3. 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 etc 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 etc 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 75, and in appendix II at page 123, 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.

3.1 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 30·2.23 = 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 $W/m^2 \cdot K$
external wall = 1.0 -"-
floor = 0.6 -"-
windows, double-glazed,
during darkness = 3.0 -"-

Ventilation:

Ventilation system type = natural
Air renewal rate, air changes/hour,
see reference [3 and 60] = 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 [81].

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 $W/m \cdot K$

New windows, U- values
- ordinary double-glazed = 3.0 $W/m^2 \cdot K$
- ordinary triple-glazed = 1.8 $W/m^2 \cdot K$
- low-emissivity, triple-glazed = 1.5 $W/m^2 \cdot K$
- low-emissivity, gas-filled, triple-glazed = 1.4 $W/m^2 \cdot K$

The reason for choosing these types is due

to the possibility of finding relevant prices.
The U-values above are comes from [80].
Slightly different values are shown in [72].

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 [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	$0 + 125 + 300 \cdot t_{af}$
External wall insulation, outside	$325 + 85 + 555 \cdot t_{ew}$
External wall insulation, inside	$100 + 175 + 555 \cdot t_{in}$
Floor insulation	$250 + 195 + 250 \cdot t_{fl}$

The values for the inside insulation above are calculated in the same way as in [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 [43] and installation costs from [3]. A_w is the area of one window and the the costs are:

Double-glazed	$2050 + 450 \cdot A_w$
Triple-glazed	$2700 + 700 \cdot A_w$
Triple-glazed, low-emissivity	$2700 + 1000 \cdot A_w$
Triple-glazed, low-emissivity, gas-filled	$2700 + 1100 \cdot A_w$

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 [73, 74 and 75] in OPERA runnings.

Ventilation equipment retrofits:

As in [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

$$10\,000 + 4\,500 \cdot P_{ehp}$$

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 = 5000 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 etc:

The cost functions etc from [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 [79]	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 II, page 129.

In [68] 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 [76] 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:

oil	0.18 SEK/kWh	= 0.05 SEK/MJ
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 86, 133 and 147.

Climate conditions:

The lowest outside temperature, see page 41 and 67 = - 14 °C
The desired inside temperature = 20 °C
The monthly mean temperatures can be found in [3 p. 43], or in appendix II page 130.

Free energy and solar gains:

The free energy per month from appliances and persons = 42.5 GJ 11.8 MWh/month, [23]. 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 [3 p. 72-74]. The values used are:

Month	North	East/West	South
Jan	4.30	8.27	29.66
Feb	8.94	17.97	43.69
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

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 coefficent 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, [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 124. It is very tedious work to find proper values for each unique building and it is hard to know if the prices etc elaborated in a case study reflect the real situation.

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 75 and appendix II. 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.

3.2 THE OPERA PRESENTATION

In table I, page 53, an OPERA running is presented. The first value in the table, 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 I 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 I, the existing oil-boiler system seems most profitable combined with some envelope retrofits.

	Exist syst	New oil	Elec tric	Distr heat	Heat p. G	Heat p. E	Diff distr	Diff elec	Biv 0-H	Biv 0-0
No env. retrof.	1.62	1.66	1.89	1.61	1.92	2.08	1.60	1.89	1.62	1.69
Savings:										
Att.ins	.02	.02	.06	.01	.04	.06	.02	.05	.01	.02
Flo.ins	---	---	---	---	---	---	---	---	---	---
Ext.ino	.09	.09	.15	.06	.13	.17	.07	.16	.06	.09
Ext.ini	---	---	---	---	---	---	---	---	---	---
3-glass	---	---	---	---	---	---	---	---	---	---
Low emi	---	---	---	---	---	---	---	---	---	---
Gas fil	---	---	---	---	---	---	---	---	---	---
Weathers	.05	.05	.08	.04	.06	.08	.04	.07	.04	.05
Exhaust	---	---	.04	---	---	---	---	.02	---	---
New LCC	1.46	1.50	1.56	1.49	1.69	1.78	1.47	1.60	1.51	1.53

TABLE I. Retrofit strategy matrix. Values in MSEK.

Table II at page 54, 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. 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 (AIII 4) and (AIII 5) in appendix III, see page 148, 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.

	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
External wall ins at the outside 0.13 m	50.9	1.499	353.7	1.816	0.882
Weatherstrip.	42.9	1.261	296.9	2.242	0.882

Table II. Retrofit oil-boiler strategy in more detail.

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 II, 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 I. However, this is not the case because of the facts discussed on page 15 and 16.

However, OPERA calculates the difference between the table I and II 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 I, 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 I will be considered as very strong candidates for an optimal solution. The amounts of money saved in table I 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 I. 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 I, 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.