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No. 180

THE OPERA MODEL

Optimal Energy Retrofits in Multi-Family Residences

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Akademisk avhandling

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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 etc. 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 optimal 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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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 a 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 existing 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 this 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 model 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 this 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

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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 optimal 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.

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	
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 etc	(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_*	Optimal 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	$(W/K \cdot m^2)$
U_{ex}	Existing U-value, insulation measures	$(W/K \cdot m^2)$
U_n	U-value for part number n	$(W/K \cdot m^2)$
U_{new}	New U-value, insulation measures	$(W/K \cdot m^2)$
U_0	Existing U-value	$(W/K \cdot m^2)$
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

1. 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 value 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 system 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. This 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 equipment, will probably be turned off for long periods of time.

From the society's point of view, the heat pump will not be profitable due to the low amount of energy it delivers. However, the insulation will probably also loose its profitability because the saved energy is so cheep. It is obvious that the subsidiary system will lead to suboptimizations 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 informs the consumer of the real cost. This cost must also include environmental drawbacks.

However, up to now, there was no method or tool present that enabled finding an optimal solution without a very tedious iterative 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 system 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 etc 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 shown that the Life-Cycle Cost, 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 economic 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 terminology 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 an 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 have 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 differs 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 aim 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.

1.1 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 remaining life.

1.2 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 most 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 aim, 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'Étude 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 install 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 [78].

At the CIB 1986 conference 11 papers about LCC were presented , but only one treated retrofitting of multi-family residences [14].

The 1987 conference presented several papers on LCC. However, they discussed the subject from a more principle point of view, e g [47] which treated the history and future of LCC. Other authors dealt with the risk analysis, [48, 70], comparisons with other economic evaluation methods, [49], and the importance of proper economical parameters, [50, 51]. One author dealt with optimization, [52], but for new government office buildings.

In [44] 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 [53].

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, 15 and 16] 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 LAMPS program, which solves linear and integer problems, using the linearization methods in [4] and also examined the OPTIVAR programming system [17 and 18]. Those systems are elaborated to solve mathematical problems and you have to start with a very strict mathematical 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 [54], 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 [55] 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 [56]. 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-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 [57]. 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 etc 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 [19] 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 [20], where about 500 works about building equipment are presented.