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DEPARTMENT OF MECHANICAL ENGINEERING

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Energy Systems

Linköping Studies in Science and Technology
Thesis No. 91

OPTIMAL ENERGY RETROFITS ON EXISTING MULTI-FAMILY BUILDINGS

Stig-Inge Gustafsson

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PREFACE

During the oil crises, some years ago, an increased interest was emphazised on energy conservation in the existing building stock. The scope of this thesis is, however, not to find out how the nation can save the most amount of energy, but instead to find out how the optimal distribution of energy conservation measures looks like, when the total cost for retrofitting and heating the building is as low as possible. In this thesis the first results from a research project dealing with optimal energy retrofits in multi-family residences are shown.

I have tried to describe, in detail, how the optimization process is elaborated. This because of the great advantage of having a suitable reference for the scientific papers that I will try to get published during this project. The initiated reader, thus, maybe will find the thesis a bit tedious in some parts. Nevertheless, I hope that this work will be a contribute to the understanding of the life-cycle cost theory and the implementation of it in the building retrofit field.

I also will take this opportunity to thank some of them who made this thesis possible:

o My mentor and the initiator of the project Professor Björn G Karlsson, who have guided me through a lot of the difficulties and also gave me a part of his engagement in this subject.

o My collegues at the division Energy Systems, who have taught me a lot about energy issues and how to handle computer equipment.

o Gunnar Andersson, who helped me with the FORTRAN computer programs and to handle the hard ware.

o Ulla Daniels, who have typed this thesis from a handwritten manuscript and also helped me with the english language.

o The people at the library, who have tried to find all of the references.

o The Swedish Council for Building Research and the community of Malmö, Sweden, who financed this project.

Thanks to them all.

Linköping in November 1986

Stig-Inge Gustafsson

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1 INTRODUCTION

1.1 HYPOTHESIS

When retrofitting old houses there is a great opportunity to change the building as an energy system. The hypothesis is that it is possible to find an optimal combination of different energy retrofit measures seen from the point of economic efficiency.

1.2 NOMENCLATURE

A	= area of walls, floors etc. (If not other is mentioned) (m^2)
a	= number of years from the base year to an event (years)
B	= recurring costs which recur on periodic bases (SEK)
b	= number of years in the calculation period (years)
C	= annual recurring costs (SEK)
^oC	= degrees centigrade
c_{pa}	= specific heat for air (KJ/kg, K)
c_{pw}	= specific heat for water (KJ/kg·K)
c_b	= heat capacity for the building (KJ/kg·K)
D	= number of degree hours. (If nothing else is mentioned) (K·h)
d_j	= distance between the joists (m)
E	= energy (J)
EC	= energy cost, present value (SEK)
e	= energy price (SEK/KJ)
F	= constant in 4.1.2.4
G	= constant in 4.1.2.4
Gr	= Grashof number
g	= acceleration of gravity (m/ 2)
H	= constant in 4.1.2.4
HEC	= heating equipment cost present value (SEK)
h	= convection heat transfer coefficient (W/m^2, K)
I	= constant in 4.1.2.4

K	=	degrees Kelvin
k	=	thermal conductivity of the material (W/m, K)
LCC	=	life-cycle cost (SEK)
M	=	ventilation flow (kg/h)
m	=	total range of indices. (If nothing else is mentioned)
Nu	=	Nusselt number
n	=	number of indices
P	=	power at the heating system (W)
PV	=	present value (SEK)
q	=	heat flow in (W)
R	=	thermal resistance ($m^2 \cdot K/w$)
RC	=	retrofit cost, present value (SEK)
r	=	discount rate, inflation excluded
T	=	temperatures (°C, or K)
t	=	insulation thickness (m)
U	=	thermal transmittance (W/m^2 K)
V	=	tap water flow (kg/h)
V_o	=	the volume of a lump (m^3)
VF	=	ventilation flow (m^3/h)
X	=	optimization variable
x	=	distance variable or multiplication sign
Y	=	optimization variable

Indices

af	=	attic floor
bo	=	board
c	=	caulking
DH	=	district heating
EB	=	electric boilers
EH	=	exhaust air heat pump
EX	=	ventilation air heat exchanger
ew	=	external wall
f	=	film conditions
HP	=	heat pump
i	=	inside. (If nothing else is mentioned)
mw	=	mineral wool
ml	=	mixed layer
OB	=	oil boiler

o = outside
sd = saw dust
exist = existing
w = wall
wd = window during darkness
wi = window
∞ = surrounding

<u>Greek</u>

η = efficiency in the heating system
β = 1/T for ideal gases, see 4.1.4.1
δ = distance between the windows glasses in a window (m)
ε = emissivity
ρ = density (kg/m^3)
τ = time (h)
ΔT = increase in tap water temperature (k)
σ = Stefan Bolzmanns constant, 5.659×10^{-8} ($W/m^2 x K^4$)

1.3 BACKGROUND

During the latest 10 years the annual production of new residential buildings in Sweden has decreased (1. p 36). Instead of building new houses the efforts of the society have been redirected towards keeping the existing housing stock in shape.

When retrofitting these old houses it is possible to change the house as an energy system. This is often done today, but the combination of retrofit measures are mostly the fruit of the national subsidy system. Unfortunately, this system also gives subsidies to retrofits that otherwise are unprofitable to both the house owner and the society. The reason for this is the fact that the housing stock mostly was heated with oil before and during the oil crises. From 1978 to 1982 the price for oil raised from about 200 to 1 000 SEK/m^3 in the price level of 1970 (2. p 47). At the same time 75 % of the buildings in Sweden were heated by oil and it was obvious that something had to be done about this situation (2. p 19). The government thus gave grants and loans for almost every energy conserving measure. During 1974 - 1981 more than SEK 5 300 millions were disbursed (3. p 51). Also the Swedish building-ordinance and code were changed in 1975 and again 1980 in order to accomodate new energy aspects. However, all those efforts from the government, mostly were used by owners of one-family houses. This led to a decrease in interest from the government and the special energy loans were abolished in 1984 (3. p 35).

The decrease in the production of new residences made a lot of building labourers unemployed and therefore the government initiated a new program for renovating existing houses where energy conservation aspects were included. This system with loans and subsided interest rate to 3 % the first year has been very successful in terms of renovated houses. This also made it interesting for the Swedish Council for Building Research to investigate how houses should be retrofitted in an optimal way.

In 1983 a report was delivered from our division at the Institute of Technology (4). In this report the life-cycle cost (LCC) for a new one-family house was calculated with different types of walls, heating- and ventilation systems etc.

The house with the lowest LCC was much more insulated than ordinary houses built following the (1980) building code used in Sweden (5). Furthermore, the house was equipped with a ventilation system that could deliver warm air into the building. The calculated annual energy demand for the house, size 200 m^2, was about 11 GJ (3 000 kWh) and the calculated power of the resistance heater in the ventilation system was 3.5 kW (6). The average demand for existing houses of this size in Sweden is about 144 GJ (40 000 kWh) (2. p 29).

Encouraged by these results the initiator of the project (4), Professor Björn G Karlsson, realized that many of the energy conserving retrofits, done to old houses, made the remaining LCC for the house higher than it was before these measures were made. It was therefore important to find out how existing houses should be renovated in the most optimal way in order to save money for the nation.

Professor Karlsson applied for financial support for this research. The Swedish Council for Building Research and the community of Malmö agreed to this, and an interested young Master of Science was engaged to do the work as a part of his post graduate education, the author of this thesis.

1.4 SYSTEM BOUNDARIES AND LIMITATIONS

In the beginning of this work there have to be certain limitations made to reduce the parameters that could apply to the energy systems considered.

After some discussions we decided to set these limitations just outside the house. The energy supply to the house, etc had to be considered as boundary conditions in the form of different energy tariffs, climate and so forth.

As is shown in (6) there are only 8 parameters that can be varied to change the building as an energy system.

An equation that relates the power supply to the power losses is:

$$P \times \eta + P_{free} = \sum_{n=1}^{m} U_n \times A_n (T_i - T_o) + M \times c_{pa} (T_i - T_o) + V \times c_{pw} \times \Delta T \quad \text{(F1)}$$

The 8 parameters mentioned above are:

o η — The efficiency of the heating system in the house

- o P_{free} — The free contribution of power from passive solar heating, heat from persons, ovens etc. in the house
- o U_n — The thermal transmittance through building part number "n"
- o A_n — The area of the building part number "n"
- o T_i — The inside temperature
- o M — The net ventilation flow
- o V — The tap water flow
- o ΔT — The increase in the tap water temperature

The impact of the sewage water temperature has been considered in P_{free}.

The outside temperature (T_o) and specific heat for air and water c_{pa}, c_{pw}, can not be changed by man and has then to be considered as boundary conditions or constants.

Putting in values in this equation (F1) gives us "P", the necessary power demand for the heating system in the house.

Further on in this thesis we shall discuss these parameters in more detail.

There are also other limitations done to make it possible to finish this work before Christmas 1986. There are only some of the many thinkable retrofits that have been considered in the optimization procedure. This is also the case for the heating equipment, because there is an immense variety of combinations. In this thesis no bivalent heating equipment is considered. My future work will treat those other kinds of retrofit solutions.

Other limitations are the need for simplification of the mathematical expressions that describe the costs for retrofitting a house. This is also the fact for the climate and, of course, the economical parameters. All of these limitations are discussed further down in this thesis.

1.5 LIFE-CYCLE COST, LCC

In the word optimization it is understood that it is possible to find the best candidate from a collection of alternatives /(7) p 1/. In this thesis I use the LCC, the sum of the building-, maintenance- and the running costs for a house during its remaining life-cycle, as a tool to find the best retrofit alternative. The solution that has the lowest LCC is considered to be the optimal one.

The different costs do not emerge at the same time and therefore the method of the Net Present Value, NPV, has been used throughout this thesis. This to make the cost flow comparable at one special occasion, the base year.

1.6 OPTIMIZATION TECHNIQUE

As is mentioned above the combination of retrofits, that gives the house the lowest LCC, shall be picked out as the best solution.

There are several different methods that can be used for optimization, but as is described later we have not found any method that always finds the true minimum point in the mathematical model field. Suboptimations can thus occur and the wrong retrofit strategy is chosen. We have therefore developed a method, where different techniques are used during the optimization for different types of retrofits. The emphasis of this thesis has been to lay out the formulation of the mathematical problem and then find the solution of this in order to find the minimum LCC.

Nevertheless, several interesting results have emerged during this work that can be implemented in real buildings and these are, of course, shown in the thesis.