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PERFORMANCE EVALUATION OF A LOW TEMPERATURE DISTRICT HEATING SYSTEM BASED ON SIMULATION, UNCERTAINTY AND SENSITIVITY ANALYSIS

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ABSTRACT

This paper describes the simulation model and the performance evaluation of a low energy district heating distribution network which supplies heat to 75 apartments. Suitable criteria of thermal operation are selected: the relative heat loss in the distribution system, the specific heat loss, the heat density, the total energy consumption and the seasonal performance factor of the system. The purpose is to investigate the uncertainties on the performance of district heating systems introduced by parameters influencing heat losses in the distribution network. An uncertainty and sensitivity analysis were conducted. The analysis was carried out by using the simnulation data of one week in winter period. Results regarding performance assessment and uncertainty are discussed. They show how sensitive the solution is in the face of different parameter values and especially the interactions between them. The results demonstrate that by using a central storage tank in the heating production plant the robustness of the system increases.

INTRODUCTION

District heating networks gain in importance, since they facilitate large scale renewable energy integration and a better matching between supply and demand (Ben Hassine and Eicker, 2011). A district heating (DH) system is composed of many elements, building a chain from the heat source to the heated buildings. At the present time, an immediate effect of reinforcing the energy efficiency standards for buildings is the reduction of the amount of energy required to heat them. Hence heating requirements are increasingly dominated by domestic hot water rather than space heating. In this context simulation tools play an important role for the design and operational optimization of complex DH networks.

Nowadays, the reduction of heat distribution losses is an important aspect of improving DH network performance. Consequently, during the last years it has been demonstrated that low-temperature district heating (supply temperatures lower than 60°C) is the next evolution in district heating systems. Recently, the optimal design of pipes for low-energy applications and present methods for decreasing heat losses were reported by Dalla Rosa et. al, (2010). While the performance of two consumer units for a low temperature district heating net was investigated using TRNsys (Jianhua Fan et. al, 2006). Rämä and Sipilä (2010) studied the problem on low heat density district heating network design in a representative case of a low heat density area.

This study is the continuation of a more holistic research concerning low temperature district heating systems. In the aforementioned research, an energy simulation model is set up for investigation of the gross energy use and energy-efficiency of district heating systems. Accordingly, the present work was conducted on a simulation model of a low temperature district heating system with consumer substation without a local storage tank.

Parameter values and assumptions of any model are usually subject to changes and deviations. Data is always associated with some uncertainty, and it is necessary to quantify these uncertainties in order to evaluate the quality of the simulation result (Goffart et. al, 2011). To be able to determine the influential parameters and especially the interactions between them, a statistical analysis is required. Hence, to evaluate the performance of the district heating system, several suitable criteria of thermal operation were selected: the relative heat loss in the distribution system, the specific heat loss, the heat density, the total energy consumption and the seasonal performance factor of the system. An uncertainty and sensitivity analysis of the district heating simulation model were conducted. An experimental design, consisting of the combinations of parameters which were varied from low to high levels was carried out.

Once the magnitude of the uncertainty is understood, this information can be used in several ways. Based on the predicted uncertainty in present or future conditions, safety factors can be included in design of network improvements. High uncertainties require increased safety factors and result in more costly designs. Thus, an understanding of the magnitude of prediction uncertainties is crucial when making decisions and operation strategies based on numerical models. Moreover, using the prediction uncertainty, the optimal network conditions and measurement locations can be identified. Uncertainty analysis can also be helpful in identifying how a network should be represented in a mathematical model, when introducing a controlling function as a part of a control strategy. Furthermore, uncertainty analysis can help to determine where and under what conditions additional data should be taken to improve model calibration.

This paper starts from the recognition that the accuracy of the current generation of simulation tools is affected by many sources of uncertainty. We have focused on one particular set of input variables, i.e. the ones regarding design and technical issues influencing heat losses in the distribution network of a district heating system. Thus, the purpose is to investigate the uncertainties on the performance of a district heating system introduced by parameters influencing heat losses in the distribution network.

DISTRICT HEATING DESCRIPTION

For the purpose of dynamic simulations, energy demand profiles for space heating (SH) and domestic hot water (DHW) were developed. A Space heating demand equation as a function of the outdoor temperature was derived for the case of a low-energy apartment in which the heat losses through transmission and ventilation are *1.9 kW* when the outside temperature is *-8°C*. For the dynamic simulations, the space heating control was designed according to a typical low-energy house from the Belgium standard regulation. Hourly outside temperatures were selected for Belgium.

Three domestic hot water profiles (low, normal and heavy) were developed. Each of them represents a typical DHW use of a household with on average three inhabitants in the course of a single day. The average energy use for DHW in a dwelling is about *5,3 kWh/day*, which is similar to *132 l/day* at *45°C*. This average value is consistent with average values in several sources (Van den Bossche, 2007 and Recknagel et al, 1996) .

The case study is composed of three multi-family buildings of 25 apartments that are placed in front of each other. The distribution networks of the buildings are connected to each other and to a central heat generation plant through buried twin pipes. The one-way network length is *475 m*. The diameters of the pipes in the network were calculated for network layouts with 75 connected dwellings with supply pipe temperatures of *50°C*. Fluid velocities were restricted to *1 m/s* inside dwellings, *1.5 m/s* in trunks, *2 m/s* in the basement and *2,5m/s* outside (Van den Bossche, 2007; Kreps et al, 2008 and Olsen et al, 2008)

In order to reduce the heat losses in the distribution system, the pipes are insulated with PUR-foam that has linear heat conductivity (*λ-value*) of *0,022 W/mK* at *50°C*. The pipes themselves are assumed to be made of copper (*λ = 401 W/mK*) and the outer casing around the insulation layer is made of polyethylene. An important function of the outer casing is to protect the pipes from direct contact with the ground, thus avoiding moisture damage of the pipes insulation material. In addition to the normal 'single' pipes, also 'twin' pipes were used in this study. In these twin pipes, the supply and return inner pipes are placed at a certain distance from each other within one insulated casing pipe.

MODELLING AND SIMULATION

As was mentioned before, a direct substation unit has been used. Once the substation model is set up, the distribution network is added to the model, as well as the heat production plant. A substation is a component that connects and separates the collective part of a district heating system and the parts within the individual dwelling. The direct substation is equipped with one heat exchanger for transferring heat from the collective heating network to the tap water, (see figure 1). For space heating, hot water from the collective network is introduced into the dwelling space heating distribution grid.

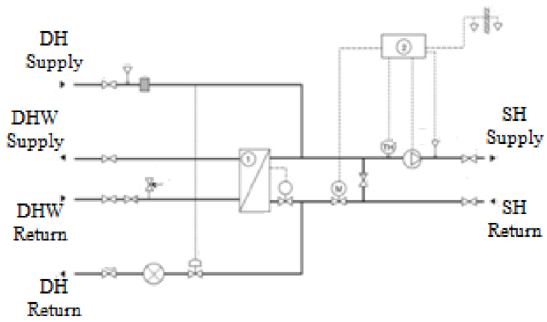

Figure 1 Scheme of the direct system (Laval A, 2012)

Following, calculations of the main components in the TRNsys model are described, based on the mathematical reference user guide of TRNsys (TRANSSOLAR, 2010). A flow mixer component (TRNsys Type11) guarantees the addition of two inlet liquid streams to one outlet stream according to an internally calculated control function. The heat exchanger (TRNsys Type 91) is a constant effectiveness heat exchanger, so the effectiveness and the inlet conditions are inputs to the type. Thermal stratification in the insulated storage tank (TRNsys Type 4) is modeled by assuming that the tank consists of a number of fully-mixed equal volume segments. In the mathematical user guide of TRNsys a detailed description of the model can be found (TRANSSOLAR,2010).

The pipe model (TESS Type 709) models the thermal behavior of the pipe by splitting the pipe in a number of fluid segments at different temperatures. The calculation of the temperature in each segment takes into account the heat losses to the environment by solving the following differential equation at every time step:

$$M_j C_p \frac{dT_j}{dt} = (UA)_j (T_j - T_{environment}) \qquad (1)$$

With UA the overall energy loss rate from the pipe (kJ/h), C_p the specific heat of the fluid in (kJ/kgK) and $T_{environment}$ the temperature of the surroundings of the pipe ($°C$).

Buried twin pipes become another important modeling component. According to the steady state theory of heat losses calculations for buried heating pipes the following assumptions has been made. In the case of twin pipes (two media pipes in the same casing), the two single pipes are identical, placed horizontally and in the same depth from the ground surface. Then the system constants are reduced to two, $U_{11} = U_{22}$ and $U_{12} = U_{21}$, and the total heat loss, q_{tot}, in (W/m), is calculated:

$$q_{tot} = 2(U_{11} - U_{12}) \left[\frac{t_1 + t_2}{2} + t_0\right] \qquad (2)$$

With Uij is the heat loss coefficient (W/mK), t_1 supply temperature ($°C$), t_2 return temperature ($°C$) and t_0 ground temperature($°C$).

The heat transfer equations for the ground buried pipe for stationary conditions are based on analytic equations presented by Wallenten (Wallentén, 1991). The models consider the heat exchange between the pipes and calculate the heat losses to the environment (Bohm et al, 2008). In figure 2 and figure 3, a summary of the simulation results is displayed.

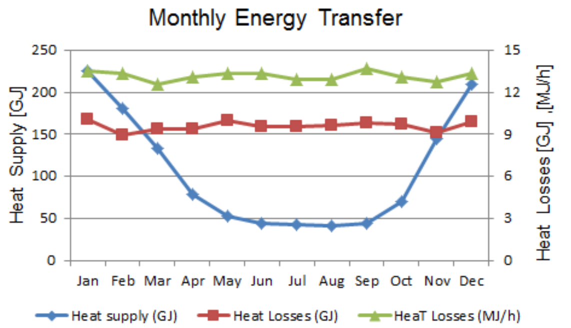

Figure 2 Monthly energy transfer of the systems

The monthly heat supplies, the heat losses and the energy consumption are drawn. The curves of the heat supplies and the energy consumption are strongly conditioned by the ambient temperature, while the curve of the heat losses is more flattened.

Although the monthly absolute values of heat losses during the whole year behaves around a well identified average value, a small reduction of the heat losses in February and November take place. This situation can be explained as a result of the different work hours of each month. Note that February is the small month of the year. When focus in the heat losses per hours of work *(MJ/h),* the curve clearly show that the values of all months behaves in a reasonable level.

In absolute terms, the heat supplied by the system consists of 1270 GJ/year while the heat losses reach values up to 115 GJ/year. The results denote that the heat losses in the supply and return network account for about 9% of the yearly energy use. In the case of the energy consumption, the electricity consumption of the heat pump represents 75% of the total energy consumption. The yearly average supply temperature was 60.2 °C and the yearly average return temperature was 25.9 °C

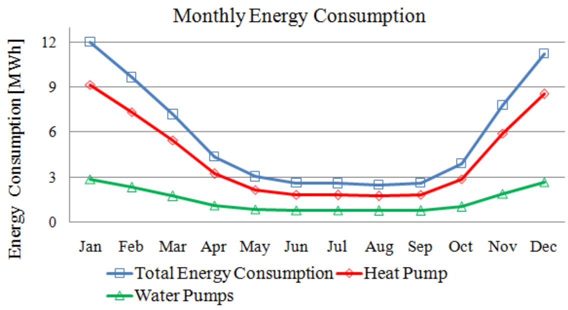

Figure 3 Monthly energy consumption of the systems

PERFORMANCE INDICATORS

The performance of the district heating system is assessed by five performance indicators: the relative heat loss (in the distribution system), the specific heat loss, the heat density, the total energy consumption and the seasonal performance factor of the system. A characteristic parameter for defining the efficiency of the DH networks is the relative heat loss in the distribution system, *RHL* (in percent). The relative heat loss is a ratio of the heat losses to the quantity of heat supplied to the DH network. The relative heat loss does not depend only on the overall heat transfer coefficient, which characterizes the efficiency of the pipe insulation. It also depends on the specific surface area of the distribution pipes, the level of water distribution temperature relative to the annual average of the outdoor temperature and even the concentration of the district heating demand among other parameters.

Another performance criterion is the specific heat loss, *SHL (MWh/m)*, which is a ratio of the heat losses to the length of the DH network. The specific heat loss is more useful when comparing different district heating systems. An additional performance indicator is the heat density *HD*, in *MWh/m*, which characterizes the concentration of the district heating demand since it represents the ratio of the heat supply (consumer's level) to the length of the DH network.

The total energy consumption in *(MWh)*, takes into account the power consumption of all water pumps of the network and the power consumption of the heat pump. This output parameter becomes one more indicator to evaluate the performance of the district heating. A further operational criterion consists of the seasonal performance factor of the system (*SPF)* which characterizes the efficiency of the system by means of the ratio of the heat supply at plant level to the total energy consumption of the DH network.

SENSITIVITY AND UNCERTAINTIES

Energy simulations make use of detailed physical relations, both differential and algebraic, that describe the way that various disturbances (from weather, humans, control systems, etc.) influence the thermodynamic behaviour of an energy system. Within this equation system a lot of parameters affect the reliability of the simulation results. To overcome these issues, uncertainty analysis is used to quantify how uncertainties in these parameters influence the conclusions that are made from the model and quantify confidence intervals of the output.

This work is focused on a well-defined section of the physical source of uncertainties influencing the simulation model outputs. In this study several parameter influencing heat losses, such as heat conductivity of the insulating material, supply pipe temperature, return pipe temperature, thickness of the pipe insulation layer, soil thermal conductivity, flow rate, and the ambient temperature were selected. A factorial analysis I^k, i.e. 2^7, with 7 parameters at two levels (low and high) was carried out. The standardized regression coefficients (SRC) were applied to determine the sensitivity of the selected performance indicators. The uncertainty analysis is then conducted by estimating the standard deviation.

$$\hat{\sigma} = \left[\sum_{i=1}^{N} \frac{(y_i - \mu(y))^2}{N-1} \right]^{1/2} \quad (3)$$

Where y is the output, μ the expected average value of y, i the sample and N is the number of samples.

As was observed by Breesch and Janssens (2005), when the input parameters x_j are independent, the SRC provide a measure of variable importance since SRC measures the effect of the variation of an input parameter x_j with a fixed fraction of its standard deviation on the variation of the output y_i, while all other input parameters equalize their expected value. The statistical model upon which the analysis of screening designs is based expresses the response variable $\hat{y}_i$ as a linear function of the experimental factors, interactions between the factors, and an error term, which can be expressed as:

$$\hat{y}_i = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon \quad (4)$$

The experimental error ε is typically assumed to follow a normal distribution with a mean of *0* and a standard deviation equal to σ. The choice of parameter range and distribution type both influence the sampled behaviour of the thermal model that is studied. Distribution on the input parameters has been estimated from data in the literature and standard.

The uncertainty of the heat conductivity of the insulating material (*InsHCond*) was estimated by using information from a test of thermal conductivity provided by the pipe manufacture (Logstor 2011). A variation of *0.00218 W/mK* for the heat conductivity of the insulating material is assumed.

Temperature measurements of fluid in pipes for control, analysis or modeling are typical practice in many thermal systems applications. Yassin, (2006), presented a temperature measurement uncertainty analysis of an actual district heating test facility. According to the results reported in reference (Yassin, 2006) a variation of *0.026°C* of the supply pipe temperature (*SupTemp*) and the return pipe temperature (*RetTemp*) have been assumed.

Determining thickness of the pipe-insulation layer is straightforward considering the variation of the casing diameter of pre insulated pipes. In this study, by using the information provided by the pipe manufacture, the tolerance of the cross section in the casing was estimated. The variation found in the cross section of the casing was assumed as the uncertainty on the thickness of the pipe insulation (*ThicPiIns*) layer (Logstor 2009). A variation of *0.265 mm* for each kind of pipe was assumed. straightforward

As was observed by Yassin, (2006), an uncertainty analysis comprising all kinds of flow meters is impossible to perform, since they are built on so many and so different technologies. In this study, according to the results described by Yassin a variation of *2.5 %* for the flow rate (*FlowRate*) was assumed (Yassin, 2006).

The soil thermal conductivity becomes another important parameter influencing the district heating network heat losses. In the last years several studies concerning soil thermal conductivity can be found. Tarnawski and Leong (2000) studied the thermal conductivity of soils at very low moisture content and moderate temperatures transport in porous media. While (Matjaz et al, 2012), presented the effect of the soil thermal conductivity coefficient on the heat loss from pre-insulated pipes during operation. Accordingly to the results reported by Matjaz et al, (2012), a variation of *0.08 W/mK* for the soil thermal conductivity (*SoilHCond*) was assumed.

The uncertainty of the ambient temperature (*TmpAmb*) is assumed the average accuracy of representative temperature loggers used in common monitoring of building management systems (Breesch, 2006). A variation of *0.125°C* for the ambient temperature was assumed. (Onset,2005).

According to the literature consulted, all the input parameters in the model simulation have been assumed normally distributed. The levels selected for each parameter correspond to [μ-2σ; μ+2σ], where μ and σ are respectively the average and the standard deviation (Breesch, 2006). This means a parameters is included in this interval with probability of *0.98*. Table 1 summarizes the low and high levels for each parameter.

Table 1

Parameters of uncertainty variants.

Parameters	**Levels (±2σ)**
Insulation heat conductivity (W/mK)	0.00436
Supply pipe temperature (°C)	0.052
Return pipe temperature (°C)	0.052
Soil thermal conductivity (W/mK)	0.16
Thickness of pipe insulation (mm)	0.53
Ambient temperature (°C)	0.25
Flow rate (%)	5

RESULTS ANALYSIS

As was aforementioned, the standardized regression coefficients measure the effect of the variation of an input parameter on the variation of a given model output. In addition, when using the standardized regression coefficients, the correlation factor R^2 has also to be calculated to evaluate how well the model $\hat{y}_i$ reproduce the actual output y_i (Breesch, 2006). The correlation factor represents the fraction of variance on the output, explained by the regression model. The regression model for four of the performance indicator approaches the real output very well as the correlation factor take value close to the unity, for instance (RHL: R^2=0.99; SHL: R^2=0.99 HD: R^2=0.94 and EC: R^2=0.92). In contrast, the *seasonal performance factor* presents a low correlation factor, R^2=0.16. Some possible reasons of this bad correlation factor are presented in the successive paragraphs.

Commonly, in order to simplify the interpretation of screening designs, by using the standardized regression coefficients the model is expressed in terms of "effects". The "Pareto Charts" display each of the estimated effects for the response surfaces. To illustrate the influence of the analyzed variables for some performance indicators figure 4 displays the estimated effect "Pareto Charts" for four indicators. The length of each bar is proportional to the standardized effect, which is the estimated effect divided by its standard error. Any bars which extend beyond the dashed line correspond to effects which are statistically significant at the *95.0%* confidence level.

The graphic shows that the *heat conductivity of the insulating material* is the most important factor for *the relative heat loss*. The *flow rate, the thickness of pipe insulation* and the *ambient temperature* have significant influence as well, while the other independent factors are not statistically significant. It should be noticed that the impact of the *heat conductivity of the insulating material* for the *relative heat loss* is considerably larger than the effect of the other parameters for all indicators. Combinations between the *flow rate* and the *heat conductivity of the insulating material*, as well as between the flow rate and the ambient temperature have also a significant influence on the *relative heat loss*. For the *total energy consumption* the significant factor are the *flow rate* the *ambient temperature.*

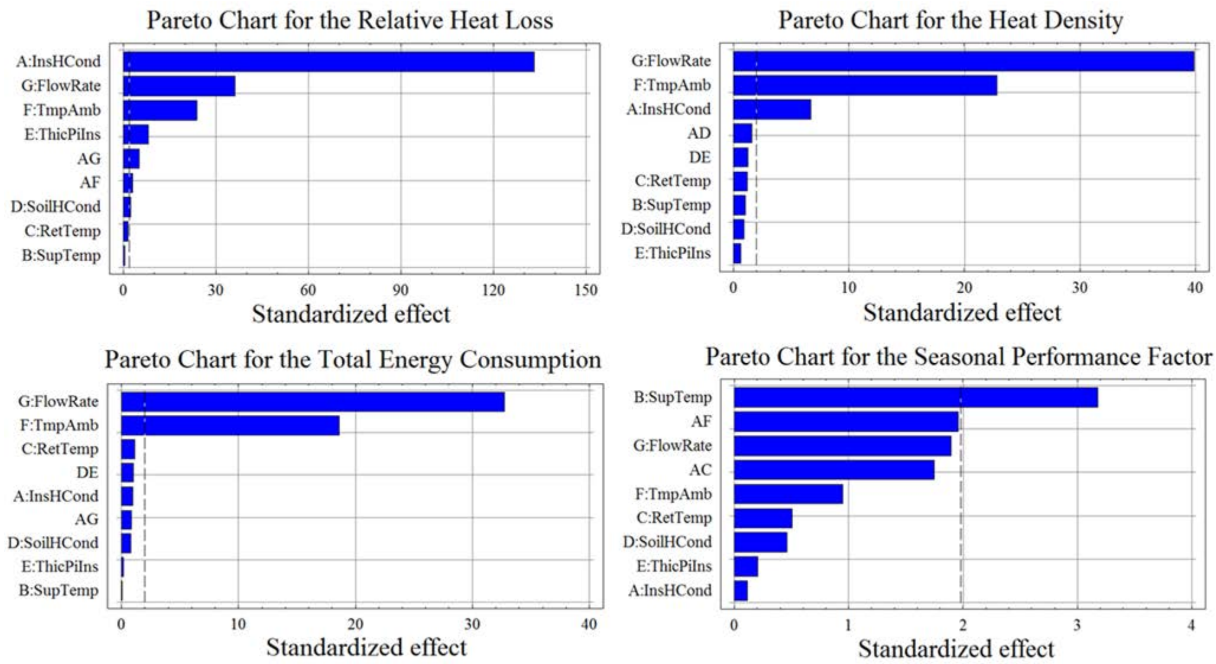

Figure 4 Pareto Charts for each indicator.

When analysing the Pareto chart for *the seasonal performance factor* only the *supply temperature* has a significant influence. The results show that the rest of the selected parameters are not statistically significant. The variation of the selected factors has minor influences on the *seasonal performance factor.* The explanation of this situation can be found in several aspects regarding the layout of the heating plant. The heating plant consists in a heat pump coupled with a central storage tank that is connected to the network distribution system. The energy consumption of the heat pump represents more than *75%* of the total energy consumption and becomes an important term when calculating the *seasonal performance factor* of the system. The heat supplied by the plant becomes another important element when calculating the *seasonal performance factor.*

On one hand the heat supply from the central storage tank to the distribution network is carried out according to the customer heat demand. Consequently, it should be noticed that during some periods of operation the heating plant covers the heat demand by using the hot water stored in the storage tank while the heat pump is not working. On the other hand, although the selected parameters have a significant influence on the heat losses of the distribution network due to the use of a modern design approach (pre-insulated pipes, buried twin pipes, low supply and return temperatures) the heat losses represents a small fraction of the heat supply. The heat supply and the heat pump energy consumption constitute the major parameters to estimate *the seasonal performance factor*. Since a mismatch occurs between the heat supply and the heat pump energy consumption *the seasonal performance factor* is hardly influence by the selected parameters.

Another important aspect consists of evaluating the main effect of factors, as well as the interactions existing amongst the experimental factors. The main effect of factor *j* can be defined as the change in the response variable y_i when x_j is changed from its low level to its high level, with all other factors being held constant midway between their lows and their highs levels.

Figure 5 shows the main effects for two performance indicators. The graphics clearly shows that in the case of the *relative heat loss,* the uncertainty of the *heat conductivity of the insulating material* has the largest influence on the *relative heat loss.* When there is a high level of the *heat conductivity of the insulating material* the *relative heat loss* reach value up to *0.06, (6,5%)*, which represents a *16%* of variation with respect to the *relative heat loss* mean value. The impact on the *relative heat loss* happens to be considerably larger than the impact on the *total energy consumption*. Varying the *flow rate* has the strongest influence on the *total energy consumption* of the system. In this parameter indicator, raising the *flow rate* towards *5%* of the base case values will increase *4.7%* the *total energy consumption*.

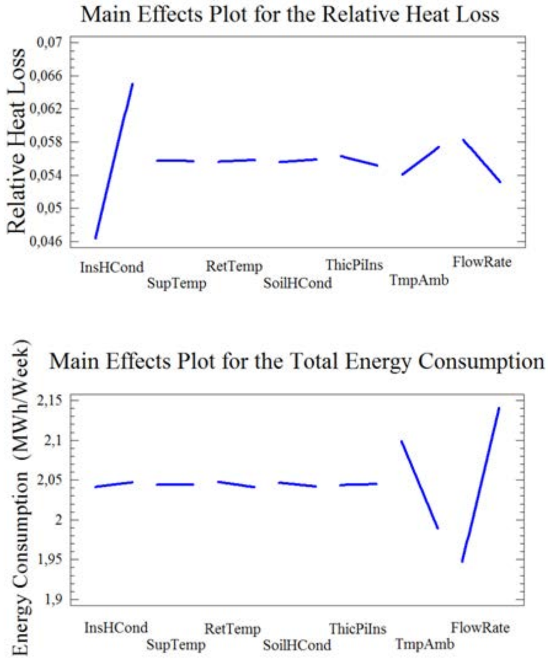

Figure 5 Main effects of factors for two indicators

To deal with the whole story about the factors interaction, the effect graphic should be produced for each pair of factors. Following the interactions between some factors for the *relative heat loss* indicator is presented. Note that several interactions were excluded since they were not statistically significant. In the graphic a pair of lines was plotted for each interaction, corresponding to the predicted response when one factor is varied from its low value to its high value, at each level of the other factor. All factors not involved in the interaction are hold at their central value

The predicted response for each combination of the low and high levels of two factors is displayed at the end of each line segment. If two factors do not interact, the effect of one factor will not depend upon the level of the other and the two lines in the interaction plot will be approximately parallel. Figure 6 shows, for the *relative heat loss,* the interaction between the *heat conductivity of the insulating material* and the *ambient temperature,* as well as the interaction between the *heat conductivity of the insulating material* and the *flow rate.* As one can see for the *relative heat loss*, the *heat conductivity of the insulating material* has little effect on the response of the output variable at a low level of the *ambient temperature*, as well as at a high level of the *ambient temperature*. The two lines in the interaction plot are approximately parallel which means that the two factors do not interact.

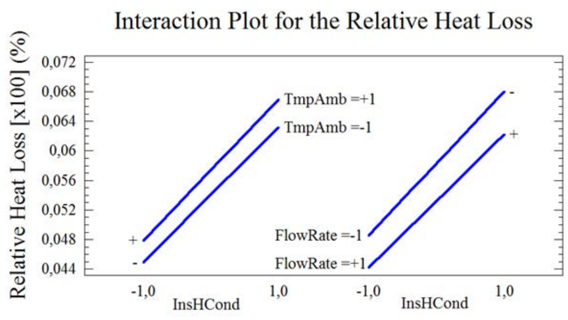

Figure 6 Interaction plot for energy consumption

The effect of the *heat conductivity of the insulating material* on the *relative heat loss* will not depend upon the level of the *ambient temperature*. Similar situation occurs when analyzing the interaction between the *flow rate* and the *heat conductivity of the insulating material*. The effect of the *heat conductivity of the insulating material* on the *relative heat loss* will not depend upon the *flow rate* level.

Once the sensitivity analysis was conducted, the uncertainty analysis was carried out. The factorial experiment allows for estimation of experimental error since the variability on the response variable because of all possible combinations of these levels across all such factors can be analysed. When considering the uncertainty, in order to accommodate the difference between the parameter indicators analyzed, a coefficient of variation (*CV*) for each of the outputs has to be calculated. The *CV* is the standard deviation divided by the mean, which allows a comparison of distributions from dissimilar sources. Figure 7 shows the outcomes of the uncertainty analysis.

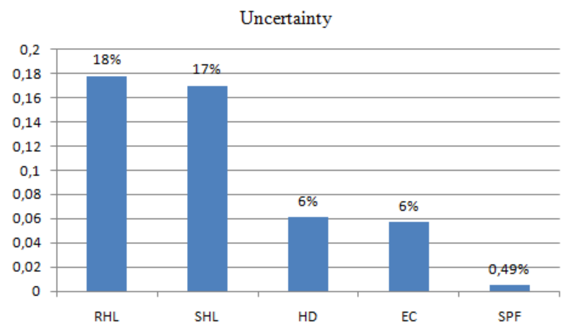

Figure 7 Uncertainty of the performance indicators

The impact on the simulation results depends on the influence and on the uncertainties of the input parameters. The graphic in figure 7 clearly shows how different can be the impact of the selected parameters on the uncertainties of the system. The uncertainties of the district heating system take values from 0.49% up to 18%, depending of the performance indicator analysed.

This variability makes the performance analysis of a DH system difficult when performance indicators are separately considered. A possible solution can be found by applying a discrete optimization methodology, for instance, a multi-criteria analysis or a multi-objective technique. Attention should be paid to the high impact of the input parameters uncertainty on the uncertainty of *the relative heat loss* since a reduction of the heat losses will contribute to the energy and economic savings of the whole system. In addition, different network representations can be evaluated by comparing their predictive uncertainties.

The present study was focused on uncertainties influencing the heat losses in the distribution network of a district heating system. However, since the performance of heat exchanger depends on inlet and outlet media temperatures on both sides, it should be noted that the assumption of constant effectiveness may hide some uncertainty. In addition, the influence of the storage tank volume, as well as the average tank heat loss coefficient per unit area should be investigated.

Finally, some of the key uncertainties affecting the costs of the installation, the heat production plant, valves, the customer substation and the dynamic heat demand were not analyzed. Thus it will be necessary to develop a more comprehensive study to explore the full range of uncertainties. The determination of the relative importance of the uncertainties on inputs can guide future research efforts.

CONCLUSION

As was mentioned previously, the present study is the continuation of a more holistic research concerning low temperature district heating system. A parametric or statistical modeling exercise on a low-temperature district heating system was presented. However, the target of the present work was not to obtain a parametric model, since detailed dynamic simulation modeling was carried out. Instead it was aim to demonstrate the capability of this kind of statistical approach in order to illustrate the influence of certain parameters on the performance indicators of district heating. Even more, the possibilities of such statistical analysis to highlight how the interaction between some input variables can influence the behavior of the output performance indicators should be accentuated.

The results demonstrate an approach to carry out the performance evaluation of a low temperature district heating system, given uncertainties in several variables. A number of parameters were investigated and ranked in terms of importance to determine which ones contribute the most to the level of uncertainty for several performance indicators. Ranking of input parameters was performed using sensitivity analysis. The most important parameters were identified by screening and sensitivity analysis.

The uncertainties of the district heating system take values from *0.49%* up to *18%*, depending on the performance indicator. The impact on *the relative heat loss* happens to be considerably larger than the impact on *the total energy consumption*, as well as on *the seasonal performance factor*. *The total* energy *consumption* only has an uncertainty of *6 %* while other two performance indicators reach values larger than *15 %* through a similar variation of the input variables. Since the selected parameters hardly influence *the seasonal performance factor* due to a mismatch between the heat supply and the heat pump energy consumption, a *0.49%* of uncertainty for this performance indicator was obtained. Furthermore, it should be highlighted that with a central storage tank in the heating plant the robustness of *the total* energy *consumption* of the system might be increased.

ACKNOWLEDGEMENT

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