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► **To cite this version:**

Mohamed Mabrouk, Pierrick Haurant, Vincent Dessarthe, Patrick Meyer, Bruno Lacarrière. Combining a dynamic simulation tool and a multi-criteria decision aiding algorithm for improving existing District Heating. *Energy Procedia*, 2018, 149, pp.266 - 275. 10.1016/j.egypro.2018.08.191 . hal-01877938

HAL Id: hal-01877938

<https://hal.science/hal-01877938>

Submitted on 20 Sep 2018

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16th International Symposium on District Heating and Cooling, DHC2018,
9–12 September 2018, Hamburg, Germany

Combining a dynamic simulation tool and a multi-criteria decision aiding algorithm for improving existing District Heating

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Abstract

The work aims to evaluate the recovering potential of excess heat in the return pipe of a district heating (DH) for heating some substations.

The proposed method combines a DH simulation tool and a multi-criteria decision aiding algorithm. It is based on the analysis of the measured return temperatures at each sub-station in order to identify those with high potential of efficiency gains by using the return flow (with support of the supply pipe when needed). Combinations of substations from this set of eligible ones define potential scenarios of connection to the return pipe. The impacts of each scenario on the DH operational performance and the energy savings are evaluated with a detailed hydro-thermal model. The technical parameters and the energy efficiency are not the only points of view in the selection process “of best compromise” scenarios for the improvement of the DH, so that we propose a complex decision aiding process, involving multiple criteria, dealing with different points of view (economic, energy, technical...) and different decision makers. The evaluations of the scenarios on the criteria are summed up in a so-called performance table and aggregated by an outranking model (MR-Sort) to identify relevant scenarios.

This methodology is illustrated by the example of a part of the DH in Nantes (France). Interpretation of data from substations of a specific branch showed the potential of connecting some of them to the return pipe. Six scenarios were generated and evaluated with four criteria. Then, the Multi-criteria Decision Aiding method associated to two actors who have different priorities lead to not obvious results at a first glance.

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Selection and peer-review under responsibility of the scientific committee of the 16th International Symposium on District Heating and Cooling, DHC2018.

Keywords: District heating, modelling, Return pipe, Multicriteria decision aiding

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Nomenclature

a	alternative
C	concordance index
c_p	specific heat capacity (J/kg)
d	diameter (m)
g_j	performance criterion j
C_h	class h
k	number of classes
b_h	separation profile between class h and class h+1
H	head (m)
L	length (m)
\dot{m}	mass flow rate (kg/s)
S	outranking relation
T	temperature (°C)
U	convection heat exchange coefficient (W/m ² /°C)

Subscripts

j	criterion index
h	class index
g	ground
in	inlet
out	outlet
p	pipe, primary
s	surrounding, secondary
w	water
0	nominal

1. Introduction

Low operational temperatures (supply and return) with high temperature differences are important conditions for increasing the efficiency of district heating (DH).

Low temperature has direct positive consequences on thermal losses and pumping cost [1, 2]. The reduction of operational temperatures also improves the efficiency of production energy systems and fosters the integration of renewable (solar thermal or heat pumps). In addition, low operational temperatures lead to a better energy efficiency as well as economic gains [3].

Despite its importance the management of temperatures is not simple to handle by DH operators due to various reasons among which the separated management and control of the DH and the secondary distribution networks in the buildings connected to the DH [4]. The secondary networks are designed, managed and controlled by independent operators what can lead to high return temperatures on the DH with limited possible actions for the DH operator. Temperature cascading is one of the possible solution for the DH operator to reduce the operational temperatures.

Temperature cascading aims to take advantage of return temperature complementary to the use of heat from the supply pipe when needed. This aims either to lower the global return temperature of the DH or to integrate new loads to the DH (low temperature loads). The implementation is done directly at the substation [5,6] or thanks to the loads management at the substation [7]. The optimal cascade functioning is conditioned to the different operational

temperatures of successive substations, as well as to an equilibrium between the loads requiring the use the supply pipe and the ones compatible with a connection to the return pipe [7]. In their study, Köfinger et al.[6] compared different configuration for connecting additional low temperature substations to an existing DH. Their work demonstrates the interest of cascading with a decrease of the return temperature whatever the scenario. In their techno-economic analysis Flores et al. [1] evaluated the impact of the penetration rate of Low Temperature substations in conventional DH.

Most of these works are based on simulation tools for which different strategies can be implemented depending on the objectives (simulation, optimization, design, control...). Various works on pseudo-dynamic or dynamic simulations of DH have been carried out with tools dedicated to the modelling of complex energy systems such as TRNSYS, MODELICA, EnergyPlan... to study the whole system performance. Other works focusing more on the distribution used more detailed models based on different numerical schemes (e.g. [8-10]). This type of models generally requires important calculation times due to the level of complexity in the description of the systems. Simplified models can be used when the objective is at the same time to have a good representation of the whole system and to take into account physical variable like temperatures and mass flows [1].

Multi-Criteria Decision Aiding (MCDA) is the study of decision problems, methods and tools which may be used in order to assist one or more Decision Makers (DMs) in reaching a decision when faced with a set of decision alternatives, described via multiple, often conflicting, properties or criteria. Usually, three types of decision problems are put forward in this context [11]: the choice problem, which aims to recommend a subset of alternatives, as restricted as possible, containing the “satisfactory” ones; the sorting problem, whose goal is to assign each alternative into predefined preferentially ordered categories; and the ranking problem, which orders the alternatives by decreasing degree of preferences.

Various models have been proposed to support DMs facing a multi-criteria decision problem [12] and to represent their preferences. Roughly speaking, they originate from two methodological schools. First, in the outranking methodologies, any two alternatives are compared pair-wisely on basis of their evaluations on the set of criteria, according to a majority rule (see for example Roy, 1996 [11]). Second, methods based on multiattribute value theory aim to construct a numerical representation of the DM's preference on the set of alternatives. The main difference between these two methodological schools lies in the way in which the alternatives are compared and the type of information required from the DM. Outranking methods are preferred if the evaluations of the alternatives are primarily qualitative, if the DM would like to include a measure of imprecision about personal preferences in the model, and when a human-readable evaluation model is desired. Value-based methods can be favored if a compensatory behavior of the DM should be modeled, and when the evaluation of the alternatives should be summarized by a single value (as in the case of accounting, for instance). These methodologies are usually integrated in a more general decision aiding process, as described in [13].

In the context of DH systems, the *DMs* are the DH operator (called the *user* later), the consumers and the municipality (as the owner of the DH infrastructure), and the alternatives are the various scenarios to improve the district heating, while the evaluation criteria are the indicators or attributes used to evaluate the various scenarios.

The present work presents a methodology to provide the DMs involved in the DH management with the relevant information for selecting the substations of an existing DH to be connected to the return temperature. The methodology is based on the combination of the analysis of monitored data of the substations, the implementation of a MCDA method to identify the relevance of different scenarios (compounded of technical and non-technical data), and a dynamic hydro-thermal simulation of the DH to assess the energy performance of the different configurations tested.

2. Methodology

2.1. District heating network model

The DHN is represented by an oriented graph where each edge represents two pipes (supply and return) and nodes represents either production units or consumer substations. The model is based on a thermal and hydraulic modeling of pipes and heat exchangers at each node.

The hydraulic model calculates the pressure drops in the pipes and guaranties the mass balances at the nodes. Assuming the water flowing throughout the pipes to be incompressible with constant properties, the hydraulic head loss ΔH in a pipe between nodes i and j can be expressed by:

$$\Delta H = k_{ij} \dot{m}_{ij} |\dot{m}_{ij}| \quad (1)$$

With \dot{m}_{ij} the water mass flow rate in the pipe and k_{ij} the Darcy-Weisbach friction factor. The mass flow balance in each node is given by:

$$\sum_{j \in \{\text{Pr}(i)\}} \dot{m}_{ji} = \sum_{k \in \{\text{Su}(i)\}} \dot{m}_{ik} + \dot{m}_i \quad (2)$$

Where $\{\text{Pr}(i)\}$, $\{\text{Su}(i)\}$ are respectively the predecessors and the successors of the node i and \dot{m}_i is the mass flow rate going to the consumer or to the production unit depending on the node's type.

The thermal model here is a pseudo-dynamic model which takes into account the heat losses from the pipe to the ground. The temperature drops in the pipes are given by:

$$T_{w,out} = T_s + (T_{w,in} - T_s) e^{-\left(\frac{2\pi d g L_p U}{c_p \dot{m}}\right)} \quad (3)$$

The heat exchangers at each node are considered to be adiabatic. The transferred heat power can be calculated using the NTU method while the global heat transfer coefficient was characterized from real data. Then the variation of this coefficient from the nominal U_0 is :

$$\frac{U}{U_0} = C_1 + C_2 \left(\frac{\dot{m}_p}{\dot{m}_{p0}}\right)^\alpha + C_3 \left(\frac{\dot{m}_s}{\dot{m}_{s0}}\right)^\beta \quad (4)$$

Where \dot{m}_{p0} and \dot{m}_{s0} are nominal mass flow rate in the primary and secondary side of the heat exchanger and C_1 , C_2 , C_3 , α and β are constants. In this study, at the secondary side, return temperature are set constant whereas and supply temperatures are controlled based on the outdoor temperature using a linear control curve.

The equations are solved as a whole problem to model the district heating. The unknown variables of this problem are the hydraulic head at each node, the primary supply and return temperature at each node, the mass flow rates in the pipes and the primary and secondary side mass flow rates at the heat exchangers. The known variables are: the loads for all the substations, the power produced by all the production units except one of them (to ensure the energy conservation, this slack node correspond to the energy exchanges with the rest of the DH), the supply temperatures of the producers and return and supply temperatures at the secondary side of the substations. In the case of a substation connected to the return pipe, the mass flow rate $\dot{m}_{p,i}$ entering the heat exchanger is the sum of mass flow rate coming from the supply pipe and the return pipe. Then, the fraction of the mass flow rate from the return pipe over the total mass flow rate flowing in the return pipe is called α . The optimal fraction depends on the temperature of the water at the return pipe, the demand power at the substation and the supply temperature at the secondary side of the heat exchanger. These fractions are optimized at each time step in order to minimize the produced power.

2.2. Multi-criteria Decision Aiding

Among the possible outranking sorting methods, we choose Majority-Rule Sorting (MR-Sort) [15]. The method allows us to build an overall qualitative scale for the evaluation of the scenarios, while presenting a very readable and operational model. It handles very easily a mix of quantitative and qualitative evaluation scales on the criteria. The preferences of the DMs which are used in MR-Sort are represented here through criteria weights, which give the relative importance of criteria, a majority threshold which indicates the weight of a coalition of criteria in order to be considered sufficient and category limits, which are used to delimit the various categories. In more complex versions, veto and dictator profiles [15] are also considered, which allow to represent more precisely the preferential behavior of the DMs.

The basic version of MR-Sort is formalized as follows. Consider a finite set A of decision alternatives (here the scenarios), a finite set of evaluation criteria indexed by J and a set of category limits $B = \{B_1, \dots, B_{k-1}\}$. Each alternative and each category limit is a vector of evaluations with respect to all criteria. The evaluation with respect to criterion j can be viewed as a function $g_j: A \cup B \rightarrow \mathbb{R}$, where $g_j(a)$ denotes the evaluation of alternative $a \in A$ on criterion j and $g_j(b_h)$ denotes the evaluation of category limit $b_h, \forall h \in \{1, \dots, k-1\}$, on criterion j . The set of category limits are used to define a set of k categories $\{C_1, \dots, C_k\}$, ordered by their desirability, from C_1 being the worst category to C_k being the best one. Each category C_h is defined through its upper limit, b_h , and its lower limit, b_{h-1} , with the exception of the worst and best categories, which have only one limit. These categories represent the various levels of the qualitative scale on which the scenarios have to be evaluated. In this section, we assume, without loss of generality, that the performances are supposed to be such that a higher value denotes a better performance. This will not be the case in the final study. Furthermore the performances of the category limits are non-decreasing, i.e. $\forall j \in J, 1 < h < k: g_j(b_{h-1}) \leq g_j(b_h)$.

An alternative a is said to outrank a category limit b_{h-1} if and only if there is a sufficient coalition of criteria supporting the assertion “ a is at least as good as b_{h-1} ”. A coalition of criteria corresponds to a subset of criteria which “agree” on how an alternative compare to a category limit, either being at least as good or strictly worse. To measure this, we define for each criterion j a function $C_j: A \times B \rightarrow \{0,1\}$ which assesses whether criterion j supports that statement or not:

$$\forall j \in J, a \in A, 1 \leq h \leq k: C_j(a, b_{h-1}) = \begin{cases} 1, & \text{if } g_j(a) \geq g_j(b_{h-1}), \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

To assess whether a coalition of criteria is in favor of the outranking or not, $\forall a \in A, 1 \leq h \leq k$, we first define the overall concordance as:

$$C(a, b_{h-1}) = \sum_{j \in J} w_j C_j(a, b_{h-1}) \quad (6)$$

where w_j is the weight of criterion j . The weights are defined so that they are positive and sum up to one. This overall concordance is then compared to a majority threshold λ extracted from the decision-maker's preferences along with the weights. As in this basic version we do not consider any veto rule here, the outranking relation S is then defined as:

$$aSb_{h-1} \Leftrightarrow C(a, b_{h-1}) \geq \lambda \quad (7)$$

If $C(a, b_{h-1}) < \lambda$, the coalition of criteria is not sufficient, the alternative does not outrank the frontier b_{h-1} and will therefore be assigned in a category lower than c_h .

Alternative a is assigned to the highest category it outranks, hence this rule can be written as:

$$a \in c_h \Leftrightarrow aSb_{h-1} \text{ and } aSb_h. \quad (8)$$

In order to model more accurately the preferential behavior of the DMs, several extensions of the MR-Sort model have been proposed in the literature. For example, [15] extended this approach in order to handle large performance

differences (resulting in what is called *dictator* and *veto* effects). These extensions lead to more flexible and more complex models as their number of parameters increases.

Several techniques have been proposed in the literature to determine the parameters of outranking-based multi-criteria sorting models. The DM could provide them directly, which is what we propose to do for the district heating problem presented hereafter. As an alternative, several authors have proposed to find the parameters of the model through the use of assignment examples.

3. Case study

Nantes’ district heating has been recently extended to link more than 380 substations with about 85 km of pipes in 2017 for only 22 km in 2012. It supplies heat to more than 16 000 dwellings and many public facilities (swimming pools, hospital, schools, museums...). The total capacity of heat production units hits 202 MW with an energy mix achieving 84 % of renewable and waste heat (Tab. 1).

Table 1. Nantes DH main production units.

Site	Number of units	Energy source	Technology	Capacity (MWth per unit)
Malakoff	2	Waste	Boiler	15
	2	Biomass (Wood)	Boiler	15
	3	Gas	Boiler	29
La Californie	3	Gas	Boiler	13
	2	Gas	CHP	8
	1	Biomass (Wood)	Boiler	8 (May 2019)

The aim of the study is to evaluate the ability of improving the efficiency of a network by implementing temperature cascades. In that view, a specific branch (Fig.1) of the network located in the East of Nantes Island has been selected since the return temperatures of most of its seven substations are usually over 60 °C: we can observe that the median, first and last quartile of return temperatures at Subs₆, Subs₄, Subs₃, Subs₂ and Subs₁ are between 62 °C and 75 °C (Fig. 2).

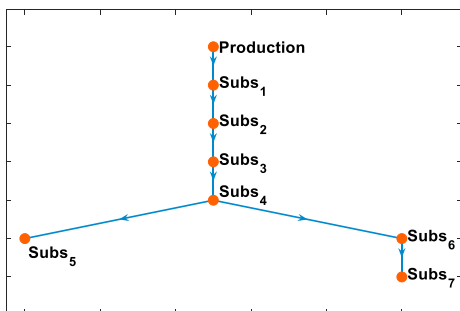


Fig. 1. Branch’s topology.

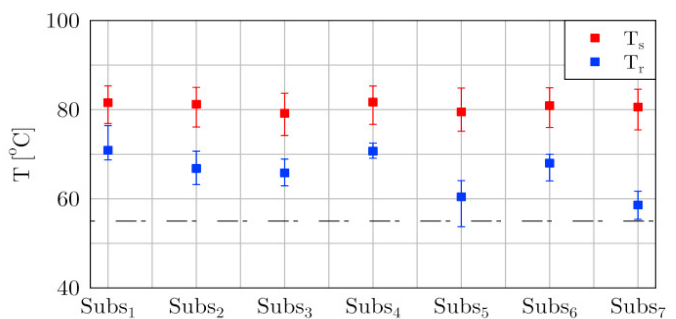


Fig. 2. Median and range between first and third quartile of supply and return temperatures in the branch.

These substations present high heat sources in their return pipe to be valorised, and particularly at Subs₆. We define the heat recovery potential as the difference between the power in the return pipe of a given substation at its functioning temperature and the power at a temperature of 55 °C. We can observe on figure 3 that for the Subs₆ the power varies from 80 kW to 200 kW in winter months, while the consumptions of Subs₄, Subs₃, Subs₂ and Subs₁ are always below 100 kW. It suggests that the high amount of heat available on the return pipe after subs₆ could be used by the other substations by connecting them both to the supply and the return pipe.

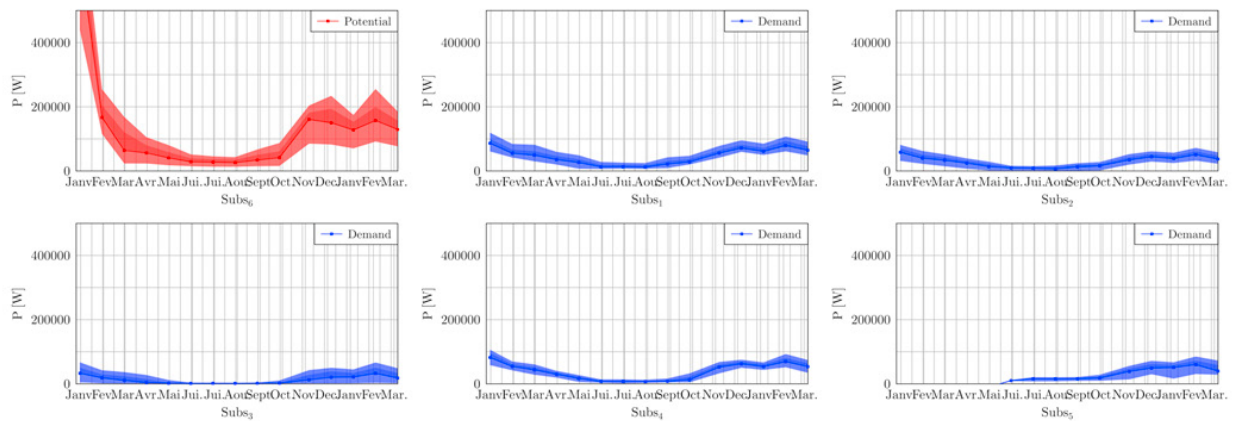


Fig. 3. Heat potential at subs₆ and heat consumptions at Subs₅, Subs₄, Subs₃, Subs₂ and Subs₁ (Median and range between 1st and 3rd quartile)

However, we cannot evaluate such a possibility only by summing the potential and the demands since the temperature cascade implies huge changes in the functioning of the branch and the substations themselves.

4. Results

For each scenario, the input data used in the simulation are demand powers in the substations and the outdoor temperature which is needed to calculate the secondary side supply temperatures using control curves. These data cover a period of 13 days in December/January 2018. The fraction of mass flow rate injected from the return pipe to the substation is calculated at each time step. As an illustration of the results obtained, the Figure 4 presents this fraction for a scenario where 3 substations are connected to the return pipe: Subs₄, Subs₂ and Subs₁. In these curves it is noticed that α in Subs₄ is always greater than those in the Subs₂ and Subs₁. This is due to the fact that Subs₄ is closer to the available heat in Subs₆ and that the temperature at the return pipe is lower as we get farther from Subs₆. This temperature drop is due to two phenomena: the heat losses in the pipes and the mixing with colder water at each substation.

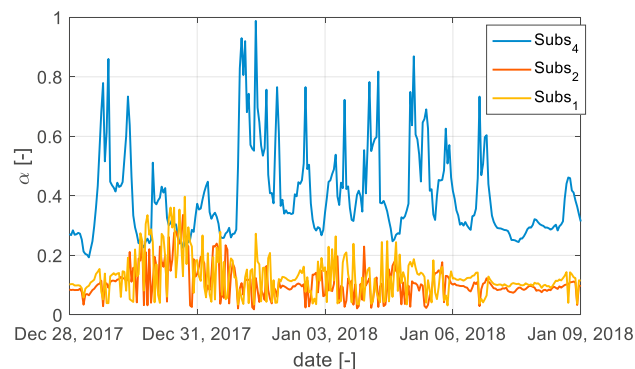


Fig. 4. Optimal fraction of the return mass flow rate injected to the substation

Two distinct decision makers are involved in the decision process of this case study: the *user* (the company that operates the secondary side of the heating network) and the *operator* (the company that operates the primary side of the network). Their goal is to evaluate each of the scenarios on a two-level qualitative scale (“bad”, “good”), i.e. each scenario will be assigned to one of the two ordered classes “bad” or “good” (in terms of the vocabulary of Section 2).

They agree on a set of 4 evaluation criteria of the scenarios (which represent energetic, economic and social perspectives of the problem):

- Criterion g_1 : Energy savings [MWh]. It is calculated as the difference between the energy produced by the production unit for each scenario and a reference case where there is not any substation connected to the return pipe.

- Criterion g_2 : Energy diagnostic of the substation consisting in the yearly energy consumption per heated surface. This criterion expresses the level of priority between connecting the substation to the return pipe and to retrofit the buildings connected to the given substation. For this criteria the results are presented with letters (inspired from the Energy Performance Certificate labels)

- Criterion g_3 : the connection cost. We do the assumption of a constant cost whatever the considered substation so that it is directly linked to the number of substations in the scenario.

- Criterion g_4 : the potential acceptance by the owners. This criterion formalizes the level of difficulty to convince the owners to accept modification in the infrastructure. In that view, we consider a scale from “-“ for strong resistance of the owners in the negotiations (e.g. multi-ownership buildings with many persons to convince), to “++” for low resistance (e.g. buildings owned by the municipality).

The evaluation of each scenario regarding the criteria are summed up in the Table 2:

Table 2. Performance table.

Scenario	Connected substations	g_1	g_2	g_3	g_4
1	Subs ₄	5.93	C	1	-
2	Subs ₄ , Subs ₂ , Subs ₁	6.21	B	3	-
3	Subs ₄ , Subs ₃	6.34	B	2	-
4	Subs ₂	4.73	A	1	-
5	Subs ₁	0.32	B	1	+
6	Subs ₃	0.56	C	1	++

The decision makers agree that criterion g_1 has to be maximized. Criterion g_2 is recoded on the following integer scale (A=1, B=2, C=3) and has to be minimized. Criterion g_3 has to be minimized, and finally, criterion g_4 is recoded on the following integer scale (-- = -1, neutral = 0, + = 1, ++ = 2), and has therefore to be maximized.

The *user* DM considers that a good value should be above 3MWh on criterion g_1 , below 2 on criterion g_2 , and below 3 on criterion g_3 . As he is not taking into account criterion g_4 when he evaluates the various scenarios, these evaluations are not important to him. This defines the separation profile between the categories “good” and “bad” for him. Besides, he cannot make a decision based on only one of the remaining three criteria. But if a scenario is good on criterion g_2 , then it is enough for him that it is good on either g_1 or g_3 to be considered on the overall as a good scenario. Finally, being good on g_1 and g_3 alone is not sufficient for him to evaluate the scenario as good. This defines the weights of the criteria, together with the majority threshold λ for this DM.

The *operator's* profile is a bit different. A good value on g_1 is above 2MWh, on g_2 below 2, on g_3 below 1, and on g_4 above 0. Again, this gives us the separation profile between the “good” and the “bad” classes. For him g_1 is clearly the most important criterion, and if a scenario is good on g_1 and either g_2 or g_4 , the scenario can be considered as good on the overall. If, however the scenario is not good on g_1 , then it should be good on the remaining 3 criteria to be evaluated as good. And finally, if a scenario is below 0.4 on g_1 , then it definitely cannot be considered as good on the overall, however good it has been evaluated on the remaining criteria. From these statements, we can deduce the weights of the criteria together with the majority threshold for this DM.

All in all, these preferential information lead to the preferential parameters of Tables 3 and 4.

Table 3. Weights, veto and majority threshold.

Decision maker	g_1	g_2	g_3	g_4	λ
User	0.25	0.50	0.25	0	0.75
Operator	0.40	0.20	0.10	0.30	0.60
Operator veto thresholds	0.40	NA	NA	NA	

Table 4. Separation profiles

Decision maker	g_1	g_2	g_3	g_4
User	3	2	3	0
Operator	2	2	2	0

For the user, the simple MR-Sort model described in Section 2 is applied to evaluate the scenarios. For the operator however, as the notion of veto has to be taken into account (no good scenario should be below 0.4 on g_1). Therefore, a classical extension of MR-Sort is used including this notion of veto. The results of the assignment are given in the following Table 5:

Table 5. Results of the assignment.

Decision maker\Scenario	1	2	3	4	5	6
User	"Bad"	"Good"	"Good"	"Good"	"Good"	"Bad"
Operator	"Bad"	"Good"	"Good"	"Good"	"Bad"	"Bad"

Consequently, a compromise decision would be to consider that scenarios 2, 3 and 4 are evaluated as "Good", as both decision makers agree. This decision aiding process should simplify their decision on which of these 3 scenarios should be implemented in practice, in order to improve the DH of this part of the city of Nantes.

It is interesting to notice that the reasons why these scenarios have been evaluated as "good" by the 2 DMs may not be the same for both of them. For example, scenario 4 has been evaluated as "good" for the *user* DM, because it is considered as good on g_2 and g_3 , which is sufficient for this DM. However, this same scenario is evaluated as "good" for the *operator* DM, because it is considered as good on the first 3 criteria, which again is sufficient for this DM. This underlines the importance of modeling the preferences of the DMs in such a process accurately, as the results depend a lot on the preferential parameters.

5. Conclusion

This work presents the interest of coupling MCDA methods with modelling tools for improving the existing DH by connecting relevant substations to the return pipe.

The MCDA method combines the information given by energy indicators by taking into account various criterion associated to divers actors who can have different points of view on the importance to be allocated to each indicator. The results show the coupled methods enable to identify strategies not obvious at a first glance and provide useful information for discussion between the different stakeholders. The proposed methodology in the example of a single branch is replicable to the whole DH as well as the list of criteria and points of view can be broaden depending of the case studied and the actors involved.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement N° 731297. This document reflects only the author's view and the European Commission (Innovation

and Networks Executive Agency) is not responsible for any use that may be made of the information it contains. The authors are grateful to ERENA, the operator of Nantes district heating, for their collaboration in the EU programme MySMARTLife.

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