URBAN HEAT DISTRIBUTION NETWORKS COMPARISON USING A GIS-BASED DISTRICT HEATING DESIGN TOOL

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ABSTRACT

This paper compares several collective heat distribution network alternatives developed to supplies heat in a neighborhood with 305 dwellings. For the collective alternatives different networks layout strategy definition, namely considering that the allocation of the distribution pipe layout is able or not to cross the main and small streets; equally, the option of crossing or not green zones, as well as, considering or not the phases of the project construction were studied. The problem definition, the structure and the solution which involves economical, technical, thermodynamic, and environmental issues are described. For the hydraulic calculations, pipe layout definition and cost estimation, a well-integrated process approach was guaranteed by mean of Comsof Heat, an automated, geographical information system (GIS) based district heating network routing and planning tool. The paper quantifies and compare the performance of different neighborhood heat supply design concepts. The results highlight the potential of the new automated district heating design tool towards solutions for sustainable energy planning.

KEY WORDS: GIS-based district heating design, Sustainable energy planning.

COMPARACIÓN DE DISEÑOS DE REDES URBANAS DE DISTRIBUCION DE CALOR DE FORMA AUTOMATIZADA USANDO EL SISTEMA DE INFORMACION GEOGRAFICA

RESUMEN

El presente trabajo, compara varias alternativas de redes colectivas de distribución de calor desarrolladas para suministrar calor en un vecindario con 305 viviendas. Para las alternativas colectivas, se consideraron diferentes opciones en la definición de la estrategia de diseño de red. Entre estas, se consideraron: a) que el diseño de las tuberías de distribución pudiera o no cruzar las calles principales y/o las calles menos importantes; igualmente, se estudió la opción de cruzar o no áreas verdes públicas, así como tomar en cuenta o no la evolución de las fases de construcción de las viviendas en el proyecto. Se describe la definición, la estructura y la solución del problema, que involucran cuestiones económicas, técnicas, termodinámicas y ambientales. Para los cálculos hidráulicos, la definición del diseño de la tubería y la estimación de costos, se garantizó un enfoque de proceso integrado a través de la utilización del programa de computación, Comsof Heat. Comsof Heat es una herramienta de planificación, diseño y enrutamiento de redes urbanas de calefacción. Dicha herramienta se basa en el Sistema de Información Geográfica (GIS, por sus siglas en inglés). El documento cuantifica y compara el rendimiento de diferentes conceptos de diseño de suministro de calor del vecindario. Los resultados destacan el potencial de la nueva herramienta automatizada de diseño de sistemas urbanos de calefacción facilitando además la planificación en el futuro de soluciones energética sostenibles.

PALABRAS CLAVES: Planificación energética sostenible, Sistema de Informacion Geografica,

1. INTRODUCTION

Worldwide the concern to achieve more environmentally friendly and sustainable global energy solutions has been increasing during the last years. Moreover, it is well-known that the energy sector is an essential and transversal component within the society, and it affects all aspects of development – social, economic, and environmental. Consequently, a sustainable energy system is usually defined in terms of energy efficiency, system reliability, and environmental impacts. These three subjects relate to – environmental concerns and energy supply security – are the main driving factors behind the growth of district heating

(DH) in most countries. A district heating system is composed of many elements, developing a value chain from the heat source to the heated buildings. District heating (DH) networks gain in importance, since they facilitate large scale renewable energy integration, recovering waste heat solutions and a better matching between supply and demand. Hence, the introduction of a district heating system provides a fundamental infrastructure to decarbonize future energy systems [1,2].

Research on the capital cost breakdown percentage of the total heat network has demonstrated that trenching cost clearly dominates the total network capital cost [3]. Moreover, as was remarked by Jebamalai in [4] routing of the pipe networks is complex, time-consuming, and expensive process. Since the route length determines the trench and pipe length, an optimized routing process allows to reduce the impacts on the total network capital cost. The aim of the study is to explore how different DH network configurations affect the network dimensions, cost, and performance. Therefore, in this paper, a comparison of several collective heat distribution network alternatives developed to supplies heat in a neighbourhood with 305 dwellings is presented. Different networks layout strategy definition, namely considering that the allocation of the distribution pipe layout is able or not to cross the main and small streets; equally, the option of crossing or not green zones, as well as, considering or not the phases of the project construction were studied. For the hydraulic calculations, pipe layout definition and cost estimation, a well-integrated process approach was guaranteed by mean of Comsof Heat, an automated, geographical information system (GIS) based district heating network routing and planning tool. The design software combines routing automation with DH network models enabling the simulation of different scenarios [4].

2. DISTRICT HEATING DESCRIPTION

The present study aims to evaluate the technical and economic feasibility of a 2-layer network namely, a transport and distribution network (see Figure 1). The transport network transfers heat from the heat source to the distribution network substations. The distribution network further distributes heat from the distribution cluster substation to the individual building heat interface unit (HIU). This is a well-extended approach which divide the large area into multiple small distribution clusters [4,5, 6].

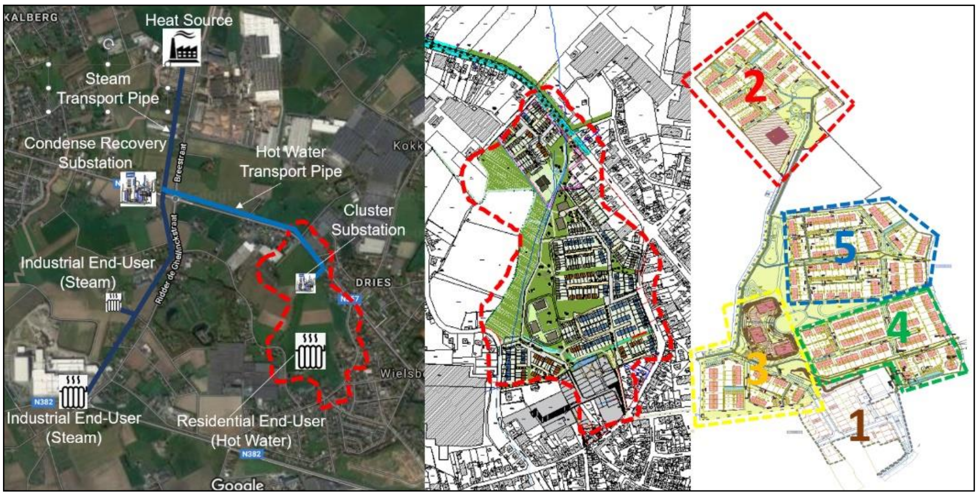

Figure 1: Case study area with building polygons, demand points, street centrelines, and project phases.

A supply and return temperature of *70 °C* and *50 °C* respectively is chosen for the hot water transport networks while a supply temperature of 65 °C and a return temperature of *40 °C* is chosen for the distribution networks in this study. Regarding the energy demand of the neighbourhood, the balance includes all energy use for space heating, hot tap water, in the entire neighbourhood. The buildings should comply with the Flemish regulation on energy performance and indoor climate. For the dimensioning of the network a space heating (SH) load demand of *5 kW* and *30 kW* for domestic hot water (DHW) per dwelling were considered.

The space heating demand is a conservative value when comparing with the case of a low-energy individual housing in which the heat losses through transmission and ventilation are somewhat around 3,5 *kW* when the outside temperature is *-8 °C*. However, the assumption of this conservative value takes into consideration the mix of low energy housing and more standard energy end user that can be found in such kind of neighbourhood. Nevertheless, in addition to the yearly demand of *9000 kWh/year* an additional evaluation assuming *6400 kWh/year* were considered.

The domestic hot water demand was estimated considering three domestic hot water profiles (low, normal, and heavy) developed by the authors in previous studies [7]. Each of the profile represents a typical DHW use of a household with on average three inhabitants over a single day. The average energy use for DHW in a dwelling is about *5,3 kWh/day*, which is like *132 l/day* at *45°C*. The case study is composed of four multi-family buildings with a total of 71 apartments and 234 individual houses distributed in the whole area. The distribution networks of the buildings are connected to each other and to a central heat distribution plant through buried single pipes. The one-way network length is approximately *2500 m*. 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.

It is well-known that building peak heat demand is less and less used for network pipe sizing to cover demand during the year, since it is unlikely that each building consumes this heat at the peak demand level, at the same time. Particularly, DHW which is characterized by very high demand in a very short duration of time. Therefore, a well-dimensioned network design is guarantee by using simultaneity factors for space heating and DHW demand respectively. Thus, to define the design heat load for every pipe segment in the network, a simultaneity factor is applied based on the number of connected buildings to that segment. District heating pipe dimensioning methods involve the selection of the lowest possible pipe diameter to transfer the required heat load with the constraint of an upper limit for the flow velocity and/or the pressure gradient [8]. For that reason, to evaluate the impact of different network pressure levels and flow velocity constraints, pipe layouts configurations, heat demand reduction and the use of different methods to calculate the simultaneity factor for DHW on network dimensions, cost, and performance several scenarios are investigated.

3. RESEARCH FRAMEWORK AND METHODOLOGY

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. In this context computational tools plays an important role for the design and operational optimization of complex DH networks. Several research papers [8,9 and 10] as well as commercial tools such as NetSim [11,12] and Termis [13] offer models or frameworks to design DH systems. Schweiger et al. [10] presented a framework for dynamic thermo-hydraulic simulation and optimization of district heating and cooling (DHC) systems. However much of these tools and application lack automation and integrated approach in their solution [4]. Chicherin et al. [14] highlighted the advantages of combining a GIS application with an energy demand forecasting model to create a tool aimed at supporting decision-making. Following paragraphs, based on reference [4], provides a concise summary of the mains characteristic of the district heating network routing and planning tool, Comsof Heat. For readers interested in the features and other procedures of the tool, a more comprehensive description about the methodology and assumptions can be found in [2 and 4].

The network operation efficiency is influenced by the DH pipe diameters, insulation material, operating temperatures, space heating, and domestic hot water demand among other parameters. Heat loss influences the operating costs of a DH network. The heat loss for supply pipes, Q_f and return pipes, Q_r are given by

$$Q_f = U_1(T_f - T_s) - U_2(T_r - T_s) \tag{1}$$

$$Q_r = U_1(T_r - T_s) - U_2(T_f - T_s) \tag{2}$$

where U_1 refers to the heat loss coefficient from pipe (supply/ return) to ground in *W/mK*, while U_2 refers to the heat loss coefficient from supply pipe to return pipe in *W/mK*, and T_f , T_r and T_s are the supply pipe, return pipe and soil temperatures, respectively. The coefficients U_1 and U_2 are taken from the European standard (EN 13941) [15]. The overall heat loss then is

$$Q_{total} = Q_f + Q_r = 2(T_r - T_s)\left(\frac{T_f+T_r}{2} - T_s\right) \tag{3}$$

The network routing process involves the evaluation of all possible routes that will connect all demand points (end-user) to the central heat source with pipes according to the specified rules. The streets can be categorized into different types: from low to high density, from low to high road material cost and from local streets to highways. The relative cost per meter and per pipe diameter can be assigned to each category. A cost factor for each pipe size (EUR/m) can be used with detailed cost information (DH pipe, trench filling material and labour costs), as well. Equipment costs such as for the HIUs, substations, and heat source can also be given as input. Higher costs can be imposed for special cases such as crossing rivers, railways, etc. The complexity lies in the fact that there are many possible combinations, and every decision must also ensure the network satisfies the rules and constraints of the user. Comsof Heat makes extensive use of existing graph algorithms from the literature [16,17,18,19, 20,21].

Performance indicators

In previous work of the authors [7], the uncertainties on the performance of a district heating systems introduced by parameters influencing heat losses in the distribution network have been investigated. In the current study suitable criteria focuses on a more general scope concerning the investment options of a potential Dcision-maker are selected. The choice of a district heating system alternative is assessed by five performance indicators: the *Total Cost of Project* (*Tot_Cost*), the *Deployment Cost per Home* (*Cost_Home*), the *Net Present Value* (*NPV*), the *Total Heat Delivery* (*Heat_Use*), and the *Heat Losses* (*Heat_Loss*).

A characteristic parameter for defining the suitability of the DH networks is the *Total Cost of Project, Tot_Cost*, (in €). The *Total Cost of Project* includes the cost of the different components of the network, namely trenching cost, transport, and distribution pipes cost, cluster substation cost, individual building heat interface unit (HIU) cost and other auxiliaries' devices cost, this parameter quantify the total technical and labor cost of the DH network. It should be noticed that cost associated to planning and designing or project management are not considered in this indicator. Another performance criterion is the *Deployment Cost per Home, Cost_Home, (€/home)*, which is a ratio of the total Cost to the number of the dwelling connected to the DH network. The Deployment Cost per Home is more useful when comparing different district heating systems. An additional performance indicator is the *Net Present Value,NPV, (in €)*, which is a method of balancing the current value of all future cash flows generated by a project against initial capital investment. It should be remarked that the cost and price have been considered according to the year 2021, however any variability on the current cost or energy price has not major impact on the conclusion since the study focuses on scenarios and alternatives comparison which would behave in a similar relative way concerning possible cost and price variation.

The *Total Heat Delivery, Heat_Use, (in MWh)*, considers the total heat delivery from the heat source to the network to cover the heat demand of the end-user. One more performance indicator that have been considered is the *Heat Losses, Heat_Loss, (in MWh)* which 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 water distribution temperature, the outdoor temperature and even the concentration of the district heating demand among other parameters.

Sensitivity analysis parameters

As was afore mentioned, in the current study, several parameters influencing the performance of district heating system have been studied. Whit this regard three influencing criteria have been selected: the network pressure levels and a flow velocity constraint, the reduction of heat demand and different methods of DHW simultaneity factor for network dimensions. As a results of the EPBD (European Energy Performance in Buildings Directive) implementation in the regional Flemish regulation on Energy Performance and Indoor Climate in Buildings (EPB), the energy performance requirements have been strengthened year after year [22]. In this context, the space heating demand is expected to be reduced with increasing insulation and energy efficiency system in the building sector. Accordingly, for the parameter *Reduction of Space Heating Demand*, (*SH_Dem*), three levels were defined (0%, 17% and 33% of space heating demand reduction). Pipe sizing starts with the farthest consumer of every branch.

In addition to the temperature difference between supply and return side, the pipe roughness and either the maximum allowed pressure loss, or the design flow velocity determine the heat flow capacity of a pipe. Therefore, the parameter *Pipe Sizing Design Constrain, (Pipe_Limit)* with four level was defined. This parameter allows to evaluate the impact of the following network design options: design by flow velocity, by pressure gradient, design by pressure number as well as, design by velocity and pressure gradient at the same time. The design by flow velocity constrains heat flow so that a given flow velocity for each pipe is not exceeded. Design by pressure gradient constrains the pipe diameter so that a pre-set value for the network pressure loss per kilometre is not exceeded. Design by pressure number constrains the pipe diameter so that a given total network pressure loss is not exceeded. While, when using design by velocity and pressure gradient, for each pipe segment the most stringent constrains is considered. The pipes in every segment are then sized based on these constraints and the heat demand. The operating pressure and temperature determine the required pipe thickness, see [15] for the applied calculations.

Space heating and domestic hot water flow rates have always been problematic to calculate, because of issues with simultaneous usage of hot water. In fact, full load conditions will result in very large flow rates and oversized pipes. To overcomes this situation when dimensioning piping a simultaneous factor have usually been applied. This is a parameter that guarantee how one works out the peak instantaneous hot water load on a heat network, based on the number of dwellings. As the number dwellings increases, the possibility of every system running at peak load reduces, and peak design load also reduces. In the literature, many calculation methods for simultaneous power and flow rates are known and used for space heating and domestic hot water piping [8,23,24,25,26]. Most of these methods make use of well-known standards; for instance, European (EN 806e3:2006) [27], Danish (DS439) [28] and/or the Swedish (SDHA F101) [29], that have been developed based on measured heat demand usage profiles and on experience.

The simultaneity factor for space heating $SF_{SH,i}$ is calculated based on the total number of homes N_i connected to the respective pipe node *i*:

$$SF_{SH,i} = x + \left(\frac{1-x}{N_i}\right) \quad (4)$$

The simultaneity factor for DHW $SF_{DHW,i}$ is calculated based on the total number of hot water taps n_i connected to the respective pipe node *i*:

$$SF_{DHW,i} = \frac{1}{\sqrt{n_i}} \quad (5)$$

The space heating and DHW load for each pipe segment are then calculated with

$$Q_{SH,i} = SF_{SH,i} Q_{CSH,i} \quad (6)$$

$$Q_{DHW,i} = SF_{DHW,i} Q_{CDHW,i} \quad (7)$$

where $Q_{CSH,i}$ and $Q_{CDHW,i}$ are the cumulative space heating peak load demand and cumulative domestic hot water peak load demand at node *i*, respectively.

The total heat load after applying simultaneity factors can be calculated for two options namely cumulative and DHW priority switching strategy. In cumulative strategy, the total heat load can be obtained by adding both space heating and DHW loads. DHW priority switching strategy means that the power is switched to DHW once the hot water taps are turned on. So, the total heat load for DHW priority switching strategy can be calculated by taking the maximum of both space heating and DHW loads. Accordingly, in the present study for the parameter *Simultaneity Methods (DHW_Simult)*, four levels were defined. Table 1 shows the set of levels for each of the selected parameters (experimental factors) to carry out the sensitivity analysis.

Table 1: Set of levels for each parameter.

Parameter	**Reduction of Space Heating Demand**	**Pipe Sizing Design Constrain**	**Simultaneity Methods**
	SH_Dem	***Pipe_Limit***	***DHW_Simult***
Level			
1	0 % Reduction of Space Heating Demand	Design by flow velocity	Space heating and Domestic Hot Water; Eq. (4); (DHW: x=0,15 SH: x=0,62)
2	17 % Reduction of Space Heating Demand	Design by pressure gradient	Space heating Eq. (4) and Domestic Hot water Eq. (5); (SH: x=0,62)
3	33 % Reduction of Space Heating Demand	Design by pressure Number	Space Heating and Domestic Hot Water Eq. (4) with priority Switching; (DHW: x=0,15; SH: x=0,62)
4		Design by velocity and Pressure gradient	Space Heating Eq. (4) and Domestic Hot Water Eq. (5) with priority Switching; (SH: x=0,62)

Sensitivity analysis is used to quantify how the variability of these parameter influences the district heating performance output. To assess the impacts of variations in the selected input variables on the district heating alternatives studied, a sensitivity analysis by means of a multilevel factorial analysis I^k have been conducted. In this kind of analysis each factor k has a specific number of I levels. Similarly, to 2^n factorial analysis, standardized regression coefficients (SRC) were applied to determine the sensitivity of the selected performance indicators (i.e. the *Total Cost of Project*, the *Deployment Cost per Home*, the *Net Present Value*, the *Total Heat Delivery* and the *Heat Losses*).

When the input parameters x_j are independent, the standardized regression coefficients 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 [30]. 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. The experimental error ε is typically assumed to follow a normal distribution with a mean of 0 and a standard deviation equal to σ.

$$\hat{y}_i = b_0 + \sum_{l=1}^{k} b_l x_l + \sum_{l=1}^{k} \sum_{j=l+1}^{k} b_{lj} x_l\, x_j + \varepsilon \quad (8)$$

4. ANALYSIS AND RESULTS

Sensitivity analysis of district heating network of scenario A1

The multilevel sensitivity analysis is presented for a single network typology of *Scenario A1*: Pipe layout definition without crossing mains streets or small green zone and not considering project phases. Table 2 shows some network configuration variables used in the current study.

Table 2 Network configuration variables

Configuration Variable	**Variable value**	**Configuration Variable**	**Variable value**
Number of Homes	305	Pipes design by flow velocity	True
Peak space heating demand (kW)	1525	Pipes design by pressure number	True
Peak hot tap water demand (kW)	9150	Installed Capacity (kW)	1525
Network deployment time (years)	5	Supply temperature (°C)	70
Network lifetime to consider (years)	35	Return temperature (°C)	40

Figure 2 summarizes the results of the 48 cases generated by the multilevel factorial analysis of scenario A1 for one of the output variables. The graph shows the variability within the total cost indicator, which reflects the impact of the *Pipe Sizing Design Constrain* parameter in the x-axis. The four different categories that are defined as the level of the parameter denotes 17% of difference between the total cost average of the alternatives where the pipe sizing was limited by flow velocity in comparison to those alternatives dimensioned including the design by pressure gradient. In this last alternative the diameters of the service connections pipe tend to be larger than the other alternatives to reach the constrains of the pressure limitation drops.

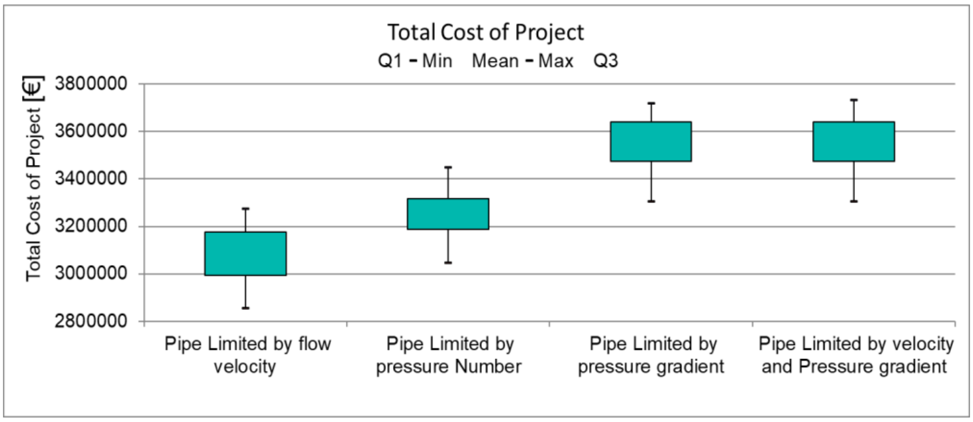

Figure 2: Box chart of *Total Cost of Project* indicator in function of one of the system parameters.

To evaluate the impact of the 3 parameters on the variability of the selected performance indicators a more detailed analysis of the statistical results is necessary. The analysis was carried out with the help of a computer program "Statgraphics Plus", which is a software designed for interactive statistical data analysis [31]. The results obtained from the software are displayed as a regression model which is fitted to the data. Commonly, to simplify the interpretation of screening designs, the model is expressed in terms of "effects" [31]. For the response surface designs, the "Pareto Charts" display each of the estimated effects (Figure 3).

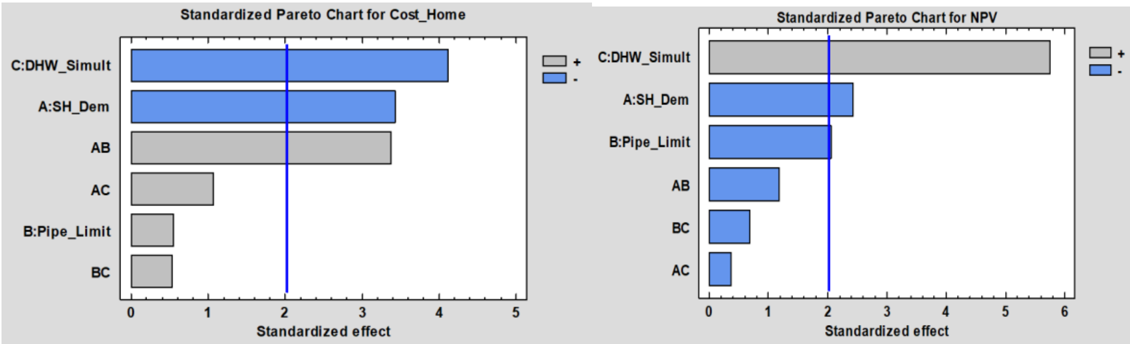

Figure 3: Pareto Chart of the *Deployment Cost per Home* the *Net Present Value* performance indicators

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 blue line correspond to effects which are statistically significant at the 95.0% confidence level. The graphic shows that the impact of the *Simultaneity Methods (DHW_Simult)* on the *Deployment Cost per Home (Cost_Home)* is statistically significant and larger than the effect of the other parameters. In this performance indicator the *Reduction of Space Heating Demand*, (*SH_Dem*) is also statistically significant. Combinations between the *SH_Dem* and the *Pipe_Limit ("AB" on the graphic)*, has also a significant influence on the *Deployment Cost per Home*. Meanwhile the three selected parameters have an effect statistically significant for the performance indicator *Net Present Value.*

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 *yi* when *xj* 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 4 shows the main effects for two performance indicators.

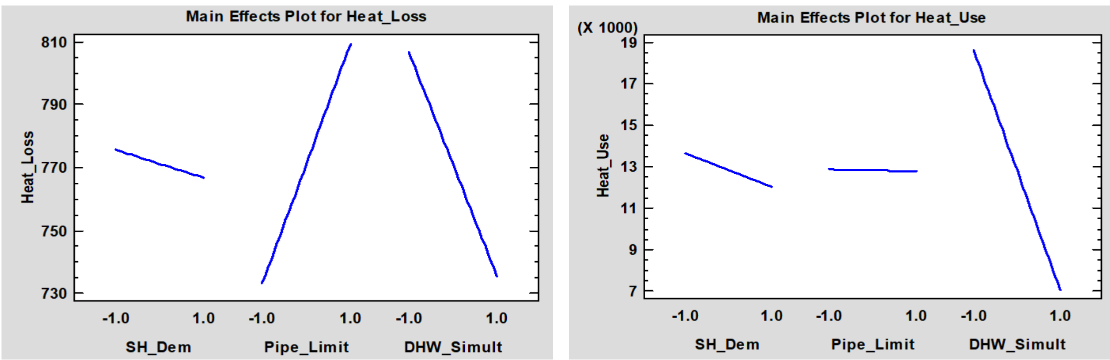

Figure 4: Main Effect plot of two performance indicators.

The graphics clearly shows that in the case of the *Heat Losses (Heat_Loss)*, when the parameter *Pipe Sizing Design Constrain* is on the level (Design by flow velocity) the *Heat Losses* reach value up to *735 MWh* per year, which represents a *10%* of variation with respect to the heat loss mean value. Similar effect of 10% heat loss reduction happens when the parameter *Simultaneity Methods* is in the upper level 4 where Domestic Hot Water with priority Switching is selected. In the same way, it is relevant the impact of the *Simultaneity Methods* parameter on the *Total Heat Delivery (Heat_Use)*. In this parameter indicator, selecting the upper level of *Simultaneity Methods* where Domestic Hot Water with priority Switching is defined will reduce 45% the *Total Heat Delivery (7000 MWh)* with respect to the *12750 MWh* mean value of this indicator.

As was observed in [30], to deal with the influence of factor interactions, an effect graph for each pair of factors should be produced. Below, the interactions plot for the *Deployment Cost per Home* indicator is presented. In figure 5, a pair of lines was plotted for each interaction, corresponding to the predicted response when one factor is varied from its lower to its upper level, at each level of the other factor. The predicted response for each combination of low and high levels of two factors is displayed at the extremes of each 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 plot are approximately parallel.

In the graphic the interaction between the *SH_Dem* and the *Pipe_Limit* ("AB" in figure 5) is significant. Notes that there is a significant difference in the response of the *Deployment Cost per Home* depending on the level. On the one hand, when the independent variable "A": *SH_Dem* is at lower level which mean without reduction of the space heating demand, thus 100% of the base case space heating load, the level of the *Pipe_Limit* ("B") has a larger effect on the *Deployment Cost per Home* with his lower value and therefore, when the district heating use *Design by flow velocity* as *Pipe Sizing Design Constrain*. In this condition the *Deployment Cost per Home* is 10% larger than the value obtained in the upper level of *Pipe_Limit* parameter, thus when the district heating use *Design by velocity and pressure gradient* as *Pipe Sizing Design Constrain*. On the other hand, when the independent variable "A": *SH_Dem* is at upper level which mean with 33% of reduction of the space heating demand, the level of the *Pipe_Limit* ("B") has a larger effect on the *Deployment Cost per Home* with his upper value and therefore, when the district heating use *Design by velocity and pressure gradient as Pipe Sizing Design Constrain.* It should be noticed that this result reflects that even if significant actions are carried out to reduce the space heating load like the upper value of the parameter "A": *SH_Dem* (33% of reduction of the space heating demand) it is possible to obtain smaller values of *Deployment Cost per Home* even if the less strength criterion is used as *Pipe Sizing Design Constrain*, that is *Design by flow velocity.*

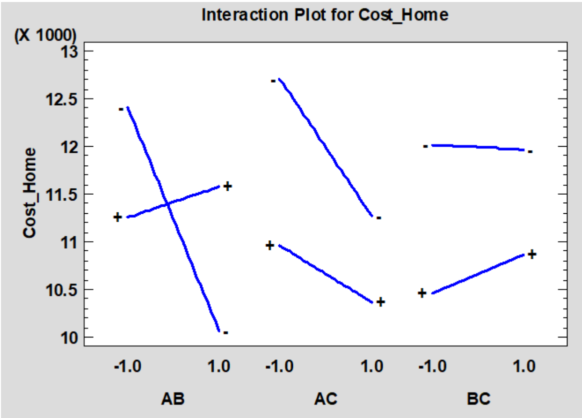

Fig. 5. Interactions plot of two performance indicators

Network configuration scenarios analysis

In addition to the sensitivity analysis, five scenarios related to district heating layout configuration have been investigated to study the impact on network dimensions, cost, and performance. All network calculations are done with similar central substation size and the rest of network variable configuration remaining similar (see table 2). The definition of the scenarios describing the pipe layout concept are presented below. In the scenarios A1, A2, A3 and A4 a network rollout strategy spreading the demand points over years was considered. For these four scenarios a maximum fluid velocity of *1,5 m/s* inside of the pipes was considered. While for the case of scenario A5 a network rollout strategy considering a fixed roll-out phase polygons in function of the project construction phases were used. In addition, in the case of scenario A5 a maximum fluid velocity of *2,5 m/s* inside of the pipes was considered. The output of the network routing algorithm in the form of polygons describing the boundary of every cluster is visualized for two of the defined scenarios in figure 6.

- A1: Without crossing streets or green zones, not seeing project phases and water velocity 1,5 m/s
- A2: Crossing streets but not green zones, not considering project phases and water velocity 1,5 m/s
- A3: Crossing streets and small green zone, not considering project phases and water velocity 1,5 m/s
- A4: Crossing streets and small green zone, considering project phases and water velocity 1,5 m/s
- A5: Crossing streets and small green zone, considering project phases and water velocity 2,5 m/s

Figure 6: Output of a simulation indicating the location of clusters, heat sources and pipe routes.

Figure 7 shows the trench length of the five different network configurations. The breakdown of distribution network pipe sizes reflects the impact on the dimensions of DH pipes of the design flow velocity and network pressure levels constraints. The *Scenario A5* presents the smaller total trench length and there are almost not pipes with diameter larger than DN65. The length of pipes with diameters *DN32* and *DN40* also are increased, which have a directly impact on the network deployment cost. The impact on the *Total cost of the project* and on the *Deployment Cost per Home* are displayed in figure 8. Results demonstrates that with *Scenario A5* a reduction of 15% to the *Total cost of project* and the *Deployment Cost per Home* in comparison with the *Scenario A1*.

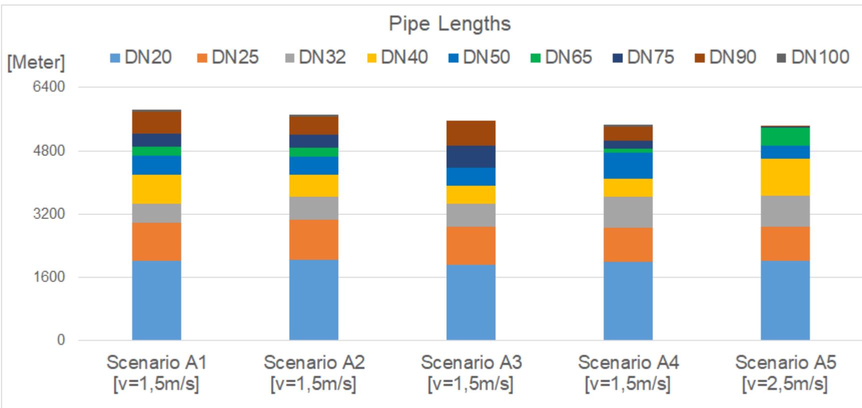

Figure 7: Impact of network configuration scenarios on the district heating pipe diameters and length.

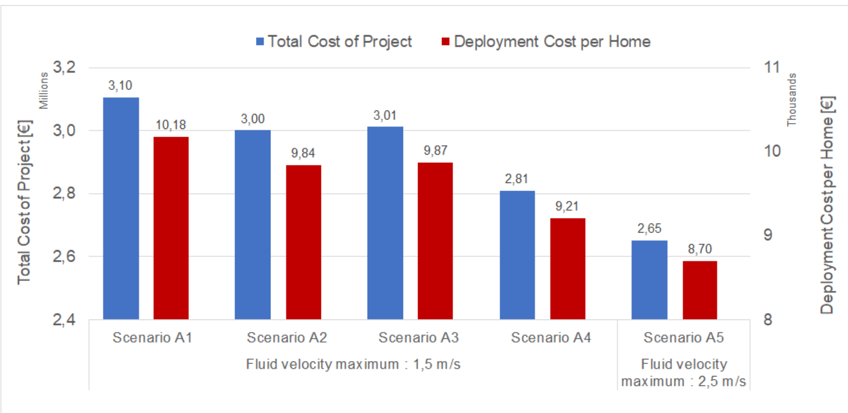

Figure 8: Impact of network configuration scenarios on two performance indicators.

Although the analysis of the cost variables can provide a good evaluation of the studied scenarios, the *Net Present Value* indicator can give a better inside of the performance of the system. As was afore mentioned the *Net Present Value, NPV*, consider the cash flows generated by a project against initial capital investment. For that reason, this performance indicator can evaluate the operational improvement introduced on the different configuration investigated. Figure 9 clearly shows that by using the configuration of *Scenario A5* a *Net Present Value* 7 times larger than the one of *Scenario A1* is achieved.

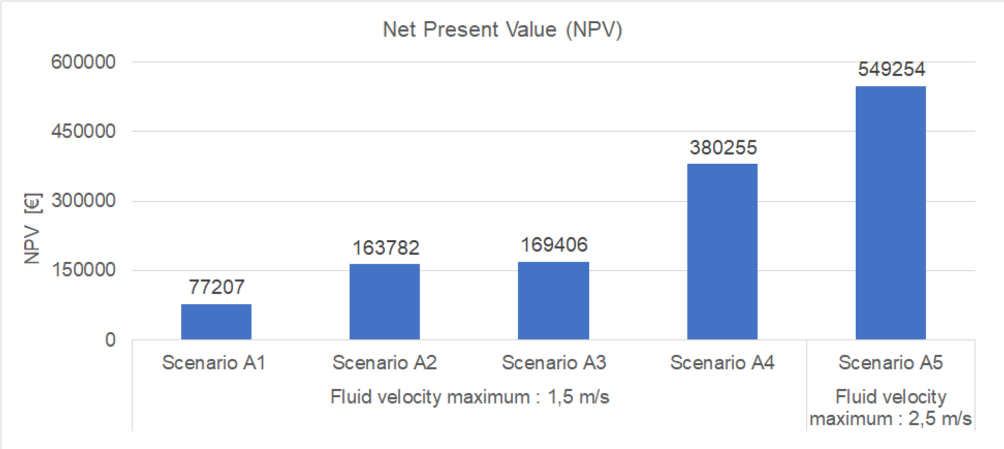

Figure 9: Impact of network configuration scenarios on the *Net Present Value* performance indicator.

Number of home reduction scenarios analysis

To see its impact on dimensions, cost, and performance, simulations have also been performed with the number of homes reduced to 50%. A reduction of the number of homes is directly related to a reduction of space heating and DHW demand. The network configuration of scenario A5 have been used as base case to carry out this analysis. For that reason, the new scenarios have been classified as scenarios A5.1 until scenario A5.6. The performance of the district heating system is assessed with two additional performance indicators: the *Relative heat loss* (also known as *Heat Loss Ratio*) and the *Heat Density*. 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 second 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 pipe length of the DH network. In figure 10, the distribution network energy breakdown for different scenarios of network pipe configuration and number of home reduction and heat demand reduction percentages is presented.

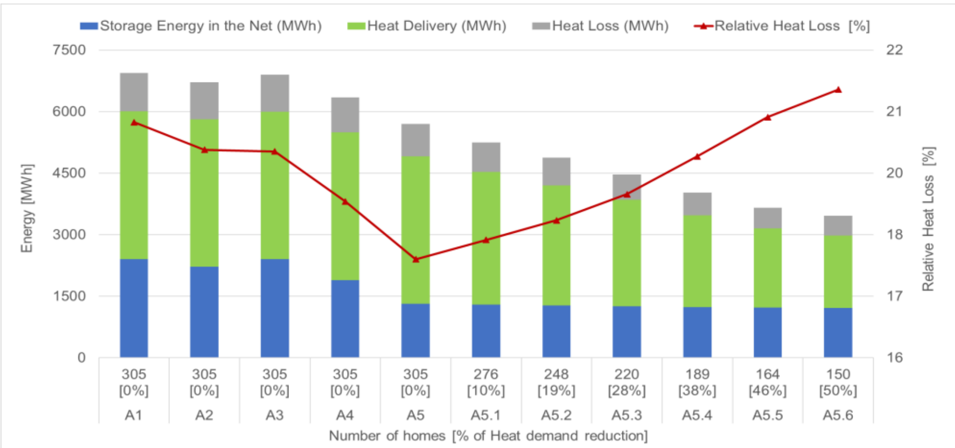

Figure 10: Impact of number of homes reduction scenarios on the energy performance parameters.

In the first part of the graphic the scenarios A1 until scenario A5 are displayed. In these cases, the number of homes remain constant, that is 305 dwellings in the network. However, since in this scenario the network configuration has been modified according to the design criterion of each scenario an impact on the pipe length and heat losses in the network occur. When the *Relative heat loss* performance indicator is observed in this section of the graphic, one can realize that the *Relative heat loss* in the scenario A5 take value of 17,6 % while the scenario A1 presents 20,8% of *Relative heat loss.* The breakdown of the energy in the network clearly shows that the amount of energy storied on the network of scenario A5 is almost the half of the amount storied in the network of scenario A1. Since a more optimal pipe routing design concept as well as the increases of fluid velocity restriction of the pipe dimensions considers on scenario A5 this result in a smaller total length of the network as well as smaller diameter of the selected pipes. Since pipes with smaller diameters have less surface area exposed to the environment the heat losses might be reduced. Hence, increasing fluid velocity restriction of the pipe dimensions improve the efficiency of the network performance. When the number of homes is reduced until the half of the base case the impact on the heat demand is also a reduction of the 50%. The energy storied on the network remains almost constant in the six scenarios from A5.1 until A5.6. However, the relative heat loss increases from 17,6% to 21,4%.

The *Heat Density* is plotted with different scenarios of network pipe configuration and number of home reduction and heat demand reduction percentages in figure 11. Results denotes that a reduction of the number of homes will produce a 33% of reduction of the *Heat Density* going from 0,66 MWh/meter in the base case until 0,44 MWh/meter in the scenario A5.6. Meanwhile a significant increase of the *Deployment Cost per Home* will occur which reach value up to 60% larger than the base case

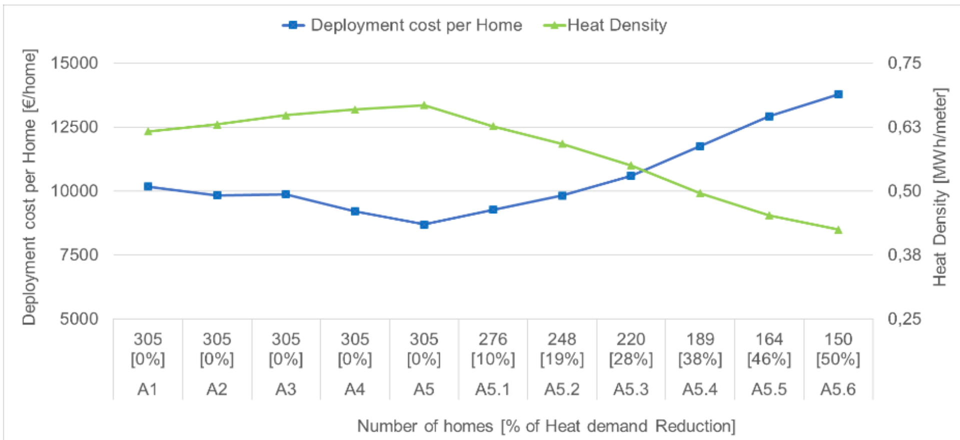

Figure 11: Number of homes reduction impact on the *Heat Density* and the *Deployment Cost per Home*.

5. CONCLUSION

A statistical exercise on a district heating system was presented. The study aims to demonstrate the capability of this kind of statistical approach to illustrate the influence of certain parameters on the performance indicators of district heating. Several parameters were investigated and ranked in terms of importance to determine which ones contribute the most to the level of variability for several performance indicators. Ranking of input parameters was performed using sensitivity analysis. The most important parameters were identified by screening and sensitivity analysis. In addition, several collective heat distribution network alternatives developed to supplies heat in a neighbourhood with 305 dwellings were analysed. For the collective alternatives different networks layout strategy definition, namely considering that the allocation of the distribution pipe layout is able or not to cross the main and small streets; equally, the option of crossing or not green zones, as well as, considering or not the phases of the project construction were studied. Results show that by using the configuration of scenario A5 a *Net Present Value* of *549254 €* which is 7 times larger than the one of Scenario A1 (*77207 €*) is achieved. Another clear conclusion of the study is the of reduction of 33% of the *Heat Density* will have a significant increase of the *Deployment Cost per Home* reaching value up to 60% larger than the base case. The results highlight both the capabilities of statistical analysis and the potential of the automated district heating design tool towards solutions for sustainable energy planning.

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