A MODEL FOR INTEGRATED DESIGN OF DISTRICT HEATING NETWORKS

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ABSTRACT

The Belgian building sector, both residential and tertiary, is accountable for almost 30% of the country's greenhouse gas emissions due to its heavy reliance on natural gas and diesel oil as a primary energy source. Improving the building thermal insulation decreases the primary consumption but not enough to meet the required decrease. Going further requires changing the primary energy supply. District heating networks are known to enable diversifying energy sources, incorporating renewable energy and waste heat recovery when available. The cost increase might be tackled by heat demand aggregation thus improving the system load factors provided that the design is able to take these effects into account. This study presents a dynamic model of district heating network bringing together building models, substations, piping losses, pumping regulation and heat supply control. The individual components of this model all embed dynamic effects yet they are first used in nominal conditions when the dynamic model is resolved for steady-state conditions for design purposes. The design values are, in turn, automatically available for the study of the dynamic behaviour. This process makes the study of interactions between the building characteristics and the design of the thermal network much faster and easier as one single platform is used for one single model thus avoiding going back and forth between a design model and a dynamic model simulation. The main contribution of this paper resides in the smooth workflow starting from the district heating network design intended to guarantee nominal performances towards the study of its operation to minimize annual transport losses. The platform used in the contribution is Dymola and the model is applied to a practical test case, focusing on a part of the heating network of the university campus in Sart Tilman Liège, comprising six buildings. The impact of a water law or over-sizing is being studied on the total energy consumption of the network, the correspondance between the demand and the supplied heat, as well as on the difference between the expected and actual temperatures inside the buildings. The results demonstrate that conclusions about the design and/or operation of the network can vary depending on the aspect being considered. This underscores the significance of possessing a dynamic and precise district heating network model, coupled with physical building models.

1 INTRODUCTION

District heating networks in Belgium are gaining increasing interest today due to their potential in decreasing our dependency to fossil fuels in the building sector. As the country is struggling to reduce carbon emissions through the use of cleaner energy sources. Especially in the building sector where fossil fuels are the main energy source used for heating, district heating networks may emerge as a viable solution. Indeed, by centralizing heat production and distribution, district heating networks optimize energy use and present high efficiency in building heating. They also foster the integration of renewable energy sources, waste heat or combined heat and power plants. Their flexibility and substantial load factor make them particularly suitable for such solutions, which may not be practical at the individual building level. As a result, district heating networks play a crucial role in minimizing emissions from individual buildings while offering a versatile and sustainable approach to meeting heating needs.

von Rhein et al. (2019) demonstrate that the Modelica language is a versatile approach for district heating network modelling since it is based on equations, is an object-oriented language, accepts acausal equation system, is capable of modelling bidirectional flows, allows steady-state or dynamic simulations, and incorporates numerous control mechanisms. Sartor and Dewallef (2017) explain the importance to have a dynamic model to represent district heating networks in order to account for delay effects caused by the long distances between the heat source and consumers. If the delay is not taken into consideration, errors can occur with various consequences, such as significant heat losses along the pipes due to excessively high temperatures, excessive over-sizing of the network leading to substantial investment costs, or a risk of thermal discomfort for consumers. Having an accurate understanding of the heat demand curve of buildings connected to the network is a crucial element for optimal knowledge of the network's operation, as explained by Remmen et al. (2018). Wüllhorst et al. (2022) present the various libraries available today in Modelica for modelling energy systems. They list 12 libraries, outlining their strengths and weaknesses to determine their utility, main function, and ease of use. This summary highlights two interesting libraries for district heating network modelling: *AixLib* and *Buildings*. For other libraries, several drawbacks may be identified, such as an insufficient library maintenance, the absence of modules for modelling buildings connected to the network, or inconsistent and complex model parametrization that makes their everyday use sometimes challenging. Regarding the *BESMod* library developed to provide a modular approach for coupling different domains of building energy system simulations, the focus has not been placed on district heating networks. *AixLib* and *Buildings* have the advantage of integrating the models necessary for building modelling and provide examples of district heating networks. However, Maier et al. (2024) explain that the development of their library *AixLib* is intended for educational and research purposes and is not designed to be user-friendly. This lack of documentation can make the use of the library or certain models complex and may potentially lead to misuse. On the other hand, Wetter et al. (2014) explain that, in the *Buildings* library, the proposed district heating network models examples are still in the experimental stage and the library models make an extensive use of object-inheritance hierarchy, which can complicate and be really time consuming for the development of new models.

This contribution is primarily concerned on offering a complete dynamic district heating network model allowing to do the design phase of the network in steady-state nominal conditions as well as running the model in dynamic mode to study the operation of the network outside of the nominal conditions. As pointed by Vaillant Rebollar et al. (2022), most of the tools dedicated to the design of district heating systems offer solutions with lack of automation and integrated approach. The district heating network is modelled and simulated in the platform Dymola, using the open modelling language Modelica, chosen for its numerous libraries for energy simulation. As discussed earlier, numerous libraries are available, and even if none of them is chosen directly for its district heating network model due to insufficient or non-existent documentation, it is advantageous to use these libraries to adopt specific models or components. This approach enables the reuse of previously developed work. To obtain the most accurate heating demand, the proposed district heating network model is associated to physical building models that allow to obtain accurate hourly load curve. The heat demand evaluation methodology is presented by Roquet and Dewallef (2023) and is conducted by using the *IDEAS* Modelica library, for which the equations are described by Jorissen et al. (2018). The model presented in this work, usable for both network design and operational evaluation, can serve various purposes. It can be employed for predicting and designing new district heating networks, or doing predictive control on existing ones. Additionally, it proves valuable to make decisions on retrofit policies for existing networks and/or associated building stock.

The district heating network model is presented in section 2. This section also explains the regulation principles of the network and the weather compensation control followed. Then, section 3 describes the real test case studied and the different considered scenarios for the design and operation of the network. Finally, section 4 shows the results concerning energy consumption and thermal comfort across the different cases, summarizing the key conclusions.

2 MODELLING METHODOLOGY

2.1 District heating network model

This article is intended to present a district heating network model that serves both for sizing the network based on nominal conditions and for being solved dynamically to observe its behaviour in operation. This model integrates various components of a district heating network, including the heat consumption of buildings, the substations, the supply and return pipes with their pressure and heat losses, the pumping system and its control, the bypass valve, the expansion tank, as well as the heat source and the associated regulation. Figure 1 represents the hydraulic model of the district heating network studied in this paper, but for only two substations, the objective being to explain the modelling principle in a simplified way.

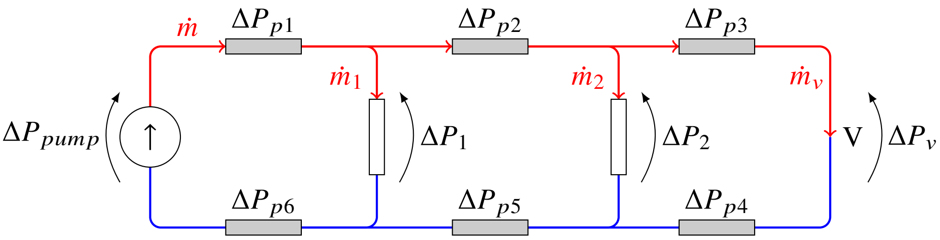

Figure 1: Simplified hydraulic district heating network model with two substation heat exchangers in white and the pipes in grey. The supply flow is in red and the return flow is in blue.

From the nominal load of the substations and the nominal operating conditions of the network, namely the supply and return temperatures, the nominal mass flow rates through the substations, $\dot{m}_{1,nom}$ and $\dot{m}_{2,nom}$, can be computed. The model requires the selection of the nominal mass flow rate through the bypass valve, denoted $\dot{m}_{v,nom}$. Thanks to the mass conservation, the nominal mass flow rate at the pump outlet, $\dot{m}_{nom}$, is computed. Pressure losses in pipes are proportional to the squared mass flow rate and function of the geometry of the network, i.e. the diameter and length of the pipes. The pressure balance over the network can be described through the following system of equations:

$$\begin{cases} \Delta P_1 = \Delta P_{p2} + \Delta P_2 + \Delta P_{p5} \\ \Delta P_2 = \Delta P_{p3} + \Delta P_v + \Delta P_{p4} \\ \Delta P_p = \Delta P_{p1} + \Delta P_1 + \Delta P_{p6} \\ \Delta P_v = \frac{\dot{m}_v \Delta P_v}{\dot{m}_{v,nom}} \\ \Delta P_1 = \frac{\Delta P_{1,nom}}{\dot{m}^2_{1,nom}} \dot{m}_1^2 \\ \Delta P_2 = \frac{\Delta P_{2,nom}}{\dot{m}^2_{2,nom}} \dot{m}_2^2 \\ \Delta P_{pump} = \Delta P_{pump,nom} \cdot 1.4 \cdot \left(\frac{N}{N_{nom}}\right)^2 + C_2 \cdot \dot{m}^2 \end{cases} \tag{1}$$

In the design phase, the objective is to size the pump (its nominal pressure head) required for the circulation of the desired mass flow rates, to establish the nominal pressure losses across components (substations and bypass valve) and to specify the necessary pipe diameters to achieve the desired flow velocity through the pipes. For this purpose, the mass flow rates, through the pump, the substations and the bypass valve, are imposed equal to the nominal mass flow rates. Under these conditions, an additional variable needs to be specified to solve the system, namely, the nominal pressure loss of the bypass valve. In the last equation of the system, the pump rotational speed ratio N/N_{nom} is assumed to be unity, reflecting nominal conditions, and C_2 is a constant specifying the nominal operating conditions. Upon solving the model to analyse its operation, the known parameters include the nominal mass flow rates and nominal pressure losses of the components. The pump rotational speed is set as a control variable (refer to section 2.3). Subsequently, the system of equations allows the computation of the different mass flow rates and pressure losses. The simplified reasoning presented can be applied in the same manner to a more complex district heating network with n substations.

Both the design and operation of the system are simulated on the platform *Dymola*. However, while it is highly suitable for dynamic simulation, the issue of steady-state simulation is sometimes more challenging. One solution is to reformulate the problem in a steady-state form by setting all time derivatives to zero. However, this solution is time-consuming and requires rewriting the entire model. Modelon suggests to perform transient relaxation instead: *"I wrote about how robust dynamic simulation is. Why not exploit this for steady state and just simulate your system until the transients are damped out of the system and reach steady state? To do this, just supply an approximation of the solution values for the state variables and simulate."*. The same model can thus be used for both sizing the system and studying its operation by imposing nominal conditions as boundary conditions for the system in the case of sizing.

From a thermal perspective, it is also necessary to size the heat exchangers in the substations. The pinch points at the primary and secondary sides are selected, which results in fixing the efficiency of the heat exchangers. By additionally imposing the mass flow rate, the substations are sized. As said before, the mass flow rates depend on the nominal load of the substations and the level of temperatures which are known parameters. The substation model is described in details in subsection 2.2. The models of the other components are presented by Roquet and Dewallef (2023).

2.2 Substation model

To estimate the temperature at the outlet of each substation, and thus the overall return temperature of the network, as well as to assess the network capacity to meet the heating demand of the different buildings, a modelling of the substation is required. This model includes the primary circuit of the substation, its secondary circuit, and the indoor air temperature. It incorporates the heat exchangers between the primary and secondary circuits and between the secondary and the indoor air of the building, as well as the mass flow rates and the temperatures as shown in Figure 2.

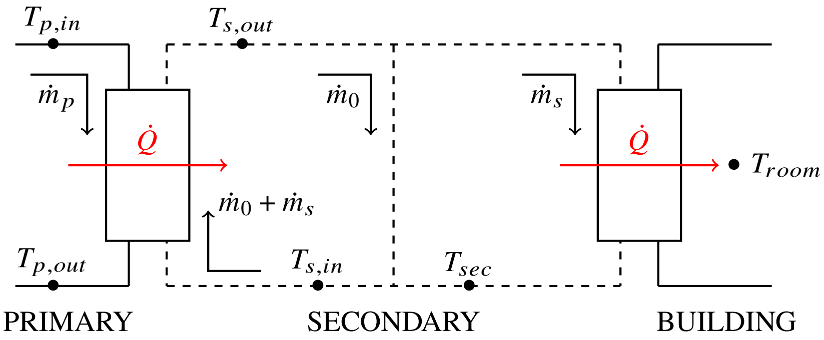

Figure 2: Diagram of the substation indicating various temperatures studied at the primary, secondary, and within the building. The diagram also includes representations of mass flow rates and exchanged power.

The substation model is based on the classical ϵ-NTU method (see Incropera et al. (2013) for further details) that implicitly supposes a steady-state operation. The exchanged power between the primary and the secondary circuits through the substation is a function of the mass flow rates and temperatures presented in Figure 2. Thanks to a system of 10 equations and 10 unknowns, the ϵ-NTU method allows to determine the three temperatures at the secondary: $T_{s,in}$, $T_{s,out}$ and T_{sec}. From the secondary temperatures, the exchanged power between primary and secondary circuits can be computed and the primary output temperature is deduced:

$$\dot{Q}_{exchanged} = \dot{m}_s cp_s \left(T_{s,out} - T_{sec}\right) \tag{2}$$

$$T_{p,out} = T_{p,in} - \frac{\dot{Q}_{exchanged}}{\dot{m}_p cp_p} \tag{3}$$

The regulation of the secondary circuit consists on a PI (proportional integral) controller. The controller takes the heating demand as the setpoint signal, the heat exchanged between the primary and secondary circuits as the input measurement signal, and it provides, as the output signal, a value between 0 and 1, which regulates the mass flow rate in the secondary circuit.

2.3 Regulation through weather compensation

In order to limit thermal losses through the pipes of the district heating network, it is interesting to reduce the circulation water temperature when the outside temperature allows it. Ionesi et al. (2015) show energy savings of 5% when using weather compensation. Instead of imposing a constant supply temperature of 80°C, this imposed supply temperature depends on the outside temperature according to a weather compensation control. In the context of this work, the chosen weather compensation control depends on 4 temperatures: the maximum supply temperature of the network ($T_{su,max}$ = 80°C), the minimum supply temperature of the network ($T_{su,min}$ = 55°C because of potential domestic hot water supply), the minimum considered outside temperature ($T_{ext,min}$ = -15°C) and the outside temperature for which the supply temperature becomes the minimum temperature ($T_{ext,const}$ = 4°C).

For the return temperature, the weather compensation control depends on a fixed temperature difference as well as a minimum mass flow rate, such as:

$$\dot{m} = \max\left(\frac{\dot{Q}}{cp\Delta T}, \dot{m}_{min}\right) \tag{4}$$

where $\Delta T = T_{su} - T_{ret}$, which gives for the return temperature:

$$T_{ret} = \begin{cases} T_{su} - \frac{\dot{Q}}{\dot{m}cp} & \text{if } \dot{m} > \dot{m}_{min} \\ T_{su} - \frac{\dot{Q}}{\dot{m}_{min}cp} & \text{if } \dot{m} = \dot{m}_{min} \end{cases} \tag{5}$$

A minimum mass flow rate is imposed as a safety factor in case the load at the substation is zero to avoid a zero mass flow rate prescribed by the regulation. Figure 3 shows the presented weather compensation control.

The supply temperature of the water provided by the weather compensation control based on the outdoor temperature is then used as an input parameter for the heat source model as the setpoint temperature. The return temperature setpoint provided by the weather compensation control is used as the setpoint input signal for a PI controller that regulates the rotation speed of the pump and, consequently, the flow at the primary side. The controller compares this setpoint temperature to the actual return temperature observed upstream of the pump to decide on the pump's rotation speed, comprised between 20% and 100% of its nominal value. Under low flow conditions (i.e., when N < 20% of N$_{nom}$), variations in the return temperature are acceptable.

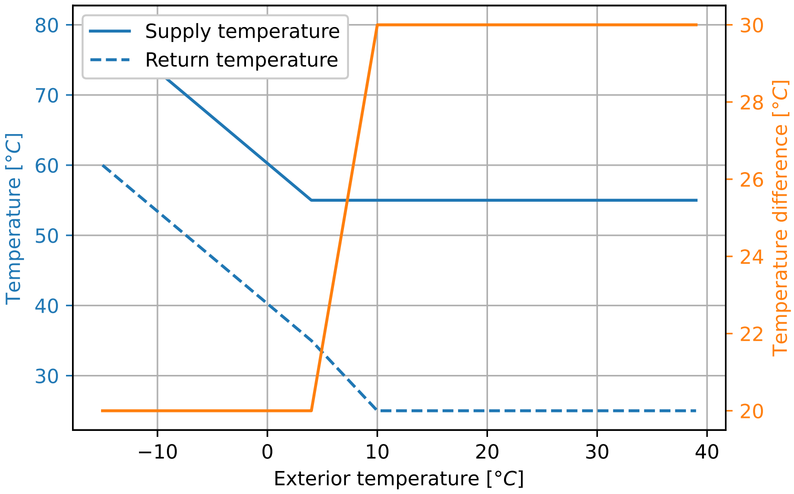

Figure 3: Used weather compensation control. In blue the supply and return temperatures of the network in function of the exterior temperature. In orange, the imposed temperature difference between the supply and return temperatures of the network in function of the exterior temperature.

3 CASE STUDY

The studied test case is the district heating network of the Polytech district on the Sart-Tilman campus of the University of Liège. This considered district is composed of 6 buildings with various functions and consumption profiles: B28, B37, B47, B49, B52 and B65. The network has a 2230 m length of supply and return pipes distributed across 11 pipe sections. The network is represented in Figure 4, with the heat source, the different substations and the path of the pipes.

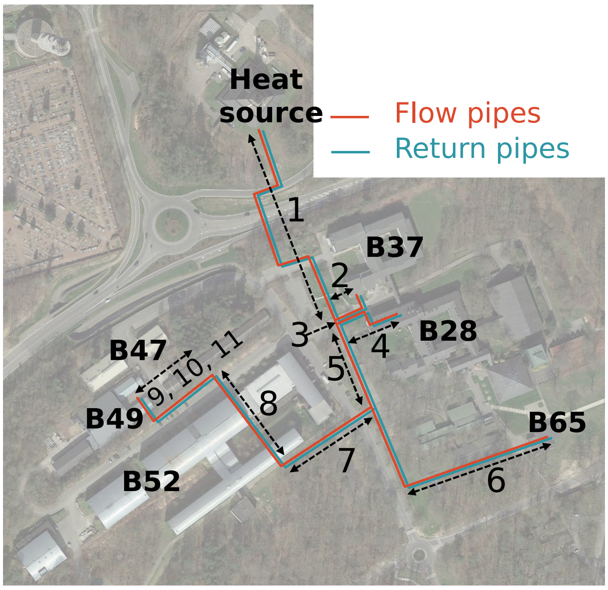

Figure 4: District heating network case study map. The numbers from 1 to 11 represent the eleven sections of pipes of the network.

The hourly heat demand of the different substations based on physical building models is obtained as explained by Roquet and Dewallef (2023). The weather file used is a TMY (Typical Meteorological

Year) file of the weather station of Uccle, the reference weather station in Belgium. The paper discusses four cases based on the considered case study, each influencing both regulation and design. In terms of regulation, two approaches are considered: one with fixed supply and return temperatures (network operated between 80°C and 60°C), and another one with variable setpoint temperatures based on external conditions (referred to as the weather compensation control, see section 2.3). Concerning design, two methods are explored: one adjust to exact nominal conditions and another incorporating a 20% safety margin for over-sizing. Table 1 presents these four cases.

Table 1: Considered cases characteristics.

	Regulation	Design
Case 1	80°C/60°C	Basic
Case 2	80°C/60°C	20% Safety factor
Case 3	Weather compensation	Basic
Case 4	Weather compensation	20% Safety factor

4 RESULTS

As discussed in section 4, fours cases are considered. The first part of this section is dedicated to examining how the design phase impacts the various scenarios. Then, the energy consumption of the network and the heat demand matching of the substations are analysed.

4.1 Impact of the design

When running the model for design purpose, the nominal pressure drop for the different substations and the bypass valve, as well as the size of the necessary pump and the diameters of the pipes are calculated. Furthermore, this phase gives the thermal losses and pressure drops through the pipes in nominal conditions. It is interesting to compare theses different values for the two considered designs, with and without a safety factor. The Tables 2, 3 and 4 present these results. For Table 2, the pressure drops along the pipes account for supply and return. Similarly, for the heat losses in Table 4, the values are given for the sum of supply and return.

Table 2: Substations characteristics (nominal load, nominal mass flow rate, and nominal pressure drop) and pressure drops along the pipes feeding the considered substations from design steady-state simulation.

	Basic design				Design with safety factor of 20%			
	$\dot{Q}_{nom}$ [kW]	$\dot{m}_{nom}$ [kg/s]	ΔP_{nom} [bar]	ΔP_{pipes} [bar]	$\dot{Q}_{nom}$ [kW]	$\dot{m}_{nom}$ [kg/s]	ΔP_{nom} [bar]	ΔP_{pipes} [bar]
B37	450	5.38	1.80	0.26	540	6.45	1.62	0.12
B28	998	11.92	1.83	0.22	1198	14.30	1.65	0.20
B65	62	0.74	0.10	1.96	74	0.89	0.10	1.75
B52	2410	28.79	1.81	0.25	2892	34.54	1.62	0.23
B47	300	3.58	1.37	0.69	360	4.30	1.23	0.62
B49	401	4.79	1.42	0.64	481	5.75	1.27	0.58

In Table 2, it is interesting to note that the network is well-balanced; an equivalent total pressure loss is found for each of the substations. When a substation requires a much lower load and is located further

Table 3: Pump and bypass valve characteristics from design steady-state simulation.

	Basic design		Design with safety factor of 20%	
	$\dot{m}_{nom}$ [kg/s]	ΔP_{nom} [bar]	$\dot{m}_{nom}$ [kg/s]	ΔP_{nom} [bar]
Pump	60.2	1.99	71.23	2.04
Bypass valve	5	1.43	5	1.25

Table 4: Pipes characteristics from design steady-state simulation.

	Length [m]	Basic design			Design with safety factor of 20%		
		$\dot{m}_{nom}$ [kg/s]	Φ [mm]	$\dot{Q}_{loss}$ [W]	$\dot{m}_{nom}$ [kg/s]	Φ [mm]	$\dot{Q}_{loss}$ [W]
Pipe 1	223	60.2	277	23674	71.23	301	25725
Pipe 4	62	11.92	123	3271	14.3	135	3554
Pipe 6	212	0.74	31	3753	0.89	34	3962

away, such as building B65, the diameter of the supplying pipe is significantly smaller, resulting in a higher associated pressure drop. This consequently leads to assigning a lower internal pressure drop to the substation. Given that there is no bypass valve at the substation level for the primary circuit, the balancing of the network under nominal conditions (the fixed nominal pressure losses of the substations) is crucial for the network's behaviour under non-nominal conditions. The analysis of this behaviour for the different scenarios is performed in the following subsections (4.2, 4.3 and 4.4). When looking at Table 3, it shows that this design phase allows to exactly know the necessary pump performances, and thus avoid to over-size it. The pump characteristic curve is the inverse of the district heating network curve. To determine the pipe diameters, a velocity of 1 m/s is imposed on the entire network. Fluid circulation speeds of 1 to 1.5 m/s are typically chosen for district heating networks as they represent a techno-economic optimal balance. This choice optimises the required heat transfer, pipe diameters and investment costs, while optimising pressure losses and pumping power consumption. When comparing the pressure losses per meter of pipe, the average value over the different pipes is 112 Pa/m, with a minimum of 28 Pa/m and a maximum of 418 Pa/m. Knowing that a value between 30 to 100 Pa/m can be set as a target, as explained by Wang et al. (2017), the flow velocity, and hence the diameter of pipes deviating significantly from this value, can be adjusted. Looking at the heat losses, Jakubek et al. (2023) show computed and measured heat losses between 8 and 35 W/m. For the considered case study, the average heat loss per meter of pipe is 31 W/m, supply and return losses mixed. The minimum heat loss is 8 W/m and the maximum is 60 W/m. Table 4 shows the length, diameter and heat losses of some pipes for the example.

4.2 Consumption analysis

Table 5 shows the total energy consumption of the district heating network (i.e. the energy provided by the heat source), the heat losses through the supply and return pipes and the electricity consumption of the pumps for the four cases. The heat losses and the electricity consumption of the pumps are given per MWh of heat produced. The total energy consumption takes into account the heat provided to the substations as well as the heat losses through the pipes. The heat losses in the network pipes represent approximatively 20% of the total annual heat injected into the network, as said by Sartor and Dewallef (2017). As expected, increasing the nominal design by a safety factor of 20% increases the heat losses and so the total energy consumption of the network, while slightly decreasing the electricity consumption of the pumps. On the contrary, using a weather compensation control instead of fixed supply and return temperatures allows to decrease the heat losses and so the total energy consumption of the network, while increasing a little bit the pump consumption. Therefore, the scenario that enables the greatest energy savings is the third one.

Table 5: Total energy consumption of the network, heat losses of the network and electricity consumption of the pumps for the four scenarios.

	Case 1	Case 2	Case 3	Case 4
$E_{heating}$ [MWh_{th}]	2617.0	2692.7	2079.0	2242.9
Heat losses [MWh_{th}/MWh_{th}]	0.223	0.232	0.181	0.180
W_{pump} [kWh_{el}/MWh_{th}]	1.03	0.93	1.49	1.34

4.3 Meeting the heating demand

In addition to energy consumption, it is interesting to examine the heating demand satisfaction of the various substations. Figure 5 presents the number of hours for which 95% of the heating demand is not satisfied for each of the scenarios. During these hours, the missing heat accounts for 63.25 MWh for case 1, 34.67 MWh for case 2, 406.36 MWh for case 3 and 269.8 MWh for case 4. The total heat demand over the 6 buildings is 1949.02 MWh. These results show that over-sizing the district heating network allows to decrease the number of hours where the demand is not satisfied for at least 95%. On the contrary, using a weather compensation control increases this number of hours. With this analysis, the scenario that meets the objective is the second one. It is interesting to note that a high number of hours for which demand is not fully satisfied does not necessarily mean that the quantity of heat not supplied is significant. The reverse remark is also true (a small number of unsatisfied hours does not imply a low quantity of heat not supplied). Case 4 serves as an example, with a quantity of heat not supplied across the entire building stock equal to 13.8% of the demand. However, when examining the details for each building, the following results are observed: 15.1% for building B28, 12.9% for B37, 25.8% for B47, 13.4% for B49, 11.5% for B52 and 13.3% for B65. These results show building B47 seems to be the one missing the most heating, contrary to the chart presented in Figure 5, where building B47 appears to be better satisfied than, for example, buildings B52 or B65. This observation indicates that the analysis of building heating load satisfaction should be conducted by considering not only the potential cold periods but also the heat quantity missing.

4.4 Analysis of the building indoor temperature

The previous section focused on examining the percentage of hours during which the heating demand was inadequately met. However, the fundamental question revolves around whether individuals experience cold conditions. To address this aspect, the building physical model, which was initially used to determine the heat demand curve, is now employed differently. Instead of using the setpoint temperature as an input and obtaining the heat demand as an output, the model now takes the heat supplied by the network as input and yields the indoor temperature as output. This analysis is specifically conducted for Building B65, as it exhibits the highest number of hours with insufficient heat supply. The model's initial setpoint temperature for establishing the heat demand curve is set at 21°C. Table 6 presents the duration of hours during which various conditions are not met for Building B65 across the four different cases. Three criteria are analysed: a temperature difference of 0.5°C between the initial temperature and the current temperature with the provided heating, a difference of 1°C, and a warning triggered when the current temperature falls below 19°C while the initial temperature is above 19°C.

The analysis of these results shows that even if the number of hours with a deficit in heating is quite important between case 1 and case 2, the inside temperature of the building is not really different in the two scenarios. The utility of over-sizing the district heating network can thus be questioned since the

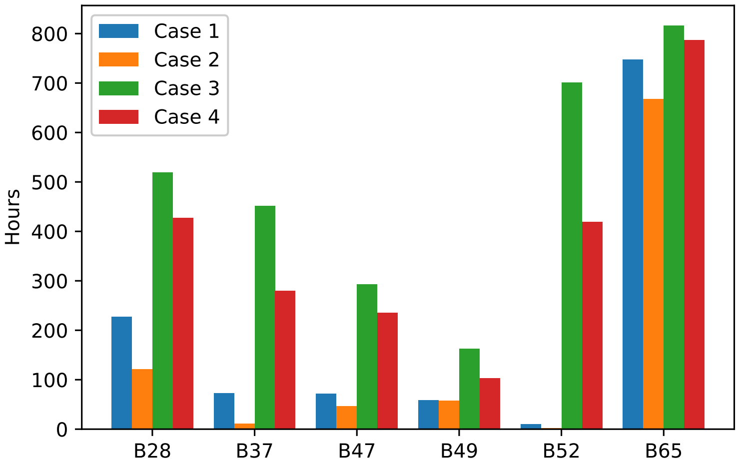

Figure 5: Number of hours with a heating demand satisfaction inferior to 95% for the different substations and scenarios.

Table 6: Number of hours for which different criteria are not met between the initial temperature to determine the heat demand curve (T_1) and the actual temperature computed from the actual heat supplied (T_2) for building B65. $\Delta T = T_1 - T_2$.

	Case 1	Case 2	Case 3	Case 4
$\Delta T > 0.5$°C	786	791	910	867
$\Delta T > 1$°C	452	421	616	551
$T_2 <$ 19°C while $T_1 >$ 19°C	220	215	331	278

total energy consumption increases in this case.

5 CONCLUSION

This work proposes a district heating network model with its various components: building consumption curves connected to the network, substation modelling, pumping elements, heat production, regulation systems, and modelling of network pipes with their pressure and heat losses. The particularity of this model lies in its ability to be employed in steady-state for nominal conditions to design the network (sizing of substations, pumping system, and pipe diameters). Additionally, it can be dynamically solved to study the network's behaviour in operation. Therefore, there is no need to switch simulation platforms between designing and operating the district heating network. Furthermore, this model is directly linked to the physical models of buildings connected to the network, ensuring accurate and realistic hourly load curves. This coupling with a building model also allows for a comparison of indoor temperatures in buildings, both expected and actual, based on the network's ability to exchange heat with buildings through substations.

Thanks to the design phase, the network is hydraulically optimized to achieve a balance, minimizing pump workload while ensuring optimal heat supply to substations. Special attention is given to small consumers or substations at the end of the line, which are more prone to under-heating issues. By employing the same model in both the design and operational phases, it becomes possible to determine both pressure and heat losses under nominal conditions.

This network model is applied to a real test case of 6 buildings. Four scenarios are considered for this test case, where two parameters can vary. The first variant involves modifying the network design; either the network is designed precisely to meet demand under nominal conditions, or a safety factor of 20% is considered for sizing. Adjusting this sizing parameter questions the relevance of the often-favoured over-sizing during network design phase. The second variable parameter is the temperature regulation of the network. Either the network operates at predetermined supply and return temperatures, namely 80°C/60°C, or the temperatures follow a weather compensation control dependent on the outside temperature. Variable operational temperatures help limiting heat losses in the pipes. With the proposed physical and dynamic network model, it is possible to verify that by decreasing operational temperatures, pump workload does not become excessive, preserving the potential savings achieved by reducing thermal losses.

The analysis of the results reveals that depending on the aspect under consideration (total network consumption, number of hours meeting heating demand, actual temperature felt in the buildings), the conclusions regarding the design and/or operation of the network can vary. This highlights the importance of having a dynamic and accurate district heating network model, coupled with physical building models. Such a model facilitates precise design but also allows for adjusting decisions based on the specific pursued objectives.

It would be interesting to test the model on larger-scale test cases because, while theoretically feasible, it is essential to verify that the design and regulation principles can be applied to more complex configurations. Another area for improvement is to make the substation model compatible with multi-zone building models since the results have proven conclusive for single-zone buildings. This would establish a direct link between the network regulation and the internal comfort temperature of the buildings.

NOMENCLATURE

Δ	difference (−)
P	pressure (Pa)
$\dot{m}$	mass flow rate (kg/s)
V	bypass valve (−)
N	rotation speed of the pump (rpm)
T	temperature (K)
$\dot{Q}$	heat flow rate (W)
cp	specific heat capacity (J/kgK)
Φ	pipes diameter (mm)

Subscripts and superscripts

p	pipe, primary
v	valve
nom	nominal
in	inlet of the substation
out	outlet of the substation
s	secondary
su	supply
min	minimum
max	maximum
ext	exterior
$const$	constant
ret	return

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