10th International Symposium on District Heating and Cooling

September 3-5, 2006

Monday, 4 September 2006

Sektion 4 b

Conceptions, drafts and studies in district heating and cooling

Design and optimization of district energy systems

C. Weber, F. Maréchal, D. Favrat,
Ecole Polytechnique Fédérale de Lausanne/Switzerland

Design and optimization of district energy systems

Céline Weber[1]*, François Maréchal[1], Daniel Favrat[1]

[1] Ecole Polytechnique Fédérale de Lausanne, LENI-ISE-STI, Bât. ME A2, Station 9, 1015 Lausanne, Switzerland Tel.: +41 21 693 35 13, Fax: +41 21 693 35 02, celine.weber@epfl.ch , francois.marechal@epfl.ch , daniel.favrat@epfl.ch

Abstract

District energy systems have the potential to decrease the CO_2 emissions linked to energy services (heating, cooling, electricity and hot water), in particular when implementing large polygeneration energy conversion technologies, connected to a group of buildings over a network. However, this cannot be done without any cost considerations. The synthesis of district energy systems, including not only the design of the energy conversion technologies but also the design of the distribution network, thus minimizing cost and CO_2 emissions, is not a trivial task. The problem requires a large number of integer and continuous variables involved in non linear models, resulting in a mixed integer non linear programming problem (MINLP). A new method is being developed to design district energy systems, by decomposing the multi-objective optimization problem in a way similar to Bender's decomposition, and to solve two optimization problems: a master problem and a slave problem. In this paper, the method developed as well as the first partial results (the results of the slave problem) are presented.

Keywords: District energy system, District heating, Network synthesis, MILP, Costs, CO_2 emissions.

1 Symbols

Roman letters

An	Annuities for a given investment [-]
$A_{i,j,p}$	Area of the pipe between nodes i and j of network p [m^2]
B	Arbitrarily big value
C^{aw}	Investment costs for air/water heat pump(s) [CHF]
C^{boiler}	Annual investment costs for the boiler(s) [CHF/year]
C^{fix}	Fix part of the investment costs for a given device [CHF]
C^{gas}	Total annual natural gas costs [CHF/year]
c^{gas}	Natural gas costs [CHF/kWh]
C^{grid}	Total annual grid costs [CHF/year]
c^{grid}	Grid costs [CHF/kWh]
C^{inv}	Investment costs of a given device [CHF]
$C^{\text{inv}}_{\text{an}}$	Annual investment costs of a given device [CHF/year]
C^{pipes}	Total annual costs for the piping [CHF/year]
C^{prop}	Fix part of the investment costs for a given device [CHF/kW]
C^{ref}	Investment costs of a device chosen as reference [CHF]
C^{ww}	Investment costs for water/water heat pump(s) [CHF]
$CO_2{}^{\text{gas}}$	Total annual CO_2 emissions due to the combustion of natural gas [kg/year]
$co_2{}^{\text{gas}}$	CO_2 emissions due to the combustion of natural gas [kg/kWh]
$CO_2{}^{\text{grid}}$	Total annual CO_2 emissions due to the consumption of electricity from the grid [kg/year]
$co_2{}^{\text{grid}}$	CO_2 emissions due to the consumption of electricity from the grid [kg/kWh]
COP^{hp}	Coefficient of performance of the central heat pump
$COP^{\text{aw}}_{t,k}$	Coefficient of performance for the air/water heat pump during period t at node k [-]
$COP^{\text{ww}}_{t,k}$	Coefficient of performance for a water/water heat pump during period t at node k [-]
cp	Isobaric specific heat [kJ/(K· kg)]
$Dist_{i,j}$	Distance between nodes i and j [m]
H_t	Number of hours in period t [hour]
$E^{\text{cons}}_{t,k}$	Electricity consumption during period t at node k [kW]
$E^{\text{exp}}_{t,e}$	Eletricity exported to the grid during period t by device e [kW]
$E^{\text{grid}}_{t,k}$	Electricity bought from the grid during period t by node k [kW]
$E^{\text{aw}}_{t,k}$	Electricity consumed by the air/water heat pump during period t at node k [kW]
$E^{\text{ww}}_{t,k}$	Electricity consumed by the water/water heat pump during period t at node k [kW]
E^{loss}_{t}	Electricity losses during period t [kW]
E^{pump}_{t}	Pumping power for the network during period t [kW]
$E^{\text{tech}}_{t,k,e}$	Electricity produced or consumed during period t at node k by device e [kW]
F_s	Scaling factor [-]
F_m	Maintenance factor [-]
Gas_t	Natural gas consumption during period t [kg]
L^{min}_{e}	Minimum allowable part-load of device e [-]
$M^{\text{build}}_{t,k}$	Water circulating during period t through the building at node k, to heat it up [kg/s]
$M^{\text{pipe}}{}_{t,i,j,p}$	Water flowing during period t, from node i to node j, in network p [kg/s]
$M^{\text{max}}{}_{i,j,p}$	Maximum flow of water between nodes i and j, in network p, over all periods [kg/s]
$M^{\text{tech}}_{t,k}$	Water being heated up by the device(s) during period t, at node k [kg/s]
$MT^{\text{tech}}_{t,k}$	Water flowing through a device during period t at node k to be re-heated, times its temperature [(kg/s)K]

$MT^{\text{pipe}}_{t,i,j,p}$	Water flowing during period t from node i to node j in the network p, times its temperature [(kg/s)K]
N	Expected lifetime for a given investment [year]
P_{loss}	Pressure losses in the pipes [Pa/m]
$Q^{\text{aw}}_{t,k}$	Heat delivered by the air/water heat pump during period t, at node k [kW]
$Q^{\text{boiler}}_{t,k}$	Heat delivered by the boiler during period t, at node k [kW]
$Q^{\text{cons}}_{t,k}$	Heat consumption during period t, at node k [kW]
$Q^{\text{net}}_{t,k}$	Heat delivered by the network during period t, at node k [kW]
$Q^{\text{net\_ww}}_{t,k}$	Heat delivered by the network to the water/water heat pump during period t, at node k [kW]
$Q^{\text{tech}}_{t,k,e}$	Heat produced during period t, at node k, by device e [kW]
$Q^{\text{ww}}_{t,k}$	Heat delivered by an water/water heat pump to the consumer at node k during period t [kW]
r	Interest rate [-]
S	Design size of a given device [kW]
S^{aw}_{k}	Design size of the air/water heat pump located at node k [kW]
S^{boiler}_{k}	Design size of the boiler at node k [kW]
S^{nom}_{e}	Design size of a device [kW]
S^{ref}	Size of a device chosen as reference [kW]
S^{ww}_{k}	Design size of the water/water heat pump located at node k [kW]
T^{atm}	Atmospheric temperature [K]
T^{cold}	Temperature of the heat source for heat pumps [K]
T^{cond}	Temperature at the condenser of a heat pump [K]
$T^{cons}_{t,k}$	Temperature at which the heat is required by the consumer during period t, at node k [K]
T^{hot}	Temperature of the heat sink for heat pumps [K]
T^{net}	Design supply temperature of the network [K]
v	Velocity of the water through the pipes [m/s]
X	= 1 if a device exists, 0 otherwise
X^{aw}_{k}	= 1 if there is an air/water heat pump at node k, 0 otherwise
X^{boiler}_{k}	= 1 if there is a boiler at node k, 0 otherwise
X^{gas}_{e}	= 1 if device e needs natural gas to operate, 0 otherwise
X^{tech}_{k}	= 1 if a device can be implemented at node k, 0 otherwise
$X^{\text{node}}_{k,e}$	= 1 if device e is implemented at node k, 0 otherwise
X^{ww}_{k}	= 1 if there is an water/water heat pump at node k, 0 otherwise
$Y_{i,j,p}$	= 1 if a connection exists between i and j for network p , 0 otherwise

Greek letters

ΔT^{heat}	Pinch at the heat-exchangers [K]
$\Delta T^{\text{net\_ww}}$	Temperature difference of the water in the network if used as heat source in water/water heat pumps [K]
ϵ^{boiler}	Thermal efficiency of the boiler(s) [-]
ϵ^{el}_{e}	Electric efficiency of device e [-]
ϵ^{grid}	Efficiency of the grid [-]
ϵ^{th}_{e}	Thermal efficiency of device e [-]
η	Exergetic efficiency [-]
ρ	Density [kg/m3]

Indices

k nodes
i, j connection from node i to node j
t time
e device
p network (*to*: from the plant to the building(s), *ret*: from the buildings back to the plant)

2 Introduction

The reduction of CO_2 emissions is a challenge for the coming decade, especially with the implementation of the Kyoto protocol. Beside transportation, heating and cooling are responsible for a large share of the total greenhouse gas emissions. For example in Switzerland, heating alone generates over 40% of the total emissions (all energy sectors considered, including transportation) [3] and [12], making it a priority candidate among energy services when considering ways to decrease the overall emissions of Switzerland. An energy service will be considered hereafter as a comfort requested by a customer and that can be met through energy. An energy service can be typically heating, cooling, electricity or hot water. To decrease the emissions generated by heating, one way is to increase the efficiency of the different energy conversion technologies that provide heating, by combining them in a polygeneration energy system. A polygeneration energy system is a system that generates more than just one single energy service. Advanced systems allow to save over 60% of the energy resources and emissions compared to conventional solutions [12]. However, to ensure that polygeneration systems operate as often as possible at or near their optimal load, they should be implemented so as to meet the requirements of more than just one building. By doing so, one can take advantage of the various load profiles of the buildings by compensating the fluctuations and having therefore a smoother operation. Besides, because these systems are complex and defacto difficult to operate, there are usually not justified in an individual building where no continuous professional control can be guaranteed. It is much more advantageous to implement them in a small plant that serves several buildings, and that is managed for instance by an energy service company. The resulting system with one (or more) polygeneration energy conversion technologies, together with the network connecting the technologies and the different buildings, is called district energy system.

Unlike district heating systems, that provide only heating, district energy systems have not yet been much studied. District heating systems are often implemented when excess heat, from a geothermal source or from the combustion of waste for instance, is to be recycled. In the latter case, the system can also be designed to generate electricity. The majority of the literature on district heating systems concerns the optimization (mainly financial) of the operation strategies and/or the thermo-economic optimization of the energy conversion technologies ([15], [5], [20], [4], [16], [18], [9]), as well as the energetic and/or exergetic performance of the complete district heating system ([13], [6]). In nearly all of these papers, the distribution network of the analysed district heating system already exists. Its design is only seldom mentioned, and if ever, then in a very simplified manner. One reason for the researchers not to be more interested in the design of distribution networks could be the believe by some of them that the design of the distribution network is anyway solved by politicians and urban planners, without involving any quantitative support [4], and that it is therefore useless to include the design of the distribution network when studying the thermo-environomic optimization of district energy systems. However, it is the believe of the authors that politicians and urban planners could be interested in using quantitative support, if they had the tools to do so. Söderman has studied the design of distributed energy systems [17] and developed a tool for decision makers. However the study doesn't take into account the temperature levels at which the energy services have to be delivered. Friedler et al. studied process synthesis and optimization for the chemical industry [7]-[8], and it would be possible, considering some analogies and modifications, to adapt his method to district energy systems. In fact his works do not take into account any spatial constraints regarding the location of the technologies. Besides, the chemical processes that are designed are of the continuous type, whereas district energy systems are more related to a batch type operating mode (the energy requirements vary from one period to the other).

In this paper a new method is developed that combines the design of the network together with the design of the technologies that are best suited to meet the energy requirements of the district. The method takes into account the *spatial* and *temporal* aspects that are characteristic of district energy systems, as well as the temperature levels at which the energy services are requested.

3 Method for the configuration of district energy systems

The method developed addresses following question: How shall a district energy system, a system that comprises the energy conversion technologies that transform the primary energy into the requested form (heating, cooling, electricity and hot water), and the distribution network from the plant to the customers, be designed, to minimze the overall costs and the CO_2 emissions while delivering the hourly energy services requested by the customers?

The design of such a district energy system is complex, for several reasons:

1. District energy systems combine spatial (location of the buildings) and temporal (consumption profiles) aspects.
2. The number of the various combinations of different locations and sizes of energy plants is high.
3. The consumption profiles of the different energy services vary during the day, and from one day to the other, in a stochastic manner. Because of these stochastic variations the problem becomes a multi-period problem, which is much more complex than if the requirements remained unchanged with respect to time or changed in a deterministic way.
4. The temperature level at which a building requires heating or cooling needs to be considered. Since this temperature level can vary from building to building, and even from period to period for a same building, the problem cannot be solved by making only energy balances.
5. There are usually a lot of different ways to link the buildings together and the diameters of the pipes are usually defined by a given, non continuous set of possible diameters.
6. The number of security and spatial constraints due to already existing equipment (for instance a technical gallery in which wires for telecommunication are implemented) is usually large in a city.

The method developped (fig. 1) comprises a structuring phase in which all the relevant data regarding the district considered are gathered, an optimization phase in which the optimal district energy system is designed, and a post-processing phase in which the total costs and CO_2 emissions of the the system are computed. Due to the complexity of the analysed problem, the opimization phase is decomposed in a master optimization and a slave optimization, similar to the Benders' decomposition. This decomposition could already be successfully implemented in a previous study on the optimal operation management of an SOFC-based energy system for a building downtown Tokyo [19].

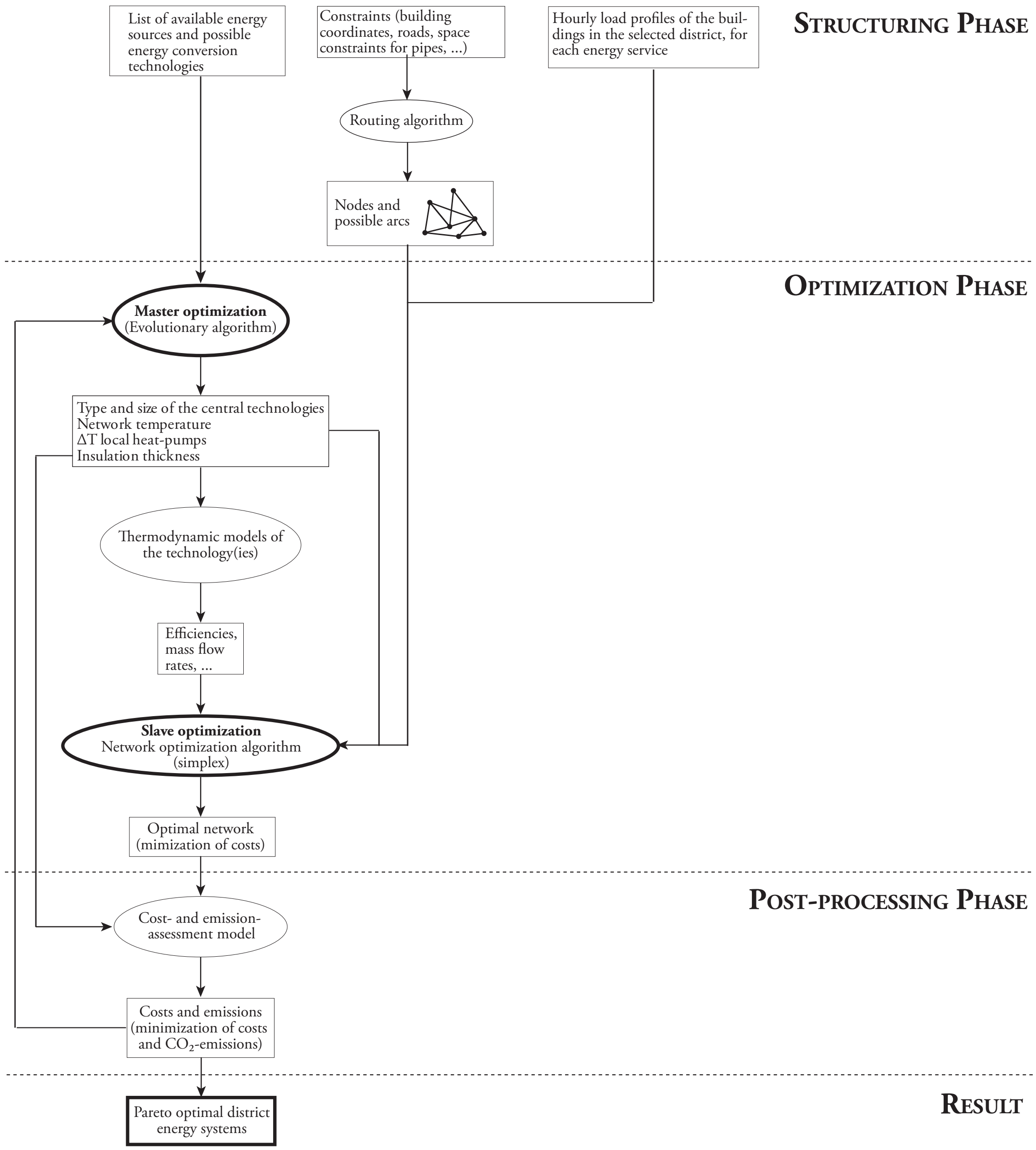

Figure 1: Resolution strategy

4 Structuring phase

At the beginning of the method, there is a structuring phase, in which all the relevant information regarding the district for which an energy system needs to be developed, is gathered, processed where needed, and further given as inputs to the different algorithms belonging to the method. If the types of inputs remain the same regardless of the location of the district analysed, the content of these three different inputs will vary greatly with the location. The three types of inputs are:

1. The list of available technologies: This corresponds to the list of possible *central* technologies, that provide the network with energy. To establish this list, a comprehensive analysis of the available energy sources has to be performed. For instance, if the district is situated in the vicinity of a lake or a river, heat pumps will be part of the list of technologies. Besides, if geothermal energy is available, an organic rankine cycle can be implemented. On the other hand, considering wind mills in a city like Geneva to produce electricity, will not lead to a feasible solution, due to the unfavorable wind conditions in Geneva.
   As will be explained later, there will also be some *local* technologies available (small heat pumps and boilers). The local technologies are implemented directly in the building they serve, in case the network cannot meet the energy requirements of this building (for instance if the temperature level at which the heat is required by the building is above the temperature level of the network). These local technologies are more comparable to back-up devices, and are not treated in this phase of the method.

2. Spatial (geographical) constraints: In many cases, the district energy system has to fit in an existing quarter, village or small town. Therefore constraints such as the coordinates of the buildings, the layout of the roads, space constraints in existing technical galleries, constraints due to the quality of the soil... have to be taken into account in the design procedure. Usually these informations will not be readily available and usable by the network optimization algorithm. A so-called routing algorithm will therefore take over the task of generating a structure with all the buildings, the possible connections and the spatial restrictions, that is readable by the network optimization algorithm. Typically a pipe will for instance not be allowed to follow the shortest way between two buildings, as this way might pass right across another building. There are certain routes that have to be followed, as shown in figure 2. Finally, specific laws or regulations might exclude certain solutions if these solutions do not respect given parameters.

3. Consumption profiles: The consumption profiles for the different energy services need to be known in order to design the layout of the network, the pipes, and the pieces of equipment properly. For heating and cooling it is important not only to know the amount of energy required, but also the temperature at which this energy needs to be provided and the requested power. Usually, these profiles are not only difficult to obtain, they also contain large uncertainties due to their stochastic nature.

5 Optimization phase

The optimization phase is decomposed into two sub-problems, a master problem and a slave problem. Both problems, the master and the slave, are solved using optimization algorithms.

The master problem is solved using a multi-objective evolutionary algorithm, the two objectives being the minimization of costs and CO_2 emissions. It is responsible for the optimal choice of following parameters:

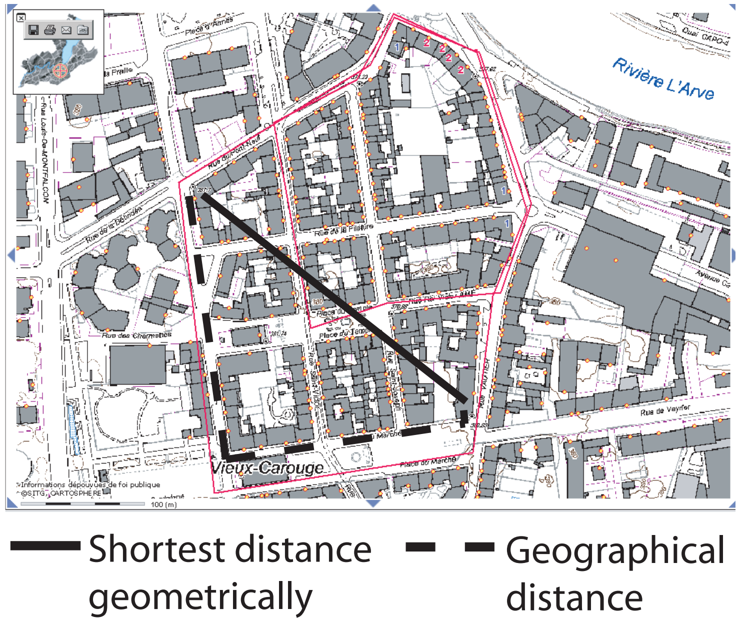

Figure 2: Difference between the fixed distance that has to be considered between two buildings, and the shortest distance geometrically

1. the type and size of the technologies (for the case studied in this paper, the possible technologies are a water/water heat pump and a gas tubine (combined or not with the heat pump)),
2. the temperature of the fluid in the ongoing-pipes of the network, the pipes that go from the heating plant to the buildings (this temperature is called hereafter *network temperature*),
3. the temperature difference of the network, between the ongoing-pipe and the return-pipe, if a local heat pump needs to be implemented in a building to elevate the temperature of the network (seen from the local water/water heat pump, this corresponds to the temperature difference of the heat source in the evaporator).
4. the thickness of the insulation around the pipes.

The choice of these parameters is based on the inputs given from the structuring phase, and the results of the optimization of the slave problem.

The slave problem is solved using the simplex-algorithm, the objective being the minimization of the costs. It is responsible for the best possible layout of the district energy system and the optimal operating strategy, given the outputs generated by the evolutionary algorithm, the output from the rooting algorithm, and the consumption profiles. It is worth noticing at this stage that some parameters generated by the evolutionary algorithm are passed directly to the slave problem (items 2 and 3), whereas the type and size of the technologies are first passed to the thermodynamic models to compute parameters such as the efficiencies and mass flow rates of the energy conversion technologies. Finally, in order to keep the slave-problem linear so it can be solved with the simplex-algorithm, the thickness of the insulation is not used directly in the slave-problem (the calculation of the heat-losses being a non linear task). It is used in the post-processing algorithm.

5.1 The multi-objective evolutionary optimizer

The multi-objective evolutionary optimizer used for this study was developed at the Laboratory of Industrial Energy Systems at the Ecole Polytechnique Fédérale de Lausanne [10]. This optimizer uses the technique of the evolutionary algorithms to compute the trade-offs between multiple objectives. In our case, two objectives have to be minimized: the costs (including operation and investment) and the CO_2 emissions. In order to find the optimal configurations with the best performances in terms of CO_2 emissions and costs, the evolutionary algorithm creates a population of individuals (a set of decision variables that define a complete system configuration and the sizes of the equipment) by choosing randomly, for each individual, a set of values (genome) representing the decision variables. The "scores" or performances of each individual are then computed using the resolution method described previously. New individuals are then selected based on the scores of the existing individuals, using a set of combination operators such as mutation and crossover. After the evolution process is continued sufficiently, keeping the best individuals in the non-dominated set (according to CO_2 emissions and costs), the optimal solutions can be found. This multi-objective strategy results in an estimation of the Pareto optimal frontier (hereafter Pareto curve) that represents the set of optimal points that can be considered to be optimal in terms of one or both of the two objectives. Each point of this curve corresponds to a set of decision variables that define one configuration of the system and the optimal way of operating it on a yearly basis.

5.2 Thermodynamic models of the technologies

The method presented allows the use of thermodynamic models with various degrees of details. However, when designing and optimizing the entire energy system, there is no need in spending much time using very detailed models. For the current study, the following simple relations were implemented:

1. Heat pump:
$$COP^{hp} = \eta \cdot \frac{T^{\text{hot}}}{T^{\text{hot}} - T^{\text{cold}}}$$
assuming that $T^{\text{cold}}= T^{\text{atm}}$.

2. Gas turbine [11]:
$$\epsilon_e^{\text{el}} = 0.1468 + 0.0179 \cdot \log(S)$$
$$\epsilon_e^{\text{th}} = 0.8 - \epsilon_e^{\text{el}}$$
S being the size of the gas turbine [kWel], ϵ_e^{el} and ϵ_e^{th} the electrical respectively thermal efficiency.

5.3 The network optimzation algorithm

The network optimization algorithm is a mixed integer linear programming model implementing the AMPL programming language [1] and the Cplex solver [2]. The algorithm minimizes the costs comprising the investment for the piping, and the operating costs (gas and grid). Besides, if the choice of technologies provided by the evolutionary optimizer is not sufficient to meet all the heating requirements, or if the network temperature is below the required heating temperature, the network optimization algorithm can choose to implement some additional *local* heat pumps or boilers. The costs for these local devices are likewise computed by the network optimization algorithm. These devices are dedicated to the building in which they are implemented and do not provide any heat to the other buildings. The local heat pumps can be **water/water** heat pumps if they are used to locally rise the temperature level of the network, or **air/water** heat pumps if the building is not connected to the network (for instance if the building is located too far away from the heating plant to justify a connection).

$$\min\left(C^{\text{gas}} + C^{\text{grid}} + C^{\text{pipes}} + C^{\text{ww}} + C^{\text{aw}} + C^{\text{boiler}}\right) \tag{1}$$

Under the constraints:
Energy balances:

$$Q^{\text{cons}}_{t,k} = Q^{\text{net}}_{t,k} + Q^{\text{ww}}_{t,k} + Q^{\text{aw}}_{t,k} + Q^{\text{boiler}}_{t,k} \qquad \forall t,k \tag{2}$$

$$\sum_{(k,j)} MT^{pipe}_{t,k,j,ret} = \begin{cases} \left(\sum\limits_{(i,k)} MT^{pipe}_{t,i,k,ret}\right) + \left(M^{\text{build}}_{t,k}\cdot\left(T^{cons}_{t,k}+\Delta T^{\text{heat}}\right)\right) - MT^{\text{tech}}_{t,k} & \text{if } \left(T^{cons}_{t,k}+\Delta T^{\text{heat}}\right) \le T^{\text{net}} \\ \left(\sum\limits_{(i,k)} MT^{pipe}_{t,i,k,to}\right) + \left(M^{\text{build}}_{t,k}\cdot\left(T^{\text{net}}-\Delta T^{\text{net\_ww}}\right)\right) - MT^{\text{tech}}_{t,k} & \text{else} \end{cases} \qquad \forall t,k \tag{3}$$

$$\sum_{(k,j)} MT^{pipe}_{t,k,j,to} = \sum_{(i,k)} MT^{pipe}_{t,i,k,to} + \left(M^{\text{tech}}_{t,k}\cdot T^{\text{net}}\right) - \left(M^{\text{build}}_{t,k}\cdot T^{\text{net}}\right) \qquad \forall t,k \tag{4}$$

$$\sum_{e} Q^{\text{tech}}_{t,k,e} = \left(cp\cdot M^{\text{tech}}_{t,k}\cdot T^{\text{net}}\right) - \left(cp\cdot MT^{\text{tech}}_{t,k}\right) \qquad \forall t,k \tag{5}$$

$$Q^{\text{net\_ww}}_{t,k} = \left(1 - \frac{1}{COP^{\text{ww}}_{t,k}}\right)\cdot Q^{\text{ww}}_{t,k} \qquad \forall t,k \tag{6}$$

Coefficients of performance:

$$COP^{\text{ww}}_{t,k} = \eta\cdot\frac{\left(T^{cons}_{t,k}+\Delta T^{\text{heat}}\right)}{\left(T^{cons}_{t,k}+\Delta T^{\text{heat}}\right) - T^{\text{net}}} \qquad \forall t,k \tag{7}$$

$$COP^{\text{aw}}_{t,k} = \eta\cdot\frac{\left(T^{cons}_{t,k}+\Delta T^{\text{heat}}\right)}{\left(T^{cons}_{t,k}+\Delta T^{\text{heat}}\right) - T^{\text{atm}}} \qquad \forall t,k \tag{8}$$

Mass balances:

$$M^{\text{build}}_{t,k} = \frac{Q^{\text{net}}_{t,k}}{cp\cdot\left(T^{\text{net}} - \left(T^{cons}_{t,k}+\Delta T^{\text{heat}}\right)\right)} + \frac{Q^{\text{net\_ww}}_{t,k}}{cp\cdot\Delta T^{\text{net\_ww}}} \qquad \forall t,k \tag{9}$$

$$\sum_{(i,k)} M^{\text{pipe}}_{t,i,k,ret} = \sum_{(k,j)} M^{\text{pipe}}_{t,k,j,ret} - M^{\text{build}}_{t,k} + M^{\text{tech}}_{t,k} \qquad \forall t,k \tag{10}$$

$$\sum_{(k,j)} M^{\text{pipe}}_{t,k,j,to} = M^{\text{tech}}_{t,k} + \sum_{(i,k)} M^{\text{pipe}}_{t,i,k,to} - M^{\text{build}}_{t,k} \qquad \forall t,k \tag{11}$$

Electricity balances:

$$\sum_k E^{\text{cons}}_{t,k} + E^{\text{pump}}_t + \sum_k (E^{\text{ww}}_{t,k} + E^{\text{aw}}_{t,k}) + E^{\text{loss}}_t = E^{\text{grid}}_{t,k} + \sum_e E^{\text{tech}}_{t,k,e} \qquad \forall t \tag{12}$$

$$E^{\text{tech}}_{t,k,e} = \frac{\sum_k Q^{\text{tech}}_{t,k,e}}{\epsilon^{\text{th}}_e} \cdot \epsilon^{\text{el}}_e \qquad \forall t,k,e \tag{13}$$

$$E^{\text{exp}}_{t,e} \leq E^{\text{tech}}_{t,k,e} \qquad \forall t,k,e \tag{14}$$

$$E^{\text{loss}}_t = \sum_e (1 - \epsilon^{\text{grid}}) \cdot E^{\text{exp}}_{t,e} \qquad \forall t \tag{15}$$

$$E^{\text{ww}}_{t,k} = \frac{Q^{\text{ww}}_{t,k}}{COP^{\text{ww}}_{t,k}} \qquad \forall t,k \tag{16}$$

$$E^{\text{aw}}_{t,k} = \frac{Q^{\text{aw}}_{t,k}}{COP^{\text{aw}}_{t,k}} \qquad \forall t,k \tag{17}$$

$$E^{\text{pump}}_t = \sum_{(i,j)} \left(\sum_P \frac{M^{\text{pipe}}_{t,i,k,p} \cdot Dist_{i,j} \cdot P_{\text{loss}}}{\rho} \right) \qquad \forall t \tag{18}$$

Location of the central technologies:

$$Q^{\text{tech}}_{t,k,e} \geq X^{\text{node}}_{k,e} \cdot X^{\text{tech}}_k \cdot S^{\text{nom}}_e \cdot L^{\text{min}}_e \qquad \forall t,k,e \tag{19}$$

$$Q^{\text{tech}}_{t,k,e} \leq X^{\text{node}}_{k,e} \cdot X^{\text{tech}}_k \cdot S^{\text{nom}}_e \qquad \forall t,k,e \tag{20}$$

$$X^{\text{node}}_{k,e} \leq X^{\text{tech}}_k \qquad \forall k,e \tag{21}$$

$$\sum_k X^{\text{node}}_{k,e} \leq 1 \tag{22}$$

Sizes and number of the local technologies:

$$Q^{\text{ww}}_{t,k} \leq S^{\text{ww}}_k \qquad \forall t,k \tag{23}$$

$$S^{\text{ww}}_k \leq X^{\text{ww}}_k \cdot B \qquad \forall k \tag{24}$$

$$Q^{\text{aw}}_{t,k} \leq S^{\text{aw}}_k \qquad \forall t,k \tag{25}$$

$$S^{\text{aw}}_k \leq X^{\text{aw}}_k \cdot B \qquad \forall k \tag{26}$$

$$Q^{\text{boiler}}_{t,k} \leq S^{\text{boiler}}_k \qquad \forall t,k \tag{27}$$

$$S^{\text{boiler}}_k \leq X^{\text{boiler}}_k \cdot B \qquad \forall k \tag{28}$$

Pipes:

$$M^{\text{pipe}}_{t,i,j,p} \leq M^{\text{max}}_{i,j,p} \qquad \forall t,i,j,p \tag{29}$$

$$M^{\max}_{i,j,p} \leq Y_{i,j,p} \cdot B \qquad \forall t,i,j,p \tag{30}$$

$$A_{i,j,p} = \frac{M^{\max}_{i,j,p}}{v \cdot \rho} \qquad \forall i,j,p \tag{31}$$

$$Y_{i,j,to} = Y_{i,j,ret} \qquad \forall i,j \tag{32}$$

Gas consumption:

$$Gas_t = \sum_k \left(\sum_e \frac{Q^{\text{tech}}_{t,k,e} \cdot X^{\text{gas}}_e}{\epsilon^{\text{th}}_e} \right) + \sum_k \frac{Q^{\text{boiler}}_{t,k}}{\epsilon^{\text{boiler}}} \qquad \forall t \tag{33}$$

Cost functions:

$$C^{\text{grid}} = \sum_t \sum_k E^{\text{grid}}_{t,k} \cdot H_t \cdot c^{\text{grid}} \tag{34}$$

$$C^{\text{gas}} = \sum_t Gas_t \cdot H_t \cdot c^{\text{gas}} \tag{35}$$

$$An = \frac{r \cdot (1+r)^N}{(1+r)^N - 1} \tag{36}$$

$$C^{\text{inv}}_{\text{an}} = (1 + F_m) \cdot An \cdot \left(\left(X \cdot C^{\text{fix}} \right) + (S \cdot C^{\text{prop}}) \right) \tag{37}$$

CO_2 functions:

$$CO_2{}^{\text{gas}} = \sum_t Gas_t \cdot H_t \cdot co_2{}^{\text{gas}} \tag{38}$$

$$CO_2{}^{\text{grid}} = \sum_t E^{\text{grid}}_{t,k} \cdot H_t \cdot co_2{}^{\text{gas}} \tag{39}$$

Eq. 36 and 37 are the general equations for investment costs. They apply to the piping and all local technologies for which the existance is defined in the network optimzation algorithm (slave problem), namely the two types of heat pumps and the boilers. The costs for the central energy conversion technologies are computed in the post-processing algorithm. Since the CO_2 emissions are directly related to the operation strategy (the emissions related to the manufacturing of the devices are negligible [19]), they can be computed directly in the network optimzation algorithm.

Following factors have been used in eq. 38 and 39:
$co_2{}^{\text{gas}}$ (0.225 kg-CO_2/kWh), $co_2{}^{\text{grid}}$ (0.554 kg-CO_2/kWh).

6 The post-processing phase

In the post-processing phase, the cost- and emission-assessment model makes the synthesis of the outputs computed by the slave problem and computes the investment costs for the *central* technologies. Besides, the post-processing algorithm also takes care of the heat-losses in the network and of the resulting correction factor that acts as a penalty factor on the costs and CO_2 emissions. The heat-losses, that would occur in the designed network with the given insulation, are computed in percent of the total heat delivered by the network. This results in a penalty factor by which the costs and CO_2 emissions, which are due to the operation of the devices, are multiplied. These final outputs are then passed back to the evolutionary algorithm to be evaluated so that a further genome can be produced by the evolutionary algorithm.

For the costs, depending on the technology and on the available information from manufacturers, one of the two following equations has been used to compute the investment costs:

$$C^{\text{inv}} = X \cdot C^{\text{fix}} + S \cdot C^{\text{prop}}$$

$$C^{\text{inv}} = X \cdot C^{\text{ref}} \cdot \left(\frac{S}{S^{\text{ref}}} \right)^{F_s}$$

The yearly investment costs have then been computed using:

$$An = \frac{r \cdot (1+r)^N}{(1+r)^N - 1}$$

$$C^{\text{inv}}_{\text{an}} = (1 + F_m) \cdot An \cdot C^{\text{inv}}$$

For the scaling factor F_s a value of 0.6 has been chosen. The values for C^{fix}, C^{prop} and C^{ref} for the different devices have been taken from the installation of the campus of the Ecole Polytechnique Fédérale de Lausanne or from the literature [11]. When needed, the investment costs were actualised with the Marshal-Swift factor.

7 Assumptions

Following assumptions and simplifications have been made:

1. There are two physical networks p (an ongoing network from the heating-plant(s) to the building(s) and a return network). However if a pipe connects nodes i and j in the ongoing network, there has to be a connection between j and i for the return network.
2. The network-fluid is water (under pressure if the temperature requires it).
3. The atmospheric temperature has been set to 10°C and the temperature of the lake to 5°C.
4. A two-period profile has been used to develop the method. Two periods are used to describe the consumptions throughout the day.
5. For the cost- and emission-calculations, the two periods have been assumed to last 12 hours/day each for 313 days per year.
6. At this stage, the energy services considered are heating and electricity.
7. The strategy adopted in the network optimization algorithm is a heat-load following strategy. This means that the central and local technologies have to meet the entire heating load. Regarding the electricity, if not all the electricity requirements can be met by the central technologies, the grid is used as back-up.
8. The pressure losses amounts 300 Pa/m.
9. The velocity of the water in the piping amounts 3 m/s.
10. The heat loss coefficient for the conduction through the pipes amounts 0.04 [W/mK] and for convection outside the pipe 8 [W/mK]. The convection inside the pipes has been neglected in the calculation of the overall heat transfer coefficient [14].
11. Minimum part-loads are set for each central technology.
12. The central technologies producing electricity are connected to the grid. However, since the grid has some losses, not all the electricity delivered by the technologies to the grid is usable (see eq.15).
13. For η a common value of 0.5 has been chosen.

8 Cases studied

Fig. 3 and 4 show the consumption profiles for heating and electricity for both periods in each building for the case studied. The temperatures indicated on the heating profile are the temperature level at which the heating is required. Fig. 5 shows the district with the buildings and all the possible connections between the buildings. The number next to the buildings correspond to the numbers in fig. 3 and 4. Some nodes are depicted without any building, these nodes represent for instance road crossings: since pipes usually follow the roads, they could take a turn at a crossing when connecting two buildings. To develop the method, the district analysed has been defined on purpose and does not correspond to any existing district. For the choice of possible technologies however (structuring phase), a district in Geneva (Switzerland), situated near the Lake of Geneva, was chosen as reference case. Therefore heat pumps have been considered, beside gas turbines. As mentioned in the abstract, the results shown here are mainly related to the network optimization algorithm of the optimization phase (the slave problem). The evolutionary optimizer and the connection between the master problem and the slave problem as been set up, but no complete run has been executed yet (a complete run requires about 10'000 iterations).

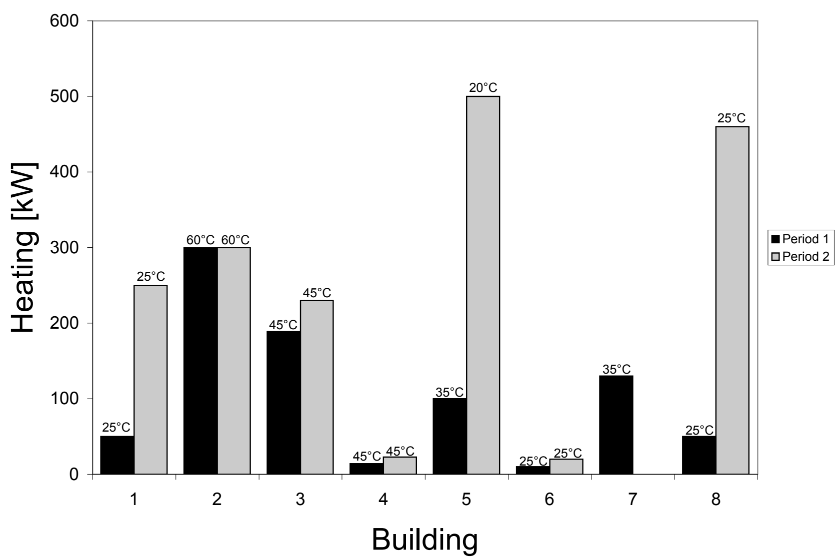

Figure 3: Heating profile for each building with the requested temperature level

9 Results

The results are shown in fig. 6 to 8. To compute these three cases, the optimality criterion for the simplex-algorithm in the network optimization algorithm has been set to 15%. In other words, the algorithm stopped when the solution found was expected to be at maximum 15% of the optimal soution. The reason for this setting is to save time, especially in the development phase of the method. However, the pertinence of this simplification will have to be tested and justified once the method is fully developed.

The computed network is shown by the thick lines on the figures. In all the examples shown, the network optimization algorithm could locate the central technologies on any existing node, provided that there is already a building located at that node. The algorithm was given the choice of a heat pump and a gas turbine, that could be combined together if necessary. For the three examples,

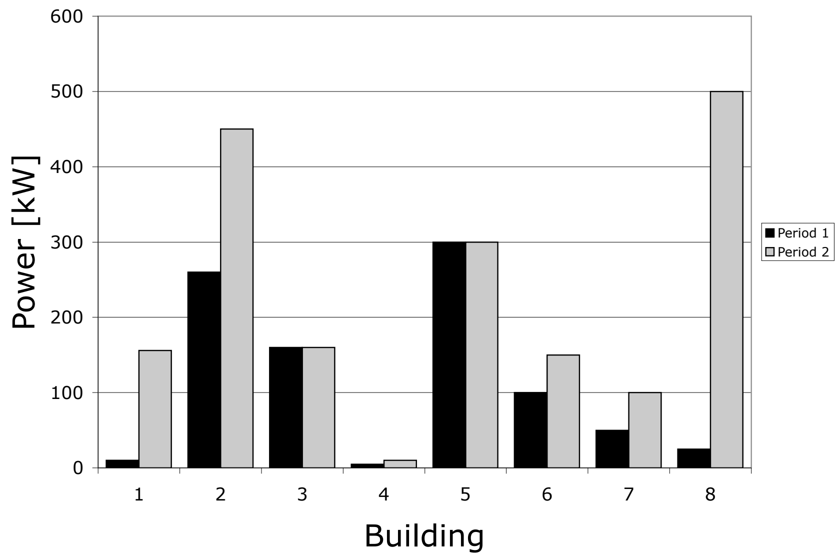

Figure 4: Electricity profile for each building

the algorithm has located the heat plant on node 5, which is indeed a very central position. In all examples, the remote building 2 is note included in the network by the algorithm. The heating requirements are met by a local boiler for this building. Regarding the piping, no restriction has been placed for the first example. For the second and the third example, there was a restriction on the size of the section for the pipe potentially running from node 10 to node 12. In the first example, the network temperature has been set to 90°C. Since this temperature exceeds the condenser temperature of the central heat pump, that was set to 60°C, the heat pump is combined with a gas turbine. In the second example, all the parameters are the same as in the first example, except for the size restriction on the pipe between nodes 10 and 12. The algorithm therefore diverts the distribution network over node 11. In the third example, the network temperature is reduced to 60°C and the condenser temperature of the central heat pump is kept at 60°C. The heat pump now operates alone and the gas turbine is not used.
On each figure the annual cost and CO_2 emissions are indicated. Because of the strong simplifications made at this stage of the development of the method (assumptions 4 and 5) to represent a year, these figures are not to be considered as absolute values. It is nontheless interesting to see that the case without gas turbine (case 3) is less expensive than the case with gas turbine (case 2) but more polluting. This shows that polygeneration systems can play an important role when the objective is to reduce the CO_2 emissions. Besides, it is striking that the first case is more expensive than the third one (2.7 mio-CHF/year versus 2.2 mio-CHF/year), in spite of the fact that the third case has the additional constraint on the pipe between nodes 10 and 12, which the first case doesn't have. The reason for this is the higher network temperature in the first case (90°C versus 60°C in the third case), requiring the implementation of the gas turbine. Whereas in the third case, there is no need for a gas turbine and therefore the investment costs are lower.

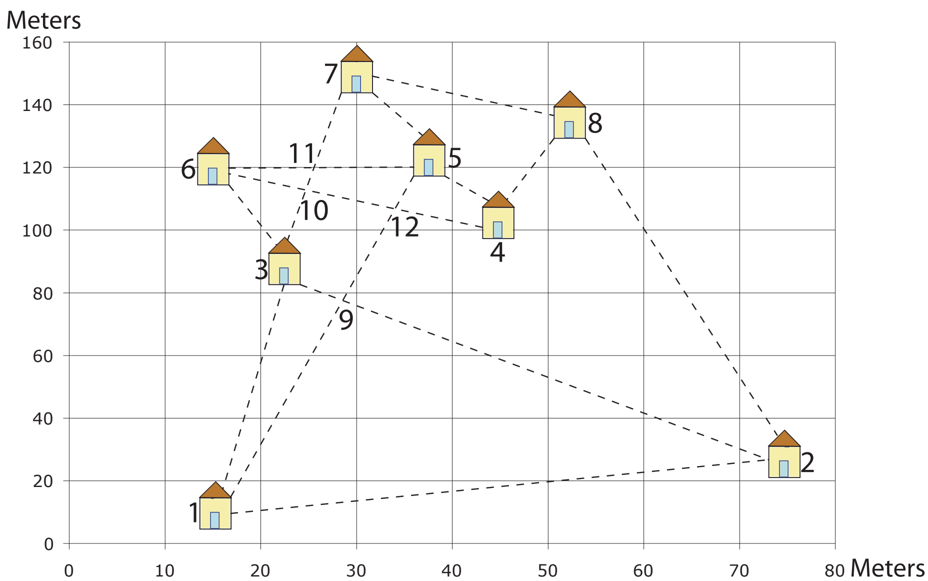

Figure 5: Buildings and possible connections for the case studied

Case	T^{net} °C	T^{cond} °C	Heat pump kW	Gas turbine kW
Case 1	90	60	219 / 738	324 / 745
Case 2	90	60	219 / 738	324 / 745
Case 3	60	60	543 / 1483	0 / 0

Table 1: Values of the main parameters for each case. The values for the heat pump and the gas turbine show the output of the respective technology for each period (period 1 / period 2)

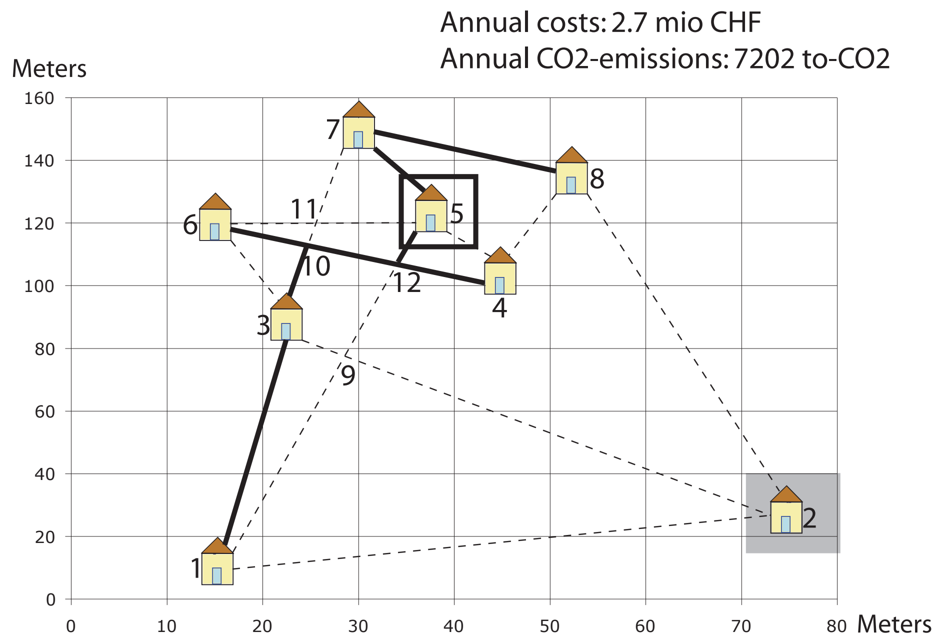

Figure 6: Resulting network for the first case

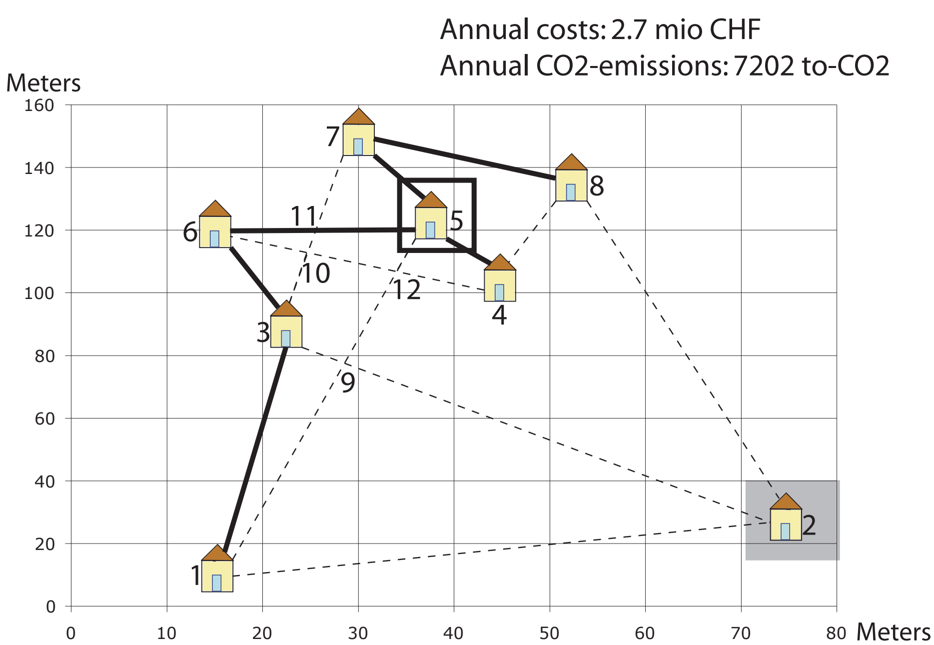

Figure 7: Resulting network for the second case

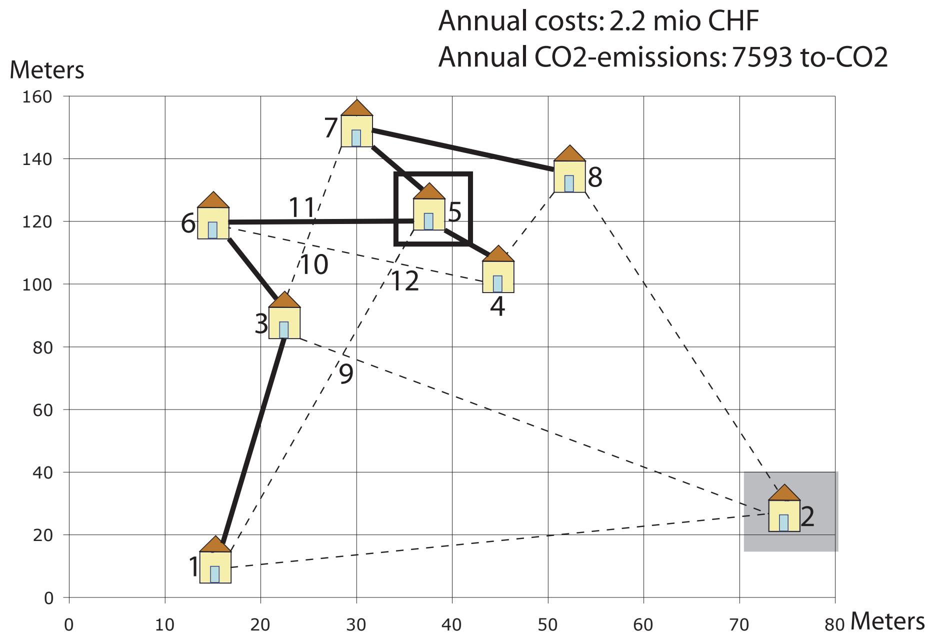

Figure 8: Resulting network for the third case

10 Conclusion

The method developed to design and optimize district energy systems shows interesting first results. The results are very much dependent on the inputs given though, especially the prices of the technologies and the piping. It is therefore very important to consider the market prices available in the analyzed district. Besides, an optimum has to be found between the requested precision (especially in the network optimization algorithm), the available precision of the inputs (the consumption profiles for instance), and the computing time. Regarding the slave problem, the method still needs to be improved in following way: the slave problem has just a financial objective. However the final results might be very different if the slave problem computed the optimal network in terms of CO_2 emissions instead. One way to overcome this issue could be to add a decision variable in the master problem defining which optimality criterion the slave problem should consider (costs or emissions). Finally, the whole method is being further developed to consider also hot water and cooling.

11 Acknowledgments

The authors would like to thank the Service Cantonal de l'Energie of Geneva (Switzerland) and the Centre de Recherche en Urbistique of Martigny (Switzerland) for their support.

References

[1] Ampl. www.ampl.com, last accessed April 30th 2006.

[2] Cplex. www.ilog.com, last accessed April 30th 2006.

[3] Statistique globale suisse de l'énergie. Swiss Federal Office of Energy, 1997.

[4] R. Aringhieri and F. Malucelli. Optimal operations management and network planning of a district system with a combined heat and power plant. *Annals of Operations Research*, 120:173–199, 2003.

[5] A. Benonysson, B. Bohm, and H.F. Ravn. Operational optimization in a district heating system. *Energy conversion and management*, 5(36):297–314, 1995.

[6] K. Comakli, B. Yüksel, and Ö. Comakli. Evaluation of energy and exergy losses in district heating network. *Applied Thermal Energy*, 24:1009–1017, 2004.

[7] F. Friedler, K. Tarjan, Y.W. Huang, and L.T. Fan. Graph-theoretic approach to process synthesis: polynomial algorithm for maximal structure generation. *Computers and chemical engineering*, (9):929–942, 1993.

[8] F. Friedler, J.B. Varga, and L.T. Fan. Decision-mapping: a tool for consistent and complete decisions in process synthesis. *Chemical engineering science*, 50:1755–1768, 1995.

[9] A. Hepbasli. Thermodynmaic analysis of a ground-source heat pump system for district heating. *International Journal of Energy Research*, 29:671–687, 2005.

[10] G.B. Leyland. *Multi-objective optimization applied to industrial energy problems.* Ph.d thesis n °2572, Swiss Federal Institute of technology Lausanne, 2002.

[11] F. Maréchal and D. Favrat. Centrales énergétiques. Lecture notes, 2004.

[12] F. Maréchal, D. Favrat, and E. Jochem. Energy in the perspective of the sustainable development: the 2000w society challenge. *Resources Conservation & Recycling*, 44:245–262, 2005.

[13] L. Ozgener, A. Hepbasli, and I. Dincer. Performance investigation of two geothermal district heating systems for building applications: Energy analysis. *Energy and Buildings*, 38:286–292, 2006.

[14] C. Rodriguez. Méthodes d'analyse et de dimensionnement de réseaux - application aux réseaux de chauffage à distance. Lecture notes, 2003.

[15] B. Rolfsman. Combined heat-and-power plants and district heating in a deregulated electricity market. *Applied energy*, 78:37–52, 2004.

[16] M.C. Rydstrand, M.O. Westermark, and M.A. Barlett. An analysis of the efficiency and economy of humidified gas turbines in district heating applications. *Energy*, 29:1945–1961, 2004.

[17] J. Söderman and F. Petterson. Strucutural optimisation of distributed energy systems. *Applied thermal engineering*, 2005.

[18] M.R. von Spakovsky, V Curti, and M. Batato. The performance optimization of a gas turbine cogeneration/heat pump facility with thermal storage. *Transactions of the ASME*, 117:2–9, 1995.

[19] C. Weber, F. Maréchal, D. Favrat, and S. Kraines. Optimization of an sofc-based decentralized polygeneration system for providing energy services in an office-building in tokyo. *Applied Thermal Engineering*, 26(13):1409–1419, 2006.

[20] Y. Yamaguchi, Y. Shimoda, and M. Mizuno. Development of district energy systems simulation model base on detailed energy demand model. *ibpsaNEWS*, (1):27–34, 2003.