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A MINLP optimization of the configuration and the design of a district heating network: study case on an existing site

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Abstract

The aim of this work is to propose a tool to help the design of district heating networks (DHN). The configuration (network layout and production technologies) and the design (mass flow rate, temperature, heat capacity to install and area of the heat exchanger) are optimized simultaneously.

The originalities of this mixed integer non-linear programming (MINLP) formulation are to: 1 - avoid any constraint on pipe forcing them to be both supply and return, 2 - permit centralized - decentralized – or individual heat productions, 3 - permit cascade connections between consumers.

A study case based on an existing DHN is discussed. First some optimal design parameters are compared to the existing ones. Then, a potential expansion of the DHN to the neighbourhood and the introduction of renewable energy are studied.

Keywords: District Heating Network (DHN) ; centralized or decentralized heat supply ; Mixed Integer Non-Linear Programming (MINLP) optimization

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Nomenclature

Sets

Cj	consumer node
HX	heat exchanger
in	inlet
inst	installed
out	outlet
Pi,k	producer node (located in i technology k)
req	required
spec	specific value
tot	total

Roman letter

Cp	specific thermal capacity [J/(kg.K)]
C	cost [€]
D	diameter [m]
DP	pressure drop [W]
H	thermal capacity [W]
L	length between two nodes [m]
M	mass flow rate [kg/s]
R	surface thermal resistance [m².K/W]
T	temperature [°C]
V	velocity [m/s]
x	node (P or C) abscissa [m]
Y	existence binary variable [-]
z	node (P or C) ordinate [m]

1. Introduction

Energy savings in the building sector are needed. Although the high efficiency standard for new constructions and the current effort on refurbishment contribute to the European energy and climate policy, further initiatives are needed to increase the savings. Indeed all the existing building stock cannot be refurbished simultaneously (technical and economic constraints) and in 2010 70 % of the city of the future 2050 are already built. Estimations evaluate that between 30 % and 40 % of buildings in 2050 would be built before 1975. Some reflexions about how to produce and distribute heat are complementary and relevant [1].

The isolated heat production ("individual" for one by dwelling or "collective" by building, illustration Fig. 2) from renewable energy (geothermal, biomass, solar panels, heat pump, etc.) is an interesting solution for suburban residential area. But such individual solutions are quite difficult to implement in collective residential buildings (where 43 % of the population live) or the services sector, especially in high density areas, because those technologies need free surface on buildings or land (geothermal, solar, heat pump) or required large fuel volume (wood).

A District Heating Network (DHN) is a technical solution to supply heat at the urban scale. It enables to consider the heat demand at a larger scale and to exploit its diversity: each consumer does not need heat at the same time, especially if the building use is different (e.g. residential or office building). Moreover with such centralized heating system, costs are shared. And most of all, a DHN enables to exploit potential renewable sources and reuse wasted heat (excess heat from the industrial sector). This economy of scope, as underlined by FREDERIKSEN and WERNER [2], is the major asset of DHN. In return, the high initial investment cost has to be paid off through heat sales. The investment cost represents around 40 % up to 60 % of the total cost of the DHN (subsidies apart), they include the cost for the pipes (trench and materials), heat exchanger in substation and thermal generating power in power plant. Investors can secure their energy bills on the long term by varying the energy mix.

This work is part of the "THERMENERGY" project and receives financial support from the energy transition institute INEF4 R&D program. It aims at the creation of a DHN design assistance tool (implemented in GAMS environment platform), to be applied in the context of new city planning - or refurbishment - projects. The core of this work is to optimize simultaneously 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, length and diameter of the pipes) and the state variables (temperatures, mass flow rates). one of the originalities 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 an old building, a hospital, or an industrial utility – to a "low temperature (LT) consumer". These connections between consumers, modelled by a heat exchanger, are depicted in (Fig. 1).

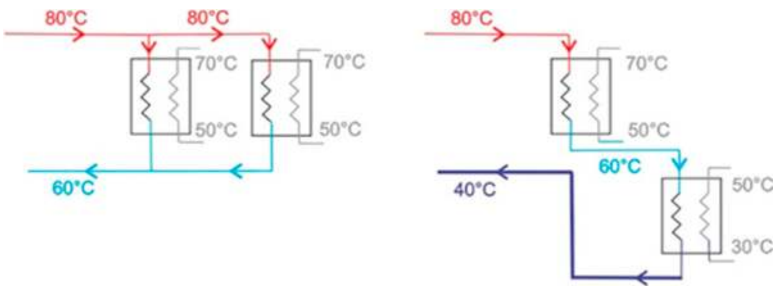

Fig. 1 Consumer connection: in parallel – classical (left) and in cascade – innovation (right)

This design helping tool helps also to choose between the following heat community supply alternatives (on the right Fig. 2 concerning DHN heat supply): one centralized heat production (like P1), numerous decentralized ones (like P2, a renewable source for instance), or a main network with isolated heat productions (like P3).

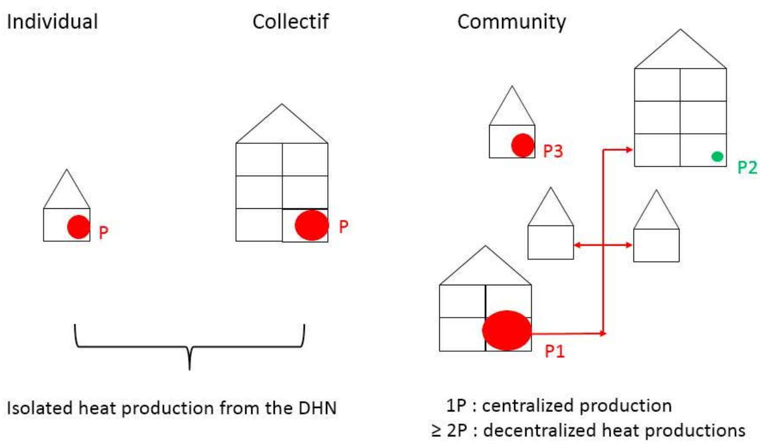

Fig. 2 Comparison of different heat supply solution

2. Optimization

2.1. Background

In this contribution, the word “optimization” refers to an algorithmic approach and not a heuristic (based on the experts experience) one. 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).

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 [3]. 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. Some studies applied to DHN:

- with continuous variables and non-linear (function and constraints), for instance [4]. In order to take into account nonlinearity such as pressure drop and thermal losses, the linear case is not suitable,
- in mixed variables (continuous and integer), most optimizations are linear [4] [5], a few are nonlinear [6],
- single objective function [4] [5] or multi-objective [6],
- single period [4], multi-period [5], [6] or even dynamic [7].

Each possibilities have pros and cons. The more complex the problem is, the more difficult the resolution is (because of the nonlinearity and the combinatory explosion). The issue of this present work is to optimize simultaneously the configuration (so mixed variables are needed) and the sizing (precisely, so nonlinear equations are included).

2.2. Problem formulation

A previous conference paper was more focused on the problem formulation [8]. Briefly the main aspects are explained bellow.

As the configuration is one of the expected results of this work, binary variables (Y letter variables) are introduced to rule the existence of the pipes and the existence of the technologies of production. They represent around 20% of the total amount of the variables. Because of these variables, lots of combinatory are introduced into the problem. And the continuous variables have to be defined only if the utility exists, as for instance the pipe length is equal to the distance only when the binary variable is not null (1) and the mass flow rate existence is ruled thanks to equation (2) with M_{max} the maximum mass flow rate allowed and. If the pipe does not exist, the mass flow rate is equal to 0, otherwise if it exists, the mas flow rate value varies between 0 and M_{max}. In these examples, equations are written for the PC line (connection between one producer node to one consumer node). Similar equations are written for the return line and for connection between consumers (in cascade or in parallel).

$$\mathrm{L}_{\mathrm{linePC}_{\mathrm{ij}}} = \mathrm{Y}_{\mathrm{linePC}_{\mathrm{ij}}} \cdot \mathrm{Dist}_{\mathrm{linePC}_{\mathrm{ij}}} \tag{1}$$

$$\forall\{i, j\}, 0 \le M_{linePC_{ij}} \le \mathrm{Y}_{\mathrm{linePC}_{\mathrm{ij}}} \cdot \mathrm{M}_{\mathrm{max}} \tag{2}$$

Concerning the sizing aspect, as the temperature, velocity and diameter are optimization variables, the energy balance equations are nonlinear, as for instance at the inlet of the consumer node. Moreover the thermal losses are calculated precisely, for example in the pipe PC equation (3). As well as the pressure drop is calculated thanks to equation (4), which helps estimating the pumping cost. More information about parameters (α, β, γ, C_p, T_{ext} and R_{tot}) in our previous paper [8].

$$\mathrm{T}_{\mathrm{linePCout}_{ij}} = T_{ext} + \left(T_{linePCin_{ij}} - T_{ext}\right) \cdot \exp\left(-\frac{\pi \cdot D_{outPC_{ij}} \cdot L_{linePC_{ij}}}{R_{tot_{PC_{ij}}} \cdot M_{linePC_{ij}} \cdot c_p}\right) \tag{3}$$

$$DP_{linePC_{ij}} \cdot L_{linePC_{ij}} = \gamma \cdot \frac{V^{\alpha}_{linePC_{ij}}}{D^{\beta}_{linePC_{ij}}} \tag{4}$$

A MINLP (Mixed Integer Non Linear programming) problem has to be solved. As the problem is modeled with numerous constraints including continuous variables, a deterministic method is chosen for its accuracy and its rapidity, compared to a stochastic method. The problem is implemented in the GAMS environment, in which numerous available solvers can be called to solve the problem. The solver used in this study is DICOPT, which uses the OA/ER/PA resolution method.

The objective function to minimize is the total cost, equation (5), of a DHN over a 30 years' time horizon. It includes the initial investment (CAPEX) for the thermal generating capacity in power plant, the heat exchanger in the substation and the pipe and also the operative cost (OPEX) related to the pumping and fuel cost, each year, including the energy inflation price.

$$C_{tot} = \left(Opex_{pump} + Opex_{heat}\right) \cdot f_{opex} + \left(Capex_{H_{inst}} + Capex_{HX} + Capex_{pipe}\right) \cdot f_{capex} \tag{5}$$

3. Study cases description

3.1. Case 1: Comparison to the existing network

For this paper, the cases are based on an existing network in the south west France, near to Bordeaux. The seven consumers, shown in a plan (Fig. 3), represents a total nominal heat demand of 496 kW. Each consumer heat demand is detailed in Table 1. To begin, only one producer is available, it requires no heat demand. The technology (k1) available in P1 is a gas boiler with a thermal generating capacity of 600 kW.

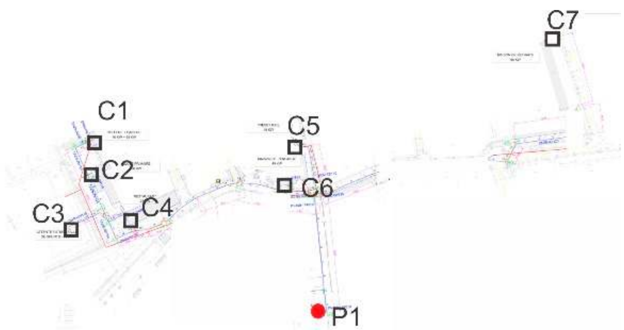

Fig. 3 Localization of the input data of the existing network P1C7 (one producer and 7 consumers)

Table 1 Input data: location (abscissa and ordinate) and nominal heat power required for the nodes

	P1	C1	C2	C3	C4	C5	C6	C7
x (m)	280	91	91	69	146	267	245	465
z (m)	24	166	136	94	105	167	133	248
H_{req}(kW)	0	135	60	90	25	45	45	96

The actual existing network layout is similar to the optimized result shown in (Fig. 4), when only one production node is available. The network total length (supply and return) is 1 224 m, so 612 m of trench (in this study, the line are both supply and return, which is not the case in [8]). In the case of the optimal configuration and design, the total cost reaches 11.13 M€ over 30 years. In (Fig. 5) is represented the costs repartition. 42 % are operative costs (OPEX), which are in huge majority due to the fuels cost. More than the half of the total cost represents an investment cost (CAPEX), 41 % for the thermal capacity to install and also 15 % for the pipes (trench and materials). The pumping cost is very low thanks to the optimization that has chosen an appropriate sizing for the diameters, the velocities and the temperatures. In case of a bad network management or for very low temperature networks, the pumping cost share can represents around 10 % [9]. The balance between thermal losses (17.4 W/m and thermal loss ratio less than 4 %) and pressure drop (1 kPa/m) is well optimized.

The optimal design (Table 2) proposes a higher supply temperature (97 °C) than the effective one (90 °C) and a lower return temperature (60 °C) than the effective one (70 °C). The optimal inner diameters are quite similar than the effective ones, around 100 mm exiting the production node and 50 mm at the end of the network. The optimal inner diameter for the return pipe is slightly bigger than for the supply pipe, which enables to reduce the pressure drops without increasing the heat losses (also possible because the return temperature is nearly 40 °C lower). The order of magnitudes are respected, even in the thermal generating capacity to install, the optimal one (574 kW) matches with the installed one (600 kW).

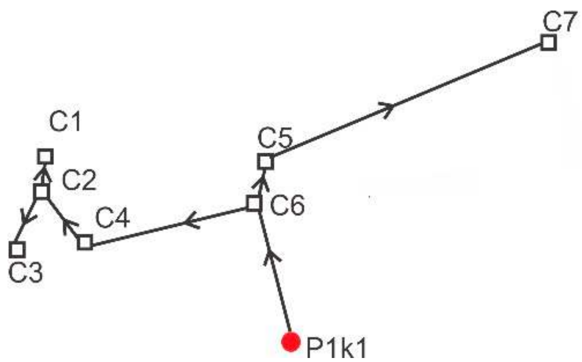

Fig. 4 Optimal configuration L=1224 m and a centralized fossil fuel heat supply (when only P1k1 allowed)

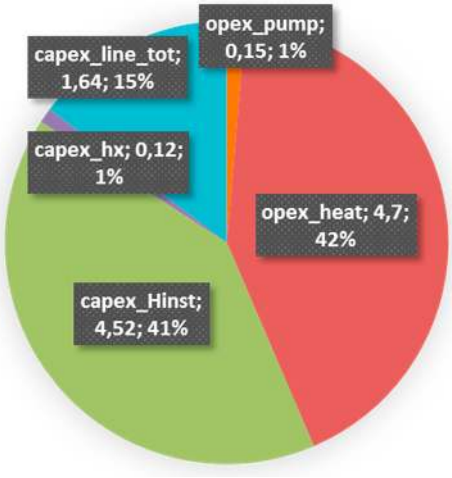

Fig. 5 Cost repartition (in M€) for the optimal result (when only P1 allowed)

Table 2 Sizing results (when only P1 allowed) comparison for the line leaving the power plant (P1C6) and the line at the end of the network (C2C1)

	P1C6		C2C1	
	supply (real)	return (real)	supply (real)	return (real)
T_{in} (°C)	97.4 (90)	59.9 (70)	96.7	60.0
T_{out} (°C)	97.1	59.8	96.5	59.9
D_{int} (mm)	100 (100)	110 (100)	50 (60)	50 (60)
V (m/s)	0.41	0.35	0.46	0.46
M (kg/s)	3.28	3.28	0.88	0.88
DP (kPa/m)	0.23	0.13	0.52	0.44

3.2. Case 2 Isolated and renewable introduction

The consumer C7 is quite isolated from the rest of the district. We propose to test if an isolated heat production (P2, located at the same place as C7) would be economically profitable or not.

Moreover, a renewable energy (technology k2) in this P2 location is now allowed. This k2 technology has not price inflation. As it is not technically feasible to supply 100 % of the heat demand with only renewable energy (peak load heat consumption profile versus weather dependant renewable production), a peak-load technology (k3) based on gas is chosen to supply at least 10 %. This technology k3 has a higher investment cost (1200 €/kW) than k1 (800 €/kW), but the same fuels unit cost (8 ct€/kWh) and the same price inflation (4 %).

The problem formulation, with 2 potential producers, 3 technologies available and 7 consumers, admit nearly 3 500 variables.

To enhance this study case, let us consider a secondary potential producer node (P2), with a "small" renewable potential (the thermal capacity of P2k2 is limited to 90 % of the nominal heat power required by C7). In this case, the obtained optimal configuration (

Fig. 6) is one network with the previous fossil fuel technology (P1k1) and an isolated heat supply for the isolated consumer C7. The total cost is reduced to 10.30 M€ (-7.5 %) when the unit operational cost for k2 is 4 ct€/kWh instead of 8 ct/kWh for k1 or k3.

If there is a "medium" potential to exploit renewable energy in P2 (the thermal capacity of P2k2 is limited to 90 % of the nominal heat power required by all the consumers), a third configuration is optimal (Fig. 7). The total cost is now reduced up to 9.90 M€ when the unit operational cost for k2 is 4 ct€/kWh instead of 8 ct/kWh for k1 or k3. This reduction is quite significant (-1.1 %) and underlines the importance to make more attractive renewable source, even if they are located further (than other classical locations, as P1) and their related investment costs are higher (1200 €/kW for k2 compared to 800 €/kW for k1).

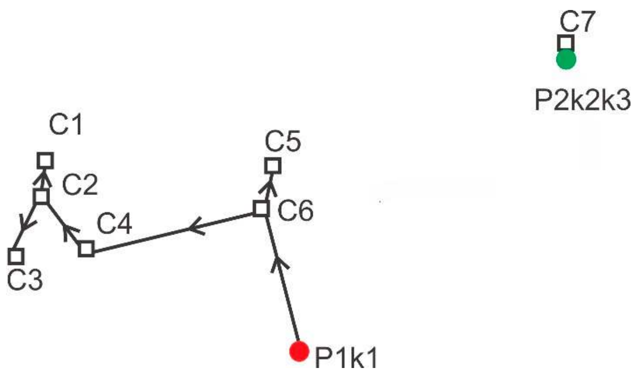

Fig. 6 Optimal configuration L=796 m with a centralized fossil fuel supply (P1k1) and an isolated renewable energy heat supply (P2k2k3)

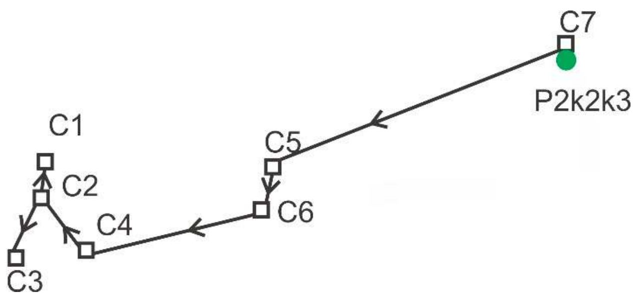

Fig. 7 Optimal configuration L=995 m with a centralized renewable energy heat supply (P2k2k3)

To answer the question of uncertainty about price estimation, a **post optimal sensibility analysis** is proposed (Fig. 8). 2 parameters about k2 cost are tested: its operative unit cost (6 values are tested, between nearly free, as in case of wasted heat reuse 1 ct€/kWh up to 6 ct€/kWh) and its investment cost (4 values tested, between 100 €/kW nearly zero investment, up to 1500 €/kW, nearly twice expensive than k1). The third parameter studied is the unit cost of the trench (3 typical values tested: 300 €/ml in the countryside, 800 €/ml the French average unit cost in city and 1500 €/ml in high density city).

To avoid locally minimum, 3 different initializations and 5 bounds are tested, only the best results are kept and represented. Which leads to solve 15 resolutions (3 different initializations times 5 different bounds) for each 3 input parameters tested (k2 capex, k2 opex and trench unit cost). As there are 72 cases in the sensitive analysis (6 k2 opex times 4 k2 capex times 3 trench cost), 1 080 resolutions are solved in this post optimal sensitive analysis.

Less than 1h20 calculation times are needed to solve these 1 080 resolutions. The results (Fig. 8) reveal that if k2 capex=100 €/kW (nearly free of investment) or 800 €/kW (same investment price than the fossil fuel technology k1) then the configuration "centralized renewable heat production" (Fig. 7) is always optimal, whatever are the k2 opex or the trench cost are. On the contrary, if k2 investment is really high (1500 €/kW), the centralized fossil fuel production with a renewable isolated heat production (
Fig. 6) is always optimal whatever the other costs are.

When the investment cost is 1200 €/kW, the two configurations could be optimal. The isolated renewable supply (
Fig. 6) is optimal when the trench cost is higher or equal to 800 €/ml and the k2 opex higher or equal to 5 ct€/kWh. Otherwise the renewable centralized heat supply (Fig. 7) is optimal.

The centralized fossil fuel heat supply (Fig. 4) is never optimal in this analysis. It is optimal, if and only if the renewable energy is really expensive (k2 capex higher than 2100 €/kW and k2 opex equal to 6 ct€/kWh). Thus in this case, the renewable energy introduction is promoted.

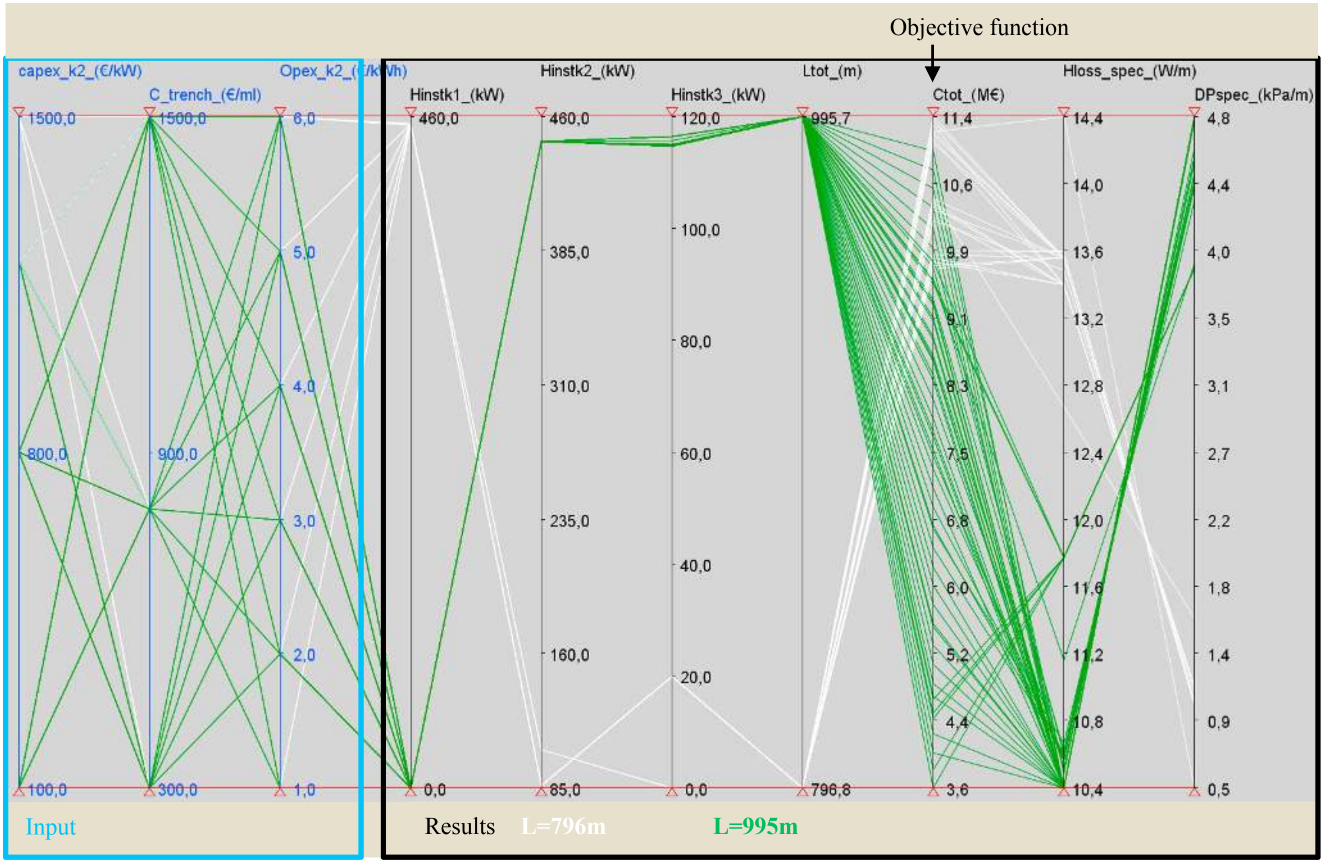

Fig. 8 Post optimal sensibility analysis for case 2

3.3. Case 3: Potential for expansion

Based on this existing district, a potential expansion study case is then proposed. In this residential area, it is assumed that the district construction are quite similar. So to build this case 2, the consumers C1-C6 are translated, horizontally (+500 m) for C8-C13 and vertically (+200 m) for C14-C19 (Fig. 9). The heat demand are based on C1-C6 input (i.e. $Hreq_{C8}$=$Hreq_{C14}$=$Hreq_{C1}$)

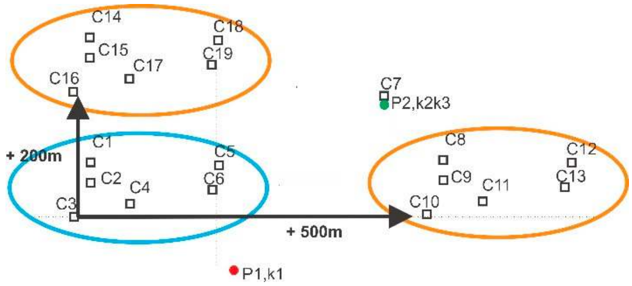

Fig. 9 Construction of the input data for the case 2

As in the previous case, there is two potential production sites: in P1 location, a fossil fuel technology is allowed (k1), whereas in P2 location a renewable energy technology (k2) could potentially supply up to 90 % of the total district heat demand, with a peak load technology (k3) in addition.

As a renewable potential is identified (study case assumption), the core question to answer is not anymore only a potential P2k2 isolated heat supply, but why not considering to extend the network to the neighbourhood, supplied by this renewable source.

Now in this bigger case (19 consumers), there are more than 22 000 variables.

In comparison to (Fig. 4) with only P1 allowed and 19 consumers, the optimal configuration is shown (Fig. 10). As a consequence of the expansion, now the subnetwork C1C7 is different. In other words, C4 is not anymore supplied by C6 as before, but by C16. This centralized fossil fuel heat supply leads to a total cost of 29.53 M€ (with k1 opex of 8 ct€/kW).

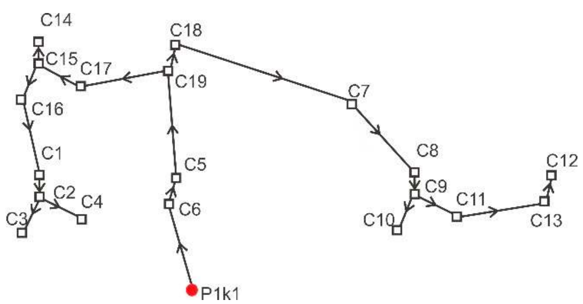

Fig. 10 Optimal configuration L=2 635m, when only P1k1 is available

As soon as a secondary potential production node is allowed, with the possibility to introduce renewable energy into the energy mix, this supply solution is optimal. In case of an “intermediate” renewable energy potential (thermal capacity of P2k2 limited to 90 % of the heat required by the consumers C7 to C13), two separated networks are optimal (Fig. 11). The total cost is reduced to 26.76 M€ (-9.4 %).

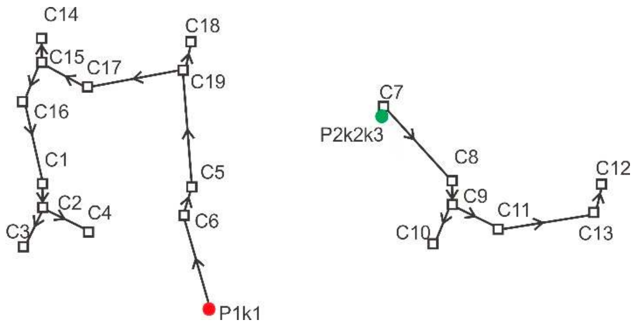

Fig. 11 Optimal configuration L=2237 m, when P2k2 capacity is limited to 90 %

In case of the highest renewable potential (but still a limitation of 90 % of the total heat demand due to technical reasons), the optimal configuration is shown (Fig. 12). This centralized renewable energy heat production enables the highest total cost reduction up to 26.33 M€ (-10.8 %). And the potential cost reduction is even higher when k2 opex is lower than 4 ct€/kWh. For instance the total cost is only 24.61 M€ (-16.7 %) when k2 opex is equal to 1 ct€/kWh, that means nearly free of charge)

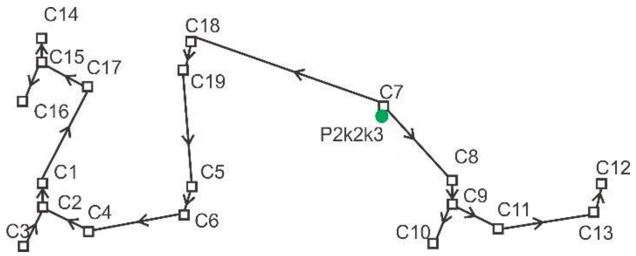

Fig. 12 Optimal configuration L=2470m, one centralized network with renewable energy supply

As before, a **post optimal sensibility analysis** is finally proposed (Fig. 13). As before, 1080 resolutions have been done, among only the 72 best results are shown, which has required 3h20 calculation time. Such a post optimal sensibility analysis is worth, because previously, with fixed unit cost, the renewable centralized heat production configuration was optimal. But what if this cost estimation is under uncertainty; will this configuration still be optimal?

The classic fossil fuel centralized heat production (Fig. 10) is optimal, only if the k2 investment is the highest (1500 €/kW) and if the k2 opex is not so interesting (higher or equal 4 ct€/kWh). Otherwise the renewable introduction is optimal.

A medium renewable energy introduction, for only one separated network (Fig. 11), is optimal if -1- k2 investment is the highest (1500 €/kW), the k2 opex is financially interesting (less or equal than 3 ct€/kWh) and if -2- k2 investment is high (1200 €/kW) and the k2 opex at its higher level (6 ct€/kWh).

Finally, when the renewable source has the highest potential, with investment cost lower or equal to 800 €/kW, whatever the operational cost, the centralized renewable heat production is optimal.

Thanks to this analysis (Fig. 13), the trench cost has no influence, nor to the optimal configuration choice, neither to the sizing (same thermal capacity installed, heat losses and pressure drop). Logically, the higher the unit cost is, the higher is the DHN total cost.

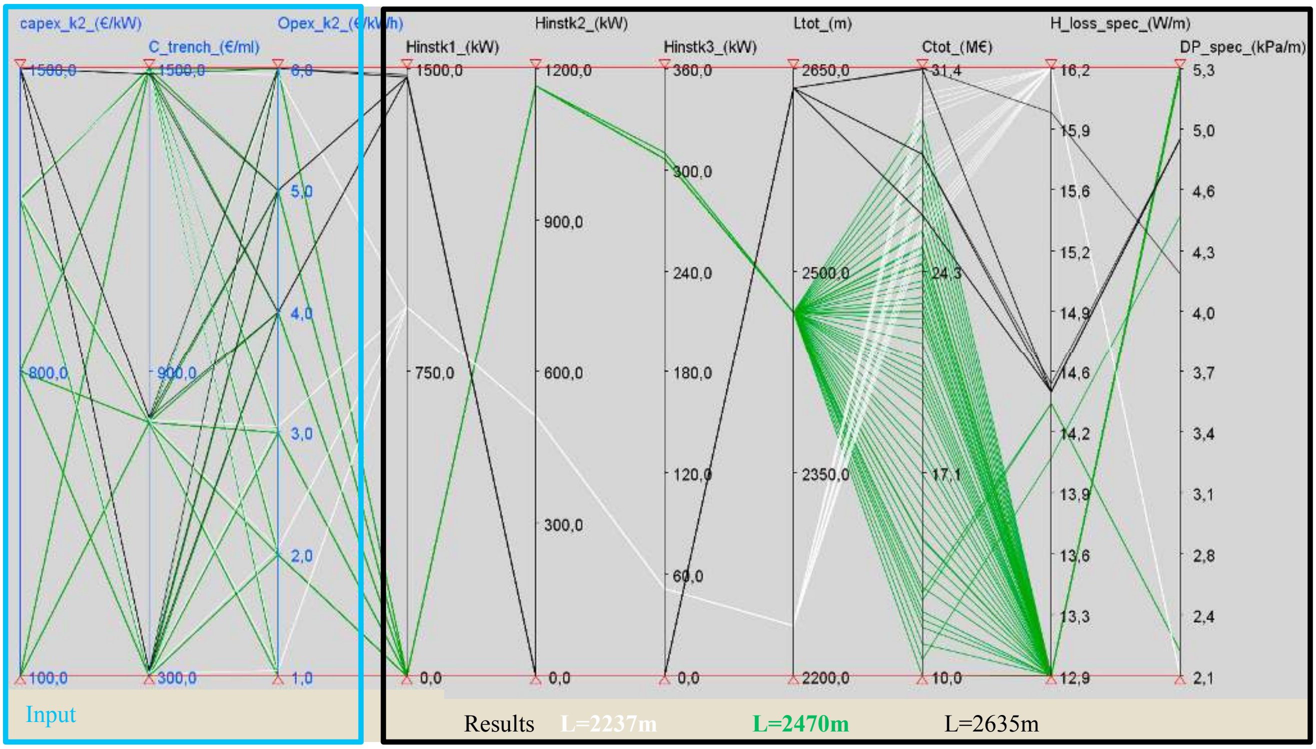

Fig. 13 Results post-optimal sensibility analysis case 3

4. Conclusion

Thanks to this design helping tool, DHN configuration and sizing can be optimized simultaneously. A MINLP problem has to be solved within GAMS environment. The time calculation is less than 2 s to solve case 1 and 11 s for case 2, on an Intel i5 CPU 2.60 GHz and 4 Go RAM. So the post optimal sensitivity analysis (1 080 resolutions) required 1h20 calculation time in case 1 and 3h20 in case 2.

The first study case, based on an existing DHN, shows that when only one producer node were allowed, the DHN optimal configuration and design is closed to the existing network (thermal capacity installed and distribution temperature). An operative feedback is waited to confirm the order of magnitude founded, especially such a low pumping cost share.

But even on such a simple example of a district area, this optimization tool can help designing, as for instance in study case 2, when one other production location is available. In this secondary potential production location, a renewable energy source was proposed. The sensitive analysis reveals that this renewable source introduction was optimal, only if its investment cost were lower than fossil fuel investment (800 €/kW) and leads to a reduction up to 10 % of the DHN total cost.

The third study case highlights the strength of such an optimizing programming method on a bigger district area example. The previous location fossil fuel heat production is optimal only if the investment (>1500 €/kW) and the operational renewable cost (≥4 ct€/kWh) are expensive in comparison. Otherwise, like previous case, the introduction of renewable energy into the energy mix is economically profitable (more than 15 % total cost reduction).

In perspective, it would be interesting to solve a multi-period MINLP problem, so that thermal energy storage could be also studied, configuration (long term storage in heating plant and/or short term storage in sub-station) and sizing (volume, temperature and heat losses).

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