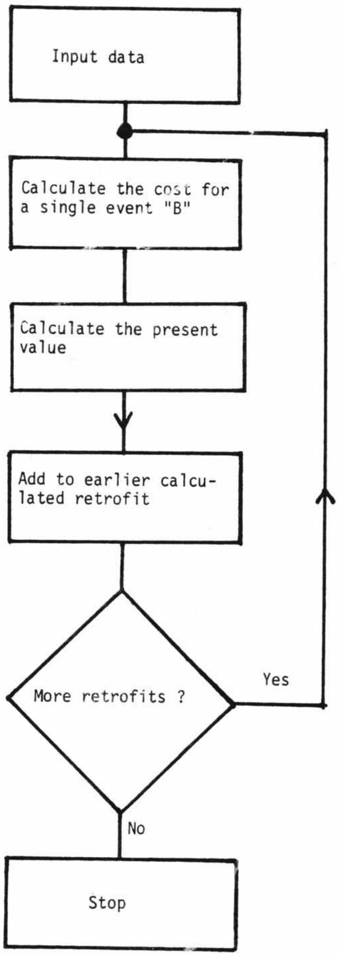

Figure 12.1: Inevitable retrofit cost subroutine, flow chart

12.4 THE ENERGY PRICE SUBROUTINE

The existing heating system in the building influence the LCC very much. One variable in the input parameters tells the subroutine which energy source that shall be used, i. e.:

- 1,2 = Oil
- 3,5,6 = Electricity
- 4 = District heating
- 7 = Differential district heating. time-of-use. rate
- 8 = Differential electricity, time-of-use, rate

- 9 = Bivalent oil-boiler, ground coupled heat pump system
- 10 = Bivalent oil-boiler, outside air heat pump system

In the main part of the thesis the heating systems are dealt with in detail and here it is only explained that the subroutine provides a proper energy price and a connection fee, if applicable.

The energy prices must be given to the model in SEK/kWh, efficiency excluded:

- The price for oil
- The price for electricity
- The price for district heating
- The price for district heating, differential rate
- The price for electricity, differential rate

The first three values are used directly as they appear in the input data file when the heating systems 1 - 6 are considered. For the systems 7 and 8 some calculations must be elaborated in the subroutine, see page 63 - 66. The bivalent systems 9 and 10 only use the subroutine to get the oil and electricity price. In Appendix 1 page 79, and in Reference [42] these systems are treated in detail.

12.5 THE ENERGY BALANCE SUBROUTINE

As mentioned above it is necessary to calculate the energy balance for the building in order to find the relevant heating cost. The subroutine uses the values of free energy from appliances and solar gains through windows as input parameters and they are not calculated in the program. Other input parameters are the monthly amount of degree hours from Formula (12.1) and the sum of the transmission and ventilation factor calculated as:

$$TRANS = \sum_{n=1}^{m} (U_n \times A_n) \tag{12.4}$$

$$VENT = H \times BA \times RN \times \rho \times cp \tag{12.5}$$

where n is the building part indices, m the number of building parts, U is the thermal transmittance and A is the area for the building parts. In the Formula (12.5) 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 the heat capacity. A more detailed discussion about Formulas (12.4) and (12.5) can be found in Reference [3]. The subroutine is depicted in Figure 12.2.

The calculations start with reading the total amount of free energy from solar gains and appliances. The values are given in monthly mean values for one year. Calculations in the main program provide the subroutine with the total energy losses in the building using the expressions (12.1, 12.4 and 12.5) above. The total losses are then subtracted from the total gains and the result is tested if negative or not. If it is negative. the gains are bigger than the losses and the heating equipment can be turned off during the whole month for space heating purposes. As is shown in [36] this is important to consider, when deciding the proper optimization values for both the heating system and the envelope retrofits. The heating system shall of course only be optimized for the heat actually produced in the facility and the free energy during 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. During 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 is not working with space heating, the free energy is of no value. It will only raise the temperature inside the building to an uncomfortable level. In those cases the free gains of course are useless. Because of this it is necessary to calculate the energy balance for the existing building, and every time a new retrofit is implemented in the model. See Table 6.6 at page 46 for an example.

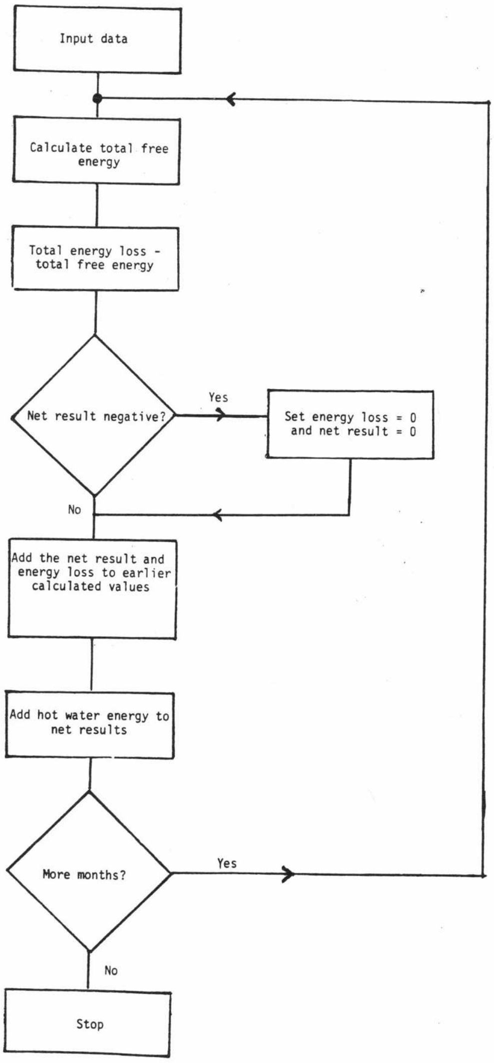

Figure 12.2: Energy balance subroutine, flow chart

Bibliography

[1] Böös B. Energy Conservation in Towns, The Swedish Concept. Report D8:1986, Swedish Council for Building Research, 1986.

[2] di Nallo E. and Canella R. Local Energy Planning. Report D3:1986, Swedish Council for Building Research, 1986.

[3] Gustafsson S-I. Optimal energy retrofits on existing multi-family buildings. Division of Energy Systems. Department of Mechanical Engineering. The Institute of Technology. Linköping, Sweden., 1986. Licentiate thesis no 91. ISBN 91-7870-118-X.

[4] Foulds L. R. *Optimization techniques.* Springer Verlag, New York Inc., 1981.

[5] Reklaitis G.V., Ravindran A., and Ragsdell K.M. *Engineering optimization.* John Wiley & Sons, Inc., 1983.

[6] Anonymous. Applied Economics Group Publications. U.S. Department of Commerce / National Bureau of Standards, 1973-1986.

[7] Ruegg, R., McConnaughey J., Sav G. and H., Kimberly A. Life-Cycle Costing: A Guide for Selecting Energy Conservation Projects for Public Buildings. Technical report, National Bureau of Standards, NBS BSS 113, Washington D.C. U.S., 1978.

[8] Petersen S. A Users Guide to the Federal Building Life-cycle Cost (FBLCC) Computer program. National Bureau of Standards Technical Note 1222, 1986.

[9] Fuller S. and Ruegg R. The Impact of Energy Pricing and Discount Rate Policies on Energy Conservation in Federal Buildings. National Bureau of Standards, NBSIR 85-3262, 1985.

[10] Lipiatt B, Weber S. and Ruegg R. Energy Prices and Discount Factors for Life-Cycle Cost Analysis. National Bureau of Standards, NBSIR 85-3273, 1985.

[11] Ruegg R. Life-Cycle Manual for the Federal Energy Management Program. National Bureau of Standards, HB 135, , 1982.

[12] Hall J., Colborne W. and Wilson N. A Methodology for Developing a Retrofit Strategy for Existing Single-Family Residences. CIB-84, Volume 2, Ottawa, Canada, 1984.

[13] Björk C. and Karlsson B. G. Optimization of Building Construction with respect to Life-Cycle Costs. CIB-84, Volume 2, Ottawa, Canada, 1984.

[14] Öfverholm I. Private communication. CIB-85, Vienna, Austria, 1987.

[15] Gustafsson S-I., Karlsson B.G. and Sjöholm B.H. Renovation of Dwellings - Life-Cycle Costs. In *Advancing Building Technology, Translating Research Into Practice*, volume 9, pages 3886–3893. CIB-86, September 1986.

[16] Szöke K. The 17 - year old W.55 is still developing. CIB-87, Keynotes Copenhagen, Denmark, 1987.

[17] Marshall H. Survey of Selected Methods of Economic Evaluation for Building Decisions. CIB-87, Keynotes Copenhagen, Denmark, 1987.

[18] Flanagan R., Kendell A., Norman G., Robinson G. Life Cycle Costing and Risk Management. In , Copenhagen Denmark, 1987. CIB - 1987 Conference.

[19] Lowe J. and Lowe H. Methods of Investment Appraisal Applied to Life-Cycle Costing. CIB-87, Session A, Copenhagen, Denmark, 1987.

[20] Grover R. and Grover C. Consistency Problems in Life-Cycle Cost Appraisals. CIB-87, Session A, Copenhagen, Denmark, 1987.

[21] Björk B. The Empiric Measurement of the Social Discount Rate. In *Building Economics, Methods of Econimic Evaluation*, volume Session A, pages 31–42, Copenhagen, 1987. CIB-87. ISBN 87-563-0664-4.

[22] Tippet H. and Sterios P. Building Value Management - Case Study Findings from the Public and Private Sectors in New Zeeland. CIB-87, Session A, Copenhagen, Denmark, 1987.

[23] Rabl A. Optimizing Investment Levels for Energy Conservation. *Energy Economics*, 7(4):259–264, 1985.

[24] Klassen J. Life-Cycle Cost Effectiveness. Heating/Piping/Air Conditioning, 1986.

[25] Bunday B. D. *Basic Linear Programming.* Edward Arnold Ltd, London, 1984.

[26] Bunday B. D. *Basic Optimization Methods.* Edward Arnold Ltd., London, 1984.

[27] Anonymous. LAMPS. Advanced Mathematical Software Ltd, 1984.

[28] Sidall J. *Optimal Engineering Design.* Marcel Dekker Inc. New York, 1982.

[29] Sun T. Decision Making in Energy Retrofit Design. Heating/Piping/Air Conditioning, 1986.

[30] Sonderegger R., Cleary p., Garnier J. and Dixon J. CIRA Economic Optimization Methodology. Technical report, Lawrence Berkeley Laboratory, U.S.A., 1983.

[31] Nilson A. The MSA - Method. Proceedings CLIMA 2000, Copenhagen, Denmark, 1985.

[32] Kirkpatrick A., Winn C. Optimization and Design of Zone Heating Systems, Energy Conservation and Passive Solar. *Journal of Solar Energy Engineering*, 107:64–69, 1985.

[33] Diamond R., Goldman C., Moders M., Rothkopf M., Sherman M. and Vine E. . Building energy retrofit research, multi-family sector. Technical report, Applied Science Division, Lawrence Berkeley Laboratory, CA 94720, U.S.A., 1985.

[34] Anonymous. Bibliography of the DOE Building equipment Research Program. U.S. Department of Energy, 1985.

[35] Markus T.A. The Window as an Element in the Building Envelope; Techniques for Optimization. In , volume 2, Copenhagen, Denmark, 1979. CIB 79.

[36] Gustafsson S-I., Karlsson B. G. and Redegren N. B. Optimal Energy Retrofits in Multi-Family Residences. In *Energy use and conservation*, pages 143–153. The Swedish-Soviet Seminar on Use and Conservation of Energy, Gävle, Sweden, 1987.

[37] Gustafsson S-I., Karlsson B.G. Renovation of multi-family houses with minimized lif-cycle cost. In *Innovation for energy efficience conference*, volume 2, pages 95–104. Newcastle upon Tyne, Pergamon Press U.K., 1987. ISBN 0-08-034798-3.

[38] Björk C. *Industrial Load Management Simulation.* PhD thesis, Department of Mechanical Engineering, The Institute of Technology. Linköping University, Linköping, Sweden., 1987. Dissertation nr 157.

[39] Sjöholm Bertil H. *Influence of differential rates on heating systems. Dissertation no. 119 Division of Energy Systems.* PhD thesis, Department of Mechanical Engineering, The Institute of Technology. Linköping, Sweden., 1984. Dissertation nr 119.

[40] Sjöholm Bertil H. Load management for buildings. In *Innovation for energy efficience conference*, volume C, pages 16–28. CIB-87, Copenhagen Denmark, 1987.

[41] Gustafsson S-I., Karlsson B.G. and Sjöholm B.H. Differential Rates for District Heating and the Influence on the Optimal Retrofit Strategy for Multi-Family Buildings. *Journal of Heat Recovery Systems & CHP*, 7(4):337–341, 1987.

[42] Gustafsson S-I., Karlsson B.G. Bivalent Heating Systems, Retrofits and Minimized Life-Cycle Costs for Multi-Family Residences. In *New Opportunities for Energy Conservation in Buildings*, volume No. 103, pages 63–74. CIB-W67, 1988.

[43] Anonymous. Enertech Värme, heat pump manufacturer. Private communication, 1985.

[44] Hagentoft C. An Analytical Model for Crawl-Space Temperatures and Heat Flows. Technical report, Institute of Technology, Lund, Sweden, 1986. Report TBVH 3012.

[45] Jonsson B. Heat Transfer Through Windows During the Hours of Darkness with the Effect of Infiltration Ignored. Document D:13, The Swedish Council for Building Research, 1985.

[46] Klems J.H. Toward accurate prediction of comparative fenestration performance. Workshop on laboratory measurements of U-values of windows, Gaithersburg, MD, U.S.A., 1985.

[47] Benson D.K. and Tracy C.E. Evacuated window glazings for energy efficient buildings. 29th annual SPIE international technical symposium on optics and electro-optics, San Diego, California, 1985.

[48] McCabe M.E. Field measurement of thermal and solar/optical properties of insulating glass windows. ASHRAE symposium on low-e coatings and films, winter annual meeting, New York City. U.S.A., 1986.

[49] Goss W. and McCabe M.E. Window U-values: Research Needs and Plans. Proceedings of the ASHRAE/DOE/BTECC Conference, Florida, U.S.A., 1985.

[50] Anderson R. Natural convection research and solar building applications. *Passive Solar Journal*, 3(1):33–76, 1986.

[51] Eriksson L., Masimov T. and Westblom S. Blocks of Flats with Controlled Natural Ventilation and Recovery of Heat. Document D:19, The Swedish Council for Building Research, 1986.

[52] Gustafsson S-I., Karlsson B.G. and Sjöholm B.H. Optimization of the retrofit strategy for a building in order to minimize its Life-Cycle Cost. In *Building Economics, Methods of Econimic Evaluation*, volume A, pages 159–169. CIB-87, 1987.

[53] Neely E. and Neathammer R. Family Housing Economic Analysis for Maintenance Requirements. CiB-87, Session C, Copenhagen, Denmark, 1987.

[54] Schröder S. The State of the Art - From the Point of View of DDV. CiB-87, Session C, Copenhagen, Denmark, 1987.

[55] Fujimoto Y. Maintenance & Management Cost in Medium-to-Highrise Private Condominums, Aspect of Repair Cost. CiB-87, Session C, Copenhagen, Denmark, 1987.

[56] Bodinson L. and Sjöberg S. Investment Costs for Heat Pump Installations in Multi-Family Buildings. Report R65, The Swedish Council for Building Research, (In Swedish), 1987.

[57] Eriksson B. et al. Technical Solutions for Ventilation Systems in Retrofitted Multi-Family Residences, part 2. Report M:12, The National Swedish Institute for Building Research, Gävle, Sweden. (In Swedish), 1987.

[58] Jaster H. and Miller R.S. Performance of air-source heat pumps. EPRI, Palo Alto, CA, U.S.A., 1985.

[59] Pientka K. Heat pump life and compressor survival in a northern climate. EPRI, Palo Alto, CA, U.S.A., 1986.

[60] Gustafsson S-I. and Karlsson B.G. Why is Life-Cycle Costing Important when Retrofitting Buildings. *The International Journal of Energy Research*, 12(2):233–242, 1988. ISSN 0363-907X.

[61] Bergenstjerna A. and Magnusson B. Ebalans - A computer program for calculation of the energy balance of a building . Technical report, Chalmers university of technology, Gothenburg, 1984.

[62] Anonymous. Myresjöfönster, window manufacturer. Private communication, 1985.

[63] Arasteh D., Selkowitz S. and Hartmann J. Detailed Thermal Performance Data on Conventional and Highly Insulating Window Systems. ASHRAE/DOE/BTECC conference on Thermal Performance of the Exterior Envelopes of Buildings III. Clearwater Beach U.S.A., 1985.

[64] Anonymous. Myresjöfönster, window manufacturer. Private communication, 1987.

[65] Greely K., Goldman C. and Ritschard R. Analyzing Energy Conservation Retrofits in Public Housing: Savings Cost-Effectiveness and Policy Implications. ACEEE Summer study, Santa Cruz, U.S.A., 1986.

[66] Goldman C. Measured Energy Savings from Residential Retrofits: Updated Results from the BECA-B Project. To be published in Energy and Buildings, 1986.

[67] Goldman C. and Greely K. Energy Savings in Retrofitted Multi-Family Buildings: New Results from the BECA-B Project. ACEEE Summer study, Santa Cruz, U.S.A., 1986.

[68] Fahlen P. Laboratory Tests From Heat Pumps. Report R1:1988, Swedish Council for Building Research, 1988.

[69] Park C., Clark D. and Kelly G. Dynamic Simulation of Whole Building Systems. Center for Building Technology, National Bureau of Standards, U.S.A., 1988?

[70] Elgestad S. *VVS-handboken, HVAC handbook*. Förlags AB VVS, Stockholm, 1963. In Swedish.

[71] Christian J. and Strzepec W. Procedure for Determining the Optimum Foundation Insulation Levels for New Low-Rise Residential Buildings. ASHRAE Transactions, Volume 93, Part 1, 1987.

[72] Gustafsson S-I., Karlsson B.G. Minimization of the life-cycle cost when retrofitting buildings. In *Third international congress on building energy management*, volume 2, pages 163–170. ICBEM - 87, Lausanne, Switzerland, 1987.

[73] Wickman K. Swedish Housing Subsidies 1960-1985. CIB-87, Session D, pages 85-97, Copenhagen, Denmark, 1987.

[74] Anonymous. Loans and Subsidies for Multi-Family Housing Retrofits. Bostadsstyrelsen, Stockholm, Sweden, 1986.

[75] Werner S. E. *The heat load in district heating systems.* PhD thesis, Chalmers university of technology, Gothenburg, 1984.