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

The Opera model

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Byggforskningsrådet
Swedish Council for Building Research

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A COMPUTER MODEL FOR OPTIMAL ENERGY RETROFITS IN MULTI-FAMILY BUILDINGS

The OPERA model

Stig-Inge Gustafsson

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ABSTRACT

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

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

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

Ten different heating systems are dealt with, e.g. simple ones like oil-boilers and more complex ones like bivalent oil-boiler heat pump systems and systems dealing with differential rates.

Insulation measures on the building envelope are optimized as well as fenestration retrofits. The program also deals with the ventilation system and calculates if weatherstripping and/or exhaust air heat pumps are part of the optimal solution.

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

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

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NOMENCLATURE

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

I_{dH}	Diffuse radiation at horiz. surface	(W/m^2)
I_{DN}	Solar irradiation	(W/m^2)
I_{DN1}	Solar irradiation on tilted surface	(W/m^2)
$I_{d\beta}$	Diffuse radiation from the sky	(w/m^2)
$I_{d\beta r}$	Diffuse radiation from the ground	(W/m^2)
$I_{T\beta}$	Total radiation at a surface	(W/m^2)
I_r	The reflected part of radiation	(W/m^2)
i_{es}	Incidence angle from the sky	(rad)
i_{eg}	Incidence angle from the ground	(rad)
i_β	Incidence angle	(rad)
k	Thermal conductivity	$(W/m \cdot K)$
k_{new}	Thermal conductivity, new insulation	$(W/m \cdot K)$
LCC	Life-cycle cost	(SEK)
m	Number of building parts	(1)
m_i	Convection heat coefficient, inside	$(K \cdot m^2/W)$
m_o	Convection heat coefficient, outside	$(K \cdot m^2/W)$
n	The number of the month, value etc	(1)
nf	Refraction index	(1)
nm	Convection heat coefficient	(1)
OPERA	Optimal energy retrofit advisory	
P	Power for e g a heat pump	(W)
P_{dim}	Maximum power demand during one hour	(W)
P_{ehp}	Power for an exhaust air heat pump	(W)
P_{fhs}	Free power gain to thermal load during the heating season	(W)
P_{som}	Free power gain to thermal load during the summer	(W)
P_1	Thermal load in bivalent system optimization	(W)
PV	Present value	(SEK)
p	Payback time	(years)
q	Annual energy price escalation	(%)
R	Reduction factor	(1)
RN	Number of air renewals	(1/h)
R_m	Mean reflection factor	(1)
R_r	Complete reflection factor	(1)

$R_{=}$	Parallel reflection factor	(1)
$R_{\#}$	Perpendicular reflection factor	(1)
r	Discount rate, inflation excluded	(%)
rd	Coefficient for the distance to the sun	(1)
re	Reduction factor	(1)
r_j	Discount rate, justified	(%)
rm	Reflection factor for the ground	(1)
rt	Total reflection factor	(1)
$r_{=}$	Parallel reflection coefficient	(1)
$r_{\#}$	Perpendicular reflection coefficient	(1)
s	Thickness of glass pane	(m)
SPV	Subsidized Present Value	(SEK)
T	Transmission value for windows	(1)
$T_{=}$	Parallel part of transmission	(1)
T_m	Mean transmission factor	(1)
$T_{\#}$	Perpendicular part of transmission	(1)
t	Thickness of insulation	(m)
t_{af}	Thickness of attic floor insulation	(m)
t_{ew}	Thickness of external wall insulation at the outside	(m)
t_{fl}	Thickness of floor insulation	(m)
t_{in}	Thickness of external wall insulation at the inside	(m)
t_*	Optimal thickness of insulation	(m)
TOD	Total energy demand	(J/year)
T-O-U	Time-of-use rates	
TRANS	The transmission coefficient	(W/K)
T_i	The desired inside temperature	(°C)
$T_{s,n}$	The monthly mean outside temperature	(°C)
t	The hour angle of the sun	(rad)
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)
v	Surface azimuth	(rad)

W	Heat transferred through windows	(W/m^2)

Greek:

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

PREFACE

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

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

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

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

The foundations of Elna Bengtsson and Helgo Zettervall has also funded some of this work. The first fund has contributed to the elaboration of a solar radiation program used for finding input data to the model, while the other has funded work with bivalent heating system optimization.

The author also wants to thank his mentor, and the supervisor of this project, professor Björn G Karlsson, for his support and for invaluable advice about the performance and the mathematical design of the model.

Much work has been sacrificed to find bugs in the programming code. Experience shows, however, that there sometimes is something that does not work as expected. The author will thus be very grateful to those readers of this document and the users of the model, who send comments and suggest further enhancements.

The author also hopes that the model will be a useful tool in the everyday work with designing optimal building retrofits in common engineering practice.

SAMMANFATTNING

Detta dokument behandlar den sk OPERA - modellen vilken används för att hitta optimala energirelaterade ombyggnadsåtgärder i flerbostadshus.

Modellen, eller dataprogrammet, är speciellt anpassat till att användas i IBM - kompatibla persondatorer med operativsystemet MS DOS. Huvudprogrammet med sina subrutiner är skrivet i FORTRAN 77 vilket innebär att det med mycket små justeringar kan användas även i andra datormiljöer.

Programmet är konstruerat för att lösa ett optimeringsproblem, dvs hur man ska hitta den billigaste kombinationen av olika energisparåtgärder som kan anbringas i eller på ett flerbostadshus. Byggnadsåtgärder, åtgärder på ventilationssystemet och förändring av uppvärmningssystem behandlas samtidigt och bästa kombination av dessa beräknas. Den bästa lösningen utgörs av den med den lägsta livscykelkostnaden vilken visar summan av ombyggnads- drift- och underhållskostnader under byggnadens antagna livstid.

Tio olika värmesystem behandlas, dels enklare som vanliga oljepannor och dels mera komplicerade som bivalenta system med oljepanna och värmepump. Dessutom kan tidsdifferentierade taxor för både fjärrvärme och el användas i modellen. Vidare optimeras en eventuell tilläggsisolerings tjocklek, bästa fönsteralternativ väljs ut och tätningsåtgärder och eller frånluftvärmepumpar undersöks vad gäller optimal renoveringsstrategi.

I manualen beskrivs också ett program, skrivet i C, som används för att utröna inverkan av det svenska bostadsfinansieringsstödet. Ett ytterligare program ger en grafisk presentation av det sk varaktighetsdiagrammet för energianvändningen i en byggnad. Detta senare program är dock speciellt anpassat till IBM PC och närbesläktade datorer och kan därför ej användas omedelbart i andra datorer.

Vidare kan bivalenta system optimeras med en diskret optimeringsmetod vilken är speciellt anpassad för tidsdifferentierade eltaxor. Detta program måste dock användas separat från OPERA men modellen genererar automatiskt den indatafil som skall användas.

Nyckelord: ROT-åtgärder, Optimering, Differentierade taxor, Livscykelkostnader, Värmepumpar, Installationsåtgärder, Tilläggsisolering

ABSTRACT

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

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

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Ten different heating systems are dealt with, e.g. simple ones like oil-boilers and more complex ones like bivalent oil-boiler heat pump systems and systems dealing with differential rates.

Insulation measures on the building envelope are optimized as well as fenestration retrofits. The program also deals with the ventilation system and calculates if weatherstripping and/or exhaust air heat pumps are part of the optimal solution.

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

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

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

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