APPENDIX II

SENSITIVITY ANALYZIS, INFLUENCE ON THE OPTIMAL SOLUTION DUE TO CHANGINGS 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 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.

Input data	Value	Quantity	LCC change in % for - 5 %	LCC change in % for + 5%	Remarks
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	$W/m^2 \cdot K$	-0.021	0.019	
Existing thermal floor insulation,	0.6	$W/m^2 \cdot K$	-0.211	0.211	

Input data	Value	Quantity	LCC change in % for - 5%	+ 5%	Remarks
Existing thermal external wall insulation,	1.0	$W/m^2 \cdot K$	-0.046	0.051	
U-value double-glazed window	3.0	$W/m^2 \cdot K$	-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	

Input data	Value	Quantity	LCC change in % for - 5 %	+ 5 %	Remarks
New thermal conductivity attic floor insulation,	0.04	W/m · K	-0.057	0.055	
New thermal conductivity floor,	0.04	W/m · K	0	0	
New thermal conductivity external wall outside,	0.04	W/m · K	-0.137	0.133	
New thermal conductivity external wall inside,	0.04	W/m · K	0	0	
U-value new triple-glazed window,	1.8	$W/m^2 \cdot K$	0	0	
U-value new triple-glazed window with low-emissivity,	1.5	$W/m^2 \cdot K$	0	0	
U-value new triple-glazed window with low-emissivity gas-filled,	1.4	$W/m^2 \cdot K$	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	

Input data	Value	Quantity	LCC change in % for -5 %	LCC change in % for +5 %	Remarks
New duration of external wall, inside,	20	years	0.217	-0.201	
New duration of windows,	20	years	0.581	-0.538	
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	$SEK/m^2 \cdot m$	-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	$SEK/m^2 \cdot m$	----	----	
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	$SEK/m^2 \cdot m$	-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	$SEK/m^2 \cdot m$	0	0	
Apartment height	2.4	m	-0.342	0.356	
Annual rent	400	$SEK/m^2 \cdot year$	0	0	

Input data	Value	Quantity	LCC change in % for -5 %	LCC change in % for +5 %	Remarks
Building cost,					
windows,					
double-glazed,					
part 1,	2050	SEK	-0.671	0.671	
part 2,	450	SEK/m^2	-0.285	0.285	
triple-glazed,					
part 1,	2700	SEK	0	0	
part 2,	700	SEK/m^2	0	0	
triple-glazed,					
low-emissivity,					
part 1,	2700	SEK	0	0	
part 2,	1000	SEK/m^2	0	0	
triple-glazed,					
low-emissivity,					
gas-filled,					
part 1,	2700	SEK	0	0	
part 2,	1100	SEK/m^2	0	0	
Oil-boiler cost,					
part 1,	20000	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,	20000	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.

Input data	Value	Quantity	LCC change in % for -5 %	+5 %	Remarks
District heating boiler					
cost, part 1,	58000	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,	30000	SEK	0	0	
part 2,	3300	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	
Heat pump, earth coupled,					
part 1,	30000	SEK	0	0	
part 2,	4300	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,	40000	SEK	0	0	
part 2,	6000	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	

Input data	Value	Quantity	LCC change in % for -5 %	LCC change in % for +5 %	Remarks
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.

Input data	Value	Quantity	LCC change in % for -5 %	+5 %	Remarks
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,	4500	SEK/apart.	0	0	
Duration,	30	years	0	0	
Exhaust air heat pump cost,					
part 1,	10000	SEK	0	0	
part 2,	4500	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	11800	kWh/month	0.214	-0.214	18.
February	11800	kWh/month	0.214	-0.214	18.
March	11800	kWh/month	0.138	-0.072	18.
April	11800	kWh/month	0	0	18.
May	11800	kWh/month	0	0	18.
June	11800	kWh/month	0	0	18.
July	11800	kWh/month	0	0	18.
August	11800	kWh/month	0	0	18.
September	11800	kWh/month	0	0	18.
October	11800	kWh/month	0	0.010	18. 19.
November	11800	kWh/month	0.091	0	18. 19.
December	11800	kWh/month	0.119	-0.138	18.
Solar gains north direction:					
January,	4.3	$kWh/m^2 \cdot$ month	0.005	-0.005	

Input data	Value	Quantity	LCC change in % for -5 %	+5 %	Remarks
February,	8.94	kWh/m^2· month	0.011	-0.011	
March,	18.57	-"-	0.015	-0.014	
April,	28.82	-"-	0	0	
May,	44.5	-"-	0	0	
June,	53.48	-"-	0	0	
July,	50.54	-"-	0	0	
August,	36.63	-"-	0	0	
September,	23.12	-"-	0	0	
October,	13.54	-"-	0	0	
November,	5.82	-"-	0	0	
December,	3.08	-"-	0.002	-0.002	
Solar gains, east direction:					
January,	8.27	-"-	0.001	-0.001	
February,	17.97	-"-	0.002	-0.002	
March,	41.86	-"-	0.002	-0.002	
April,	61.97	-"-	0	0	
May,	87.58	-"-	0	0	
June,	90.91	-"-	0	0	
July,	89.07	-"-	0	0	
August,	75.07	-"-	0	0	
September,	53.11	-"-	0	0	
October,	28.30	-"-	0	0	
November,	10.75	-"-	0	0	
December,	5.36	-"-	0	+0.0003	20.
Solar gains, south direction:					
January,	29.66	-"-	0.027	-0.027	
February,	43.69	-"-	0.040	-0.040	
March,	73.68	-"-	0.044	-0.044	
April,	75.29	-"-	0	0	
May,	82.59	-"-	0	0	
June,	76.28	-"-	0	0	
July,	78.50	-"-	0	0	

Input data	Value	Quantity	LCC change in % for -5 %	+5 %	Remarks
August,	79.81	$kWh/m^2 \cdot$ month	0	0	
September,	79.37	-"-	0	0	
October,	61.57	-"-	0	0	
November,	32.70	-"-	0	0	
December,	21.22	-"-	0.013	-0.013	
Solar gains, west direction:					
January,	8.27	-"-	0.001	-0.001	
February,	17.97	-"-	0.002	-0.002	
March,	41.86	-"-	0.002	-0.002	
April,	61.97	-"-	0	0	
May,	87.58	-"-	0	0	
June,	90.91	-"-	0	0	
August,	75.07	-"-	0	0	
September,	53.11	-"-	0	0	
October,	28.30	-"-	0	0	
November,	10.75	-"-	0	0	
December,	5.36	-"-	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,	2400	SEK	0	0	23.

Input data	Value	Quantity	LCC change in % for -5 %	+5 %	Remarks
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	-"-	-0.109	0.109	
March,	0.19	-"-	-0.078	0.078	
April,	0.10	-"-	-0.036	0.036	
May,	0.10	-"-	-0.036	0.036	
June,	0.10	-"-	-0.036	0.036	
July.	0.10	-"-	-0.036	0.036	
August,	0.10	-"-	-0.036	0.036	
September,	0.10	-"-	-0.036	0.036	
October,	0.10	-"-	-0.036	0.036	
November,	0.19	-"-	-0.073	0.073	
December,	0.19	-"-	-0.119	0.119	
Electricity rate:					
Demand charges,					
Fuse less than,					
35 Ampere,	1640	SEK/year	0	0	
50 -"- ,	2060	-"-	0	0	
63 -"- ,	2380	-"-	0	0	
80 -"- ,	2900	-"-	0	0	
100 -"- ,	3520	-"-	0	0	
125 -"- ,	4300	-"-	0	0	
160 -"- ,	5420	-"-	0	0	
200 -"- ,	6760	-"-	0	0	
250 -"- ,	8400	-"-	0	0	

Input data	Value	Quantity	LCC change in % for -5 %	LCC change in % for +5 %	Remarks
Energy price, differential electricity heating:					
January,	0.33	SEK/kWh	0	0	
February,	0.32	-"-	0	0	
March,	0.32	-"-	0	0	
April,	0.23	-"-	0	0	
May,	0.23	-"-	0	0	
June,	0.23	-"-	0	0	
July,	0.23	-"-	0	0	
August,	0.23	-"-	0	0	
September,	0.23	-"-	0	0	
October,	0.23	-"-	0	0	
November,	0.32	-"-	0	0	
December,	0.33	-"-	0	0	
Demand tariff, electricity:					
Connection fee,	4500	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	-"-	0	0	
March,	0.31	-"-	0	0	
April,	0.23	-"-	0	0	
June,	0.19	-"-	0	0	
July,	0.19	-"-	0	0	
August,	0.19	-"-	0	0	
September,	0.23	-"-	0	0	
October,	0.23	-"-	0	0	

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

TABLE AII 1. OPERA input data values and sensitivity analysis.

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 16.

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 7 in the main part of the thesis.

10. In appendix 1 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 2400 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.

From the above table 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 Malmö, 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 $W/m^2 \cdot K$ 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 $W/m^2 \cdot K$ 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 XIV, at page 68, 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 $W/m^2 \cdot K$ 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 8, page 66, 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 7, page 64, and 13, page 78, 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 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.