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# FACTORIAL DESIGN FOR ENERGY-SYSTEM MODELS

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**Abstract**—Mathematical models are extensively used in energy analysis and have increased in scope as better and faster computers have become available. With complicated systems, it is difficult to predict accurate results if doubtful input data are changed. Traditionally, sensitivity analysis with a change of one or more of the parameters is used. If the influence of a change is very small, the first result is believed to be accurate. Problems may arise when sensitivity analysis is applied to a vast amount of data. The aim of this paper is to examine whether the calculation effort can be decreased by using factorial design. Our model, called Opera (Optimal Energy Retrofit Advisory), is used to find the optimal retrofit strategy for a multi-family building. The optimal solution is characterised by the lowest possible life-cycle cost. Three parameters have been studied here: length of the optimisation period, real interest rate and existing *U*-value for an attic floor. The first two parameters are found to influence the life-cycle cost significantly, while the last is of minor importance for this cost. We also show that factorial analysis must be used with great care because the method does not reflect the complete situation.

## INTRODUCTION

Researchers nowadays use computer-simulation techniques to evaluate the performance of many aspects of a building during design and operation. The models are often large and may include hundreds of parameters. Traditional sensitivity analyses, where only one factor is changed at a time and the result is calculated “from scratch“, are often very tedious, as may be seen in Ref. 1, where a sensitivity analysis is presented in about 20 pages. Another problem with this method arises when the composite influences of different variables are studied. The problem is dealt with to some extent in Ref. 2, where the authors suggest three different methods, i.e. differential sensitivity analysis, Monte Carlo analysis and stochastic sensitivity analysis, for solving the problem. The first of these uses the method described above, i.e. to change one parameter and then study the difference in output. In Monte Carlo analysis, all the uncertain inputs must be assigned a probability distribution, which is not an easy task. The third method is restricted to models that operate in discrete time steps, which may not be fully applicable when studying the Opera model. We have thus used a fourth method, factorial design, in order to find out which data are of vital interest for the output of the model and whether other parameters can be left unstudied.

## THE MODEL STUDIED

The Opera (Optimal Energy Retrofit Advisory)[1] model is used for finding the optimal retrofit strategy for a multi-family building. This optimal solution is then characterised by the lowest possible life-cycle cost, LCC. Inputs to the model include, for example, the geometry of the building, maintenance costs for the envelope as well as insulation measures, climatic conditions, solar radiation, economic parameters, and the prices of electricity and heating. Some 200 parameters are dealt with which describe the building as an energy system. Insulation measures, window retrofits, weather-stripping, and exhaust-air heat pumps are studied for the envelope and ventilation system. Ordinary heating equipment such as oil-fired boilers, as well as more complex systems such as district heating with differential or time-of-use rates and bivalent or dual-fuel heating systems, are treated. In the bivalent system, a heat pump provides the base load and an oil-fired boiler the peak load. Insulation optimisation is elaborated by using a derivative method while window optimisation is fulfilled by a trial-and-error method. The model is equipped with an energy-balance routine which is used for the existing building, each retrofit assessment and the optimisation procedure. Proper attention is thus paid to the influence of solar gains, dissipated heat from appliances etc. A detailed description of the Opera model is given in Ref. 3. In Table 1, the result from an Opera session is shown when the real interest rate, optimisation time and existing $U$-value are 5%, 50 years and 0.8 W/m$^2$K, respectively.

The heating systems under consideration are presented on the horizontal axis. The vertical axis first shows the LCC for the building with no envelope retrofits; below, the savings assumed for each retrofit are presented. The first value at the top left, i.e. 1.48, shows the LCC in MSEK for the existing heating system if no building or ventilation retrofits are introduced (one USD equals about 8 SEK). The value below 1.48, i.e. 0.0, shows that attic floor insulation was not profitable and hence not implemented. The same is valid for floor insulation, but external wall insulation results in a saving of 0.05 MSEK. Also, triple-glazed windows are selected as a retrofit that is assumed to save 60,000 SEK for the optimisation period. Further, weather-stripping was found to be profitable and saves 0.01 MSEK. When only the existing heating system is dealt with, the resulting LCC becomes 1.36 MSEK. The lowest LCC, however, is achieved when a natural gas system is introduced. In this case, the external wall retrofit is unprofitable and triple-glazed windows are the only retrofit selected by the model. The new LCC is assumed to be 1.20 MSEK or 160,000 SEK cheaper than the strategy chosen for the existing heating system. The lines below the resulting LCC show the distribution between the different cost components, e.g., the salvage value for the existing boiler and so forth. A detailed explanation of the listed items is given in Refs. 4 and 5.

## CASE STUDY

In order to compare the traditional sensitivity analysis with factorial design, we list in Table 2 125 Opera runs. For an existing attic floor $U$-value of 0.5 W/m$^2$K, an interest rate of 3% and an optimisation time of 10 years, the optimal LCC is calculated to be 530,000 SEK (see the top left value). We have also included a sign showing the retrofit strategy. A □-sign means triple-glazed windows, external wall insulation and attic floor insulation; a #-sign means triple-glazed windows and attic floor insulation; a *-sign means triple-glazed windows: a § tells us there are no optimal retrofits at all. Following the top left value, a $^*$ indicates that only triple-glazing was optimal.

Table 1. LCC and savings in MSEK calculated by using the Opera model.[4]

| TYPE OF RETROFIT | Existing system | New oil | Electric heating | District heating | Ground water heat pump | Natural gas | T-O-U district h. | T-O-U electric h. | Bivalent ground w. | Bivalent air heat p. |
|---|---|---|---|---|---|---|---|---|---|---|
| No building retrofits | 1.48 | 1.54 | 1.69 | 1.45 | 1.57 | 1.23 | 1.45 | 1.69 | 1.38 | 1.48 |
| SAVINGS: | | | | | | | | | | |
| Attic floor insulation | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| Floor insulation | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| External wall insulation | 0.05 | 0.05 | 0.11 | 0.04 | 0.06 | 0.0 | 0.04 | 0.11 | 0.0 | 0.03 |
| Inside wall insulation | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Triple-glazing | 0.06 | 0.07 | 0.09 | 0.06 | 0.08 | 0.04 | 0.06 | 0.08 | 0.05 | 0.06 |
| Triple-glazing, low emis | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Triple-gl. low e. + gas | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Weatherstripping | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.0 | 0.01 | 0.01 | 0.0 | 0.0 |
| Exhaust air heat pump | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sum of retrofits | 1.36 | 1.41 | 1.46 | 1.34 | 1.42 | 1.20 | 1.34 | 1.48 | 1.33 | 1.39 |
| Sum of combination | 1.36 | 1.41 | 1.46 | 1.34 | 1.42 | 1.20 | 1.34 | 1.46 | 1.33 | 1.39 |
| DISTRIBUTION: | | | | | | | | | | |
| Salvage value oil-boiler | 0.0 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| New boiler cost | 0.08 | 0.10 | 0.03 | 0.06 | 0.28 | 0.09 | 0.06 | 0.03 | 0.25 | 0.31 |
| Piping cost | 0.0 | 0.01 | 0.0 | 0.01 | 0.16 | 0.01 | 0.01 | 0.0 | 0.07 | 0.01 |
| Energy cost | 0.60 | 0.59 | 0.62 | 0.56 | 0.28 | 0.63 | 0.56 | 0.61 | 0.34 | 0.35 |
| Connection fee | 0.0 | 0.0 | 0.0 | 0.01 | 0.0 | 0.01 | 0.01 | 0.0 | 0.0 | 0.0 |
| Building retrofit cost | 0.43 | 0.43 | 0.54 | 0.43 | 0.43 | 0.19 | 0.43 | 0.54 | 0.40 | 0.44 |
| Inevitable cost | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |

Table 2. Life-cycle cost in MSEK for varying values of the existing attic floor *U*-value, interest rate and optimisation time.

| U-value [W/m$^2$K] | Interest rate [1] | Life-cycle cost in MSEK Optimisation time [years] 10 | 20 | 30 | 40 | 50 |
|---|---|---|---|---|---|---|
| 0.5 | 0.03 | 0.53* | 0.88* | 1.13* | 1.29# | 1.4# |
| | 0.05 | 0.55* | 0.84* | 1.00* | 1.11* | 1.17* |
| | 0.07 | 0.56* | 0.80* | 0.91* | 0.97* | 1.00* |
| | 0.09 | 0.57* | 0.77* | 0.84* | 0.87* | 0.89* |
| | 0.11 | 0.58§ | 0.74§ | 0.79* | 0.81* | 0.82* |
| 0.75 | 0.03 | 0.54* | 0.90* | 1.15* | 1.32# | 1.43# |
| | 0.05 | 0.56* | 0.85* | 1.02* | 1.13* | 1.19* |
| | 0.07 | 0.57* | 0.81* | 0.93* | 0.99* | 1.02* |
| | 0.09 | 0.58* | 0.78* | 0.86* | 0.89* | 0.90* |
| | 0.11 | 0.59§ | 0.75§ | 0.80* | 0.82* | 0.83* |
| 1.0 | 0.03 | 0.56* | 0.92* | 1.18* | 1.34¤ | 1.45¤ |
| | 0.05 | 0.57* | 0.87* | 1.04* | 1.15* | 1.22* |
| | 0.07 | 0.58* | 0.83* | 0.94* | 1.01* | 1.03* |
| | 0.09 | 0.59* | 0.79* | 0.87* | 0.91* | 0.92* |
| | 0.11 | 0.59§ | 0.76§ | 0.82* | 0.84* | 0.84* |
| 1.25 | 0.03 | 0.57* | 0.94* | 1.19# | 1.35¤ | 1.45¤ |
| | 0.05 | 0.58* | 0.89* | 1.07* | 1.17# | 1.23# |
| | 0.07 | 0.59* | 0.84* | 0.96* | 1.03* | 1.05* |
| | 0.09 | 0.60* | 0.81* | 0.89* | 0.92* | 0.93* |
| | 0.11 | 0.60§ | 0.77§ | 0.83* | 0.85* | 0.85* |
| 1.5 | 0.03 | 0.58* | 0.95# | 1.19# | 1.35¤ | 1.45¤ |
| | 0.05 | 0.59* | 0.91* | 1.07# | 1.17# | 1.23# |
| | 0.07 | 0.60* | 0.86* | 0.98* | 1.04# | 1.07# |
| | 0.09 | 0.61* | 0.82* | 0.90* | 0.94* | 0.95* |
| | 0.11 | 0.61§ | 0.79* | 0.84* | 0.86* | 0.87* |

If the real interest rate is increased to 5%, while retaining a 10-year project life, the LCC will increase to 0.55 MSEK, a behaviour opposite to that expected. This result is obtained because of the short project life and is described in more detail in Ref. 1. The same retrofit strategy is, however, optimal because a $^{*}$-sign is present after both values. It is not until the rate is 11% that the strategy changes and no retrofits at all are profitable (see the §-sign after 0.58). The next column shows the result for a project life of 20 years. Triple-glazing is again optimal for low rates and now the LCC decreases when the interest rate is increased. For a rate of 11%, no retrofits are again found to be optimal. When the project life is changed to 30 years, triple-glazed windows are optimal for all interest rates considered. Still longer project lives and low rates also result in extra attic floor insulation. However, the extra thickness is not the same for project lives of 40 and 50 years. Extra external wall insulation will not be optimal until the existing *U*-value is over 0.75 W/M$^2$K and then only for low interest rates and long project lives. The level of this extra insulation also results in minute changes in the LCC. For an existing *U*-value of 0.5 W/m$^2$K, a project life of 50 years and an interest rate of 3%, the LCC was calculated to be 1.4 MSEK. If the *U*-value is 1.5 W/m$^2$K, the LCC increases only to 1.45 MSEK. This result depends on the use of much thicker insulation in the last case, and thus the LCC does not change as much as was first expected. It should also be noted that the natural gas heating system was optimal for all combinations considered and no differences occurred which would further complicate the result.

Changing the interest rate and project life results in a significantly greater influence on the LCC. It is obvious that there is an interaction between interest rate and project life, which is also clear from net present-value calculations. Keeping the above discussion in mind, it is not obvious that the interest rate and project life are of greater importance than the *U*-value simply because of the fact that the LCC changes more for these variables when there was no change in retrofit strategy.

The LCC has been shown for 125 different runs of the OPERA model which were used for the sensitivity analysis. Using factorial design enables the operator to find the main result with a smaller number of simulations. The theories about factorial design and other statistical methods are given in detail in Refs. 6 and 7. This paper contains only a brief summary to explain the method and terminology. To perform a general factorial design, a fixed number of "levels" is selected for each number of variables (factors) and the model is then run with every possible combination of these levels. Usually, only two levels are studied in the different factors with a high level indicated by a "+" sign and a low level by a "−" sign. It is possible to use more levels but problems may then arise when interactions between variables are to be studied. Here, we will show use of the method for two levels of each variable. There will be eight different simulations because there are two levels and three variables which are shown in Table 3, the so-called design matrix. The variables are labelled with the following numbers: 1 = project life, 2 = real interest rate and 3 = existing *U*-value for the attic floor. In the first run, all variables are set to their lowest levels (see columns 1, 2 and 3, where minus signs appear).

The first column represents the first variable, the second represents the second variable or factor, and so on. The fourth column represents a combination of the first and second columns. This column is used when interaction between the first and second factors is to be studied, i.e. row number 1 is multiplied by row number 2. One of the greatest benefits with factorial design is the possibility to determine the importance of each factor on the result. This result is obtained by calculating the so-called main and interaction effects. In Table 2, the resulting LCC is found for the first case when all three variables are low, i.e. 0.53 MSEK (see the top left LCC in Table 2 and the top right value in Table 3). The second simulation shows a case where the project life (variable number 1) has a high value, i.e. a plus sign, while the others have low values. This case is found in the upper right corner of Table 2, i.e. 1.4 MSEK. In the same way, the value for $y_8$ is found in the lower right corner of Table 2, i.e. 0.87 MSEK. The so-called main effects of the factors or variables are calculated by adding the LCC averages while noting the signs in the table (see p. 309 of Ref. 6). For a variable number 1, (i.e. project life), the main effect becomes $[(1.40 + 0.82 + 1.45 + 0.87)/4]-[(0.53 + 0.58 + 0.58 + 0.61)/4] = 0.56$. The same calculation for the second variable is shown by $[(0.58 + 0.82 + 0.61 + 0.87)/4]-[(0.53 + 1.40 + 0.58 + 1.45)/4] = -0.27$. As can be seen from Table 3, the main effect of the *U*-value is very low and we may conclude that it is of little interest. Both the project life and the interest rate have much larger effects. The interesting step now is to study interaction effects, which are calculated in the same manner but using columns 4–7 instead of 1–3. The interaction effect between the *U*-value and the other two factors is low, i.e. 0.005 (see columns 5 and 6 in Table 3), while the interaction between project life and interest rate is relatively high, i.e. −0.31 (column 4). The interaction

Table 3. Design matrix used for factorial design.

| Run | Variable and combinations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4=(1·2) | 5=(1·3) | 6=(2·3) | 7=(1·2·3) | y | = LCC |
| 1 | - | - | - | + | + | + | - | $y_1$ | = 0.53 |
| 2 | + | - | - | - | - | + | + | $y_2$ | = 1.40 |
| 3 | - | + | - | - | + | - | + | $y_3$ | = 0.58 |
| 4 | + | + | - | + | - | - | - | $y_4$ | = 0.82 |
| 5 | - | - | + | + | - | - | + | $y_5$ | = 0.58 |
| 6 | + | - | + | - | + | - | - | $y_6$ | = 1.45 |
| 7 | - | + | + | - | - | + | - | $y_7$ | = 0.61 |
| 8 | + | + | + | + | + | + | + | $y_8$ | = 0.87 |
| Effect | 0.56 | -0.27 | 0.045 | -0.31 | 0.005 | 0.005 | 0.005 | | |

between all three variables is also small (column 7). It is common practice to use a normal distribution to select the variables of interest (see p. 332 of Ref. 6) but this is not necessary here because of the obvious result with the effects differing by a factor of 10. The factorial design therefore clearly shows that the important factors to study are project life, interest rate and interaction between the two variables.

There is still, however, a problem not earlier discussed. In Ref. 1, it was shown that some parameters were of no interest as long as some other parameters had certain limited values. A factorial design made for these levels of the parameters would show that the first variable was of no interest in the sensitivity analysis. When these other parameters changed, the result could be that the first variable would suddenly become active. Table 2 shows that the optimal result for the upper left LCC included only triple-glazed windows. Extra attic floor insulation was of no interest. Suppose that the cost for this retrofit was selected in the sensitivity analysis. As long as both the high and low levels for the insulation cost exceed the cost used when Table 2 was calculated, no change in the cost would occur when the two levels of insulation cost were tested. The factorial design will therefore tell us that the insulation cost is of no interest at all. If different levels were chosen, the insulation cost may become active and in that case the factorial design will also show some (small) effect.

The existing *U*-value does not have a considerable influence on the LCC. As found in Table 4, the only difference in LCC originates from the increase in the energy cost from 0.41 to 0.47 MSEK. Extra insulation was not optimal in the Opera sessions shown in Table 4, i.e. extra insulation should not be added to the attic floor, even if the existing *U*-value is as high as 1.5W/m$^2$K. This result may be explained by reference to the optimal natural gas boiler, which uses a very cheap fuel (0.175 SEK/kWh). The real interest rate is also high (7%), while the project life is rather short at 30 years. In other case studies, added insulation is a very suitable retrofit. As long as the optimal solution excludes extra insulation, the LCC will change according to a straight line (see, for example, the LCC in Table 2 for different *U*-values) while keeping the interest rate at 3% and the optimisation period constant at 20 years. This will result in LCCs of 0.88, 0.90, 0.92, and 0.94 MSEK but changes when extra insulation is added (see the LCC for attic floor insulation of 1.5 W/m$^2$K). For a still higher existing *U*-value, it may be optimal to add more insulation, after which a curved behaviour of the LCC will suddenly occur. This result is obvious if the LCCs are studied for a project life of 50 years and an interest rate of 3%. The series will now become 1.40, 1.43, 1.45, 1.45, and 1.45 MSEK (see Table 2). The important thing to notice here is that there is a small interaction between the level of existing attic floor insulation and the LCC. This influence may also be important at the point when extra insulation is to be added, but this fact is not revealed by factorial analyses.

Table 2 also shows the influence of the project life on the LCC. The project life has a significant influence on the LCC compared with the *U*-value influence (see Tables 2 and 4). The difference in LCC for e.g. a 10-year increase is larger when the project life is relatively short. If the assumed life is 50 years, an increase of 10 years will only result in a minute increase in the LCC. A change in the project life will influence almost all parts of the LCC because of the included present value calculations. From Table 4 and the factorial analysis, it would be easy to conclude that project life is a very important

Table 4. Details of the LCC in MSEK for varying parameters.

| | Project life = 30 years<br>Interest rate = 0.07 | | Interest rate = 0.07<br>U-value = 1.0 W/m$^2$K | | Project life = 30 years<br>U-value = 1.0 W/m$^2$K | |
|---|---|---|---|---|---|---|
| Retrofit action | U-val = 0.5 | U-val = 1.5 | Life. = 10 | Life. = 50 | Rate = 0.03 | Rate = 0.11 |
| No building retrofits | 0.93 | 1.00 | 0.59 | 1.06 | 1.23 | 0.82 |
| Triple-glazing saves | 0.02 | 0.02 | 0.01 | 0.02 | 0.05 | 0.01 |
| Sum of retrofits | 0.91 | 0.98 | 0.58 | 1.03 | 1.18 | 0.82 |
| Distribution: | | | | | | |
| Salvage value old boiler | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| New boiler cost | 0.07 | 0.07 | 0.04 | 0.08 | 0.08 | 0.07 |
| Piping cost | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Energy cost | 0.41 | 0.47 | 0.25 | 0.49 | 0.69 | 0.31 |
| Connection fee | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Building retrofit cost | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Inevitable cost | 0.20 | 0.20 | 0.06 | 0.24 | 0.18 | 0.21 |

variable. This is only partly true. Firstly, buildings normally have very long lives and thus the influence will be smaller than first expected. Secondly, it is necessary to study the difference in retrofit strategy, not only the LCC. It is unwise to calculate the LCC and use short project lives only to obtain a lower LCC value. Our experience shows that the overall strategy will not change very much if the assumed life cycle is misjudged by a few years.

The real interest rate seems to influence the LCC more than the change in $U$-value but less than the project life (see Tables 2 and 4). A higher interest rate will normally lower the LCC. This does not mean that it is better to use a high interest rate when calculating the LCC. Instead, the retrofit strategy must be considered. For small changes in interest rate, the overall strategy will only undergo minute changes and, as with project life, this fact must be properly considered.

## CONCLUSIONS

This study shows that factorial design is useful in sensitivity analyses. By using this method, it is possible to study how much each variable will influence the final result. The calculation effort is significantly decreased because only two levels of the variables are used instead of several levels, as are commonly employed in other methods. In addition, we also obtain a value for this interaction. We also show that factorial design cannot be used without considering drawbacks of the method. The magnitudes of the different levels must be selected with great care. Otherwise much information will not be revealed. For some cases, the results may be misinterpreted as suggesting that important variables are of no or of minute interest.

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