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# A MINLP optimization of the configuration and the design of a district heating network: Academic study cases

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Centralized or decentralized heat productions

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Total cost analysis

## A B S T R A C T

The aim of this work is to propose a tool for the design assistance of District Heating Network (DHN). Two goals of DHN optimization are handled simultaneously: the optimization of the configuration and its design. The optimization objective is to minimize the global cost of the DHN over 30 years. It includes both operating costs (heating and pumping cost, including thermal losses and pressure drop) and investment costs (line, trench, heating plant, heat exchanger). The formulation leads to a mixed integer non-linear programming (MINLP) problem in steady state. The model is solved with DICOPT within GAMS (around 5s for this study cases).

One of the outputs of these academic study cases is the layout of the DHN, supplied in parallel or in cascade: a consumer with hot temperature requirement can supply another consumer with lower temperature requirement. Even a looped network in cascade is optimal (−4.6% total cost reduction) when the cost of the trench is lower than 500 €/m. Furthermore, different structures are optimal (between −4 and −8% of total cost reduction) depending on whether the heat production(s) are decentralized, centralized, isolated collective, renewable or not. Finally the balance between heat loss and pressure drop is detailed.

## 1. Introduction

The use of energy in building sector accounts for a large share (around one third worldwide) of the total end use energy. Thanks to the European energy and climate policy, the French government targets a reduction of 40% of greenhouse gas emissions, 27% of energy saving and 32% of renewable energy by 2030.

A District Heating Network (DHN) is a relevant technological solution to supply heat. DHN are more and more considered in the long term prospect to tackle energy transition issues, as for instance the vision of the District Heating and Cooling platform [1]. Heat is required for industrial purpose, space heating or domestic hot water production. In comparison with individual (at each apartment) or collective (at each building) heat supply, a DHN supplies heat at the urban district scale. This enables a better

introduction of renewable energies and also the exploitation of waste heat (like excess heat from waste incineration or from other industries). Since DHN heating plants can be better monitored and can integrate energy sources other than fossil fuels, more pollution could be avoided in the inner city. Thanks to a mix of various energy sources, the energy price can be better balanced to a lower price over the long term. Nevertheless one of the major drawbacks is the high initial investment cost, which has to be paid off through the heat sales. However a DHN is an economically profitable solution to supply heat, especially when its conception is optimized as soon as possible in an urban project.

The core of this project is both to optimize in steady state the configuration (network layout and choice of the production technology), the design parameters (thermal generating capacity to install, exchange area of the Heat Exchanger – HX, length and diameter of the pipes) and the state variables (temperatures, mass flow rates). The originality of this work is to enable different network layout alternatives: consumer connection in parallel (classical design) or in cascade, the latter allowing the supply from a “hot temperature (HT) consumer” – such as old building, hospital, industrial utility – to a “low temperature (LT) consumer”. These

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connections between consumers, modelled by a HX, are depicted in (Fig. 1).

First, the state of the art concerning the mathematical programming and previous optimization works applied on DHN is realized. Then the formulation of the optimization problem is detailed. Finally the results on an academic study case are discussed.

## 2. State of the art

### 2.1. Optimization problem

This subsection aims to answer the following questions: What does exactly the well-known word “optimization” mean? What kind of problem can be tackled with it? And how can it be solved?

#### 2.1.1. Characteristic of the optimization problem

The word «optimization» sometimes refers to a heuristic approach that aims to improve the design of the system under consideration (in our case DHN). In this contribution, we refer to an algorithmic approach. A mathematical formulation of the problem is stated: minimization of an objective function submitted to a set of constraints. Then an adapted method (algorithm) is selected in order to compute the optimal values of the optimization variables (both continuous and binary). The two approaches are complementary since heuristics may help to formulate and solve the mathematical problem: the superstructure definition and the initial point guess are, for example, two critical steps that require deep insights of DHN design and operation. A superstructure is a flowsheet (or a scheme) gathering all the different feasible configurations, among the optimal one could be chosen.

For a global overview of the different formulations of optimization problems (and their different ways to be solved), please refer to the retrospective on optimization from BIEGLER and GROSSMANN [2]. Briefly, an optimization problem is characterized thanks to the types of variables, the linearity or not of the equations (objective function and constraints), the number of objective function and the consideration of the time:

- In this present work, a MINLP problem is solved. A Mixed Integer Programming means that the problem contains both binary and continuous variables. The binary variables introduce lots of combinatory, but this is necessary to rule the existence or not of such utilities (Subsection 3.1, the producer node and its technology, the connection and its direction). The last term NLP is used for Non Linear Programming, that means that the constraints added to the model or the objective function are non-linear.
- If numerous objective functions are considered, a multi-objective problem has to be solved. This is not the case here.

The studied problem solved in this paper tends to minimize the global cost (Subsection 3.3). In this context, there is no restriction to provide additional indicators, as for instance greenhouse gas emission, primary energy use, or renewable energy mix. However for such a type of urban project, the economic point of view is usually the key element. Other indicators can be added to the problem as additional constraints (e.g. minimum renewable energy share or maximum greenhouse gas emission).

- The term “multi-period” optimization is used if time is a discontinuous variable, otherwise “dynamic optimization” is the right term. For sack of simplification, Multi-period Optimization is generally used with the assumption of linearity while Dynamic Optimization generally does not involve binary variables. In our case, we have chosen to focus on a detailed description of the physical phenomena that impact the cost evaluation (pressure drops and heat losses). As a consequence, the stated problem is nonlinear. Since, at this stage of an urban project, it is important to have both information about the configuration (see Subsection 2.2.1) and the design (Subsection 2.2.2) of a potential DHN, binary variables arise too. As a first step in our methodology, we only consider the DHN in steady state, with fixed values of the various parameters (consumer’s duties, ambient temperature...). Thus the problem results in a MINLP formulation. Mixed Integer Dynamic Optimization (MIDO) should be the next step.

#### 2.1.2. Resolution of a MINLP problem

There are two main ways to solve an optimization problem: using stochastic methods or deterministic ones. BIEGLER and GROSSMANN compared them in a second review [3], in which pros and cons are detailed.

For the stochastic methods, the choices of the parameters are very sensitive and a huge calculation time is needed. Some methods introduce randomness into the search-process to accelerate progress. Such randomness can also make the method less sensitive to modelling errors. Furthermore, the injected randomness may enable the method to escape a local optimum and eventually approach a global optimum.

On the other hand, deterministic methods are able to ensure that a global optimum has been reached for a convex problem. Even in cases of non-convex problems, recent progress allows to find optimums very quickly. The major drawback is the need to understand precisely the mathematical structure of the optimization problem in order to solve it with the suitable algorithm. It is important to separate the characterization of the problem from the way to solve it. In this work, the problem type is known as MINLP and the adopted approach to solve it focuses on deterministic methods.

Among the deterministic methods, a MINLP problem can be

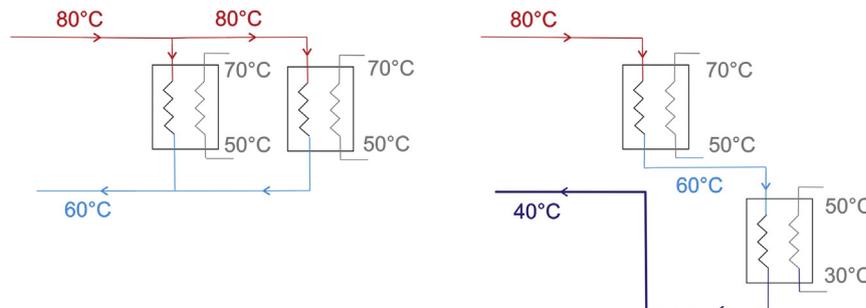


Fig. 1. Consumer connection: in parallel – classical (left) and in cascade – innovation (right).

mainly solved with a Branch and Bound (BB), an Outer Approximation (OA), a Generalized Benders Decomposition (GBD) or the Extended Cutting Plane (ECP) method [4]. The BB consists of a tree enumeration in which each relaxed subproblem is a NLP problem to solve. This resolution is relevant only if the NLP subproblems are relatively inexpensive to solve. Indeed not all the combinations between all the binary variables have to be solved, but in the best case at least 10% has to be explored. The OA and the GBD are iterative methods in which NLP subproblems are solved with fixed binary variables, which are predicted together with lower bounds by the means of a master MILP problem. The ECP method does not rely on the resolution of any NLP subproblem. Linearizations of the most violated constraints are added successively in the MILP main problem. But the objective function has to be linear, which is not our case.

The algebraic modelling environment chosen is GAMS due to the high performance of its integrated solvers. The solver DICOPT is used in this paper to solve the MINLP problem, the solver CPLEX for the MILP master problem and the solver CONOPT for the NLP subproblem. DICOPT is based on three main ideas [5]: the outer approximation algorithm [6], an equation relaxation strategy to handle the equations as inequality constraints and an augmented penalty to better handle inequalities in non-convex problem. CONOPT is based on the efficient and reliable generalized reduced gradient algorithm [7]. In our study case the total calculation time is less than 5 s on an Intel i5 CPU 2.60 GHz and 4 Go RAM.

## 2.2. DHN optimization

This second subsection of the state of the art is focused on the main works dealing with the optimization applied to the DHN. Three different goals in the field of DHN optimization are identified. The first one is the optimization of the configuration, i.e. the spatial layout of the network and the choice of the heat production technology. The second is the optimization of design parameters. The third kind of optimization deals with the operative control of the DHN, in which the state variables have to be predicted at each time step. This third part is not covered by this work. The first two goals are optimized simultaneously in steady state. Such simultaneous attention on both these optimization goals has been barely done up to now.

### 2.2.1. Optimization of the DHN configuration

The optimization of the DHN configuration takes place as soon as possible in urban planning project. The results of these studies help the choice of the heating plant technologies and the structure of the network. Some references on MINLP DHN optimization are detailed below. The state of the art concerning other MINLP optimization applications (such as heat exchanger network [8], water network [9], electrical network [10], distillation [11] or scheduling [12]) are not detailed here. Numerous other works are dedicated to MILP applied to DHN, as detailed in the last paragraph of this section. In such MILP studies, the losses (thermal and pressure drop) are not precisely taken into account.

The industrial energy systems laboratory of the EPFL is working on DHN optimization. CURTI considers different required temperature levels in his PhD thesis by developing a modelling and optimization tool for DHN. The competence of multi-objective optimization is then added to this work. A synthetic overview can be seen in MOLYNEAUX et al. [13]. Despite of a consequent calculation time, the DHN is designed by minimizing the pollution cost and the DHN global cost. The considered superstructure allows different technologies in heating plants (heat pump, gas turbine cogeneration and/or an auxiliary boiler) and also in user substations (HX or heat pump connected to the supply and/or the

return line). But all the heating plants locations, users and connections between them are previously defined (input information).

Following on, WEBER's thesis [14] deals with the optimization of Distributed Energy System (DES). She insists on the polygeneration optimization in order to optimize globally and simultaneously the supply of heat, cold and power. In order to solve her problem, WEBER chooses to split it in two parts, according to the linearity or non-linearity of the problem, and independently from the kind of variables (binary or continuous) as usually considered. She improves a multi-objective evolutionary algorithm (EMOO). FAZLOL-LAHI et al. [15] solves this MINLP multi-objective problem with a mix of an Integer Cut Constraint and  $\epsilon$ -constraint method. They found out that this deterministic resolution works better than previous stochastic resolution with the EMOO, especially in terms of calculation time. Another interesting work [16] has been done concerning the pre-treatment of the dynamic heat demand, in order to select the number of representative periods and the related required heat demand in average (reduction of one year data into 7 representative periods over 34 time steps).

Other studies deal with the optimization of DHN, but not with the same precision on heat and pressure losses and not considering during the same calculation time both configuration and design issues. On the other hand, as the problem is less difficult to solve, other considerations could be included: interactions between networks (electricity, gas, cold or water), multi-period and storage issues.

SODERMAN [17] works on the optimization of DES in order to help political decisions. He solves MILP problem with a Branch and Bound algorithm over 8 periods. The objective function to minimize is the overall global cost. SODERMAN optimizes DES at a much larger scale (more for a region than a city) and optimizes both electrical and heat supply. A multi-period optimization is performed, with the introduction of thermal storage. But he does not consider different temperature level requirements, the heat losses or various technology of heat production.

OMU et al. [18] work on optimizing the solar fraction thanks to a MILP optimization to help whether the thermal energy storage (TES) should be centralized, decentralized or both and how it should be designed. TES is required to achieve more than 10% of solar fraction. And a mix of short term decentralized and long term centralized TES is needed to achieve more than 60% of solar fraction.

Some studies are about the efficiency of the algorithm, for instance HOHMAN et al. [19] solve a MILP problem applied to design and the operation of DHN. In their formulation case, the determinist method MINLP enables to find "in much shorter time" the optimal solution than the stochastic NGS-II method.

### 2.2.2. Optimization of DHN design

Concerning the DHN optimization, some trends for its design are seen worldwide:

- Lower supply temperature [20]: The lower the supply temperature is, the lower are the heat losses. But the supply temperature reduction cannot be achieved without respecting numerous constraints, such as the temperature level or the heat demand required by the consumer.
- Lower pipe diameter: The lower the diameter is, the lower are the pipe investment and the heat losses, but the higher are the pressure drop. An optimization is then needed to find the optimum between reducing the heat losses and increasing the pumping cost (Section 4.3). Some work are focused on this issue at a fixed configuration, such as the German software STEFaN [21] based on a Geographical Information System (GIS).

- Lower thermal generating capacity: in the context of a community supply, FREDERIKSEN and WERNER [22] explain how relevant it is to use a diversity and capacity factor while designing. Indeed the numerous different uses of the buildings lead to different heat demand profiles. Including a diversity factor reflects that the total thermal generating capacity to install in the community heating plant is much lower than the sum of “isolated collective” (from the main grid) or individual ones (boilers). In order to not only consider an average thermal generating capacity as input data to estimate the thermal generating capacity to install, a capacity factor is included. This capacity factor is the average thermal generating capacity divided by the maximal thermal generating capacity. It can be estimated (as in this study around 0.33 for space heating in south France [22]) or calculated previously with a dynamic thermal simulation at the district scale [23].

Dynamic consideration is one of the issues underneath the design. In steady state, the studies about DHN could be more complex and wider: more heating plants and more consumers can be taken into account. Ideally the heat demand and the heat load have to be considered with their daily and seasonal variations. More and more dynamics modelling are used to design the DHN, such as [24]. As concerns the optimization, two terms are used: multi-period optimization and dynamic optimization (previous Section 2.1.1). But such problems are already tough enough to solve, this is why these optimization cases are usually done at a fixed configuration. Numerous design optimizations can indeed be studied for a fixed configuration. For instance the IEA has a team working on this topic [25]; a NLP problem is solved with the solver MINOS within GAMS.

This present study focuses simultaneously on the optimization of the configuration and the design of a DHN in steady state. The considered problem is MINLP, in order to take into account detailed calculations for the heat losses and the pressure drop.

### 3. Problem formulation

First of all the superstructure allowed in this problem is explained, thus defining the scope of the problem. And then the model, programmed within the GAMS environment, is explained into three main parts: the input data and the variables, the constraints and finally the objective function to minimize.

#### 3.1. Superstructure, input data and variables

In this subsection, the description of the problem is explained with schematics, in order to better illustrate the combinatory of the problem on an illustrative example, as well as to highlight the modelling of the pipelines (connections between two nodes) and the – consumer or producer – nodes.

(Fig. 2) is a schematic representation of all the potential connections. Even with such a simplified urban district (one Producer node  $P_i$  and two Consumers  $C_j$  and  $C_o$ ), the combinatory issue of optimizing the network layout can be underlined in 3 questions. The first one is: which consumer is directly supplied by the heating plant  $P_i$ ? In other words, which pipeline exists (line  $P_iC_j$  connecting  $P_i$  to  $C_j$  or line  $P_iC_o$  connecting  $P_i$  to  $C_o$ ). Let assume for this example that  $C_j$  is supplied by  $P_i$ . The second question concerns the other consumer ( $C_o$ ): is it also supplied by  $P_i$  (line  $P_iC_o$ ) or by the consumer  $C_j$ ? And in the case of the latter solution, how to connect them together (Fig. 1 for details): in parallel (line  $C_jC_o\_parallel$ , before the HX) or in cascade (line  $C_jC_o\_cascade$ , after the HX)? In (Fig. 2) the connection PC is represented in red line, the connection  $CC\_parallel$  in dotted red line and  $CC\_cascade$  in green line. The

blue lines represent the returns lines.

After those first questions concerning the topology (Fig. 3), represents the pipe description. Note that other lines ( $CP$ ,  $CC\_parallel$ ,  $CC\_cascade$  or  $CC\_return$ ) are detailed in the same way. The input parameters are clearly identified in blue, whereas the variables are represented in green. Please note that the binary variables (letter Y in prefix) are represented in orange, they represent around 20% of the total amount of variables. So for each pipe, the parameters are: the distance, the thickness (of the steel and the insulation) and the unit cost (of the insulation, the steel and the trench). The thickness of the insulation is not a variable, for an industrial reason: the inner diameter and the outer diameter can change, the insulation has to deal with the free place between those pre-fabricated pieces. It is necessary to let the diameter as a variable, in order to let the algorithm optimize the balance between the heat losses and the pressure drop (Section 4.3). The inlet and outlet temperature, the mass flow rate and the existence of the pipe are also part of the variables of this problem.

The producer and the consumer superstructure can be seen on (Fig. 4). On the left side, the producer allows numerous kinds of technologies ( $k$ ). The model is kept simple. The technology is represented by 4 main variables: two temperatures (inlet/outlet), one mass flow rate and one binary variable (which deals with its existence). Moreover each technology has in input: its localization, an eventual maximal thermal generating capacity, an efficiency  $Eff(k)$ , a maximal outlet temperature and a minimal inlet temperature, the investment ( $\text{€}/\text{kW}$ ) and operational costs ( $\text{€}/\text{kWh}$ ).

On the right side of (Fig. 4), the consumer is assumed to be a plate heat exchanger, with an area  $A_{hx}$ , a couple of temperatures inlet/outlet and a mass flow rate. The consumer is described in input with its localization, the nominal heat power required and the temperature (departure and return) required in the secondary network. In addition, some bifurcations are taken into account in the consumer node. Bifurcation “A”: the supply for the consumer node can come from some pipes from a producer node and also from other consumers (in parallel or cascade). Bifurcation “B”: the flow before the HX can divide itself to supply in parallel another consumer. Bifurcation “C”: if the bifurcation is after the HX, a connection in cascade is potentially allowed. Bifurcation “D”: the return pipe between consumers is the last potential bifurcation included in this node. Bifurcation “E”: The outlet of this consumer node can return to a producer node or to another consumer.

The originalities of this formulation are, *first*, to optimize simultaneously the configuration and the design, *secondly*, to allow the connection between consumers in cascade and not only to consider parallel connections. This second originality means that the residual heat from a “hot temperature consumer” (HT) could directly supply a “lower temperature consumer” (LT) (Section 4.1). That explains why two subscripts ( $j$  and  $o$ ) for the consumer node are required. The third originality is to think about different network configurations to supply an isolated consumer (Section 4.2). No constraint is added to force a supplying pipe for the nodes. The existence or not is the result of the optimization.

#### 3.2. Constraints

After the input data and the enumeration of the variables, the model is described by adding some constraints. Actually, as an equation-oriented approach is used, no equation is implicit. Three main types of equations are written: logic, physics and cost.

The first type of equations uses binary variables, which ensure the coherence of the existence of some utilities. For instance, Equation (1) prohibits the existence of a connection  $CC_{jj}$ , i.e. the connection between the same consumer. Equation (2) defines the distance of a PC pipe (between a node producer  $i$  and a node

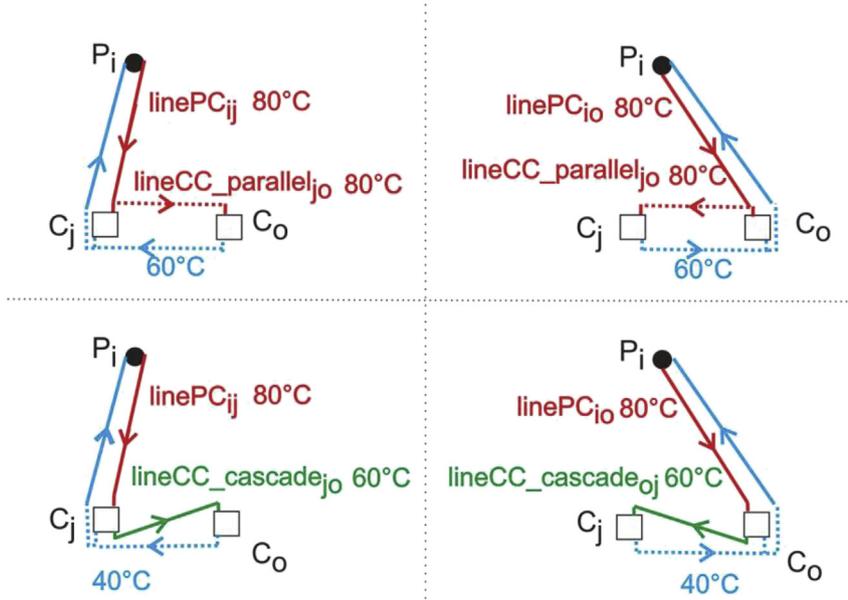
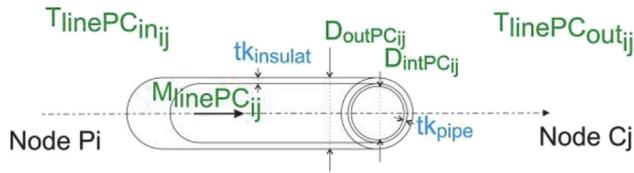


Fig. 2. Four configurations schemes of the potential connections between nodes.



$$L_{PCij} = \begin{cases} \text{Dist}_{PCij} & \text{when the line exists } Y_{PCij} = 1 \\ 0 & \text{otherwise} \end{cases}$$

$C_{insulunit} \quad C_{pipeunit} \quad C_{trunit}$

Fig. 3. Scheme of one of the line between two nodes, here the PC line.

consumer  $j$ ) only if the connection exists ( $Y_{lineLPij} = 1$ ). If this connection does not exist ( $Y_{lineLPij} = 0$ ), the mass flow rate has to be null, as defined in (3). No constraint is added to force in one trench to have both a “supply” and return pipe. The supply pipe is at least one pipe among the pipes PC, CC\_parallel or CC\_cascade (4). Similarly, each consumer node has to have at least one return pipe that could be CC\_cascade, CP or CC\_return.

$$\forall j, Y_{lineCC(j)} = 0 \quad (1)$$

$$L_{linePC(ij)} = Y_{linePC(ij)} \cdot \text{Dist}_{PC(ij)} \quad (2)$$

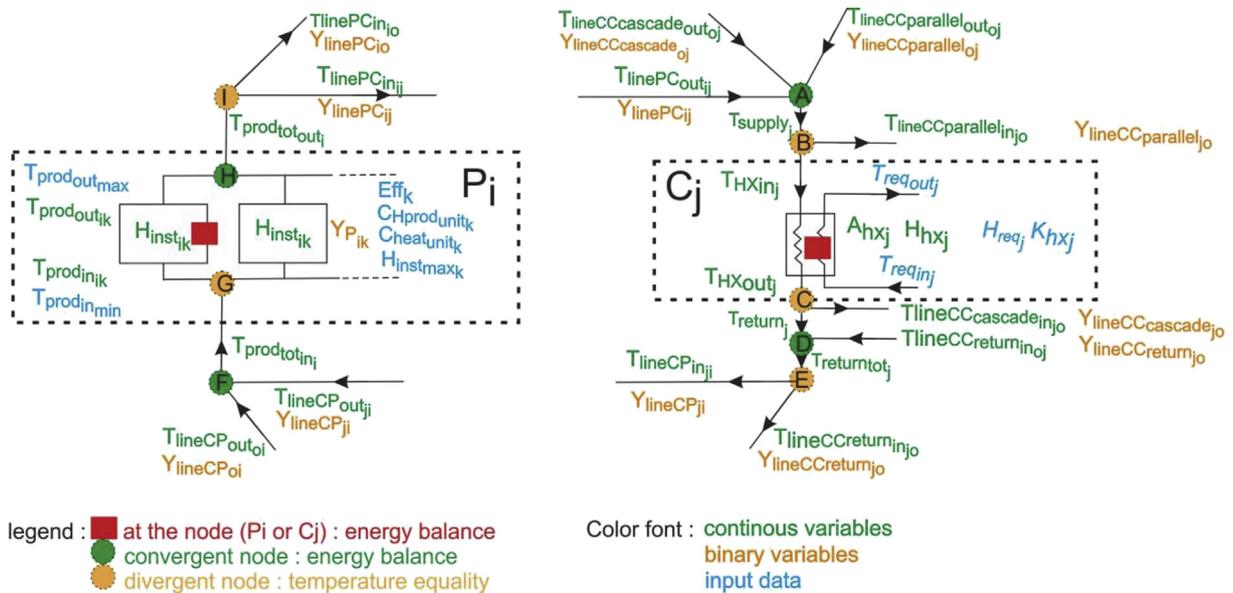


Fig. 4. Superstructure of typical producer node  $P_i$  (left) and consumer node  $C_j$  (right), in the pipe only the temperatures are represented but same nomenclature for diameters, velocities and pressures.

$$\forall \{i, j\}, 0 \leq M_{linePC(i,j)} \leq Y_{linePC(i,j)} \cdot M_{max} \quad (3)$$

$$Y_{linePC(i,j)} + Y_{lineCC_{parallel}(o,j)} + Y_{lineCC_{cascade}(o,j)} \geq 1 \quad (4)$$

The second type are equations about physics, like all energy conservation and mass flow balance. They are not all detailed here because they are common. At each node (convergent or divergent), a mass flow balance has to be respected, as for instance (5) for the bifurcation A in (Fig. 4).

$$M_{supply(j)} = \sum_i M_{linePC(i,j)} + \sum_o M_{lineCC_{parallel}(o,j)} + \sum_o M_{lineCC_{parallel}(o,j)} \quad (5)$$

Then if you come across a convergent node, the energy conservation must be used. For instance the bifurcation A in (Fig. 4), the energy balance is written (6) the consumer node has to be supply by a producer or by another consumer (in cascade or in parallel). In Equation (6), the specific thermal capacity of liquid water is assumed to be constant and enthalpy is equal to zero in the reference state: liquid at 0 °C.

$$M_{supply(j)} \cdot C_p \cdot T_{supply(j)} = \sum_i M_{linePC(i,j)} \cdot C_p \cdot T_{linePC_{out}(i,j)} + \sum_o M_{lineCC_{parallel}(o,j)} \cdot C_p \cdot T_{lineCC_{parallel_{out}}(o,j)} + \sum_o M_{lineCC_{parallel}(o,j)} \cdot C_p \cdot T_{lineCC_{parallel_{out}}(o,j)} \quad (6)$$

Otherwise for a divergent node, an equality of temperature has to be written. For a modelling reason, the equality (for example for the temperatures between the outlet of a producer node and the inlet of the PC line, bifurcation I in Fig. 4) has to be defined as two inequalities (7). If the PC line exists ( $Y_{linePCij} = 1$ ), then the equality of temperature is respected, otherwise as the bigM value is around 1000 times higher than the other temperature,  $T_{linePCin}$  is not under any constraint. The same equations are written also for the equality of pressure at each node (convergent or divergent), except at the HX (between bifurcation B and C in Fig. 4) in which a constant pressure drop is taken into account (8) and also at each technology of production (between bifurcations G and H in Fig. 4) in which a pump is considered (9).

$$\begin{aligned} T_{linePC_{in}(i,j)} &\leq T_{prod_{tot_{out}(i)}} + T_{bigM} \cdot (1 - Y_{linePC(i,j)}) \\ T_{linePC_{in}(i,j)} &\geq T_{prod_{tot_{out}(i)}} - T_{bigM} \cdot (1 - Y_{linePC(i,j)}) \end{aligned} \quad (7)$$

$$P_{hx\_in(j)} = P_{hx\_out(j)} + DP_{hx\_unit} \quad (8)$$

$$P_{prod\_out(i,k)} = P_{prod\_in(i,k)} + P_{pump(i,k)} \quad (9)$$

The heat power exchanged in the heat exchanger ( $H_{hx}$ ), between bifurcation B and C in (Fig. 4), is calculated with a logarithmic mean temperature difference (LMTD) method (10). For this paper, the logarithm is approximated (11) thanks to [26] and the global coefficient  $K_{hx}$  is estimated constant at 2000 W/(m<sup>2</sup> K). To fulfil the demand,  $H_{hx}$  must be equal or higher than the heat power required by the consumer (12).

$$H_{hx(j)} = K_{hx} \cdot A_{(j)} \cdot LMTD_{(j)} \quad (10)$$

$$LMTD_{(j)} \approx \left[ DT1_{(j)} \cdot DT2_{(j)} \cdot \frac{1}{2} \cdot (DT1_{(j)} + DT2_{(j)}) \right]^{\frac{1}{3}} \quad (11)$$

$$\begin{aligned} DT1_{(j)} &= T_{HX_{in}(j)} - T_{req_{out}(j)} \\ DT2_{(j)} &= T_{hx_{out}(j)} - T_{req_{in}(j)} \\ H_{hx(j)} &\geq H_{req(j)} \end{aligned} \quad (12)$$

Moreover as the optimal distribution in a DHN is a balance between the heating and the pumping cost, both are carefully taken into account in this model. The results dealing with this balance of the losses are treated in Section 4.3.

The heat losses are calculated thanks to Equation (13). All the following equations are written for the PC line. Similar equations for the other lines are also included. The thermal capacity is assumed to be constant (taken for 80 °C [27], an average between the classical temperature range - supply 90 °C and the return 70 °C - a temperature dependency is not relevant as soon as the temperature is lower than 100 °C). With such a calculation, the heat losses are dependent on the temperature level, the diameter and the mass flow rate. The total thermal resistance (17) in m<sup>2</sup> · K/W is the sum of the thermal resistances of the insulation (14) and the soil (15). The thermal resistances are represented in (Fig. 5). The influence between the supply and the return pipe could be calculated (16), according to [22], but this latter resistance is neglected (as the contribution is 3rd importance and as the pipe are not forced to be both supply and return). The thermal resistance for the inner convection, the outer convection and the conduction in the steel are neglected too, they represent less than 1% of  $R_{tot}$ . For the range of the Rauthermex pipe [28], the calculations done enable us to only consider those two thermal resistances:  $R_{insulat}$  represents around 85–90%,  $R_{soil}$  5–10% and  $R_{influence}$  3–6% of  $R_{tot}$ . For more detailed thermal heat loss (2D and influence between supply and return pipe), please refer to [29]. The insulation conductivity is taken 0.03 W/(m.K) and the ground conductivity 1.5 W/(m.K) [29].

$$T_{linePC_{out}(i,j)} = T_{ext} + \left( T_{linePC_{in}(i,j)} - T_{ext} \right) \cdot \exp \left( - \frac{\pi \cdot D_{outPC(i,j)} \cdot L_{linePC(i,j)}}{R_{totPC(i,j)} \cdot M_{linePC(i,j)} \cdot C_p} \right) \quad (13)$$

$$R_{insulatPC(i,j)} = \frac{D_{intPC(i,j)}}{2\lambda_{insul}} \cdot \ln \left( \frac{D_{outPC(i,j)}}{D_{intPC(i,j)}} \right) \quad (14)$$

$$R_{soilPC(i,j)} = \frac{D_{intPC(i,j)}}{2\lambda_g} \cdot \ln \left( \frac{4z_{pipe}}{D_{outPC(i,j)}} \right) \quad (15)$$

$$R_{influencePC(i,j)} = \frac{D_{intPC(i,j)}}{2\lambda_i} \cdot \ln \left( \left( \left( \frac{2 \cdot z_{pipe}}{\Delta x_{pipe}} \right)^2 + 1 \right)^{0.5} \right) \quad (16)$$

$$R_{totPC(i,j)} = R_{insulatPC(i,j)} + R_{soilPC(i,j)} \quad (17)$$

The linear pressure drop is calculated in Equation (18), with a coefficient of friction estimated from the Blasius formula (19) (the Reynolds range of application is always respected; in DHN the flow is always turbulent). The singular pressure drops are estimated to be 30% of the total pressure drop. A calculation with the number of angles or valves is not detailed, because the network layout is not known previously, it is part of the results. This leads to an expression (20) to calculate the pressure drop (in Pa), for the PC line for

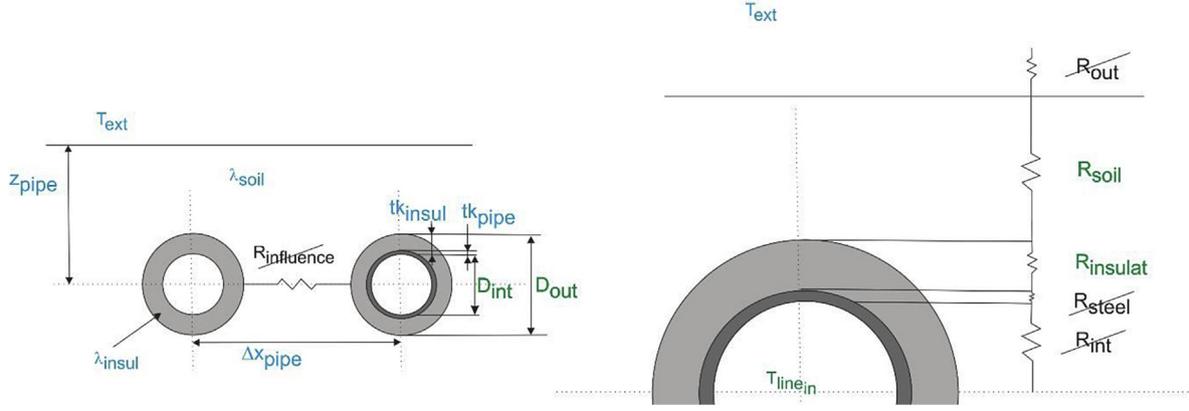


Fig. 5. Scheme of the pipe and thermal resistances.

example, with the following constant factors:  $\alpha = 2.25$  and  $\beta = 0.75$ . Gamma is calculated in the model thanks to (21). It depends on the dynamic viscosity (22), which is a linear function of the temperature, with  $\mu_a = -0.0073$  Pa.s/K and  $\mu_b = 0.9599$  Pa.s. The other characteristics of water are assumed not to be dependent on the temperature for the classical temperature range in DHN (supply 90 °C – return 70 °C). They are considered for a temperature of 80 °C:  $C_p = 4.196$  kJ/(kg.K) and  $\rho = 974$  kg/m<sup>3</sup> [27].

$$DP_{PC(i,j)} = f_{PC(i,j)} \cdot \frac{L_{PC(i,j)}}{D_{int(i,j)}} \cdot \rho \cdot \frac{V_{PC(i,j)}^2}{2} \quad (18)$$

$$f_{PC(i,j)} = 100 \cdot \left( \frac{\mu_{PC(i,j)}}{\rho \cdot V_{PC(i,j)} \cdot D_{int(i,j)}} \right)^{-1/4} \quad (19)$$

$$DP_{PC(i,j)} = \gamma_{PC(i,j)} \cdot \frac{L_{PC(i,j)} \cdot V_{PC(i,j)}^\alpha}{D_{int(i,j)}^\beta} \quad (20)$$

$$\gamma_{PC(i,j)} = \frac{100}{70} \cdot \left( \frac{100 \cdot \mu_{PC(i,j)}}{2 \cdot \rho^{1.25}} \right)^{1/4} \quad (21)$$

$$\mu_{PC(i,j)} = \mu_a \cdot T_{linePC\_out(i,j)} + \mu_b \quad (22)$$

The last set of equations represents the cost. This is the subject of the following part.

### 3.3. Objective function: total cost

These equations deal with the economic part. The chosen objective function in this study is the global cost over 30 years because it is the core issue in urban planning, as underlined by the French organisation CEREMA [30] or [31]. Equation (23) is the sum of the operating cost (pumping and heating cost) and the investment cost (thermal generating capacity installed, heat exchanger and line).

$$C_{total} = (C_{pump} + C_{heat}) \cdot f_{opex} + (C_{Hinst} + C_{HX} + C_{line}) \cdot f_{capex} \quad (23)$$

The total pumping pressure is the sum of the saturated pressure and the sum of each pumping pressure (24). The saturated pressure is calculated in order to avoid cavitation (aspiration pressure, before the pump, should be always higher than the saturated pressure),

thanks to Equation (25) with the following parameters  $Psat_3 = 0.0005$  Pa/K<sup>3</sup>;  $Psat_2 = -0.0731$  Pa/K<sup>2</sup>;  $Psat_1 = 4.3368$  Pa/K and  $Psat_0 = -68.085$  Pa calculated with thermophysical properties of water taken from Ref. [27]. This leads to the expression of the pumping cost (26), as calculated by RAMOS-BERMUDEZ [32], thanks to the previously calculated total pumping pressure and some other parameters like the duration (8760 h), the efficiency of the volumetric pump  $\eta_{pump} = 70\%$  and the unit cost for pumping (unit cost of electricity in France around 0.11 €/kWh).

$$P_{pump_{tot}} = P_{sat} + \sum_{i,k} P_{pump(i,k)} \quad (24)$$

$$P_{sat} = P_{sat_3} \cdot T_{prod_{out_{max}}}^3 + P_{sat_2} \cdot T_{prod_{out_{max}}}^2 + P_{sat_1} \cdot T_{prod_{out_{max}}} + P_{sat_0} \quad (25)$$

$$C_{pump} = c_{pump_{unit}} \cdot P_{pump_{tot}} \cdot \frac{duration}{\eta_{pump}} \cdot M_{prod_{tot}} \cdot \frac{1}{\rho} \quad (26)$$

The operating cost for the heating (27) is the sum of the heat produced in the heating plant multiplied by the duration and a unit cost. To design the thermal generating capacity to install, an energy balance is written with the bigM method (28) between the bifurcation G and H in (Fig. 4). The heat losses are already included (13). The unit cost for the heat is assumed to fluctuate between 0.8 and 1.2 ct€/kWh. An energy efficiency for each technology of production is also introduced, 90% was used as a first assumption.

$$C_{heat} = \cdot duration \cdot \sum_{i,k} c_{heat_{unit}(k)} \cdot H_{inst(i,k)} \quad (27)$$

$$H_{inst(i,k)} \leq \frac{M_{prod(i,k)} \cdot Cp \cdot (T_{prod_{out}(i,k)} - T_{prod_{in}(i,k)})}{Eff_{(k)}} + H_{inst_{BigM}} \cdot (1 - Y_{P(i,k)})$$

$$H_{inst(i,k)} \geq \frac{M_{prod(i,k)} \cdot Cp \cdot (T_{prod_{out}(i,k)} - T_{prod_{in}(i,k)})}{Eff_{(k)}} - H_{inst_{BigM}} \cdot (1 - Y_{P(i,k)}) \quad (28)$$

Concerning the investment cost, the main part concerns the thermal generating capacity to install, which is related directly to Equation (29) of the nominal thermal generating capacity installed in each producer node (28). The range of the unit cost is between 800 and 1200 €/kW. And a capacity factor (0.33 south France) in denominator is used, thanks to the previous Scandinavian research [22].

$$C_{Hinst} = C_{Hinst_{unit}} \cdot \frac{\sum_{i,k} H_{inst_{(i,k)}}}{F_{cap}} \quad (29)$$

The total cost of the line is the sum of the cost of the trench and the cost of the pre insulated pipe (30). Firstly, the main cost is due to dig the trench, which has to be summed up for each connection (31). And as the connection is not forced to be both supply and return in the same trench, a logical variable  $Y$  is added. For example, Equation (32) calculates the cost of the trench for the connection PC. If the pipe is both supply and return in the same trench, the trench cost is divided by half. The unit cost of the trench is one of the main assumptions in economic calculation. To see the influence of this parameter, please refers to the results of Section 4.1. Secondly, the insulation and the pipe material costs are summed up for each connection (33). For example for the connection PC, this cost depends linearly on the diameter of the pipe (34). The prices are calculated with a unit cost based on the costs of pre insulated pipes from INPAL Energy ( $C_{pipe\_unit\_a} = 0.372 \text{ €/m}^2$  and  $C_{pipe\_unit\_b} = 12.5 \text{ €/m}$ ).

$$C_{line_{tot}} = C_{tr} + C_{pipe} \quad (30)$$

$$C_{tr} = C_{tr_{PC}} + C_{tr_{CP}} + C_{tr_{CC_{parallel}}} + C_{tr_{CC_{cascade}}} + C_{tr_{CC_{return}}} \quad (31)$$

$$C_{tr_{PC}} = \sum_{ij} \frac{C_{tr_{unit}}}{2} \cdot L_{PC_{(ij)}} \cdot Y_{line_{CP_{(j,i)}}} + C_{tr_{unit}} \cdot L_{PC_{(ij)}} \cdot (1 - Y_{line_{CP_{(j,i)}}}) \quad (32)$$

$$C_{pipe} = C_{pipe_{PC}} + C_{pipe_{CP}} + C_{pipe_{CC_{parallel}}} + C_{pipe_{CC_{cascade}}} + C_{pipe_{CC_{return}}} \quad (33)$$

$$C_{pipe_{PC}} = \sum_{ij} L_{PC_{(ij)}} \cdot (C_{pipe_{unit_a}} \cdot D_{int_{PC_{(ij)}}} + C_{pipe_{unit_b}}) \quad (34)$$

The last investment cost included in this model is the cost of the plate HX. A linear function is used (35), based on French Batiprix economic database [33], with the coefficients  $C_{hx_{unit_a}} = 5.3 \text{ €/kW}$  and  $C_{hx_{unit_b}} = 5045 \text{ €}$ .

$$C_{hx} = \sum_j (C_{hx_{unit_a}} \cdot H_{hx_{(j)}} + C_{hx_{unit_b}}) \quad (35)$$

The cost is multiplied by some terms that represent the actuarial calculation -  $X \text{ €}$  today do not have the same value in  $N$  years - and the energy price inflation. More details about the total cost evaluation can be found in the French norm [34]. As only an initial investment ( $C_{capex}^0$ ) is required in the reference year 0, so  $N$  years (a 30-years' time horizon is considered in this study) later the sum of the investment cost is the actuarial calculation with an actuarial rate ( $r_a$ ) taken as 0.04, as represented in (36). Equation (37) calculates the  $f_{capex}$  factor related to the investment.

$$\sum_{p=0}^N C_{capex}^p = C_{capex}^0 (1 + r_a)^N \quad (36)$$

$$f_{capex} = (1 + r_a)^N \quad (37)$$

The factor for the operating cost includes this actuarial rate and also the energy price inflation. So for a year  $p$ , the cost for an operating cost will be calculated thanks to (38). The sum of the operating cost over  $N$  years is calculated like a geometrical series in (39). Equation (40) is the identification of the factor  $f_{opex}$  for the operating cost.

$$C_{opex}^p = C_{capex}^0 (1 + r_a)^p \cdot (1 + r_i)^p \quad (38)$$

$$\sum_{p=0}^N C_{opex}^p = C_{opex}^0 \cdot \frac{1 - (1 + r_a)^N \cdot (1 + r_i)^N}{1 - (1 + r_a) \cdot (1 + r_i)} \quad (39)$$

$$f_{opex} = \frac{1 - (1 + r_a)^N \cdot (1 + r_i)^N}{1 - (1 + r_a) \cdot (1 + r_i)} \quad (40)$$

With such a formulation, it is possible to compare two technologies, see section results below. For instance on the one hand, the technology k1 is assumed to be a fossil fuel technology, like gas, with a certain price (capex 800 €/kW and opex 0.8 ct€/kW) and a relatively high inflation (6%). On the other hand, k2 represents a renewable energy, like solar panel, with high initial cost (1200–1400 €/kW), place limitation (south oriented roof) but without any inflation and a lower opex (0.2–0.6 ct€/kWh). A total cost analysis enables a financial reflexion over the long terms. The time horizon of 30 years is taken in order to neglect the maintenance cost.

#### 4. Results on an academic study case

In order to illustrate the possibilities of our formulation, three chosen study cases are optimized. As input data, one main producer P1 and four consumers are considered (Fig. 6). Each consumer requires 80 kW during the whole period. In Section (4.1), the advantage of the cascade connection is illustrated. The sensibility of the trench cost is also tested. Then in Section (4.2), an eventual “isolated collective” heat production (P2) is added for the isolated consumer (C4), which is three times further from the producer than the other consumers. This second section focuses on the best choice between one centralized production, a decentralized complementary heat production, or “isolated collective” heat production. Finally Section (4.3) details some operational variables when balancing the heat losses and the pressure drop.

##### 4.1. Advantage of allowing the connection of consumers in cascade

This first study focuses on one of the main innovation, which is to allow parallel and cascade connections between consumers. A cascade connection from  $C_j$  to  $C_o$  starts after the HX of  $C_j$  to supply  $C_o$  (Fig. 4), whereas a classical parallel connection starts before the HX of  $C_j$ .

Four different cases are optimized in this study. (Table 1). resumes the differences on the input data between these cases. Consumer C2 requires hot temperature (HT) level in case one: the secondary network distributes the heat through the building between 80 °C (supply) and 60 °C (return). In the other cases, C2 is considered as a low temperature (LT) consumer: the heat is distributed between 60 °C (supply) and 40 °C (return). In case 3, the cost of the trench is reduced by –50%. In case 4, C4 is also assumed to require very low temperature (VLT) between 40 °C (supply) and 20 °C (return). Otherwise all the other consumers are taken to be HT consumers. For instance, the HT consumer could represent a

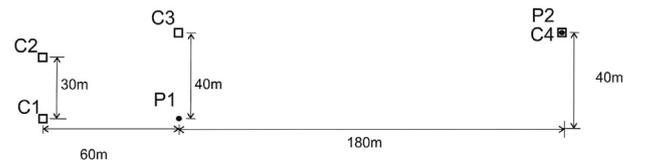


Fig. 6. Spatial localization of the considered nodes in this study case.

**Table 1**  
Input data to illustrate the interest of the connection of consumers in cascade.

	<i>case 1</i>	<i>case 2</i>	<i>case 3</i>	<i>case 4</i>
C1	HT	HT		
C2		LT		
C3		HT	VLT	
C_trench	1 000 €/m		500 €/m	

building with old heaters, a hospital or an industrial process. The LT consumer could be a new residential building or offices, with highly efficient heaters.

Please note that whether the line exists between two nodes or not is one of the results. The main results of the optimizations are detailed in (Table 2), the grey coloured backgrounds match with the same coloured optimized structures of the network seen in (Fig. 7). In comparison to the conventional design (case 1), the design innovation of allowing the cascade connection between consumers permits to slightly reduce the global cost ( $-0.7\%$ ) if C2 requires LT. The main difference concerns the specific heat losses that are significantly reduced ( $-29\%$  from 25.9 to 18.4 W/m). This is not an important reduction, as the reference case is already optimized,

although it represents 30 k€. However it can represent an interesting solution in the case of the potential extension of an old DHN, designed for hot temperature level, to new customers in the neighbourhood. Indeed the inlet temperature in heating plant ( $T_{\text{prod\_in}}$ ) is lower when cascading (58 °C) than without (69 °C). Cascading enables to better use the temperature difference between production inlet and outlet. This could be seen also in case 4, when one cascade follow another; the temperature drops then even more, from 90 °C to 30 °C.

In cases 3 and 4, as the cost of the trench is reduced by  $-50\%$ , it is now profitable to dig one or two more trenches and to reduce the number of connections (from 6 to 4). The total cost reduction is then higher ( $-1.3\%$  for 1 cascade and  $-4.6\%$  for 2 cascades) than in

**Table 2**  
Results to illustrate the interest of the cascade connection.

		<i>case 1</i>	<i>case 2</i>	<i>case 3</i>	<i>case 4</i>
$C_{\text{pump}}$		0.03	0.02	0.02	0.01
$C_{\text{heat}}$		3.33	3.31	3.31	3.27
$C_{\text{Hinst}}$	M€	2.17	2.16	2.16	2.13
$C_{\text{hx}}$		0.05	0.05	0.05	0.05
$C_{\text{line tot}}$		0.53	0.53	0.49	0.37
$C_{\text{tot}}$	M€	6.11	6.07	6.03	5.84
	%		<b>-0.7%</b>	<b>-1.3%</b>	<b>-4.6%</b>
$T_{\text{prod out}}$	°C	100	100	100	90.6
$T_{\text{prod in}}$	°C	69	58	58	30
$M_{\text{prod}}$	kg/s	1.95	1.42	1.42	0.96
$E_{\text{tot}}$	MWh	2 417	2 401	2 403	2 374
$L_{\text{tot}}$	m	320	320	<b>295</b>	<b>223</b>
$D_{\text{th}}$	MWh/m	7.55	7.51	8.14	10.6
$E_{\text{loss}}$	MWh	73	51	53	18
$T_{\text{Xloss}}$	%	3.0	2.1	2.2	0.8
$H_{\text{loss\_spec}}$	W/m	25.9	<b>18.4</b>	<b>20.7</b>	<b>9.6</b>
$DP_{\text{spec}}$	kPa/m	0.57	0.53	0.55	0.34

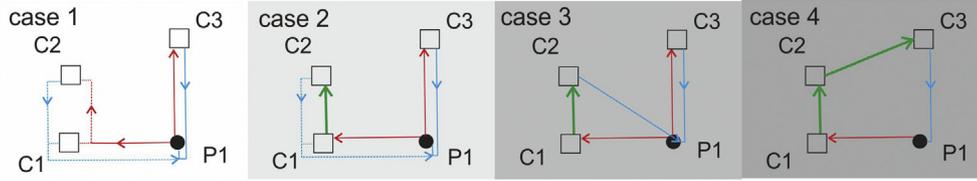


Fig. 7. Optimal structure of the network for the 4 different cases.

the previous case. It is mainly due to the total length of the network that is reduced, without any deterioration concerning the specific heat loss and specific pressure drop. On the contrary, these aspects are improved in such a looped network in cascade.

The operating cost, including the heating and pumping, stands for around 55%. As explained in the introduction, even if the initial investment cost is impressive, in the long term the operative cost represents also a significant part. If the primary objective is to minimize the total cost, the efficiency of the system is also taken into account. Indeed, the total heat loss drops from 3.0 to 0.8% of the total heat delivery. Concerning these cases, the heat density is around 8 MW h/m. That is more than enough (upper than 1.5 MW h/m) to be eligible to the “fond de chaleur”, a financial subsidy from the ADEME (French agency for the environment and the energy efficiency).

#### 4.2. Centralized, decentralized or “collective isolated” heat supply

In this second study, only C2 is a LT consumer, the other are HT

**Table 3**  
Input data to illustrate a centralized, decentralized or “isolated collective” heat supply.

		case 5	case 6&8	case 7	case 9	Case 10
$C_{\text{pump}}$		0.01	0.03	0.01	0.02	0.01
$C_{\text{heat}}$		4.63	4.45	4.09	<b>3.79</b>	4.89
$C_{\text{Hinst}}$	M€	3.02	2.9	3.19	3.16	3.19
$C_{\text{hx}}$		0.07	0.07	0.07	0.07	0.07
$C_{\text{line\_tot}}$		0.49	1.09	0.49	1.09	0.49
$C_{\text{tot}}$	M€	8.22	8.543	7.85	8.13	8.66
	%	<b>-4.0%</b>	<b>-0.3%</b>	<b>-8.4%</b>	<b>-5.1%</b>	<b>+1.4%</b>
$H_{\text{inst}}$	P	k1	272	<b>368</b>	272	296
	1	k2	-	-	-	-
	P	k1	X	X	X	X
	2	k2	89	-	89	<b>70</b>
$E_{\text{tot}}$	MWh	3164	3231	3164	3209	3164
$L_{\text{tot}}$	m	300	668	300	668	300
$D_{\text{th}}$	MWh/ m	10.5	4.8	10.5	4.8	10.5
$E_{\text{loss}}$	MWh	40	<b>100</b>	40	80	40
$T_{X_{\text{loss}}}$	%	1.3%	3.1%	1.3%	2.5	1.3%
$H_{\text{loss\_spec}}$	W/m	15.3	17.1	15.3	13.7	15.3
$DP_{\text{spec}}$	kPa/m	4.2	4.7	4.2	2.3	4.2

consumers. In addition, a potential secondary heat production P2 is added in input in the same localization than C4, the isolated consumer (three time further than C1 compared to P1). The optimization has to select whether this heat production is economically profitable or not and how it is connected to the network. That means whether the production is better to be centralized (only one central heating plant) or decentralized (more than one heating plant) or even isolated from the main grid. Different input data, detailed in (Table 3), are tested:

- The investment price ( $C_{\text{capex}(k2)}$ ) of the technology k2 in P2 is higher (+25%) than the one of the technology k1. In case 5, the technology k2 is assumed to be a collective gas boiler (building scale), as it is the most common one in France [35]. It has a higher (+25%) operational cost  $C_{\text{opex}(k2)}$ , because of a reduced power of negotiation. Case 6 goes in the same direction as case 5, except that the price increase (capex and opex) is +50%.
- The following case deals with a technology k2 assumed to be a renewable energy: the capex is higher than for k1, but the opex

**Table 4**  
Results to illustrate the interest of a centralized heat supply.

	case 5	case 6	case 7	Case 8	Case 9	Case 10
k2 cost (compared to k1)	+25% capex +25% opex	+50% capex +50% opex	+50% capex -25% opex	+50% capex -75% opex	+50% capex -75% opex	+50% capex +50% opex
P2,k2	Free (ok if 80 kW)			<70 kW		>70 kW

is now cheaper (-25% case 7-8, -75% case 9). On the contrary, in case 10, k2 is considered to be an expensive renewable energy, as well investment as operative cost (+50%). And at least, 70 kW of this technology has to be installed.

- In cases 8 and 9, the thermal generating capacity of P2k2 has to be lower than 70 kW. In other words, if it is profitable, a maximum of 70 kW of k2 could be installed in P2 localization. This value of 70 kW is a technical reality. That means that C4 needs another technology (P1k1) for its peak load and, as a consequence, a connection to the main grid or the isolated P2k1. This limitation could also be justified in the case of a place limitation (in substation or a limited south roof surface for solar panels).

The results are summarized in (Table 4) and the layout of the optimized network structures are illustrated in (Fig. 8). As before, the grey coloured backgrounds help for the comparison. The first observation is that the optimal structure depends on the context: no generalized topology can be advised. To sum up, the heat supply (centralized, decentralized or centralized with "isolated collective" heat supply) is a compromise between the unit cost (capex/opex) of the heat supply, the eventual thermal generating capacity limitation and how far they are located (here 3 times further from P1 compared to C1). The results of this study can be compiled in three different topologies where the details are given as follows:

- One main grid and an isolated collective heat production configuration (Fig. 8 left).

**Case 5:** Even if P2k2 is a little more expensive (capex and opex), it is still profitable to use this secondary heat production for the isolated consumer C4 instead of connecting it to the main network. In that case, a reduction of 4% of the total cost is achieved. The main reduction cost concerns the line cost (from 1.09 to 0.49 M€).

**Case 7:** While testing the introduction of a renewable energy, with a high investment cost but a lower operational cost and with no thermal generating capacity limitation, the same configuration as case 5 is seen as optimal. That means that an isolated consumer does not have to be connected to the main grid, if it is located far away and if the renewable energy has a cheap operational cost. A total cost reduction up to 8% is calculated. This total reduction is a combination between two significant reductions: the heating cost (from 4.45 to 4.09 M€) due to heat losses decrease and the line cost (as in case 5). There is only one meaningful increase of the thermal

generating capacity to install (2.90-3.19 M€).

**Case 10:** A choice dictated by the decision maker could be to force the introduction of renewable energy, for instance in the case that P2k2 has a lower bound of 70 kW (instead of an upper limitation - case 8). In that case, the total cost is nearly equal (+0.06%). This case is nevertheless interesting in terms of renewable energy introduced into the energy mix.

- One grid with a centralized heat production (Fig. 8 middle):

**Case 6:** Now when the price increases (capex and opex) up to +50%, it becomes profitable to connect C4 to the main grid. In this case, the cheapest solution is no more to build and use P2k2. It is more profitable to build the connection P1C4 and pay for the losses. Although the thermal losses are the highest (100 MW h), they represent only 3.1% of total heat consumed. The total cost is only reduced by 0.3% compared to the classical design (case 1 without C4 - 0.7% reduction see Section 4.1 and upper bound analysis see Section 4.3).

**Case 8:** When the introduction of renewable energy (as case 7) is limited with an upper bound, 10 kW has to be supplied by the main grid or the whole need (80 kW) has to be provided by the main grid. This second option is optimal when the potential renewable energy does not have enough operational cost reduction (compared to fossil fuels). The same results are found as in case 6.

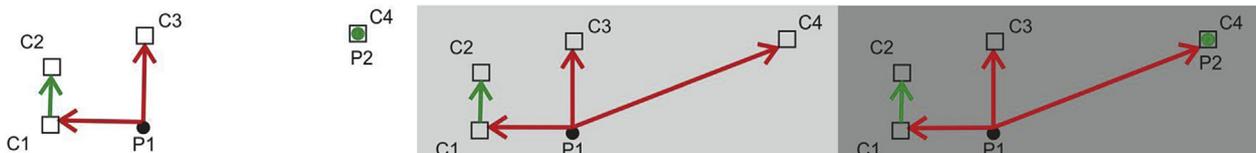
- Decentralized heat productions (Fig. 8 right):

**Case 9:** Finally when the renewable energy has a very low operational cost, even if C4 has to be connected to the main grid and that P2k2 is installed, such a configuration (one main grid with two heating plants) is optimal. This is significantly profitable (-5.1%).

#### 4.3. Balance between the heating and the pumping cost

This section deals with some aspects of the operational design, such as temperature, heat loss, mass flow rate, inner diameter and pressure drop. Moreover this section highlights that, even in such a combinatory optimization problem, the balance between pressure drops and heat losses is well tackled with this formulation and has a non-negligible impact on the final results.

Some physical evidences:



**Fig. 8.** Optimal structure: "isolated collective" production for C4 case 4, 5 and 7 (left), centralized heat production cases 6 (middle) and decentralized heat productions cases 8 and 9 (right). Return pipe not represented.

- The higher the supply temperature is, the higher the heat losses are. It could be a design choice or a decision driven by the temperature required by the consumer as in (Fig. 9).
- At a fixed inner diameter, the higher the velocity is, the lower the temperature drop (between inlet and outlet) is but the higher are the heat loss and the pressure drop.
- Finally, the lower the inner diameter is (to decrease the investment cost), the lower heat losses are (lower exchange area), but that leads to increase pressure drop (higher velocity).

These first evidences are well known, though they are not easy to observe in the context of a combinatory optimization of DHN (in most of the previously published works, the non linearities are avoided, so the losses are not physically taken into account). However the formulation adopted here enables to verify these evidences and takes them into account in the optimization process. As seen in (Fig. 9), the decreasing of the temperature requirement (from 80/60 to 30/10 departure/return in the secondary network for all the consumers) gives the following significant reductions: -45% of the supply temperature (from 99 °C to 53 °C), -64% of the specific heat losses (from 13 to 5 W/m) and - 2% of the total cost of the DHN (from 8.53 to 8.34 M€). For all these cases, the optimal layout of the network is the same (case 6 Fig. 8 middle). There is no denying that the 4th generation of DHN represents an interesting opportunity [36], even if the percentage reduction is low (comparison to optimized solution), for instance 4th GDH enables to exploit low temperature source renewable energy.

The issue of the growing pumping cost, which is often the problem when lowering the network temperature, is now analysed with a specific focus on the balance between the pressure drop and the heat loss.

Such contradictory goals need to be considered all together in order to globally reduce the total cost of a DHN. An easy way could be to consider some “specific loss parameters” for the heat loss and pressure drop calculations. For instance with a specific heat loss ratio in W/m (range between 2 and 25 W/m) or with a specific pressure drop in Pa/m (range between 100 and 1000 Pa/m). Such simplified calculations are tempting, but it does not enable quicker and easier resolutions in our formulation and it is not accurate enough to tackle the design issue. Otherwise, how to choose those specific loss parameters according to the following 3 variables (temperature, velocity and inner diameter)? And, as seen in the previous results, confirmed by the following results, the variations of these specific loss parameters are non-negligible.

Thanks to this formulation (Section 3.2) the heat losses are calculated in Equation (13) depending on the temperature level, the

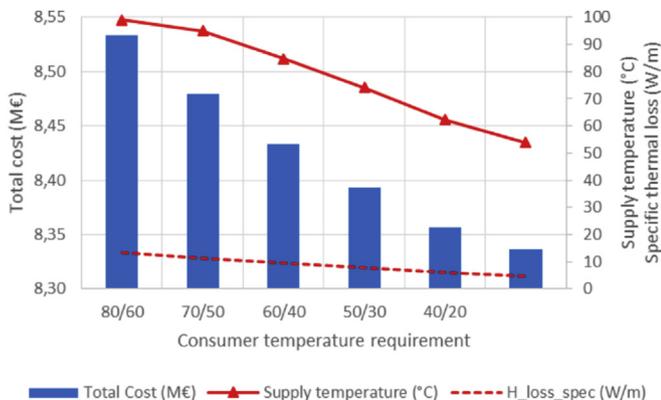


Fig. 9. Comparison (in total cost, supply temperature and specific heat losses) while lowering the consumer temperature requirement for all the consumers.

inner diameter and also the velocity. The two latter variables (diameter and velocity) are also used to calculate the pressure drop in Equation (20). The “specific loss parameters” are in this study only used for variable bounds.

In (Fig. 10) are represented some sizing results depending on consumer temperature requirement, from very high temperature requirement (80/60) to very low (40/20). Only the results concerning the line between P1 to C1 are represented, but in such a small district, the results are the same for all the other lines. The bar chart represents the inner diameter design (in mm), whereas the curves represent the velocity (in m/s) and the dotted lines the specific pressure drop (in kPa/m). In blue, with square motif, are represented the values for the return line, otherwise it concerns the supply line. The results are calculated by considering the prices of case 6. For the specific pressure drop, a value between 0.1 and 0.3 kPa/m is usually advised for classical design, but these ratio are not accurate enough to ensure a high quality balance between pressure drop and thermal losses, especially when trying to lower the distribution temperature of the network. In the return pipe indeed, as the return temperature is lower (than in supply pipe), the inner diameter could be higher and the velocity lower in order to keep acceptable the thermal losses and also the pressure drops.

Thanks to this analysis (Fig. 10), the specific pressure drop for the return pipe are always lower than the specific pressure drop for the supply pipe. For the supply pipe, the specific pressure drops decrease from 0.53 to 0.25 kPa/m, higher than the classical value advised. In detail, the inner diameter is designed between 54 and 65 mm and the velocity respectively around 0.48–0.39 m/s. For the return pipe, the specific pressure drops are lower (than for supply pipe), they decrease from 0.34 to 0.08 kPa/m, which is close to the order of magnitude advised. The inner diameter for the return pipe is always higher than for the supply, it increases from 58 to 81 mm. Respectively, the velocity decreases from 0.43 to 0.25 m/s.

Although such a MINLP formulation is hard to solve, the results confirm that the **configuration and the design are closely linked together**. Even with physical considerations and combinatory optimization, the resolution is rather quick (around 5s) and seems to ensure a global optimum.

## 5. Conclusion

To sum up, the type of the optimization problem depends on the different DHN optimization goals to be considered:

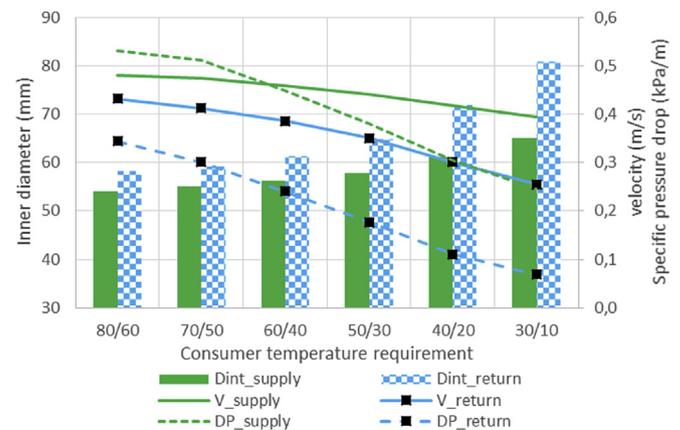


Fig. 10. Optimal sizing results (inner diameter and velocity) compared for the supply or return line depending on the consumer temperature requirement.

- If the DHN configuration is studied, there are necessarily binary variables, which are used to let the choice whether such technology of production exists or not, or whether there is one direct pipe connection between two sites or not. According to the level of modelling expected, the problem could include some non-linear equations (such as energy conservation or heat loss equation). The problem is then called MINLP, otherwise MILP.
- If the design or the operative management of a DHN is optimized, at a fixed configuration, no discrete variable is considered. If any equation is non-linear, the problem is NLP, otherwise LP.
- If the consideration of the time variation has to be included, the problem should be multi-period optimization or dynamic optimization.

In this contribution, we propose a model of DHN that allows optimizing simultaneously the configuration of the network (the choice of the heat production technology and the network topology) and the design of some key variables (such as supply and return temperature, mass flow rate, exchange area of the HX, thermal generating capacity to install). The resolution of the MINLP problem is achieved with the solver DICOPT in GAMS in approximately 5 s with 2 cores CPU of 2.60 GHz and 4 Go RAM.

In the first study case is illustrated the cascade connection between two consumers. This innovative design permits a reduction of 0.7% of the total global cost over 30 years. Although it is a slight reduction, remember that the reference case is already optimized and even such a reduction represents an amount of 30 k€. But most of all, such a connection in cascade enables to reuse excess heat from one HT consumer to a LT consumer. It could also be a solution to extend existing DHN to new consumers. A looped network, which connects three consumers in cascade, permits to achieve a significant total cost reduction of 4.6%. In our study case, this looped network in cascade is optimal, if and only if, the cost of the trench is lower than 500 €/m.

In the second study case, is analysed the supply of the isolated consumer C4, as well as the profitability of introducing renewable energy in the energy mix. The design innovation is to introduce P2k2, P2 being a potential secondary heat production, with a technology k2, located at the same place as the isolated consumer C4. Three optimal configurations have been found, depending on the price (capex and opex) and on the thermal generating capacity limitation of P2k2. The first optimal configuration, the classical design, is obtained when the main grid with one centralized heat production supplies C4. It is the most expensive solution (only -0.3% decrease in cost compared to the reference case 1 without any consideration of the consumer temperature requirement). This configuration is optimal if the unit cost of the isolated collective heat plant is prohibitive (+50% capex and opex) or if the renewable energy has a high investment cost (+50%) without an operational cost reduction lower than -25%. The second optimal configuration is one main grid with decentralized heat productions. It is optimal when P2k2 has a thermal generating capacity limitation in C4 and an attractive opex (-75%), which could be the case with solar panel for instance. It leads to a meaningful reduction of the global cost (-5.1%). Finally the third optimal configuration is an "isolated collective" heating plant for the isolated consumer C4. This is found to be optimal when there is no thermal generating capacity limitation and when the unit cost of P2k2 is not too high compared with the unit cost of P1k1. It permits to reduce significantly the total global cost over 30 years: -4% case 5 if P2k2 uses fossil fuels (capex\_k2 and opex\_k2 +25%), up to -8.4% if a renewable energy (capex\_k2 +50% and opex\_k2 -75%) is introduced.

The third study case is focused on the arbitrage that has to be

made between heat losses and pressure drop. Results confirm the importance of optimizing simultaneously configuration and design. Intuitively the 4th generation of DHN can exploit lower temperature renewable sources, but with the reduction of the temperature (here studied from a departure in the secondary network of 80 °C–30 °C), it raises usually the issue of the growing pumping cost. This present optimization leads to a reduction of the supply temperature in the primary network (from 99 °C to 54 °C) and also of the specific heat losses (from 13 to 5 W/m). The economic profitability is certain (a total cost reduction of -2%, compared to sizing optimized solution). The results highlight that in supply pipe a higher pressure drops is advised (between 0.3 and 0.5 kPa/m), compared to the specific pressure drops for the return line which are in the same order of magnitude as the classical range advised (between 0.1 and 0.3 kPa/m). Indeed, in the return pipe compared to the supply pipe, the temperature is lower, so the inner diameter can be higher, without excessive specific heat losses (lower than 13 W/m), which can reduce the specific pressure drop.

In the short term, some evolutions will be implemented to the model, such as additional constraints (minimum percentage of renewable energy in the energy mix and maximal greenhouse gas emissions) or modelling water for a temperature range higher than 100 °C (the water characteristics cannot be assumed to be constant anymore). Moreover the economic data (investment and operative unit cost) will be consolidated and other costs will be added (maintenance cost) with an engineering partner and some direct applications on existing sites. Some modelling assumptions (specific pressure drop or HX global coefficient) could be checked thanks to monitoring data. The major limit of such a detailed formulation is the complexity of the MINLP model that has to be solved. To handle the combinatory explosion (with two producers, two technologies and 4 consumers, around 10 possibilities and when more than 10 consumers, more than one million different configurations) and to ensure the detection of eventual local optimum, a strategy of resolution has to be properly implemented and automatized. Different options could be: numerous automatic initialization values and various model combinations (with or without losses, fixed or free network layout). The sizing of the pipe exiting the heat production will be compared to the sizing of the pipe at the end of the network.

In the future, it could be relevant to analyse the optimal structure over different periods, especially with different heat loads requirements. In comparison, the calculation concerning the capacity factor and the diversity factor could be achieved in details with dynamic DHN modelling. As soon as the formulation is multi-period, the core question of the storage could be considered.

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## Nomenclature

### Acronyms (optimization field)

LP	Linear Programming
NLP	Non Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming

### Acronyms (energetic field)

DHN	District Heating Network
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HT hot temperature level requirement  
 LT low temperature level requirement  
 HX heat exchanger  
 DES Distributed (or decentralized) Energy System  
 TES Thermal Energy Storage

#### Sets

*i* set of a producer node  
*j, o* set of a consumer node  
*k* set of the technology of production

#### Shortcuts in subscript

*P* related to a producer node  
*C* related to a consumer node  
*lineXZ* related to the line which connects a node X (*P* or *C*) to a node Z (*C* or *P*). Between two consumers (*CC*), the direction is managed with sets *j* and *o*, also the subset parallel or cascade is added. *PP* is excluded.

*int* interior  
*ext* exterior  
*in* inlet  
*out* outlet  
*tot* total  
*heat* related to heat consumption  
*unit* related to unit cost  
*insul* insulation  
*pipe* related to the line between two nodes  
*req* required  
*tr* trench  
*hx* heat exchanger  
*inst* installed

#### Input data

*c* cost, €  
*x* abscissa of a node, *m*  
*z* ordinate of a node, *m*  
*Dist* distance between two nodes, *m*  
*S* surface free in a node, *m*<sup>2</sup>  
*tk* thickness of the pipe, *m*  
*K<sub>hx</sub>* global coefficient of exchange of the heat exchanger, *W/(K.m*<sup>2</sup>*)*  
*Eff* efficiency of the technology of production, -

#### Variables

*Y* *Y* letter in prefix means the variable is binary, dealing with its existence  
*L* distance of an existing pipe between two nodes, *m*  
*D* diameter of the pipe, *m*  
*M* mass flow rate, *kg/s*  
*V* velocity, *m/s*  
*T* temperature, °C  
*P* pressure, *Pa*  
*DP* pressure drop, *Pa*  
*H* thermal energy capacity, *W*  
*E* heat energy, *Wh*  
*A* exchange area in a heat exchanger, *m*<sup>2</sup>  
*R* surface thermal resistance, *m*<sup>2</sup> *K/W*  
*C* cost, €

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