Int. J. Therm. Sci. (2000) 39, 731–741
© 2000 Éditions scientifiques et médicales Elsevier SAS. All rights reserved
S1290-0729(00)00225-8/FLA

An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part II: Application

Vinicio Curti [a,1], Daniel Favrat [a*], Michael R. von Spakovsky [b]

[a] *Laboratoire d'énergétique industrielle, Département de génie mécanique, École polytechnique fédérale de Lausanne, LENI-DGM-EPFL, CH-1015 Lausanne, Suisse*

[b] *Energy Management Institute, Virginia Polytechnic Institute and State University, Department of Mechanical Engineering, Blacksburg, VA 24061, USA*

(Received 31 August 1999, accepted 10 January 2000)

Abstract — Applying the general environomic methodology presented in the first of this series of two articles (i.e. Part I [1]), details of the environomic model for a district heating network based on centralized and decentralized heat pumps are presented. A complete set of results for the optimal synthesis, design and operation of the network is given and discussed. The resulting solution space is highly nonlinear and noncontiguous and is effectively searched using a genetic algorithm. Results are shown for various district heating user distributions as well as fuel and electricity prices. When properly optimized, solutions with heat pumps are economically very close to traditional district heating solutions, particularly when the main pollution costs are internalized. For comparison purposes, the same approach and models can be used to identify the life cycle exergetic optimum, which is also given. These results illustrate the power of this new engineering tool for the synthesis and design of more sustainable energy systems and networks. © 2000 Éditions scientifiques et médicales Elsevier SAS

energy / exergy / environment / economics / environomics / optimization / district heating / heat pump / pollution

Résumé — Approche « environomique » pour la modélisation et l'optimisation d'un réseau de chauffage urbain utilisant des systèmes centralisés et décentralisés de pompes à chaleur, cogénérateurs et/ou chaudières à gaz. 2^e partie : Applications. Ce deuxième article d'une série de deux articles (voir 1^{re} partie [1]), démontre l'application de la méthodologie environomique générale présentée sous [1] au cas particulier de réseaux de chauffage à distance alimentés par pompes à chaleur centralisées et décentralisées. Un ensemble de résultats donnant les configurations et dimensionnements optimaux est présenté et analysé. L'espace de solutions est fortement non linéaire et non contigu mais la procédure d'optimisation par algorithme génétique qui est brièvement présentée permet de résoudre ce type de problème de façon robuste. Les résultats montrent que les configurations avec pompes à chaleur sont économiquement très proches des solutions traditionnelles impliquant également des réseaux de chauffages urbains, surtout lorsque les principaux coûts de pollution sont internalisés. A titre de comparaison, la même approche est utilisée pour déterminer la solution exergétiquement optimale sur le cycle de vie qui apporte un autre éclairage au concepteur ou décideur. Ces résultats illustrent la puissance de ce nouvel outil de conception et d'optimisation de systèmes et réseaux énergétiques intégrés et répondant mieux au concept de développement durable. © 2000 Éditions scientifiques et médicales Elsevier SAS

énergie / exergie / environnement / économique / environomique / optimisation / chauffage urbain / pompe à chaleur / pollution

Nomenclature

B	sum of the revenues from the products delivered	CHF
C	cost	CHF or J
c	specific costs	$\text{CHF}\cdot\text{kg}^{-1}$
c	concentration	$\text{kg}\cdot\text{m}^{-3}$
c_p	specific heat at constant pressure	$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
Cen	central plant	
DHN	district heating network	
Ex	exergy	J
f	penalty factor	

---

[*] Correspondence and reprints.
Daniel.Favrat@epfl.ch

[1] Now at Globes—Global Energy Solutions SA, P.O. Box 1219, CH-6501 Bellinzona, Switzerland.

GA	gas engine	
GT	gas turbine	
GF	gas furnace	
HP	heat pump	
HDW	hot water	
HX	heat exchanger	
i	interest rate	
K	sum of the fixed costs	CHF
M	mass	kg
$\dot{M}$	massflow	$\mathrm{kg \cdot s^{-1}}$
MINLP	mixed integer nonlinear programming	
N	number	
n	period of amortization	year
OBJ	objective function	$\mathrm{CHF \cdot s^{-1}}$
P_g	penalty function of inequality constraint	
$\dot{p}$	pollutant flowrate	$\mathrm{kg \cdot s^{-1}}$
Q	heat	J
r	pollutant mass flow/heat delivered	$\mathrm{kg \cdot J^{-1}}$
RL	return line	
S	entropy	$\mathrm{kJ \cdot K^{-1}}$
s	specific entropy	$\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$
SL	supply line	
T	temperature	K
x	independent variable	
y	dependent variable	
VR	relative violation of constraint	
V	volume	$\mathrm{m^3}$
$\dot{V}$	volume flowrate	$\mathrm{m^3 \cdot s^{-1}}$

Greek symbols

$\dot{\phi}$	environmental pollution rate	$\mathrm{J \cdot K^{-1} \cdot s^{-1} \cdot m^{-3}}$
κ	pollutant level	$\mathrm{J \cdot K^{-1} \cdot m^{-3}}$
Π	new pollution function	

Subscripts

Aux	auxiliary
0	reference (or environment)
$0i$	current condition
$0i$-nat	natural or pure state
a	amortization
build	building
c	critical
e	exhaust gas
equip	equipment
LHV	lower heating value
maint	maintenance
n	designation of a given component
net	network
pol	pollution
prod	production
res	resources
RL	return line
SL	supply line
total net	total
uQ	user heat
uE	user electricity
un	user n
w	water

1. INTRODUCTION

The simulation of the environomic model of the district heating network (DHN) system described in Part I [1] was coupled to an optimization algorithm in order to illustrate the potential of such an approach for determining the optimal solution or a set of near-optimal solutions for a very complex system synthesis and design problem (strongly nonlinear with mixed integer variables). The problem itself consists of simultaneously determining the optimal system configuration, component sizes and operational sequences for a variety of seasonal heating periods and users. The present paper solves a simplified version (in relative terms only) of this problem whereby the operational sequences, which vary with seasonal heating demand, are taken into account by multiplying the nominal operational energy values and costs by operational weighting factors. These factors account for changes in atmospheric conditions and, therefore, in user heat demand as well as for variations in performance of system components with atmospheric conditions (e.g., the performance variations of the heat pumps with respect to seasonal temperatures change). This avoids having to integrate over several time intervals at the operational level. The weighting factors employed are functions of the expected average yearly contribution of each major component based on the cumulated heat rate demand curve, with supply contributions determined from a strategy giving priority to the central plant's heat pump (if chosen), followed by the cogeneration units and then the furnace. This strategy is justified by the fact that, once decision is made to implement investment intensive components like heat pumps, they should be used in priority as they are more efficient and therefore imply lower operational costs.

For the environomic model presented here, the option of selling electricity to the outside utility grid is not included[2]. In addition, when the electricity required by the central plant's heat pump is provided by cogeneration,

---

[2] A cogeneration unit, when present, could potentially be used to generate, for example, peak power at lunch time with the heat pump momentarily shut down (playing with the inherent short term thermal storage in the network). Such a strategy, which would most likely be linked with an elevation of the network temperature beforehand,

the capacity of both units is modulated simultaneously in order to prevent the waste of thermal energy. Furthermore, all super-configuration units (components) are represented by thermodynamic models as opposed to a set of performance characteristics. The heat pump models are based on the simulation of thermodynamic heat pump cycles, with two stages for the central unit and a single stage for the decentralized heat pumps. The models for the cogeneration units are based on constant isentropic efficiencies for the turbomachinery components of the gas turbine and on a constant mechanical efficiency for the gas engine. The cogeneration heat rate is based on a calculation, using fixed pinch temperature differences, of the heat exchange between the network water and the lubrication oil, the cooling water and/or the exhaust gases from the engine or the turbine.

What follows is a discussion of the environomic model and any additional simplifying assumptions used to obtain the results shown in this paper.

2. THE APPLIED MODEL FORMULATION

The model formulation for the presented application is based on the super-configurations presented in Part I [1]. The independent variables considered, some specific equations and the inequality constraints are given in this section. For additional details, the reader is referred to [3]. Note that in the presented formulation, only monetary units have been used for the objective function.

2.1. The independent variables

The models independent variables appear in *tables I* and *II*. Each independent variable may vary continuously between specified limits.

Note that the last user on the users line does not have elements on the return line. Thus, for the particular application presented here and with four classes of users, the model has 33 independent variables or degrees of freedom.

TABLE I
The independent variable set for the main network and the central plant.

$T_{\text{net}-\text{s}}$	Nominal network supply temperature
$\dot{Q}_{\text{H}-\text{HP}}$	Central plant's heat pump nominal delivery heat rate
$\dot{M}_{\text{fuel}-\text{GT}}$	Gas turbine's nominal fuel mass flow rate
$\dot{M}_{\text{fuel}-\text{GE}}$	Gas reciprocating engine's nominal fuel mass flow rate
$\dot{M}_{\text{net}-\text{GT}}$	Gas turbine's nominal network water mass flow rate

2.2. The objective function and equality constraints

The amortization factor used to define $\dot{C}_{\text{equip}}$ in equation (21) of Part I [1] is expressed by

$$f_{\text{a}} = \frac{(1+i)^n i}{(1+i)^n - 1} \tag{1}$$

where i is the applied interest rate, n is the period of amortization.

For the super-configuration modeled, the sum of equipment costs is expressed by

$$\begin{aligned}\sum_{n=1}^{N} (C_{\text{equip}})_n = (&C_{\text{equip}_{\text{cen\_HP}}} + C_{\text{equip}_{\text{GF}}} + C_{\text{equip}_{\text{GE}}} \\ &+ C_{\text{equip}_{\text{GT}}} + C_{\text{equip}_{\text{pump}}} + C_{\text{equip}_{\text{net}}}) \\ &+ \sum_{uQ} (C_{\text{equip}_{\text{SL\_HX}}} + C_{\text{equip}_{\text{SL\_HP}}} \\ &+ C_{\text{equip}_{\text{RL\_HX}}} + C_{\text{equip}_{\text{RL\_HP}}} \\ &+ C_{\text{equip}_{\text{HW\_HX1}}} + C_{\text{equip}_{\text{HW\_HX2}}} \\ &+ C_{\text{equip}_{\text{HW\_Aux}}})_{uQ}\end{aligned} \tag{2}$$

Although the terms for the augmented maintenance costs $\dot{C}'_{\text{maint}}$ and the augmented building costs $\dot{C}_{\text{build}}$ do not explicitly appear in the objective function (equation (1)) of Part I [1], they are taken into account in this application. However, the pollution cost contribution of each component is ignored due to the fact that it is small when compared with those for operation and resource preparation. The augmented maintenance cost rate, thus, simply becomes the maintenance cost rate [3], $\dot{C}_{\text{maint}}$, and is defined

---

would require more complex modeling than which was considered in this study. These considerations as well as considerations of variable electricity rates between day and night, for example, can be treated with a two-level optimization scheme (synthesis/design + operation, see [2]), but were outside the scope of the present project.

[3] The factor of proportionality f_{maint} can be obtained from the literature for each of the main components and is based on the idea that maintenance costs can be fairly adequately estimated in terms of percentage of the investment costs for each component. Obviously, for the purposes of this paper, the approximation used is more than adequate. A mean value of 0.0897 for all components was used.

TABLE II
The user independent variable set (a similar set for each user class).

$\Delta T_{\mathrm{C-SL\_HP}}$	Supply line local heat pump nominal evaporator temperature difference
$\dot{Q}_{\mathrm{H-SL\_HP}}$	Supply line local heat pump nominal delivery heat rate
$\Delta T_{\mathrm{min-SL\_HX}}$	Supply line heat exchanger nominal temperature pinch difference
$\dot{M}_{\mathrm{net-HDW2}}$	Hot domestic water heat exchanger 2 nominal network water mass flow rate
$\dot{Q}_{\mathrm{RL\_HX}}$	Return line heat exchanger nominal heat rate exchange
$\Delta T_{\mathrm{min-RL\_HX}}$	Return line heat exchanger nominal temperature pinch difference
$\Delta T_{\mathrm{C-RL\_HP}}$	Return line local heat pump nominal evaporator temperature difference
$\dot{Q}_{\mathrm{H-RL\_HP}}$	Return line local heat pump nominal delivery heat rate

for this application as a fraction of $\dot{C}_{\mathrm{equip}}$, i.e.

$$\dot{C}_{\mathrm{maint}} = f_{\mathrm{maint}} \dot{C}_{\mathrm{equip}} \tag{3}$$

The augmented building cost rate reduces likewise to $\dot{C}_{\mathrm{build}}$, and is defined as the sum of a contribution due to the size of the central plant and a contribution due to the size of the n single elements (components) installed in the central plant. It is, thus, written as

$$\dot{C}_{\mathrm{build}} = f_{\mathrm{build}} \dot{Q}_{\mathrm{net}} + \sum_{n} f_{\mathrm{build\_}n} f_{Qn} \dot{Q}_{n} \tag{4}$$

where

f_{build} is the factor of proportionality between the central plant size and the related building cost contribution[4];

$f_{\mathrm{build\_}n}$ is the factor of proportionality between the size of element n and the related building cost contribution;

f_{Qn} is a factor that multiplies the element size contribution in order to take into account a scaling factor;

$\dot{Q}_{n}$ is the nominal heat rate delivered by element n installed in the central plant.

As to the pollution cost rates associated with the equipment, resources and operational sequences of the DHN system, they are determined as sums of the pollution cost rates associated with the NO_x and CO_2 emissions emanating from the entire chain of processes considered. The environmental pollution rate for NO_x associated with the pollution penalty factors used to penalize these cost rates is expressed by

$$\dot{\phi}_{\mathrm{NO}_x} = \frac{1}{V} s_{\mathrm{NO}_x} c_{\mathrm{NO}_x} \dot{V}_{\mathrm{e}} \tag{5}$$

while the critical value of the environmental pollution rate for NO_x is given generally as

$$\dot{\phi}_{\mathrm{cNO}_x} = \frac{1}{V} s_{\mathrm{cNO}_x} c_{\mathrm{cNO}_x} \dot{V}_{\mathrm{e}} \tag{6}$$

When considering the environmental pollution rate associated with the quantity of CO_2 emitted by the combustion of a given fuel, a somewhat different approach is proposed, since this rate depends essentially on the quantity of fuel burned and, therefore, cannot be expressed by a concentration in the exhaust gases as was done for the case of the NO_x [3]. The environmental pollution rate for CO_2 is, thus, expressed as a function of the ratio r_{CO_2} between the mass flow rate of emitted carbon dioxide per heat rate provided to the users. This ratio[5] is written as

$$r_{\mathrm{CO}_2} = \frac{\dot{M}_{\mathrm{CO}_2}}{\dot{Q}_{\mathrm{heating}}} \tag{7}$$

and the environmental pollution rate for CO_2 becomes

$$\dot{\phi}_{\mathrm{CO}_2} = \frac{1}{V} s_{\mathrm{CO}_2} r_{\mathrm{CO}_2} \dot{Q}_{\mathrm{heating}} \tag{8}$$

For the critical environmental pollution rate, the above ratio can be expressed as a function of the ratio between the mass of CO_2 emitted in Switzerland for space heating during 1990 and the heat provided to buildings during the same year:

$$r_{\mathrm{cCO}_2} = f_{r_{\mathrm{CO}_2}} \frac{M_{\mathrm{CO}_2}^{1990}}{Q_{\mathrm{heating}}^{1990}} \tag{9}$$

where $f_{r_{\mathrm{CO}_2}}$ is the maximum fraction of the total CO_2 emissions per unit of heating $M_{\mathrm{CO}_2}^{1990}/Q_{\mathrm{heating}}^{1990}$ which the DHN can emit and still have Switzerland meet its national goal of CO_2 reduction. This formulation of the ratio r_{cCO_2} is based on the fact that the Swiss government, like many others, declared in June 1992 at the UN

---

[4] In this application an average value for f_{build} of 154 CHF·kW^{-1} has been used.

[5] The amount of CO_2 emitted in Switzerland in 1990 is estimated at $20.9 \cdot 10^6$ t·year^{-1} and the use of final (distributed) energy for the heating of buildings is estimated at 345 PJ [8].

Conference for the Environment and Development held in Rio de Janeiro its intention to reduce and stabilize by the year 2000 the total emission of CO_2 to its 1990 level. A similar approach could be used for other global pollutants such as chlorofluorocarbons, methane, etc.

Of the set of equality constraints represented by equations (2) of Part I [1], only the principal balances satisfied by the model are presented below since the remaining equality constraints are too numerous to mention. The first balance equation is that for the heat rate for the user uQ connection given by

$$\begin{aligned}(\dot{Q}_{\text{heating}} + \dot{Q}_{\text{HW}})_{uQ} &= (\dot{Q}_{\text{SL\_HX}} + \dot{Q}_{\text{SL\_HP}} + \dot{Q}_{\text{RL\_HX}} + \dot{Q}_{\text{RL\_HP}} \\ &\quad + \dot{Q}_{\text{HDW\_HX1}} + \dot{Q}_{\text{HDW\_HX2}} + \dot{Q}_{\text{HDW\_Aux}})_{uQ}\end{aligned} \tag{10}$$

where $(\dot{Q}_{\text{heating}})_{uQ}$ represents the user uQ's heat rate demand for space heating and $(\dot{Q}_{\text{HW}})_{uQ}$ the heat rate for domestic hot water production. The total heat rate demanded by the network from the central plant is given by

$$\begin{aligned}\dot{Q}_{\text{central}} = \sum_{uQ} (&\dot{Q}_{\text{net\_SL\_HP}} + \dot{Q}_{\text{net\_SL\_HX}} + \dot{Q}_{\text{net\_RL\_HP}} \\ &+ \dot{Q}_{\text{net\_RL\_HX}} + \dot{Q}_{\text{net\_HW\_HX1}} \\ &+ \dot{Q}_{\text{net\_HW\_HX2}})_{uQ}\end{aligned} \tag{11}$$

This heat rate must be supplied by the central plant in the following manner, namely

$$\dot{Q}_{\text{cen\_HP}} + \dot{Q}_{\text{GT}} + \dot{Q}_{\text{GE}} + \dot{Q}_{\text{GF}} = \dot{Q}_{\text{central}} \tag{12}$$

The heat rate $\dot{Q}_{\text{central}}$ is also linked to the main network supply temperature by

$$\dot{Q}_{\text{central}} = \dot{M}_{\text{net}} c_{p\text{w}} (T_{\text{supply}} - T_{\text{return}}) \tag{13}$$

where $\dot{M}_{\text{net}}$, $c_{p\text{w}}$, T_{supply} and T_{return} are, respectively, the mass flow rate, the specific heat of the water and the supply and return water temperatures of the main network. The temperature required by each user's local supply circuit results from the mixing of the water provided by each connection element. Under the assumption of constant water specific heat, this is expressed by

$$(T_{\text{supply}})_{uQ} = \left[\frac{\sum_n (\dot{M}_{\text{u}n} T_{\text{u}n})}{\sum_n (\dot{M}_{\text{u}n})}\right]_{uQ} \tag{14}$$

where $\dot{M}_{\text{u}n}$ and $T_{\text{u}n}$ are the user-side mass flow rate supplied by connection element n and its temperature. Models of the single elements have to be considered in order to define for each of them its performance as well as relationships between the heat rates and the input/output water temperatures in the main network and on the user-side in order to evaluate the fuel and electricity needs and the emission of pollutant substances.

2.3. The inequality constraints

The formulation of the inequality constraints (equation (3) of Part I [1]) depends on the choice of independent variables and the formulation of the equality constraints. These inequalities control the physical and numerical feasibility of the model. For example, the gas furnace must exist when other elements in the central plant do not deliver the heat requested. However, several combinations of valid independent variable values exist for which the gas furnace's nominal heat rate, found through equation (12), could be negative. Therefore, one inequality constraint must be that

$$\dot{Q}_{\text{GF}} \geq 0 \tag{15}$$

A number of other inequality constraints exist in the model but are too numerous to list here, but can be found in [3]. They control the operating limits of the heat pumps and other elements, the various mass flow rates, etc. Violating these constraints is handled as a penalty on the objective function. Thus, the optimization searches for the minimum value of a penalized objective function which is equal to the original objective function (equation (1) of Part I [1]) multiplied by the product of functions of inequality constraints violated, i.e.

$$OBJ = \dot{C}_{\text{total net}} \prod_k P_{gk} \tag{16}$$

where P_{gk}, a monotonic function[6] of the inequality constraint k violated, is equal to one when the inequality constraint k is not violated.

3. OPTIMIZATION

Optimizing the DHN system's environomic model is a daunting task due to its complexity (e.g., thirty-three independent variables and many infeasible regions). The resulting optimization problem is a mixed integer, nonlinear programming (MINLP) problem which, for the

---

[6] $P_{gk} = 1 + \log(1 + |VR|)$, VR being the relative violation (difference between the constraint k and the violating value) divided by the value of the constraint itself.

1. **Population initialization**
   Random generation of a population (set) of solutions (individuals);
2. **Score evaluation for each individual**
   Objective function calculation for each solution of the generated set;

Repeat the following until a stopping criterion is satisfied:

3. **Selection of a couple of individuals (The Parents)**
   Random selection of 2 solutions in the current set;
4. **Crossing of the 2 Parents**
   Combination, by the Blend Crossover technique, of information associated with each one of the 2 considered solutions for the generation of a combined solution;
5. **Mutation**
   The mutation rate is maintained at a very low value;
6. **New individual score evaluation**
   Calculation of the score for the generated individual;
7. **Replacement**
   Calculation of the distance between the new individual and all the other individuals in the population;
   Comparison of the new individual's score and the score of the closest individual;
   Replace the closest individual if the new individual's score is better;

Figure 1. Modified Struggle GA procedure used for the present application.

methodology described in this paper, is solved using only continuous (real) variables. The methodology itself, however, is not restricted to such variables. Effectively searching the multi-dimensional space of feasible solutions described by this problem and arriving at the global optimum (i.e. the configuration and set of component designs, which optimally meet all demands placed on the system) requires a powerful algorithm. A deterministic or geometric (gradient) based approach for solving this problem (e.g., see [4, 5]) is perhaps possible but only under very restricted conditions, conditions which would handicap the generality of the methodology used to develop the environomic model presented here.

In contrast to deterministic approaches, nondeterministic or heuristic ones use neither gradients nor geometry to search out the global optimum. Thus, they are less likely to be tricked into finding local optima. They also pose no restrictions on model development (i.e. on the nature or make-up of the model itself), can be very comprehensive in thoroughly searching the region of all feasible solutions, and can, in fact, produce a set of completely independent near-global optima in addition to the global optimum itself (a process called niching). Some heuristic approaches, which have shown a great deal of promise, are genetic algorithms (GAs). These algorithms simulate the process of evolution with the "survival of the fittest" principle as the driving force and key biological concepts such as populations, generations, mating, and mutation as the corner stones of the procedure. A Struggle GA, developed at MIT [6] and modified at the Swiss Federal Institute of Technology in Lausanne (see the acknowledgement below) was used to solve the environomic synthesis and design optimization problem formulated above. A procedure for the application of this type of algorithm is reported in *figure 1* [7]. It should be noted that the GA used and, in particular, the crossover operator (Blend Crossover) employed uses real variables and not a binary mapping. This has been found to improve the performance of the algorithm. The distance between individuals (important both for selection and mating) was devised based on a biased Cartesian distance, with appropriated differentiation made between the weighting factors for the main network's and the central plant's independent variables found in *table I*.

4. RESULTS AND DISCUSSION

A major failure of many databases on the heating needs of buildings or areas of cities is that they only refer to energy or heat rate values without a proper documentation of the actual heating temperature required. Although most buildings in existing city areas have been designed for the typical hydronic radiator heating range of 70–90 °C, over-design and recent improvements of building envelopes have contributed in many instances to significantly reduce the actual temperature requirements. This was confirmed by a recent investigation of the buildings in a relatively old part of Lausanne (Lausanne-Ouchy) supplied primarily by oil-fired central heating systems and demanding a nominal heat rate of 62.7 MWth [7]. *Figure 2* shows the actual heating needs of all users in this part of Lausanne divided into four major categories on the basis of their temperature requirements. Alternative demand structures also appear in the same figure. These are characterized by higher heat rates demanded at lower temperatures. These demand typologies will be used later in the presentation [8].

---

[7] *Figure 1* does not specifically mention any stopping criteria. For such a complex, nonlinear solution domain, pursuing several good families of solutions in parallel, it is difficult to propose a general formulation of stopping criteria. In this study we limited the number of generations to 4 000 which gave an adequate margin for all cases tested and produced robust and repetitive results.

[8] For the results presented in this paper the four user categories are introduced through constraints on the hydronic temperatures and the demanded heat rate for each user. The users are connected to a single couple of supply and return network lines and have a predefined order in space but this space order could be introduced in the optimization procedure as well.

The first set of results obtained with the Lausanne-Ouchy demand structure appears in *figure 3* as well as in *tables III* and *IV* and shows the optimum configuration and component designs based on a moderate, constant price for electricity (13 CHcts·kWh^{-1}) as well as on three different prices for natural gas covering a broad range of potential market conditions. Results are shown with or without internalization of the pollution costs for the two main pollutants considered in this study, NO_x and CO_2. *Table V* gives the specific costs considered for these two pollutants.

At the lowest gas price (2 CHcts·kWhLHV^{-1}), the thermoeconomic optimum provides a configuration, which relies almost exclusively on a gas furnace to satisfy all the heating needs (62.5 MWth). A very minor portion of this heating need is met by a small cogeneration gas engine, which produces the electricity consumed by the plant internally (for the pumps primarily). The supply temperature corresponds to the maximum value admitted in the model (97 °C) since with combustion in a single furnace dominant, there is little incentive to further reduce the temperature at the expense of increased network and user equipment costs. In contrast, the environomic model results in a furnace reduced to a little more than 40 % of that of the thermoeconomic model. The remaining heat demand is provided by a heat pump and a cogeneration gas turbine sized to provide the electricity needed by the plant (HP plus pumps). However the optimum network temperature is maintained at its maximum value.

The latter solution (furnace, heat pump and cogeneration gas turbine) also prevails for the case of an intermediate gas price of 5 CHcts·kWh^{-1} and no pollution

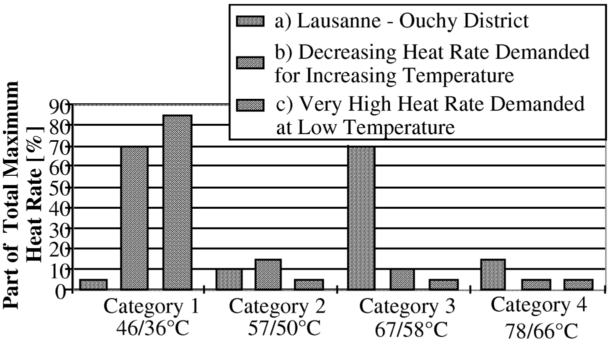

Figure 2. Typical heating demand for an area of the city of Lausanne (i.e. the Ouchy district) taken as the Reference Case [7] and for lower temperature districts taken as representative of districts with rather recent building topology. Temperatures indicated are supply and return temperatures at the nominal conditions depending on the location.

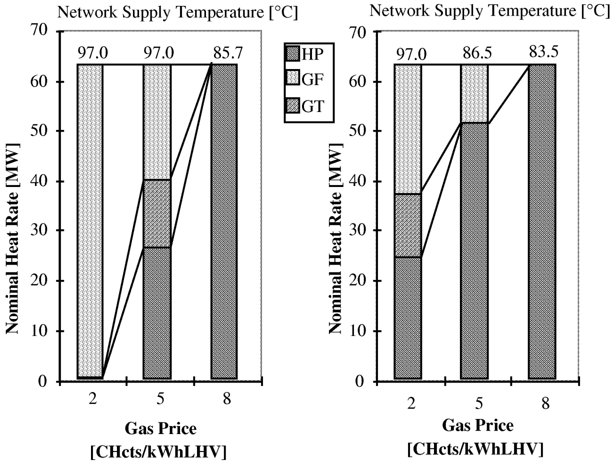

Figure 3. Optimized nominal heat rates of the central plant components based on a constant electricity price of 13 CHcts·kWh^{-1}.

TABLE III
Cost breakdown of the unit of heat energy delivered.

	Cost breakdown [CHcts·kWh^{-1}]					
Electricity 13 CHcts·kWh^{-1}	Without pollution costs (thermoeconomic model)			With pollution costs (environomic model)		
Gas price [CHcts·kWh^{-1}]	2.0	5.0	8.0	2.0	5.0	8.0
Building	0.89	1.21	0.88	1.21	1.03	0.88
Equipment	0.44	1.57	1.64	1.52	1.54	1.65
Network	0.86	0.88	0.94	0.88	0.94	0.96
Administration	1.18	1.18	1.18	1.18	1.18	1.18
Energy	2.27	3.20	3.88	1.30	3.84	3.87
Pollution	0.00	0.00	0.00	1.13	0.07	0.06
Total	5.63	8.04	8.53	7.22	8.60	8.60

TABLE IV
Pollution cost distribution for the optimal solution at an electricity price of 13 CHcts·kWh^{-1} and a gas price of 5 CHcts·kWh^{-1} given as a % of the total pollution cost which in this case amounts to 0.07 CHcts·kWh^{-1}.

Main system elements	Manufacture & removal	Operation	Resources	Preparation & transport
Central heat pump	6.12	–	Natural gas	7.19
Furnace	0.47	17.01	Electricity	54.71
Gas turbine	0.00	0.00	–	–
Gas engine	0.00	0.00	–	–
Network	13.69	–	–	–
User connections	0.81	–	–	–
Total	21.10	17.01	Total	61.89
NO_x part	13.85	3.33	NO_x part	42.20
CO_2 part	7.25	13.68	CO_2 part	19.69

TABLE V
Unit damage pollution costs considered in the environomic model [8].

Emitted substance	Unit damage pollution cost [CHF·kg^{-1}]
NO_x	13.8
CO_2	0.0420

considerations (thermoeconomic model). However, with pollution, a heat pump fed by electricity from the grid is chosen to deliver almost all the heat required and the network temperature is dropped accordingly to 86.5 °C. For a very high gas price (8 CHcts·kWh^{-1}), the optimal solution for both the thermoeconomic and the environomic models is a heat pump using grid electricity satisfying the whole demand.

The different contributions to the pollution costs for the case of 13 CHcts·kWh^{-1} and 5 CHcts·kWhLHV^{-1} for electricity and gas, respectively (configuration: central plant heat pump with gas furnace), appears in *table IV*. As can be seen, the major contributions to the pollution costs are due to electricity preparation, furnace emissions and network manufacture and removal.

The value of κ_0/κ_{0c} used in the environomic model and the various scenarios given above is the same for all processes and is equal to 0.9 for NO_x and 0.61 for CO_2 [9]. Since the manufacture and removal processes are assumed to emit at the critical conditions[10], the value of $\dot{\phi}_{0NO_x}/\dot{\phi}_{0cNO_x}$ is equal to 1 and the associated pollution penalty factor has a value of 1.903. For the process of operation of the DHN system, the concentration limit of NO_x in the combustion gases used is 250 mg·Nm^{-3} NO_x. Since the concentration of NO_x in the combustion gases for the gas furnace is 80.0 mg·Nm^{-3}, the pollution factor is equal to 1.083. For CO_2, the value of this factor is 1.00653. This is based on a present global concentration for CO_2 of 330 ppmV, a natural concentration of 280 ppmV, a critical concentration of 400 ppmV[11], a value of 0.3 for $f_{r_{CO_2}}$ (see equation (9) above), and r_{CO_2}/r_{cCO_2} equal to 0.133.

Results for the second type of heating demand structure, characterized by the higher heat rate demanded at a lower temperature given in *figure 2(b)*, are summarized in *tables VI* and *VII*. They show that when pollution costs are not taken into account, the configuration is the same as for the reference demand case described above, i.e. a central plant heat pump, cogeneration gas turbine unit and gas furnace. Since 70 % of the heat demand corresponds to category 1 buildings with supply and return nominal temperatures of 46 and 36 °C, the temperature of the water returning to the central plant is very close to 36 °C[12] (compared with 53 °C for the reference de-

---

[9] Values given in this paragraph are based on data from references [8–10] as reported in [3].

[10] This simplification is based on a rough estimate that production of energy intensive components is often done in industrial areas, which are, environmentally speaking, already highly solicited. The assumption is made that the production units just meet the local standards (critical limit) as there are no economic incentives to do much better. When sensitivity studies show that this parameter is important, which happens not to be the case here, a more refined evaluation of this parameter would be recommended.

[11] Short of better results in damage assessment of global warming and of the relative importance of CO_2 in this issue, this value has been estimated for the sake of this application and should be reevaluated as atmosphere modeling improves in the future.

[12] The values of the return temperature result from the mixing of the return flows from all users.

TABLE VI
Optimized network supply temperature and nominal heat rate of the main components of the system (table valid for the heating demand structure scenario of *figure 2(b)*, electricity price of 13 CHcts·kWh^{-1}, gas price of 5 CHcts·kWh^{-1}).

	Without pollution costs	With pollution costs
Network temperature [°C]	85.8	69.5
Nominal heat rate [MW] of:		
Heat pump	29.0	50.9
Cogeneration gas turbine	12.7	0.00
Cogeneration gas engine	0.00	0.00
Gas furnace	20.9	11.4

TABLE VII
Cost breakdown of the unit of delivered heat energy (table valid for the heating demand structure scenario of *figure 2(b)*).

Electricity: 13 CHcts·kWh^{-1} Gas price: 5 CHcts·kWh^{-1}		
	Cost breakdown [CHcts·kWh^{-1}]	
Pollution costs	No	Yes
Building	1.20	1.03
Equipment	1.61	1.61
Network	0.79	0.87
Administration	1.18	1.18
Energy	2.79	3.17
Pollution	0.00	0.07
Total	7.57	7.92

TABLE VIII
Optimized nominal heat rate of the main components of the system (table valid for a high share (85 %) of the heat rate at low temperature, *figure 2(c)*).

	Nominal heat rate [MW]	
Prices [CHcts·kWh^{-1}]: Electricity: 13 Gas: 5	Without pollution costs	With pollution costs
Network temperature [°C]	89.8	52.0
Heat pump	31.7	61.1
Cogeneration gas turbine	14.6	0.00
Cogeneration gas engine	0.00	0.00
Gas furnace	16.4	0.00

TABLE IX
Cost breakdown of the unit of delivered heat energy (table valid for a high share (85 %) of the heat rate at low temperature, *figure 2(c)*).

Electricity: 13 CHcts·kWh^{-1} Gas price: 5 CHcts·kWh^{-1}		
	Cost breakdown [CHcts·kWh^{-1}]	
Pollution costs	No	Yes
Building	1.20	0.87
Equipment	1.64	1.74
Network	0.74	0.84
Administration	1.18	1.18
Energy	2.82	2.99
Pollution	0.00	0.05
Total	7.59	7.66

mand case). The COP for the central plant heat pump is at the better value of 4.25 (compared with 3.51 for the reference demand case). The cogeneration unit is, therefore, smaller. The network temperature is 85.8 °C instead of 97.0 °C, because a bigger ΔT between network supply and return can be achieved with a lower network temperature, something which is not possible for the reference demand case. When pollution costs are taken into account, the solution configuration includes a gas furnace of the same size as in the reference demand case (11.4 MW), but the network temperature is 69.5 °C instead of the 86.5 °C found for the reference demand case. This means that the high temperature category (category 4) is connected via a local heat pump (on the supply line).

With the increasing importance of the heat rate demanded by the lowest temperature category, a scenario which would probably be consistent with that for a new district, the interest for working at low temperature is shown by the results appearing in *tables VIII* and *IX*. These were obtained with 85 % of the total heat rate demanded at 46–36 °C and 5 % of the demand for each one of the other categories as illustrated in *figure 2(c)*.

Although the solution without pollution costs is relatively similar to the one seen for the case of the demand structure of *figure 2(b)*, when pollution costs are considered, the optimum network temperature drops to 52 °C. Therefore, the category at 46–36 °C can be connected by heat exchanger to the main distribution network, while all the other categories need a local heat pump to connect them to the main network line. In particular, category 2 is connected by a return line heat pump, thus, leading to a return temperature of 36 °C and a COP for the central plant heat pump of 4.62.

Coming back to the reference demand of Lausanne-Ouchy (*figure 2*) and optimizing on the basis of an exergy formulation alone (exergy life cycle) but without pollution costs, results in a central configuration with a heat pump alone and user configurations shown in *figure 4*. The optimum network configuration is 68.9 °C which is sufficient to satisfy the first three categories

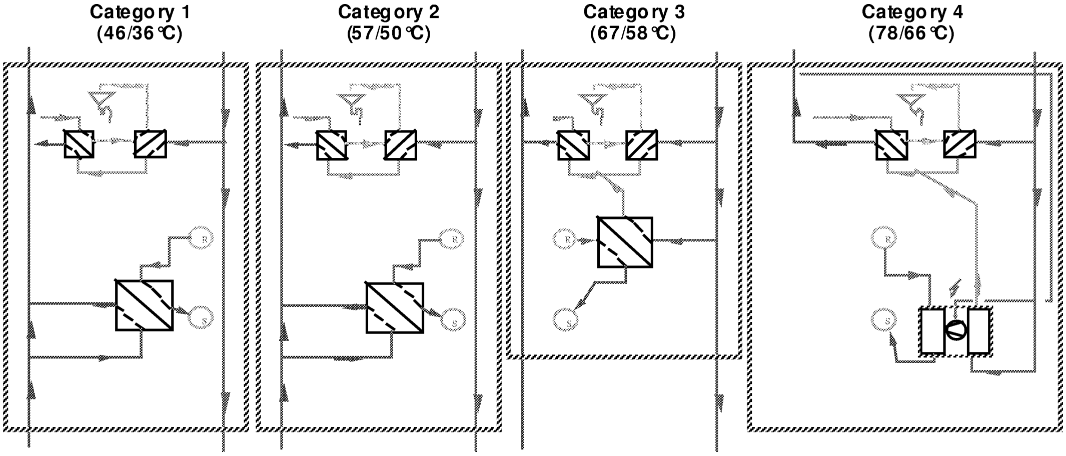

Figure 4. Optimized user configurations resulting from an exergetic formulation for the reference case of Lausanne-Ouchy (see *figure 2*).

TABLE X
Life cycle exergy distribution from an optimization based on exergy terms alone (without pollution costs) for the demand of Lausanne-Ouchy.

Life cycle exergy amounts	[kWh·year^{-1}]
Equipment	1.12 E+05
Network	7.52 E+05
Operation	1.72 E+07
Total	1.81 E+07

of users with heat exchangers but requires decentralized heat pumps for the fourth category. For this case, *table X* shows that around 95 % of the total life cycle exergy is linked to the operation, slightly more than 4 % to the construction of the network and less than 1 % to the manufacture of the equipment.

5. CONCLUSIONS

The results presented above illustrate the potential to the design engineer of this new and powerful approach to the synthesis and design process. This approach provides for a fast, comprehensive and optimal reassessment of design options when economic conditions or the emphasis on pollution vary. Among the promising technical combinations, which resulted from the above application, the case is made for connecting the most exigent users by local heat pumps to the supply line and, in some cases, to the return line as well. Although not presented here, results for costs expressed in exergetic units also show the interest for considering both centralized and decentralized heat pumps for district heating. However, in the range of the parameters considered in our sensitivity analysis, solutions relying on decentralized heat pumps for all users were always superseded by solutions relying either exclusively on central plant components or on a mix of centralized and decentralized solutions.

Finally, the introduction of pollution costs and of pollution penalty factors suggest a move towards environmentally more sustainable choices and designs. In addition, the process of integrating the major factors of decision-making into a single and flexible approach opens new avenues to facilitating the communication between engineers and policy-makers.

Future steps in our formulation will include a completely time-dependent optimization of the operational sequences involved as well as an extension of the model to include satisfying a cooling demand with, for example, a four-pipe network (one pair for heating and one pair for cooling). The modular structure of the program also opens the way to extending this approach to other technologies such as absorption heat pumps, fuel cells, combined cycles with fuel cells and gas turbines, etc.

Acknowledgements

The authors wish to thank Adam K. Molyneaux for the implementation of the optimization programs and Prof. D. Wallace for sharing algorithms initially developed at MIT. They also would like to acknowledge the financial support provided by the Swiss National Science Foundation and recognition by the Alliance for Global Sustainability between MIT, University of Tokyo and the Swiss Federal Institutes of Technology.

REFERENCES

[1] Curti V., von Spakovsky M.R., Favrat D., An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part I: Methodology, Int. J. Therm. Sci. 39 (6) (2000).

[2] Olsommer B., von Spakovsky M.R., Favrat D., An approach for the time-dependent thermoeconomic modeling and optimization of energy system synthesis, design and operation (Part I: Methodology and application), Int. J. Appl. Thermodyn. (1999).

[3] Curti V., Modélisation et optimisation environomiques de systèmes de chauffage urbain alimentés par pompes à chaleur, Ph.D. Thesis No. 1776, Swiss Federal Institute of Technology of Lausanne, Lausanne, 1998.

[4] Grossman I.E., Mixed-integer, non-linear programming techniques for the synthesis of engineering systems, Res. Eng. Des. 1 (1990) 205–228.

[5] Floudas C.A., Non-linear and mixed integer optimization: Fundamentals and applications, in: Topics in Chemical Engineering Series, Oxford University Press, 1995.

[6] Grüninger T., Wallace D., Multimodal optimization using genetic algorithms, MIT CADlab Technical Report 96.02, 1996.

[7] Utzmann C., Curti V. et al., Valorisation de l'énergie thermique des lacs pour le chauffage urbain, Project PACLAC, Final Report, Nationalen Energie-Forschungs-Fonds (NEFF), Switzerland, March 1995.

[8] Ott et al., Externe Kosten und Kalkulatorische Energiepreiszuschläge für den Strom- und Wärmebereich, Swiss Federal Office of Energy (OFEN), Report 724.270 D, 1994.

[9] Swiss Federal Office on Environment, Forests and Countryside, Taxe CO_2: l'écologie dans l'économie, Documents environnement-économie No. 15, Bern, 1994.

[10] Swiss Government, Ordonnance sur la protection de l'air OPair (Regulation concerning air protection), Bern, 1994.