A MINLP optimization of the configuration and the design of a district heating network: academic study case

Théophile MERTZ[ab], Sylvain SERRA[b], Aurélien HENON[a] and Jean-Michel RENEAUME[b]

[a] LATEP-ENSGTI, Université Pau & Pays Adour, Pau, France, theophile.mertz@univ-pau.fr, sylvain.serra@univ-pau.fr, jean-michel.reneaume@univ-pau.fr
[b] NOBATEK-INEF4, 33400, Talence, France, tmertz@nobatek.com, a.henon@nobatek.com

Abstract:

The aim of this work is to propose a tool for the design assistance of District Heating Network (DHN) at the beginning of an urban project, as well as for an extension of an existing network. Two goals of DHN optimization are handling at the same time: the optimization of the configuration (network layout, choice between the different production technologies, existence or not of such utilities) and the optimization of the design (mass flow rate, temperature, thermal generating capacity to install, area of the heat exchanger -HX- in sub-station...). The optimization objective is to minimize the global cost of the DHN over 30 years. It includes both operating cost (heating and pumping cost) and investment cost (line, trench, heating plant, HX).

The formulation of the optimization problem leads to a mixed integer non-linear programming (MINLP) problem. That means the optimization problem has a single nonlinear objective function (the global cost) subject to numerous linear and nonlinear constraints (mass flow rate, energy conservation...) with both continuous variables (mass flow rate, temperature distribution, area of the HX, thermal generating capacity to install) and discrete (logical existence of the pipe between sites).

The originalities of this work are the potential offered by the formulation and the method of resolution. The optimization of an academic example is discussed. One of the results is the layout of the DHN, supplied in star or in cascade: a first consumer with high temperature (HT) requirement can supply another consumer with lower temperature (LT) requirement. Furthermore, the localization of the heating plant(s) and which technologies of production are analysed in the case of an isolated consumer.

Concerning the optimization issue, the problem is described globally within GAMS. The model is solved with DICOPT, a MINLP solver which uses the deterministic Outer Approximation (OA) method.

Keywords:

Centralized or decentralized heat production, Consumers in potential cascade connection, District Heating Network (DHN), “Isolated collective” heat production, Mixed integer non-linear programming (MINLP).

1 Introduction

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

A District Heating Network (DHN) is one of the technological solutions to supply heat. Heat could be required for industrial purpose, space heating or domestic hot water. In comparison with individual (at each apartment) or collective (at each building) heat supply, 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 others industries). Since the DHN heating plant is better monitored and especially as fossil fuels are no longer the only energy source, more pollution could be avoided in the inner city. Thanks to a mix of various energy sources, the energy price is 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. There is no doubt that a DHN is a rentable solution to supply heat, moreover when its conception is optimized as soon as possible in urban project. This “collective solution at the urban scale” (also named “community”) is a better solution to supply heat, in terms of economic and environmental issues, than numerous collective gas boilers at each collective buildings and even more than individual gas boilers at each apartments. A DHN is more and more considered in the long term prospection to tackle the energy transition, as for instance the vision of the District Heating and Cooling platform [1].

The core of our project is both to optimize in steady state the configuration (network layout and the choice of the technology of production), design parameters (thermal generating capacity to install, exchange area of the Heat Exchanger – HX, length and diameter of the pipes...) and state variables (temperatures, mass flow rates). The originality of our work is to let it possible different network layouts: connection in star (each consumer is directly connected to a producer) or in cascade, i.e. the supply from a “hot temperature (HT) consumer” – such as old building, hospital, industrial utility... – to a “low temperature (LT) consumer”.

First of all, the state of the art concerning previous works on DHN optimization will be realized. The characteristic of the optimization problem will be underlined in order to choose a suitable algorithm for the resolution. Then the formulation of the optimization problem will be detailed. Finally the results on an academic study case will be discussed.

2 DHN optimization: State of the art

There are three different goals in the field of DHN optimization. The first one is the optimization of the configuration, where the layout of the network and which heat production technology are chosen. The second is the optimization of design parameters (thermal generating capacity to install, exchange area of the Heat Exchanger – HX, length and diameter of the pipes...) and the optimization of state variables (temperatures, mass flow rates). 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 in the same time in steady state, but they will be detailed apart for didactic purpose. Such simultaneous attention on both optimization goals is barely done, as far as we know.

2.1 Optimization of the configuration

The optimization of the DHN configuration takes place as soon as possible in urban planning project. The results of these studies will help the choice of the heating plant technologies and the structure of the network. Two main institutions results on MINLP DHN optimization are detailed below. The state of the art concerning other optimization applications (such as heat exchanger - water - electrical - network, distillation, reactors, scheduling...) or other optimization problems are not detailed here.

The industrial energetic systems laboratory of the EPFL is working on the optimization of DHN. CURTI has already considered different required temperature levels in his PhD thesis [2] when he developed a modeling and optimization tool of a DHN under Fortran 77. The competence of multi-objective optimization is then added to this work. A synthetic overview could be seen in the publication MOLYNEAUX et al. [3]. 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 plant (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, the users and the connections between them exist. Our work will include those existence variables in the model. For the moment, only two technologies of production and the existence of the connection between the nodes are considered.

Recently in the same laboratory, WEBER [4] worked on the optimization of Distributed Energy System (DES). She insisted on the polygeneration optimization in order to optimize globally and simultaneously the supply of heat, cold and power. To solve her problem, WEBER has chosen to split it in two parts, according to the linearity or non-linearity of the problem, and not separating the kind of variables (binary or continuous) as usual. She has improved a multi-objective evolutionary algorithm (EMOO). Currently FAZLOLLAHI et al. [5] solved this MILP multi-objective problem with a mix of an Integer Cut Constraint and ε-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 [6] has been done concerning the pre-treatment of the dynamic heat demand, in order to select the number of representative period and its related required heat demand in average.

In another laboratory from the Abo University in Finland, SODERMAN [7] has also worked on the optimization of DES in order to help political decisions. He managed to solve MILP problem with a Branch and Bound algorithm over 8 periods to optimize simultaneously the supply of heat and power demand. So in common, we work on the structural and operational optimization of network. The objective function to minimize was the overall global cost. SODERMAN had chosen to optimize in a larger scale (more for a region than a city) and optimize both electrical and heat supply, in lower details. That’s why he could afford to solve a multi-period optimization and also included a thermal storage. But he didn’t consider different temperature level requirements, the heat losses or various technology of heat production.

2.2 Design

Concerning the optimization of the design of a DHN, some trends are seen worldwide:

- Lower supply temperature [8] : The lower the supply temperature is, the lower are the heat losses. Still an optimization is needed to find the optimum between reducing the heat losses and increasing the pumping cost, while fulfilling the heat demand subjected to numerous constraints such as the temperature level required by the consumer, for space heating and domestic hot water preparation.
- Lower pipe diameter: some work are focused on this issue, such as the German software STEFaN [9] based on a Geographical Information System (GIS).
- Lower thermal generating capacity: in such community supply, FREDERIKSEN and WERNER [10] explained how much it’s relevant to use a capacity factor while designing. Indeed the numerous different uses of the buildings lead to different heat demand profiles. 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).

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. In the field of the optimization, two terms are used: multi-period optimization (the time is a discontinuous variable) and dynamic optimization (the time is continuous, ordinary differential equations have to be included). But such problems are already tough enough to solve that it is done at a fixed configuration. But the fact is that we want to think about the optimization of the configuration too. Numerous design optimizations are studied, at a fixed configuration. For instance the IEA has a team working on this topic [11], a NLP problem is solved with the solver MINOS within GAMS.

3 Optimization problem

In order to choose the appropriate method to solve an optimization problem with a deterministic method, the optimization problem has to be well characterized.

3.1 Characteristic of the optimization problem

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 [12]. In general the structure of the optimization problem depends on the different DHN optimization goal considered, as seen in previous section:

- If the DHN configuration is studied, there is necessarily binary variables which are used to let the choice whether such technology of production exists or not or whether such pipe connects two sites or not. The optimization problem is called MIP for Mixed Integer Programming. According to the level of modelling expected, the problem could include some non-linear equations such as energy conservation or heat loss equation. In that current case we have to face a MINLP problem.

- If the design or the operative management of a DHN are optimized, at a fixed configuration, no discrete variables are used. If any equation is non-linear, the problem is called NLP, otherwise LP is used.
- If the consideration of the time variation has to be included, the problem should be multi-period optimization or dynamic optimization.

Please keep in mind that we will focus on the MINLP optimization of the configuration and the design of a DHN in mono-period and in steady state.

3.2 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 well in a second review [13], in which pros and cons had help us to choose our resolution method.

For the stochastic methods, the choices of the parameters are very sensitive and a huge time calculation is needed. Moreover those methods do not assure an optimum to be global. But still, they better tend not to be stick into a local solution, as the resolution path is never the same.

In the other hand, deterministic methods are able to assure global optimum for convex problem. Even if the problem is non-convex, considerable progress had been done and optimums can be found very quickly. The major drawback is to understand well 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. As the problem we come across is an MINLP, we will focus on the main line of resolving such a problem.

Among the deterministic methods, a MINLP problem is mainly solved with a Branch and Bound (BB), an Outer Approximation (OA), a Generalized Benders Decomposition (GBD) or finally the Extended Cutting Plane (ECP) method [14]. 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. And those fixed binary variables and lower bounds are predicted with a master MILP problem. The ECP method does not rely on the resolution of NLP subproblem. Linearization of the most violated constrained are added successively in the main MIP problem. But the objective function has to be linear, which is not our case.

The algebraic modelling environment chosen is GAMS for the high performance solvers integrated. The solver DICOPT is used in this paper, which call the CPLEX solver for the master MIP problem and the CONOPT solver for the NLP subproblem. DICOPT uses the OA method, which seems to be appropriate. In our study case the calculation time is less than one second.

3.3 Problem formulation

A superstructure allowing each possible solution of the optimized network has been thought Fig. 1. The originalities are first to optimize simultaneously the configuration and the design, secondly to allow the connection between consumers in cascade and not only to consider a branched network and thirdly to think about different network configuration to supply an isolated consumer. The second originality means that the residual heat from a “hot temperature consumer” (HT) could directly supply a “lower temperature consumer” (LT). That explains why two subscripts for the consumer node are required. No logical equation is added to force the connection between the nodes. The existence or not is the result of the optimization.

The input parameters are clearly identified at the top of the Fig. 1, whereas otherwise the variables are represented in the scheme. We tried to indicate the value for the technical input parameters, but not for the unit cost. Those last crucial parameters come from the national French database batiprix 2011. Please note that the binary variables (letter Y in prefix) are not represented, even if they represent around 20% of the total amount of variables.

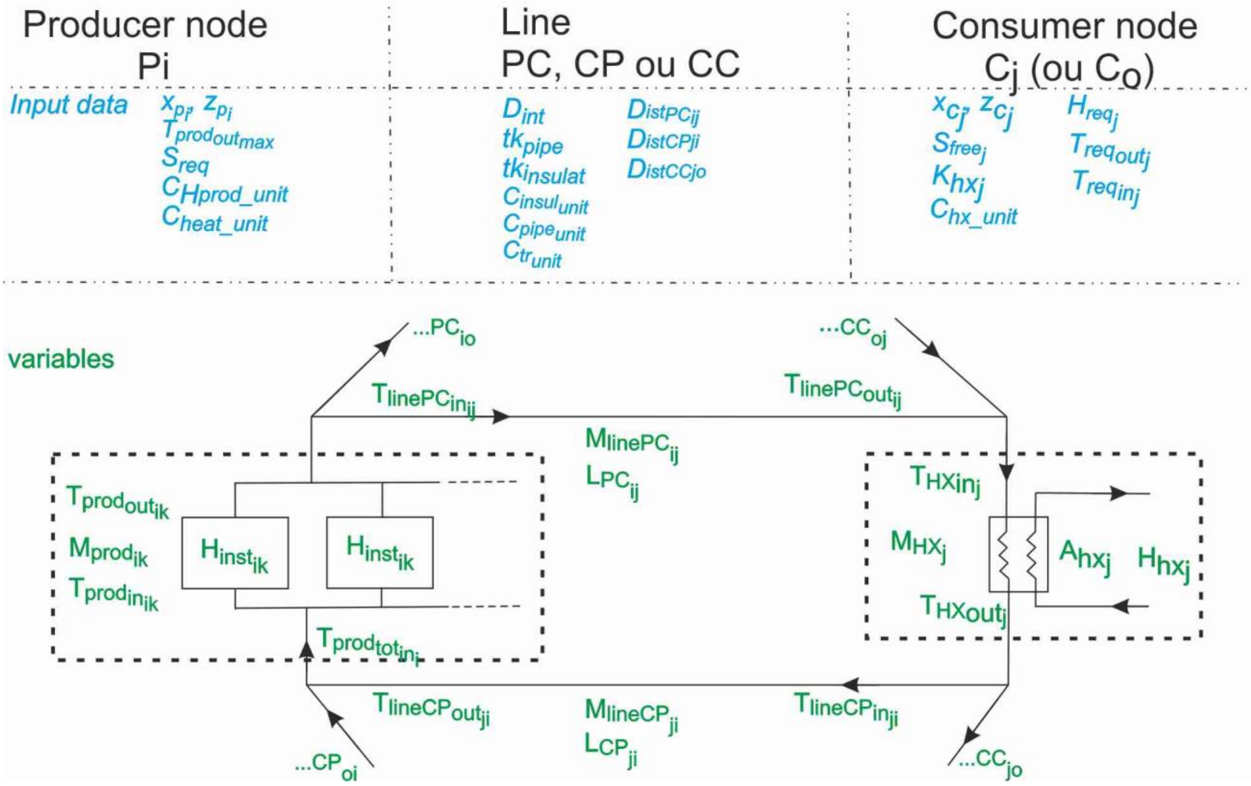

Fig. 1 Scheme of the superstructure of the DHN considered for our optimization problem

After the input data and the enumeration of the variables, the model is described by adding some constraints. In fact, as we used an equation oriented approach, no equation is implicit. Three main types of equations are written.

The first kind of equations uses binary variables, which ensure the coherence of the existence or not. For instance, the equation (1) prohibits the existence of a connection CC_{ii}, i.e. the connection between the same consumers. The equation (2) defines the distance PC, i.e. the distance between a node producer i and a node 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 define in (3). It's redundant to add a constraint with a lower bound equal to zero, because those variables are already declared as positive variables.

$$\forall j,\ \mathrm{Y}_{\mathrm{lineCC}_{\mathrm{jj}}} = 0 \tag{1}$$

$$L_{linePC_{ij}} = \mathrm{Y}_{\mathrm{linePC}_{ij}} \cdot \mathrm{Dist}_{\mathrm{PC}_{ij}} \tag{2}$$

$$\forall \{i,j\},\ M_{linePC_{ij}} \leq \mathrm{Y}_{\mathrm{linePC}_{ij}} \cdot M_{max} \tag{3}$$

Secondly, there are equations about the physics, like all energy conservation and mass flow rate balance. They are not detailed here because there are common. At each node (convergent or divergent), a mass flow rate balance has to be respected. Then if you come across a divergent node, an equality of temperature has to be written. For a convergent node the energy conservation has to be respected. To know the heat capacity to install (H_{inst}) or the heat power exchanged in the HX (H_{hx}), a power balance between outlet and inlet is done. To fulfil the heat required by the consumer and design the HX, H_{hx} is calculated with a logarithmic mean temperature difference (LMTD) method, in which the global coefficient K_{hx} is estimated constant at 20 kW/(m².K) for this paper.

Moreover as the optimal distribution in a DHN is a balance between the heating and the pumping cost, both are taken into account in this model even if there are not discussed in detail in this paper (which is focused on the results concerning the configuration). First the heat losses are calculated thanks to (4), with a global heat transfer coefficient $h=0.5\ W.K^{-1}.m^{-2}$, which had been estimated thanks to [10] for a pipe diameter D=0.1m, an insulation thickness $tk_{insul}=0.1$m and a thermal conductivity of insulation material $\lambda_{insul}=0.03$ W/(m.K). Secondly, the linear pressure drop is calculated with a coefficient of friction estimated from the Blasius formula (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. So the pumping power is expressed in kW (5) with the following constant factors $\alpha=2.25$, $\beta=5.25$ and $\gamma = \frac{100^{-1/4}}{2\cdot\rho\cdot\mu^{1/4}}$.

$$T_{linePC_{out_{ij}}} = T_{ext} + \left(T_{linePC_{in_{ij}}} - T_{ext}\right)\cdot\ exp^{-\frac{h\cdot S\cdot L_{linePCij}}{M_{linePCij}\cdot cp}} \tag{4}$$

$$H_{pump_{\mathrm{PC_{ij}}}} = \gamma\cdot\frac{L_{PC_{ij}}\cdot M_{PC_{ij}}{}^{\alpha}}{D_{PC_{ij}}{}^{\beta}} \tag{5}$$

The last kind of equation deals with economics. For example, the pumping cost are expressed thanks to the previous calculated pumping cost and some others parameters like the duration (8760 hours), the efficiency of the volumetric pump $\eta_{pump}=70\%$ and the unit cost for pumping, see (6).

$$C_{pump} = \ C_{pump_{unit}}\cdot\sum_{i\neq j,j\neq k}(H_{pump_{PC_{ij}}} + H_{pump_{CP_{ji}}} + H_{pump_{CC_{jk}}})\cdot\frac{duration}{\eta_{pump}} \tag{6}$$

The objective function to minimize is the global cost over 30 years. Until now, just the cost is considered as it is a core issue in urban planning, as underlined by the French organisation CEREMA [15] or [16]. In perspective, some environmental analysis could be added. The equation (7) is the sum of the operating cost (pumping and heating cost) and the investment cost (thermal generating capacity installed, heat exchanger and the line). In the cost of the line, the trench, the insulation and the pipe material are included. In the operating cost for the heating is included the heat consumed in the substation and also the heat lost in the network:

$$C_{total} = \left(C_{pump} +\ C_{heat}\right)\cdot \mathrm{f_{opex}} + \left(C_{H_{inst}} + C_{HX} +\ C_{line}\right)\cdot f_{capex} \tag{7}$$

The factors multiplying the cost are needed in order to take into account the actuarial calculation – X€ today does not have the same value in N years – and the energy price inflation. As just an initial investment (C_{capex}^{0}) is required in the reference year 0, so N years later the sum of the investment cost is “just” the actuarial calculation with an actuarial rate (r_a) taken as 0.04, see (8). The equation (9) calculates the factor f_{capex} related to the investment.

$$\sum_{p=0}^{N} C_{capex}^{p} = C_{capex}^{0}(1+r_a)^N \tag{8}$$

$$f_{capex} = (1+r_a)^N \tag{9}$$

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 (10). The sum of the operating cost over N years is calculated like a geometrical series in (11). The equation (12) is the identification of the factor f_{opex} for the operating cost.

$$C_{opex}^{p} = C_{capex}^{0}(1+r_a)^p\cdot(1+r_i)^p \tag{10}$$

$$\sum_{p=0}^{N} C_{opex}^{p} = C_{opex}^{0}\cdot\frac{1-(1+r_a)^N\cdot(1+r_i)^N}{1-(1+r_a)\cdot(1+r_i)} \tag{11}$$

$$f_{opex} = \frac{1-(1+r_a)^N \cdot (1+r_i)^N}{1-(1+r_a)\cdot(1+r_i)} \quad (12)$$

4 Results on an academic study case

In order to illustrate the possibilities of our formulation, we will optimize two chosen study cases. We considered one main producer P1 and four consumers as input data, as seen in Fig. 2. Each consumer requires 80 kW during the whole period (8760 hours). In section 4.1, the advantage of the cascade connection will be illustrated. Then in the following section 4.2, an eventual “isolated collective” heat production (P2) will be added for the isolated consumer (C4), which is three times furthest. They are not represented in the same location, even if they are, just to better represent the eventual connection between them. This section 4.2 will focus on the best choice between one centralized production, decentralized complementary heat productions, or "isolated collective" heat production.

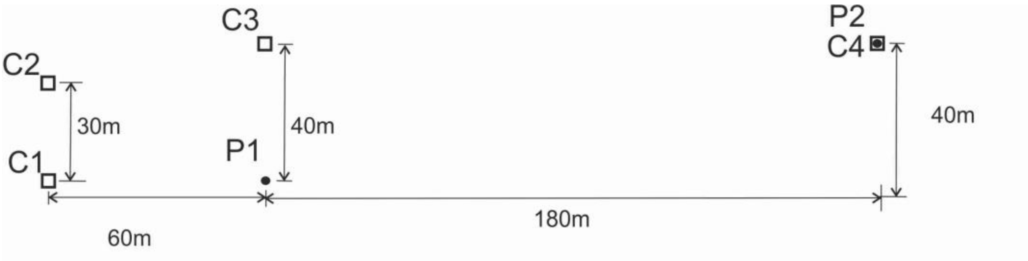

Fig. 2. Spatial location of the considered nodes in this study case

4.1 Advantage of allowing the connection of consumers in cascade

In this first study, the influence of the level of temperature required by consumers and the cascade connection between consumers are tested. The input data are detailed in Table 1. The consumer C2 required hot temperature (HT) level in the case one: the secondary network distributes the heat through the building between 70°C (supply) and 50°C (return). And in other cases, C2 is considered as a low temperature (LT) client: the heat is distributed between 50°C (supply) and 30°C (return). All the other consumers are taken to be HT consumers. For instance, the HT consumer could represent an old building with old heaters or also a hospital, an industrial process... And the LT consumer could be a new residential buildings or offices, with high efficient heaters. One other important entry is tested: whether the connection between two consumers (connection CC) is allowed (case 3) or not (case 1 and 2, known as conventional DHN design).

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

	case 1	*case 2*	*case 3*
C1	HT	HT	
C2		LT	
C3		HT	
C4			
connection CC	No		Yes

The resolution of this problem leads to the following results. Please note that whether the line exists between two nodes or not is one of the results. Some optimization results are detailed in Table 2, the grey coloured backgrounds match with the same coloured optimized structures of the network seen in Fig. 3. Taking into account the level of temperature required from the consumer is technically relevant, even if the reduction in term of total thermal generating capacity installed or in term of overall global cost is very low (-1%). In comparison to the conventional design (case 1), the design innovation of allowing the cascade connection between consumers permits to reduce significantly the global (-7%).

The operating cost, including the heating and the pumping, stands for around 70%. As explained in the context, even if the initial investment cost is impressive, in the long term it is not the main share. Concerning these three cases, the heat density is around 5 MWh/m. That is enough (upper than 1.5 MWh/m) to be eligible to the “fond de chaleur”, a financial subsidy from the ADEME (French agency for the environment and the energy efficiency).

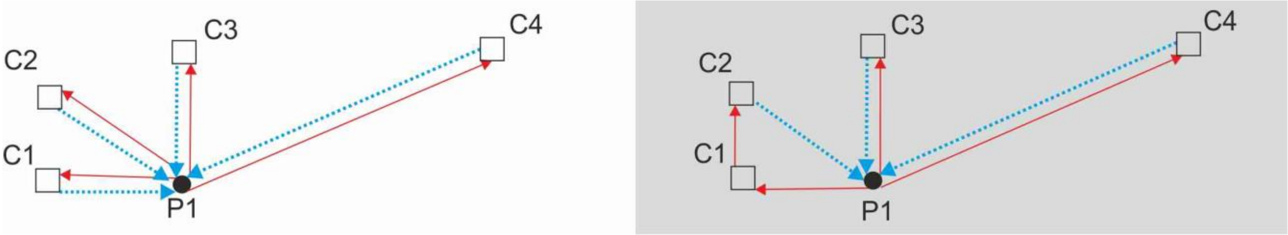

Fig. 3. Optimal structure of the network for the case 1 and 2 (left), case 3 (right)

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

			case 1	*case 2*	*case 3*
C_{pump}			1 570	1 530	1 420
C_{heat}			5 000	4 990	4 800
C_{Hinst}		k€	1 070	1 070	1 030
C_{hx}			6	6	6
C_{line_tot}			1 990	1 990	1 730
C_{tot}		k€	9 630	9 580	8 990
		%	-	-1%	-7%
H_{inst}	P1	kW	410	410	400
	P2		-	-	-
E_{tot}		MWh	3 630	3 620	3 490
L_{tot}		m	740	740	650
D_{th}		MWh/m	5	5	5

4.2 Centralized, decentralized or “collective isolated” heat supply

In this second analysis, a potential secondary heat production is added in input. The optimization has to select whether this heat production is rentable or not and how it is connected to the network, i.e. whether the production is better to be centralized (just one central heating plant) or decentralized (more than one heating plant) or even isolated from the main grid. Different input data, as detailed in Table 3, are tested:

- The case 5, the reference for the comparison in percentage, does not allow the previous “collective-grid” technology (k1) in the free area available in P2 for a technology (k2) corresponding to a collective heat production isolated from the main grid. This technology (k1) represents around 2/3 from the operating and investment unit cost of the technology (k2).
- The case 6 tests the influence of the unit price of the production (k2) in order to help the decision whether a decentralized heat supply is rentable or not. The price difference is lowered by 10% compared to the reference case 5.
- Finally the cases 7, 8 and 9 permit to analyse the stress that the real estate price could have on the optimized structure. That means, sometimes it is known in the beginning of urban project that just a limited area is available (S_{max}) to install a potential capacity (H_{max}) for an “isolated collective” heat supply, in addition to the place needed for the HX in the substation. Three cases are tested, when S_{max} permits to install a thermal generating capacity of the “isolated collective” production in P2, up to 60kW (case 7), up to 30kW (case 8) and, only, up to 10kW (case 9). Please remind that the consumer C4 required 80kW, as all the other consumers, so C4 cannot be only supplied by his own collective isolated heat plant.

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

	case 4	*case 5*	*case 6*	*case 7*	*case 8*	*case 9*
P2,k1	allowed	prohibited				
k2 cost	3/2.Cost_{k1}		3/2.Cost_{k1} -10%			
H_{max}	No			60kW	30kW	10kW

The results are summarized in Table 4 and the layout of the optimized network structures are illustrated in Fig. 4, as before the grey coloured backgrounds help the comparison. First report, the optimal structure depends on the context: no generalized topology could be advised. To sum up, the heat supply (centralized, decentralized or centralized with "isolated collective" heat supply) is a compromise between the unit cost of heat supply, the free area available in the substation of the isolated consumer and how far they are located (here 3 times more further from P1).

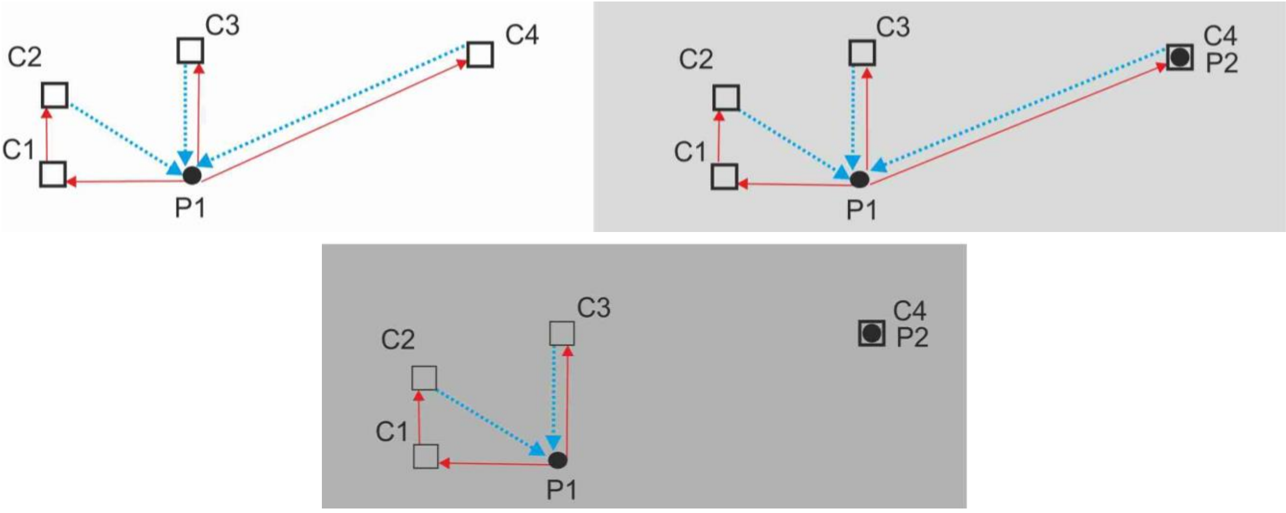

Fig. 4. Optimal structure: centralized heat production cases 5 and 9 (top left), decentralized heat productions cases 7 and 8 (top right) and "isolated collective" production for C4 case 4 and 6 (bottom)

- In the case 5 and 9, a single centralized heat plant is optimal (Fig. 4 top left). In the case 5, C4 is supplied by the main network because of a higher unit cost for the "isolated collective" heat supply. Such a centralized heat supply is also optimal in the case 9, in which just a little area is available to install less than 10 kW. The optimal topology and the design of the network are the same in those cases. Usually in the optimization of DHN the assumptions made lead to such optimal topology, without thinking of a potential non connection to the main network. Note that such a design has the highest global cost.
- In the cases 7 and 8, it is rentable to have a decentralized heat supply (Fig. 4 top right). It reduces the global cost by -7% if the thermal generating capacity is limited to 60kW (case 7) and just -4% if the thermal generating capacity is less than 30kW (case 8). This lower reduction is explained by a lower pumping cost, a lower heat loss and a lower heat capacity installed.
- In the case 4 and 6 an "isolated collective" heat supply for the isolated consumer is optimal (Fig. 4 bottom). That means the cost of the "isolated collective" heat production is lower than the sum of the investment cost and the distribution cost in the pipe (including the heat loss). The heat density (D_{th}) is the highest, around 11.2 MWh/m. The total length of the pipe (L_{tot}) is the shortest (277m instead of 398m). In the case 4, as the cheapest "collective-grid" technology (k1) is not prohibited in P2 location, a theoretical auxiliary heat supply (P2, k1) is chosen. That underlines the fact that the solver chose the cheapest solution (-28% of the global cost compared to case 5). The case 6 is more realistic: the heat required for the isolated consumer (C4) is entirely supply by an "isolated collective" supply (P2, k2). A significant reduction of the global cost is achieved, around 22% with our assumptions of unit cost.

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

				case 4	*case 5*	*case 6*	*case 7*	*case 8*	*case 9*
C_{pump}				520	1 420	520	681	958	1 421
C_{heat}				4 260	4 800	4 741	4 856	4 839	4 804
C_{Hinst}			k€	920	1 030	994	1 083	1 060	1 033
C_{hx}				6	6	6	6	6	6
C_{line_tot}				740	1 730	740	1 725	1 725	1 725
C_{tot}			k€	6 440	8 990	7 005	8 352	8 589	8 990
			%	-28%	-	-22%	-7%	-4%	0%
H_{inst}	P1	k1	kW	270	400	270	335	367	398
		k2		-	-	-	-	-	-
	P2	k1		80	X	X	X	X	X
		k2		-	-	80	60	30	-
E_{tot}			MWh	3 090	3 488	3 092	3 460	3 481	3 488
L_{tot}			m	280	646	277	646	646	646
D_{th}			MWh/m	11	5	11	5	5	5

5 Conclusion

This model of DHN allows to optimize both the configuration of the network (the choice of the technology of heat production and the network topology) and the design of the some key parameters (such as supply and return temperature, mass flow rate, exchange area of the HX, thermal generating capacity to install...) The results in this paper are only focused on the DHN configuration. The resolution of the MINLP problem is achieved with the solver DICOPT in GAMS in approximately one second.

In the first study case, the innovative design to connect the consumer in cascade is illustrated, especially to use excess heat from one HT consumer to a LT consumer. It permits a reduction of 7% of the total global cost over 30 years.

In the second study case, the supply of the isolated consumer C2 is studied. The classical design reference case is when C2 is supplied by the main grid with one centralized heat plant. It is the most expensive solution, but still optimal if the unit cost of the isolated collective heat plant is prohibitive or if C2 has very few surface available to install an auxiliary heat plant. Otherwise, with some reasonable surface limitation in C2 substation for auxiliary heat supply, one main grid with decentralized heat plants is optimal. It leads to a little reduction of the global cost (up to -7%). Finally with no surface limitation and a little unit cost difference between the "isolated collective" and the community heat production, an "isolated collective" heating plant for the isolated consumer C2 is optimal. It permits to reduce significantly (-22%) the total global cost over 30 years.

In the short term, some evolutions will be implemented in the model, such as diameter in variable, potential bifurcations, consumer supply in parallel, additional constraint (minimum percentage of renewable energy in the energy mix)...Despite the unit costs have to be consolidated. This task will be achieved with an engineering partner and some direct applications on an existing site. In the long term, it could be relevant to analyse the optimal structure over different periods, especially with different heat load requirements. As soon as the formulation is multi-period, the core question of the storage could be considered.

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Nomenclature

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, 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, *k€*
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^2
tk	thickness of the pipe, *m*
D	diameter of the pipe, *m*
h	global heat transfer coefficient between the hot water and the average air outside, $W/(K.m^2)$
K_{hx}	global coefficient of exchange of the heat exchanger, $W/(K.m^2)$

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*
M	mass flow rate, *kg/s*
T	temperature, *°C*
H	thermal energy capacity, *kW*
E	heat energy, *kWh*
A	exchange area in a heat exchanger, m^2

Acronyms (optimization field)

LP	Linear Programming
NLP	Non Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
BB	Branch and Bound
OA	Outer Approximation
GBD	Generalized Benders Decomposition

Acronyms (energetic field)

DHN	District Heating Network
HT	hot temperature level requirement
LT	low temperature level requirement

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