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Multi-objective, multi-period optimization of district energy systems: Networks design

Samira Fazlollahi[a,b], Gwenaelle Becker[a], Michel Guichard[a], François Maréchal[b*]
[a] *Veolia Environnement Recherche et Innovation; VERI; Limay, France*
[b] *Industrial Energy Systems Laboratory; EPFL; Lausanne, Switzerland*

Abstract

A systematic procedure, including process design and integration techniques for designing district heating networks (DHN) is presented in this paper. In the developed model a simultaneous multi objectives and multi-period optimization is principally investigated.
The proposed method helps the decision maker to decide; which type and configuration of poly-generation technologies, centralized or decentralized, are best suited for the district, where in the district shall these equipments be implemented (geographically), what are the optimal flow, supply and return temperatures of the networks, taking into account the heat losses, the district's requirements and the technical limits of equipments. The design and the extension of DHN based on the geographical information system (GIS) is the novelty of this work.
Finally the proposed model is demonstrated by means of a case study.

Keywords: CO_2 mitigation, District heating networks, Mixed Integer Linear Programming, Evolutionary algorithm (MILP), Geographical information system (GIS)

1. Introduction

Poly-generation technologies, joined with the integration of DHN, have a good potential for CO_2 emissions reduction (Weber et al. [2007]). A systematic optimization procedure is needed to select and size the equipments and design the physical distribution heating networks.
The optimization of energy systems that includes one or more technologies to meet the requirements of energy systems is extensively studied by many authors. It is referred to Connolly et al. [2010] for a detailed review. Most of publications carried out only simulations, while system design optimization is neglected.
Diverse procedures exist to size cogeneration plants, like a structural optimization approach based on the mixed-integer linear programming by Papoulias and Grossmann [1983]. The role of optimization modeling techniques in power generation is reviewed in Bazmi and Zahedi [2011]. However, most of these optimization models only consider a mono economic objective function, completed with environmental and energetic targets as constraints, rather than following multi objective optimization.
Soderman and Pettersson [2006] have studied the network configuration of energy systems and developed a tool for decision makers to design the layout of the networks. They work does not take into account the temperature levels at which the energy services have to be delivered. Moreover, Soderman and Ahtila [2010] developed a mixed integer linear programming model with mono economic objective function to select the location and

*Francois.marechal@epfl.ch

capacity of the cooling and heating equipments, and to route the distribution pipe lines to individual consumers. The similar work is done by Keirstead et al. [2012]. They present an optimization model with a mono objective function for the strategic design of integrated urban energy systems.

A multi-objective, multi-period optimization model including process design and energy integration techniques for designing energy systems is proposed by Fazlollahi and Marechal [2013]. The pipeline connections between consumers and suppliers were not included in the optimization model. This model is developed here by considering the pipeline connections between subsystems, the investment costs and the heat losses of networks based on the GIS data. The goal is to optimize the networks' layout and temperatures, together with the configuration and locations of centralized and decentralized plants. Finally the developed model is demonstrated by means of a case study.

2. Methodology

The multi-objective optimization techniques are used in order to investigate sizing and operating effects of district energy systems on CO_2 emissions. The basic concept of the developed model is the decomposition of the problem into several parts, as illustrated in Figure 1. Three major steps (Weber et al. [2007]) are; a **Structuring phase** in which required data will be collected and structured. Secondly the **Multi-objective nonlinear optimization phase** will solve the district energy system design and produce results in the form of a Pareto frontier. In the third step, the **Post-Processing phase**, the Pareto frontier and associated results will be evaluated and compared in details by doing a sensitivity analyses.

2.1. Structuring phase

In the structuring phase geo localized information is collected to characterize the available endogenous resources, the energy demand profiles, the existing heat distribution networks and energy conversion systems. This analysis is completed by including other alternative energy conversion systems in the list. The demand profile is characterized by power requirement and corresponding temperatures for different typical days. The typical days selection method is presented in Fazlollahi et al. [2012].

2.2. Multi-objective nonlinear optimization phase

The aim of optimization algorithm (Fazlollahi and Marechal [2013]) is to solve a complex non linear problem consisting of minimizing the investment costs (CAPEX), operational costs (OPEX) and CO_2 emissions simultaneously. The goal of this step is to optimize the system configuration including the storage system and design the networks' pipeline. This phase is decomposed into four major parts, a **master optimization**, a **thermo-economic simulation**, a **slave optimization**, and the **environomic evaluation**.

In the present work the slave optimization is extended by adding the district network design model (Part.3). It is used to optimize the networks' layout and temperatures, together with the configuration and locations of centralized and decentralized plants based on the GIS data

2.3. Post-processing phase

The results of the optimization phase will be shown by a Pareto frontier. In the post processing phase, the Pareto frontier is analyzed by several performance indicators. This evaluation allows stakeholders to compare different solutions and select one.

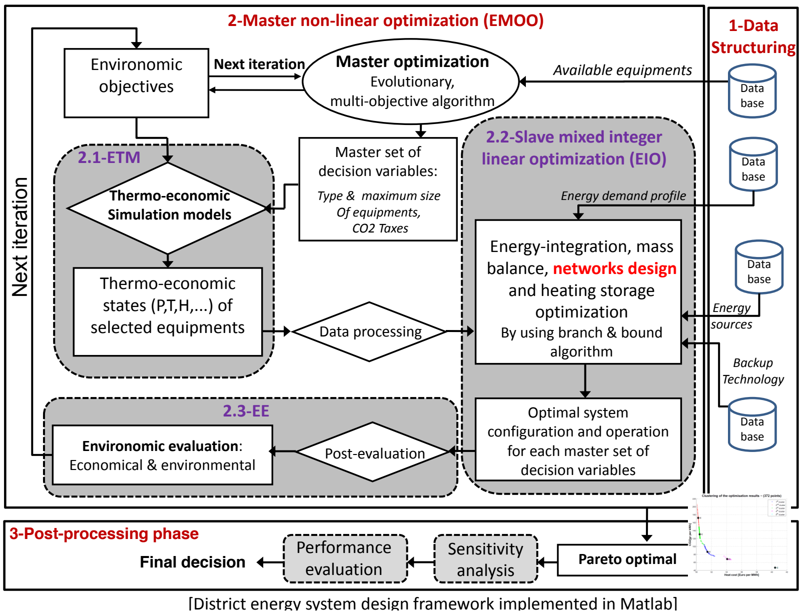

Figure 1. Multi objective, multi period optimization of energy systems: framework

3. Network design optimization model

The network design model is used to optimize the district networks' layout and temperatures, together with configurations and locations of centralized and decentralized plants. The investment costs, the pipeline lengths and the heat losses of networks are determined by using the GIS data.

The model comprises several subsystems, s, including suppliers and consumers. The geographical coordinates of each subsystem s are shown by s_{l_x} and s_{l_y}, where l shows a set of locations. Heat can be transferred from one location, $m \in l$, to another, $n \in l$, through the network's pipelines $P_{m,n}$. The geographical information (GIS data) of each subsystem including a district heating network routing has been determined in the regional map as an input data.

The proposed slave optimization model has the following networks' constraints in addition to the energy integration, the heat cascade, the mass balance and the storage constraints (Fazlollahi and Marechal [2013]);

- Heat balance in each location $m \in 1,\ldots,N_l$ and the temperature interval $r = 1,\ldots,N_r$, during time step $t = 1,\ldots,N_t$:

$$\sum_{s,i,j} \mathbf{f}_{s,m,t}(\dot{Q}^+_{s_j,m,r,t} - \dot{Q}^-_{s_i,m,r,t}) + \dot{\mathbf{R}}_{m,r+1,t} - \dot{\mathbf{R}}_{m,r,t} + \dot{\mathbf{Q}}^+_{P_m,r,t} - \dot{\mathbf{Q}}^-_{P_m,r,t} = 0, \quad (1)$$

$$\dot{\mathbf{Q}}^+_{P_m,r,t} \geq 0, \quad \dot{\mathbf{Q}}^-_{P_m,r,t} \geq 0, \quad \dot{\mathbf{R}}_{m,r,t} \geq 0, \quad \dot{\mathbf{R}}_{m,1,t} = 0, \quad \dot{\mathbf{R}}_{m,N_r+1,t} = 0 \quad (2)$$

Where $\dot{Q}^{-}_{s_i,m,r,t}$ is a parameter for representing the heat requirement of the cold stream i in subsystem s at time t and location m, while $\dot{Q}^{+}_{s_j,m,r,t}$ shows the available heat of the stream j. $\dot{\mathbf{R}}_{\mathbf{m},\mathbf{r},\mathbf{t}}$ is a continuous variable for the residual heat from the temperature level r in time t and location m. There is a possibility of cascading the residual heat from the higher temperature level $r+1$ to the lower one in each location. $\dot{\mathbf{Q}}^{+}_{P_m,r,t}$ shows available heat comes from other locations and $\dot{\mathbf{Q}}^{-}_{P_m,r,t}$ shows residual heat from temperature level r which transfers to other locations through the networks.

- Heat balance through the network's pipeline in each location $m \in l$ and temperature interval r during time step t:

$$\sum_{n \in l, n \neq m} \mathbf{f}_{P_{n,m},t} \times (\dot{Q}^{+}_{P_{n,m},r,t} - \dot{Q}^{loss}_{P_{n,m},r,t}) = \dot{\mathbf{Q}}^{+}_{\mathbf{P_m},\mathbf{r},\mathbf{t}}, \qquad \forall r,t,m \in l \tag{3}$$

$$\sum_{n \in l, n \neq m} \mathbf{f}_{P_{m,n},t} \times \dot{Q}^{-}_{P_{m,n},r,t} = \dot{\mathbf{Q}}^{-}_{\mathbf{P_m},\mathbf{r},\mathbf{t}}, \qquad \forall r,t,m \in l \tag{4}$$

Where $\dot{Q}^{+}_{P_{n,m},r,t}$ is a parameter for representing the reference heat transfer from location n to m at time t in the temperature interval r. $\mathbf{f}_{P_{n,m},t}$ is the continuous variable for showing the utilization rate of each pipeline P. $\dot{Q}^{loss}$ shows heat losses in each pipe and defined with the length of pipeline and the temperature difference of the heat flow (Girardin [2011]).

- The maximum utilization rate in each pipeline, $\mathbf{f}_{P_{n,m}}, m \neq n$, during different periods is defined as:

$$\mathbf{f}_{P_{n,m},t} \leq \mathbf{f}_{P_{n,m}}, \qquad \forall m,n \in l, \quad \forall t, \tag{5}$$

- The existence of each pipeline $p_{n,m}$, $m \neq n$ is defined by using a binary variable $\mathbf{y}_{P_{n,m}}$ together with sufficiently large numbers, denoted by U:

$$\mathbf{f}_{P_{n,m}} - U \times \mathbf{y}_{P_{n,m}} \leq 0, \qquad \forall m,n \in l, \tag{6}$$

The pipeline investment cost is estimated based on the length and the diameter of each pipe line (Girardin [2011]). This cost is added to the slave objective function. The diameter of each pipe is optimized by considering the investment cost and the maximum heat load, $\dot{\mathbf{Q}}^{\mathbf{max}}_{\mathbf{P_{n,m}}}$, transferred through the networks.

$$\mathbf{f}_{P_{n,m},t} \times \dot{Q}^{+}_{P_{n,m},r,t} \leq \dot{\mathbf{Q}}^{\mathbf{max}}_{\mathbf{P_{n,m}}}, \qquad \forall m,n \in l \quad and \quad \forall t, \tag{7}$$

$$(\pi \times \mathbf{d}^2_{n,m}/4) = \dot{\mathbf{Q}}^{\mathbf{max}}_{\mathbf{P_{n,m}}} / (\rho \times \nu \times C_p \times (T^0_s - T^0_r), \qquad \forall m,n \in l, \tag{8}$$

In this equation $d_{n,m}$ shows the diameter of pipe, ν (m/s) is a nominal velocity, T^0_s and T^0_r are networks' design supply and return temperatures which are defined as decision variables in the master optimization.

3.1. Illustrative example

The case study presented in Fazlollahi and Marechal [2013] is used to illustrate the advantage of the networks design model. The case comprises 5 consumption nodes, d1 to d5, connected to the main DHN networks. We would like to add 12 new consumption nodes with cold streams. Their heating requirement could be supplied with the central plant via DHN or individually with decentralized equipments. Alternative equipments are; gasifier for producing biogas, fuel-oil, biomass, coal and natural gas boilers, gas turbine and incinerator integrated with steam turbine. Any combinations of these equipments are allowed. Economical and technical data of technologies were taken from Fazlollahi and Marechal [2013]. The goal is to optimize the networks' layout, together with the configuration and location of centralized and decentralized plants respect to the economic and the environmental targets.

The hourly heat demand profile of each node is estimated by using meteorological data and the heating signature (Girardin et al. [2010]). In order to reduce the optimization size the hourly profile, with 8760 time steps, is compressed to 7 typical days with 5 segments (Fazlollahi et al. [2012]). It is shown for node C1 in Fig.2.

Fig.3 shows a set of optimal solutions respect to three objectives in a Pareto frontier.

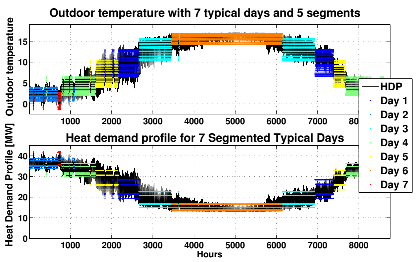

Figure 2. Typical day load curve

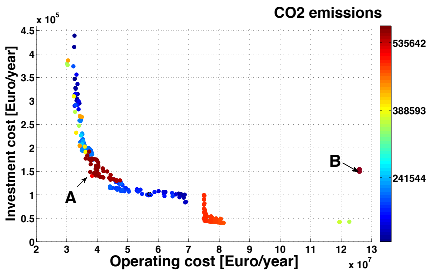

Figure 3. First 10 Pareto frontier

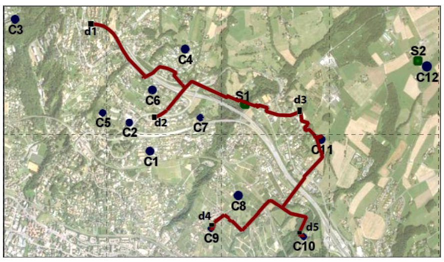

Figure 4. Original networks' layout

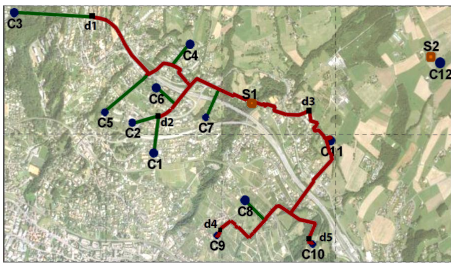

Figure 5. Network extension pipelines

Configuration **A** is selected for more details evaluation. In this solution, centralized plant S1 supplies heat via DHN to nodes C1 to C11. However, it is economically viable that S2 supplies heat directly to the node C12 as a decentralized solution. The incinerator, biomass and coal boilers are selected in the central plant S1. The extension of the district

heating lines from the main pipes to nodes C1 to C11 is shown in Fig.5.
Configuration **B** shows a solution where heat requirements of all 12 new nodes are supplied by individual decentralized boilers. The operating cost and CO_2 emissions are higher compare to the solution **A**.

4. Conclusion

A systematic procedure including the network design, process and energy integration techniques with simultaneous consideration of multi-period and multi-objective aspects, for district energy system design and operation is explained. The network design model is introduced in order to optimize the networks' layout, configurations and locations of centralized and decentralized plants in an urban area. There is a tradeoff between centralized and decentralized solutions. In the developed model we consider not only the quantity of services but also the quality of heat requirements in terms of the temperature.

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