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An Approach for the Time-Dependent Thermoeconomic Modeling and Optimization of Energy System Synthesis, Design and Operation
Part I: Methodology and Results

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Abstract

From the standpoint of an energetically and economically efficient waste elimination, the design and operation of optimized incineration power plants with the cogeneration of electricity and heat has become today an important issue. Decision models developed to minimize the total costs associated with such systems only partially respond to the problems associated with the choice of configuration (synthesis), component design, and the operation of the waste incineration/cogeneration unit. In fact, the time factor which greatly affects certain key parameters such as the amount of wastes and the electrical and heating demands placed on the system (to name just two) renders the problem of synthesis, design and operation very complex. A thermoeconomic methodology and the results of an application of it to a waste incineration system with cogeneration and a gas turbine topping cycle are presented here as Part I of a series of two articles. The second article (Part II; Olsommer et.al., 1999) presents details of the approach used to incorporate reliability and availability considerations into the methodology.

Key words: energy systems optimization, waste incineration, genetic algorithm

1. Introduction

An awareness of environmental problems due to pollution and a concern for long-term resource availability has lead to a search for ways of producing and using energy which are not based on economic factors alone. This awareness coincides with another current concern: the growth and necessary revaluation of wastes. For the moment, incineration remains one of the most common, best controlled and most mature ways of treating such wastes. In Switzerland, for example, domestic waste incineration coupled with heat recovery for the production of the steam used in cogeneration cycles represents, in terms of electricity, the potential equivalent of a quarter of their largest nuclear power plant, and, in terms of heating, the potential to supply the needs of a city of about 150,000 inhabitants. However, typically, there are a number of time-dependent parameters associated with waste incineration cogeneration plants which make the problem of synthesis, design and operation quite complex. These parameters include: i) the fluctuation of economic parameters, ii) variations in the amount and quality of the wastes, iii) changes in heat and/or electricity demands, iv) planned extensions of district heating networks, etc. In practice, it has been very difficult to effectively design, build and operate these types of plants as noted in Switzerland by the over-capacity (or under-capacity) and/or operational problems of several waste incineration power plants. Waste treatment costs are, thus, heavily penalized.

In order to account for the variations mentioned above, this type of plant as well as others cannot be designed based on a single operating point as is the common practice in industry today. To determine how these variations affect plant synthesis (changes in configuration), design (component size and nominal performance) and operation (both nominal and non-nominal), changes in these parameters and their effects on the plant must be integrated over the entire lifetime of the plant in order to answer to the following questions:

- when to invest and to reinvest;
- how to choose and to interconnect the components;
- how to choose the design parameters (size, nominal performance values, etc.) of the different equipment subsystems in the plant.

The methodology proposed in this paper offers to the decision-maker a tool which minimizes a system's total costs over its entire lifetime, taking into account the time-dependencies just outlined. The methodology is applied to a domestic waste treatment incineration power plant with cogeneration and with a gas turbine topping cycle.

The methodology presented here is used to develop a thermoeconomic model of the system, a model which can then be optimized to simultaneously determine the optimum synthesis, design and operational modes for the system. Such a model is formed from engineering economic and physical (or thermodynamic) simulation models of the system and its components. One of the difficult tasks is to produce simulation models which predict with accuracy the component behavior during operation at nominal or subnominal conditions. The time-dependency of operation is handled by a series of steady state models, which model the overall quasi-steady state behavior of the system.

Once developed, the thermoeconomic model is optimized at two levels: (i) structural (synthesis-design) and (ii) operational (synthesis-operation). This reduces the complexity of the optimization which forms a solution space of typically highly non-linear, continuous / discontinuous, and non-contiguous surfaces. At the latter level, interdependent time-intervals are grouped together in order to identify a limited series of optimization sub-problems. These sub-problems are optimized individually for a fixed structure and the results summed (integrated) and introduced at the structural level. At this level, a new choice of system configuration (synthesis) and component design is made based on minimizing the system's total costs. An iterative procedure is pursued which moves back and forth between the two levels of optimization, terminating once the global minimum for the total costs has been found. This two-level optimization procedure was developed and applied using heuristic optimization approaches (genetic algorithms (GA)) to solve the problem. Among others, the GA used in this work have the ability to explore the entire solution domain while optimizing several interesting design alternatives in parallel.

In this paper a brief background perspective is given, followed by a description of the formulation of the thermoeconomic model as well as of the procedure and algorithm used to optimize it. Results from an application of this methodology for a waste incineration system with cogeneration and a gas turbine topping cycle appear here. Multiple solutions, all close to the global optimum of minimum cost for the system, are presented since in practice engineers more often than not are interested in having several good solutions instead of a single one. Being able to automatically find such a set of solutions as part of the optimization procedure was made possible by a modified release of the "Struggle" GA (Wallace, 1996). This process in GAs of finding multiple optimal solutions is called "niching".

2. Brief Background Perspectives

The best practical design of an energy system, the best operation of an existing one, or the synthesis of either (i.e. the choice of configuration) which best meets a specific goal (e.g., a given demand or demands) should be determined on the basis of not only thermodynamic criteria but economic and perhaps environmental ones as well. In the real world, these additional considerations are necessary despite the shortcomings of including monetary and environmental functions which by definition are of a temporary nature in an engineering analysis. It is desirable to use an approach which mathematically models one or more of these aspects in a unified fashion so that optimization algorithms could be used to search the solution space of all possible solutions for the synthesis, design and/or operation of a new or an existing system.

The development of such an approach falls within the domain of Thermoeconomics which originated with the work of Tribus (1956); Evans (1961); El-Sayed and Evans (1970); and Gaggioli (1977) and has continued to grow and mature in the 1980's and 1990's with the work of, for example, von Spakovsky (1994), Frangopoulos (1994), Tsatsaronis and Pisa (1994), Valero et al. (1994), von Spakovsky and Evans (1993), El-

Sayed (1996), Lazzaretto and Andreatta (1995), da Silva and Nebra (1996), Benelmir et al. (1991), Olsommer et al. (1997), Curti et al. (1998), and Pelster et al. (1998). Thermoeconomic models when expanded to include environmental criteria associated with long-term resource use and pollution have been called environomic models (Frangopoulos and von Spakovsky, 1993). When fully developed, they include those thermodynamic, economic and environmental aspects associated with the entire life cycle[1] of a system. The formulation presented in this paper though limited to thermoeconomic considerations can easily be expanded to include these additional considerations (von Spakovsky and Frangopoulos, 1994, von Spakovsky, 1998, Curti et al., 1998).

3. The Thermoeconomic Model: General Formulation

What follows is a general, quasi-static[2] formulation of the thermoeconomic model describing the time-dependent optimization problem from which the optimum synthesis, design and operation of an energy system can be found:

$$\min C_{tpn}(\mathbf{z},\mathbf{y},t) = C_{TCI} + C_{dep} + C_{res} - C_{rev} + C_{maint} + C_{ins} + C_{tax} + C_{fix} \quad (1)$$

$$\text{w.r.t.} \quad \mathbf{z} = \{\mathbf{w},\mathbf{x}\},\ t \quad (2)$$

$$\text{subject to} \quad \mathbf{h}(\mathbf{z},\mathbf{y},t_k) = \mathbf{0} \quad (3)$$

$$\mathbf{g}(\mathbf{z},\mathbf{y},t_k) \le \mathbf{0} \quad (4)$$

$$\mathbf{L}(\mathbf{z},\mathbf{y},t_k) = \mathbf{TRUE} \quad (5)$$

where t is time, **z** the independent variable set (composed of **w** which characterizes the structural level decisions and **x** which denotes the operational level decisions), and **y** the dependent variable set. The equality constraints (Eq. (3)) represent mass, energy and/or exergy balances as well as equipment performance characteristics while the inequality constraints (Eq. (4)) represent physical limits placed on the system as well as function and variable limits. The logical expressions (Eq. (5)) represent conditional relations. k = 1,..,K, represents the sequence index and K corresponds to the sequence number over the time horizon (N_e) (see Eq. (10) below).

The overall objective of the optimization problem given by (Eq. (1)) is to minimize the total net present costs of the system over its entire economic lifetime. These costs (Eqs. (6) through (9) below) are expressed by means of continuous functions. They consist of those associated with the

- capital (equipment, facilities construction, land purchase and preparation, various fees (Eq. (6));
- resource costs (purchased services for primary energies, etc. (Eq.7);
- product benefits or revenues (sales of transformed energy, recyclable products and other services (Eq.8);
- depreciation (C_{dep}), maintenance (C_{maint}), insurance (C_{ins}), taxes (C_{tax}) and fixed costs (C_{fix}) (Eq.9).

$$C_{TCI}(\mathbf{z},\mathbf{y},t) = \sum_{gr}^{Gr}\left\{\sum_{e}^{E}\left[\dot{C}_{TCI}\right]_e \sum_{j}^{J}\left[PWF(N,i_m)\right]_j\right\}_{gr} \quad (6)$$

$$C_{res}(\mathbf{z},\mathbf{y},t) = \sum_{gr}^{Gr}\left\{\sum_{i}^{I}\left[\sum_{r}^{R}\left(\dot{C}_{res}\right)_r \Delta t\right]_i \sum_{j}^{J}\left[PWF(N,i_m)\right]_j\right\}_{gr} \quad (7)$$

$$C_{rev}(\mathbf{z},\mathbf{y},t) = \sum_{gr}^{Gr}\left\{\sum_{i}^{I}\left[\sum_{p}^{P}\left(\dot{C}_{rev}\right)_p \Delta t\right]_i \sum_{j}^{J}\left[PWF(N,i_m)\right]_j\right\}_{gr} \quad (8)$$

$$C_b(\mathbf{z},\mathbf{y},t) = \sum_{gr}^{Gr}\left\{\dot{C}_b \sum_{j}^{J}\left[PWF(N,i_m)\right]_j\right\}_{gr}$$

with b = dep, maint, ins, tax, fix (9)

$$K = \sum_{gr}^{Gr} I_{gr} \quad (10)$$

In the expressions above, the $\dot{C}$ are cost rates (detailed in Eqs. (11) to (15) below); PWF the present worth factor; i_m the market interest rate; N the number of years from the initial time (t=0) to the corresponding anticipated year of purchase[3]; J_{gr} the number of one year periods of the corresponding group gr (Eqs. (6) to (9)); Gr the number of groups; E, R, and P the number of capital, resource, and revenue costs, respectively; I_{gr} the sequence number of the corresponding group gr (Eq. (10)); and Δt the duration of this sequence. Cost rates appearing in Eqs. (6) and (9) are given in (CHF/yr), whereas resource and revenue costs (Eqs.7 and 8) are given in (CHF/s). In order to be consistent with several of the yearly economic parameters used (e.g., inflation rates, interest rates, etc.), $\sum_i^I \Delta t_i$ is typically one year (Eqs. 7 and 8).

[1] The "entire life cycle" includes the cycles related to the economic lifetime of the system, and those dealing with the processes both upstream and downstream of the system, i.e. those related to the system's use of fuel resources and the manufacture and removal of the system's equipment.

[2] The more general formulation would have integrals over time instead of summations.

[3] $N = \{1, .., N_e\}$.

The quasi-stationary approximation used here works well as long as the time intervals are independent and unsteady-state or transient conditions are insignificant. Such an assumption can be made for number of systems with which we are concerned (i.e energy conversion systems). In the case of interdependent operating modes, the separate integrals of the operating intervals (Δt_i) affected have to be grouped and optimized in a single block with respect to additional constraints (Olsommer, 1998). The time decomposition procedure consists of first identifying, for each time-dependent parameter, sequences which are representative of the parameter fluctuation over the considered time horizon. In a second step, the number of sequences can at times be reduced by grouping several sequences characterized by identical sets of parameters into so called "groups of sequences". If the mathematical complexity of the problem can be widely reduced by grouping sequences, the chronology of the sequences can be broken. For the model, this implies that structural changes can only be made at the beginning of a group of sequences.

The cost rates integrated in Eqs. (6) to (9) are expressed as a function of the time (t) in Eqs. (11) to (15) below:

$$\dot{C}_{TCI_t} = [\,(1-s-h)\cdot TCI \cdot CRF(N_h,i_m) + h \cdot TCI \cdot CRF(N_h,i_h)]_t + \dot{C}_{TCI_{t-1}} \quad \text{(CHF/year)} \quad (11)$$

$$TCI_t = C_{AE_t} + C_{CL_{t=0}} + C_{H_{t=0}} \quad \text{(CHF)} \quad (12)$$

$$\dot{C}_{res,rev_t} = \left[c\,\dot{\Phi}\right]_t \quad \text{(CHF/s)} \quad (13)$$

$$\dot{C}_{dep_t} = \left[\gamma\left(C_{AE} - C_{AE_S}\right)\frac{i_m}{\left(1+i_m\right)^{N_e}-1}\right]_t + \dot{C}_{dep_{t-1}} \quad \text{(CHF/year)} \quad (14)$$

$$\dot{C}_{b_t} = \left[f_b\, C_{AE}\right]_t + \dot{C}_{b_{t-1}},$$

with b = dep, maint, ins, tax, fix, (CHF/year) (15)

With s and h the TCI fractions corresponding to subsidy and loan, respectively[4]; N_h and i_h the loan period and loan rate; respectively; CRF the capital recovery factor; C_{AE} the equipment purchase costs; C_{CL} and C_H all other capital costs (civil engineering / land and various fees, respectively); c a unit cost rate; $\dot{\Phi}$ a resource or revenue rate; C_{AE_S} the equipment salvage value, γ the rate of reinvested depreciation set-aside; and N_e the equipment economic life. The $\dot{C}_b$ are assumed proportional to equipment purchase costs.

[4] Note that the 2nd and 3rd right hand side terms in (Eq. (12)) equal zero if t≠0.

4. Optimization and Decomposition: General Approach

The quasi-stationary formulation proposed above (Eqs. (6) to (9)) permits a split of the original optimization problem into several optimization sub-problems. The advantage of this sort of decomposition is that it produces a number of simpler optimization problems equal to the number of independent time intervals present. In addition, another kind of split based on the conceptual divisions of the problem, i.e. structural and operational, is also possible (Frangopoulos, 1989; Yokoyama and Ito, 1995). Synthesis deals with the number of components and connections present; design with a choice of component technologies, capacities and nominal performances and operation with the various operating states of the system throughout its entire lifetime. This type of decomposition results in two levels of optimization: i) structural and ii) operational[5]. Both the quasi-stationary and conceptual decompositions reduce the complexity of the original problem at the appreciable expense of the computational time involved. The latter, however, is more readily overcome than that of solving without decomposition a problem which is far too large and far too complex and may, in fact, be impossible to define completely a priori (Olsommer et al., 1997).

For the two levels of optimization defined above, the structural level is the controlling level, determining the system components available for each of the time intervals, the optimization of which is done in the second or operational level of optimization. The independent variables belong either exclusively to the first level (**w**) or to the second (**x**). The variables may be binary, integer or real. The **w** variables typically represent the absence or presence of a component, its acquisition date, its size or nominal performance, etc. The **x** variables represent shutting a component off or turning it on, the state of a valve, a temperature, a pressure, etc. The interdependency of these two levels is clear: the optimizations at the second level depend on the choice of values made for the variables at the first level and vice-versa.

The problems envisioned here describe highly non-linear, continuous / non-continuous, and non-contiguous (disjoint) solution spaces as, for example, depicted in *Fig. 1* below[6] where the horizontal axes represent the two levels of optimization and the vertical one the optimization

[5] Note that synthesis also occurs at the operational level but only in terms of component start-up and shut-down.

[6] Note that the smooth surfaces shown are a simplification for illustration purposes only.

criteria or objective function used. This type of optimization problem belongs to the Mixed Integer Non-Linear Programming (MINLP) class of problems. The cost functions (investments, etc.) which make up the objective function; the energy, exergy and / or mass balances which define the equality constraints; and both the thermodynamic and transport fluid property functions used in calculating system operating modes are all typically very non-linear, continuous and non-continuous. The binary and integer variables present lead to the non-contiguous or disjoint nature of the surfaces defined by the problem (see *Fig. 1*). The space between two domains (the surfaces shown) constitutes a zone where the constraints are violated.

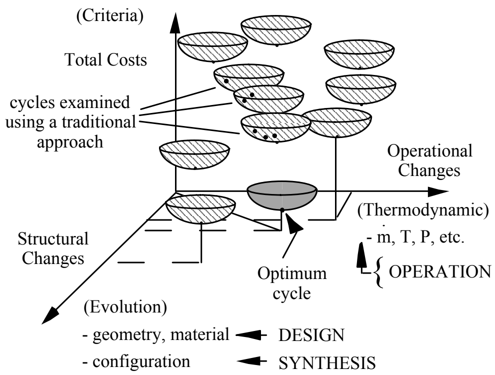


Figure 1. The structural (synthesis-design) and operational (synthesis-operation) space of energy systems (von Spakovsky, 1998).

In order to model this type of space, a superconfiguration for the system, taking into account the schedule of conditions for the plant, is chosen. This superconfiguration must include a finite number of interconnected components. So as to limit the number of possibilities, the knowledge and experience of the expert (namely the engineer or a team of engineers) is applied directly: (i) in straightaway dismissing useless solutions (possible sub-configurations) and (ii) in judiciously choosing the independent variables. In fact, an appropriate choice of variables may have a direct influence on the stability and/or speed of convergence of the optimization.

The equality constraints (Eq. (3)) which express the causal links (or transfer functions) between all points of the system and are based on the fundamental equations of thermodynamics (continuity, momentum, energy and state equations) must be sufficiently accurate in representing the real physical components in the system so that a high level of confidence can be given to the optimization results. This remark has particular meaning for the second level (operating modes) optimizations since it assumes that it is possible to predict with sufficient accuracy and certainty the behavior of components in operating modes often far from their nominal or design points. Thus, it is necessary to develop effective modules of simulation for the different components of the system. This step constitutes a preponderant part of the overall task of modeling.

The inequality constraints (Eq. (4)) which typically represent technological system limits are introduced into the objective function through penalties. This may involve simply adding a constant value (most often high) to the objective function. This approach is usually not the best since it can introduce discontinuities into the objective function which discourage the optimization algorithm from approaching too near to the limits set by the inequality constraint(s). The solution may well lie at one or more of these limits. A more attractive possibility is to penalize the objective function in a progressive fashion depending on the distance one is from the feasible region.

Finally, a solution space such as the one depicted in *Fig. 1* is not easily nor effectively searched with standard mathematical programming algorithms (e.g., Generalized Reduced Gradient (GRG) and Sequential Quadratic Programming (SQP); Reklaitis et al., 1983). Those more adapted to this space (e.g., Generalized Outer Approximation and Generalized Benders Decomposition; Floudas, 1995) tend to be restrictive both in the type of problem that can be handled and in the problem formulation required. Approaches which circumvent these difficulties, i.e. heuristic ones (e.g., genetic algorithms (GAs)), are not only well-adapted to searching such a space but do not a priori place restrictions on the problem formulation nor on the type of problem that can be handled. This type of search method has been used in our optimizations and is discussed below.

5. Two-Level Decomposition Optimization Procedure

The decomposition formulation of the time-dependent MINLP problem (Eqs. (1) to (5)) is given below:

$$\min C_{tpn}(\mathbf{w},\mathbf{x},\mathbf{y},t) = \tag{16}$$

$$[C_{TCI}(\mathbf{w},\mathbf{y},t)+C_{dep}(\mathbf{w},\mathbf{y},t)+C_{maint}(\mathbf{w},\mathbf{y},t)+ C_{ins}(\mathbf{w},\mathbf{y},t)+C_{tax}(\mathbf{w},\mathbf{y},t)+C_{fix}(\mathbf{w},\mathbf{y},t)]_{L1} + \sum_{k}^{K}[C_{res}(\mathbf{w},\mathbf{x}_k,\mathbf{y}_k,t_k)-C_{rev}(\mathbf{w},\mathbf{x}_k,\mathbf{y}_k,t_k)]_{L2}$$

$$\text{w.r.t. } \mathbf{z} = \{\mathbf{w},\mathbf{x}_k\},\ t_k \qquad k=1,\dots,K \tag{17}$$

subj. to :

$$[\mathbf{h}(\mathbf{w},\mathbf{y},t)]_{L1}=0\,,[\mathbf{h}(\mathbf{w},\mathbf{x}_k,\mathbf{y}_k,t_k)]_{L2}=0 \quad (18)$$

$$[\mathbf{g}(\mathbf{w},\mathbf{y},t)]_{L1}\le 0\,,[\mathbf{g}(\mathbf{w},\mathbf{x}_k,\mathbf{y}_k,t_k)]_{L2}\le 0 \quad (19)$$

$$[\mathbf{L}(\mathbf{w},\mathbf{y},t)]_{L1}=\text{TRUE},$$
$$[\mathbf{L}(\mathbf{w},\mathbf{x}_k,\mathbf{y}_k,t_k)]_{L2}=\text{TRUE} \quad (20)$$

where the L1 and L2 subscripts refer to the level of optimization. For each iteration at the structural level of optimization (level L1), K sub-problems must be solved (optimized) at the operational level (level L2). In subdividing the original optimization problem into a primary problem (L1) and K sub-problems, particular care must be taken with the reformulation of equality and inequality constraints at the second level since the second of the paired constraints in Eqs. (18) to (20) depend on the structural decisions resulting from the optimization at level L1. GAs are used at both levels. A modified release (Olsommer, 1998) of the Struggle GA (Wallace, 1996) is used at the structural level, while a Steady-state GA (GALIB, 1998) has been used at the operational level.

In order to circumvent the penalty in CPU time paid with this sort of decomposition, the procedure has been parallelized for execution on multi-processor computers. This can be done in several ways including assigning an individual processor to each time interval, writing parallel code for solving the thermoeconomic model, etc. The former of these techniques has been implemented with the two level procedure used here.

6. Application to a Waste Incineration Cogeneration Plant with a Gas Turbine Topping Cycle.

6.1 Superconfiguration

The two-level procedure depicted above was applied to the optimization of the thermoeconomic model developed for the waste incineration power plant shown in *Fig. 2*, which is partly derived from an existing plant used for comparison purposes. It includes cogeneration and the possibility of adding a gas turbine topping cycle. The model itself consists of a plant superconfiguration which comprises all the practical structural degrees of freedom (a finite number) for the plant (e.g., multiple units in parallel, bypasses, auxiliary units, etc.). Potentially, three waste incinerators (furnace plus steam generator - (F)) exist as well as one steam turbine without extraction (T1), one steam turbine with extraction (T2), two generators (G), two aero-condensers (C), one heat exchanger for district heating (DH), one auxiliary boiler (AB), one deaerator (D), four pumps, several valves, one bypass, several motors (M), a gas turbine cycle (GT), a waste heat recovery heat exchanger (RH), etc. The superconfiguration is optimized taking into account all the time-dependent constraints and parameters.

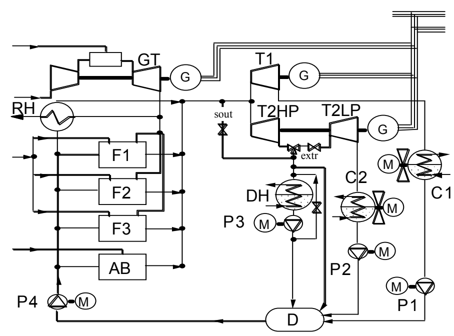


Figure 2. Superconfiguration for the waste incineration cogeneration plant with a gas turbine topping cycle.

The objective function used represents the waste specific total treatment costs expressed in CHF/ton. The plant must minimize its waste treatment costs over a fixed period (N_e). The amount of wastes to be treated and the amount of heat delivered to a district heating network (DH) are fixed within a given group of time intervals and for a given time interval, respectively.

6.2 Identification of time intervals

A necessary step in the development of the overall thermoeconomic model is the identification of typical time intervals representative of the most important operating modes. Three main operating modes were identified: (i) winter (W), (ii) mid-season (M) and (iii) summer (S). By analyzing the time-dependence of each parameter over the projected lifetime of the plant, it was possible to reduce the size of the overall problem by regrouping some consecutive years into a single group of operating modes. Without this type of grouping, every year would have to be included in the optimization, leading to a much larger problem, i.e. more sub-problems. Over a given group of time intervals, certain parameters from levels I and II are fixed. For our particular set of optimization problems, four groups were formed (see TABLE I)[7]. Note that components are only acquired at the beginning of a group of time intervals.

[7] Average seasonal temperature and thermal power differ from the maximum seasonal temperature and thermal power, respectively, used for aero-condenser and DH designs.

TABLE I. Scenario: Time Interval Decomposition and Grouping.

Group (gr)	1			2			3			4		
Period	1996 - 2000			2001 - 2005			2006 - 2010			2011 - 2015		
Marshall & Swift Cost Index (-)	1020			1151			1299			1467		
Sequence (k)	1	2	3	4	5	6	7	8	9	10	11	12
Season	W	M	S	W	M	S	W	M	S	W	M	S
Duration (h)	14610	14610	14610	14610	14610	14610	14610	14610	14610	14610	14610	14610
Ambient temp. (°C)	2	9	16	2	9	16	2	9	16	2	9	16
DH ($\dot{Q}_{DH}$) (MW)	3.47	1.81	0.54	5.34	2.79	0.82	7.31	3.82	1.13	8.54	4.46	1.32
Wastes ($\dot{m}_w$) (kg/s)	2.03	2.03	2.03	2.23	2.23	2.23	2.42	2.42	2.42	2.63	2.63	2.63
Δh_0 (MJ/kg)	12.39	12.39	12.39	12.89	12.89	12.89	13.18	13.18	13.18	13.34	13.34	13.34
c_m (CHF/kg)	0.154	0.154	0.154	0.179	0.179	0.179	0.200	0.200	0.200	0.205	0.205	0.205
c_{gas} (CHF/kg)	0.321	0.321	0.321	0.331	0.331	0.331	0.340	0.340	0.340	0.344	0.344	0.344
c_{el} (CHF/kWh)	0.095	0.075	0.055	0.100	0.078	0.058	0.107	0.084	0.062	0.123	0.096	0.071
c_{DH} (CHF/kWh)	0.023	0.023	0.023	0.024	0.024	0.024	0.025	0.025	0.025	0.025	0.025	0.025

Parameters which are fixed with respect to the overall model and do not depend on the time interval or a particular group of intervals are given in TABLE II. Important independent parameters held constant for purposes of simplification and didactic reasons include the pressure and temperature of the steam at the furnace outlet (*Fig. 2*) with values of 40 bar and 424 °C, respectively.

TABLE II. Fixed Economic Parameters.

Description	Symbol	Value	Unit
Economic life	N_e	20	(year)
Loan rate	i_h	AE: 0.08 CL,H: 0.05	(-)
Market interest rate	i_m	0.03	(-)
Inflation rate	i_n	0.03	(-)
Repayment period	N_h	20	(year)
Subsidy fraction	s	0.3	(-)
Loan fraction	h	0.6	(-)
Depreciation factor	γ	1	(-)
Salvage value	C_{AE_S}	0	(CHF)
Waste exportation	c_{export}	0.3	(CHF/kg)
Maintenance	f_{maint}	0.089	(-)
Insurance	f_{ins}	0.007	(-)
Taxes	f_{tax}	0.016	(-)
Fixed	f_{fix}	0.001	(-)

6.3 Independent variables

The independent variables **w** and **x** are grouped by type together with their bounds in TABLES III and IV. The descriptions given are self-explanatory.

TABLE III. The operating independent variables (**x**).

Description	Symbol	Lower bound	Upper bound	Unit
Binary variables[8]				
On/off operation of GT	δ_{GT}	0	1	(-)
On/off operation of RH	δ_{RH}	0	1	(-)
On/off operation of AB	δ_{AB}	0	1	(-)
Real variables				
Gas turbine (GT)				
Load	x_{TG}	0. 6	1.0	(-)
Furnaces (F1,F2,F3)				
Load of F1	x_{F1}	0.6	1.0	(-)
Load of F2	x_{F2}	0.6	1.0	(-)
Auxiliary boiler (AB)				
Load of AB	x_{AB}	0.0	1.0	(-)
District heating heat exchanger (DH)				
High pressure extraction rate	x_{sout}	0.0	1.0	(-)
Turbo generator sets				
Steam distribution between T2 and T1	x_{T2HP}	0.0	1.0	(-)
Condensing steam turbine (T1)				
Condensing pressure	$p_{cond_{T1}}$	0.06	0.5	(bar)
Extraction steam turbine (T2)				
Extraction pressure	p_{extr}	3.0	5.0	(bar)
Condensing pressure	$p_{cond_{T2}}$	0.06	0.5	(bar)

[8] δ=0 means that the equipment is shut-off.

TABLE IV. The structural independent variables (**w**).

Description	Symbol	Lower bound	Upper bound	Unit
Integer or binary variables[9]				
Acquisition date F1[10]	δ_{F1}	1	1	(-)
Acquisition date F2	δ_{F2}	0	Gr	(-)
Acquisition date F3	δ_{F3}	0	Gr	(-)
Acquisition date GT	δ_{GT}	0	Gr	(-)
Presence of RH[11]	δ_{RH}	0	1	(-)
Acquisition date AB	δ_{AB}	0	Gr	(-)
Acquisition date T1	δ_{T1}	0	Gr	(-)
Acquisition date T2	δ_{T2}	0	Gr	(-)
Direct injection in furnaces[11]	δ_{inj}	0	1	(-)
Real variables				
Gas turbine (GT)				
Gas mass flow rate	$\dot{m}_{B_{GT}}$	0.0	3.0	(kg/s)
Pressure ratio	Π_{GT}	6.0	22.0	(-)
Compressors thermal efficiency[12]	$\eta_{t_{K_{GT}}}$	0.75	0.9	(-)
Turbines thermal efficiency	$\eta_{t_{T_{GT}}}$	0.75	0.9	(-)
Heat recovery steam generator (RH)				
Pinch	ΔT_{RH}	10.0	25.0	(K)
Auxiliary boiler (AB)				
Fuel mass flow rate	$\dot{m}_{B_{AB}}$	0.0	0.5	(kg/s)
Efficiency	η_{AB}	0.7	0.95	(-)
Furnaces (F1,F2,F3)				
Dilution rate in F1[13]	$x_{dil_{F1}}$	0.0	1.0	(-)
Dilution rate in F2	$x_{dil_{F2}}$	0.0	1.0	(-)
Dilution rate in F3	$x_{dil_{F3}}$	0.0	1.0	(-)
District heating heat exchanger (DH)				
High pressure extraction rate	x_{sout}	0.0	1.0	(-)
Pinch	ΔT_{DH}	10.0	15.0	(K)
Turbo generator sets				
Steam distribution between T2 and T1	x_{T2HP}	0.0	1.0	(-)
Condensing steam turbine (T1)				
Thermal efficiency	$\eta_{t\,T1}$	0.7	0.95	(-)
Condensing pressure	$p_{cond_{T1}}$	0.06	0.5	(bar)
Pinch in aerocondenser	ΔT_{C1}	5.0	30.0	(K)

[9] δ=0 means that the equipment is absent.

[10] The plant must have at least one furnace.

[11] Has a meaning only if the GT is present.

[12] In the case of a turbine, the thermal efficiency ($\eta_t=\Delta h_w/\Delta h_s$) is defined as the ratio between the energy absorbed by the "wheel" (rotor), i.e. the enthalpy drop minus the exhaust losses, and the energy available after an isentropic expansion.

[13] Gas dilution rate is defined as the ratio of GT exhaust gas mass flow and the overall mass flow (air + GT exhaust gas) injected in each furnace.

TABLE IV. (continued).

Extraction steam turbine (T2)				
Thermal efficiency of T2HP	$\eta_{t\,T2HP}$	0.7	0.95	(-)
Extraction pressure	p_{extr}	3.0	5.0	(bar)
Thermal efficiency of T2LP	$\eta_{t\,T2LP}$	0.7	0.95	(-)
Condensing pressure	$p_{cond_{T2}}$	0.06	0.5	(bar)
Pinch in aerocondenser	ΔT_{C2}	5.0	30.0	(K)

6.4 Thermodynamic simulation models

Developing adequate thermodynamic models for Eq. (18) and efficient solution schemes is essential. Furthermore, the simulation models for the systems depicted in *Fig. 2* vary depending on whether or not it is a question of structure (level L1: synthesis-design) or operation (level L2: synthesis-operation). For example, the simulation model of the DH heat exchanger at level L1 provides the exchanger's area whereas at level L2 it determines the pinch temperature. The level of confidence with which the optimization results can be treated depends greatly on the quality of these models. Certain well-known, standard types of components (e.g., pumps, valves, deaerators, etc.) are quite easily simulated. This is not the case for the incinerators, steam and gas turbines or aerocondensers and heat recovery steam generators, which are crucial (major) pieces of equipment from an economic and energy standpoint. For this equipment, more detailed developments are needed, i.e. (also see Olsommer et al., 1997; Olsommer, 1998):

1) Level L1: Each piece of equipment must be simulated at nominal (design-point) conditions. Detailed knowledge-based models and correlations are used for the major components. A brief description of each model follows (note that some of the parameters resulting from these simulations must be passed to level L2 in order to properly define the optimization problems at L2, e.g., properly reset certain inequality constraint limits):

- furnaces (F): nominal efficiency and steam mass flow rate as a function of waste mass flow rate, heating value, exhaust GT gas dilution rate (see TABLE IV above), excess air ratio, and specific vapor enthalpy difference;
- steam turbines (T): simulated utilizing thermal efficiency;
- aero-condensers (C): nominal electrical fan consumption as a function of the nominal steam pressure, mass flow rate, and pinch temperature difference;

– gas turbine (GT): modeled with two groups of stages in the compressor and three in the turbine, using parameters such as gas mass flow rate, thermal efficiency for both compressor and turbine stages, inlet first stage turbine temperature, excess air for combustion, air humidity, and bypass cooling air at several pressure levels;
– heat recovery steam generator (RH): simulated using the pinch temperature difference, design steam pressure level[14], GT exhaust gas thermodynamic properties;

2) Level II: Although representation-based models are used at this level, sophisticated thermodynamic models were developed for determining the operating characteristics of the primary components. They were all validated on several subsystems of the existing plant mentioned above. The following additional comments can be made:

– furnaces: the correlation for steam mass flow rate (a function of the waste mass flow rate, of the heating value, of the exhaust GT gas dilution rate (see TABLE IV above), and of the excess air ratio) is normalized with respect to the design point of existing equipment so that it can be applied for different component sizes[15];
– steam turbine: the correlation for thermal efficiency (a function of steam mass flow rate and inlet and outlet pressures) is normalized with respect to the design (nominal) point of existing turbines for the reason given above;
– aero-condensers: pressure controlled by varying the fan speed. Electricity use is proportional to the cube of the normalized air mass flow rate normalized with respect to the nominal (design) air mass flow rate;
– gas turbine: the correlations (i.e. electrical efficiency, thermodynamic states) as a function of the load are normalized with respect to the design (nominal) point of existing gas turbines for the reason given above;
– heat recovery steam generator (RH): simulated using average global heat transfer coefficients as a function of the GT exhaust gas properties (Kehlhofer, 1991).

6.5 Physical limits / inequality constraints

Appropriate inequality constraints (Eq. (19)) ensure that the simulation models employed remain valid within the physical limits placed on the system. In this particular application, the inequality constraints used are expressed on both levels either in terms of mass flow rate, enthalpy, temperature, excess air or availability[16]. Fourteen inequalities have been used at the structural level (L1) and twenty-one for each of the K sequences (see Eq. (10)) at the operational level (L2). Penalties, expressed as functions of active inequality constraints (i.e. g > 0) and used in this application for penalizing either the objective function directly or some dependent variable, are listed in TABLE V[17].

TABLE V. Penalty Functions (P) and Penalties Applied to the Objective Functions (levels L1 and L2) or Dependent Variables ($\mathbf{y}_{L1,L2}$) for the Case of Active Inequality Constraints ($\mathbf{g}_{L1,L2} > \mathbf{0}$).

	Penalty function P	Penalty
Constant	$P = 10^{20}$	F = F + P
Logarithmic	P = 1 + ln(g)	F = F * P
Exponential	$P = e^g$	F = F * P
Power	$P = g^b$, b>1	F = F * P

6.6 Economic model

The objective function[18] at level L2 is given for each sequence k by:

$$\dot{C}_k = \left\{\dot{C}_{res}(\mathbf{w},\mathbf{x}_k,\mathbf{y}_k,t_k) - \dot{C}_{rev}(\mathbf{w},\mathbf{x}_k,\mathbf{y}_k,t_k)\right\}$$
$$= \Big\{ [\, c_{gas}\dot{m}_{B_{GT}} + c_m \dot{m}_{B_{AB}} + c_{export}\dot{m}_{w_{export}} \,] - \left[c_{el}\left(\sum_n \dot{E}_{el_n} - \sum_m \dot{E}_{el_m}\right) + c_{DH}\dot{Q}_{DH} \right] \Big\}_k ,$$
$$\text{with } k=1,..,K \qquad (21)$$

with n={GT,T1,T2} and m={C1,C2,P1,P2,P3, P4,P5} and where $\dot{m}_{w_{export}}$ is the amount of waste which has to be exported to other plants due to availability considerations (see Olsommer et al., 1999).

The component investment cost functions developed consist of highly complex non-linear functions based on the literature and/or directly on manufacturers' data. A comprehensive description of these functions are beyond the scope of this paper and can be found in (Olsommer et al., 1997; Olsommer, 1998).

6.7 Genetic algorithms

The algorithm used with the optimization procedure at level L1 was the modified release of

[14] Single pressure level assumed.

[15] This assumes that the correlations exhibit the same behavior around different design points.

[16] In the sense of reliability and availability analysis.

[17] In this table, F expresses either the objective function or the dependent variable and is assumed to be strictly positive (F>0).

the "Struggle" GA mentioned above, which in addition to not converging too rapidly to a unique configuration (does a more effective search of the entire solution space) also develops niches, i.e. multiple independent optimal solutions including the global optimum. The main challenge of niching is the ability of defining a suitable criterion for each niche in a current population of individuals. This can be achieved by defining a distance function between individuals, which describes the extent of the similarities between them. This function can be defined in several ways either based on the objective function (Goldberg, 1989) or on the genotype or the phenotype (Grüninger & Wallace, 1996, Mahfoud, 1995). The latter is the only one which can take into account the real practical representation of the individuals. The distance function $\Delta(\mathbf{z_1}, \mathbf{z_2})$ between individuals $\mathbf{z_1}$ and $\mathbf{z_2}$ defined below (Eqs. (22) to (25)) represents an enhanced form of the Euclidian distance. It can deal with a mix of integer, binary and real variables and can take into account the relative importance between independent variables in an efficient way. This formulation based on a bunched tree representation of an individual (as schematically depicted in *Fig. 1*), which allows for more flexibility than a linear formulation, takes the following form:

$$\Delta_r(\mathbf{z_1},\mathbf{z_2})=\sqrt{\frac{\sum_j \alpha_j\left(\frac{abs\left(z_{1_j}-z_{2_j}\right)}{z_{j_{up}}-z_{j_{low}}}\right)^2}{\sum_j \alpha_j}} \in [0,..1] \qquad (22)$$

$$\Delta_{d_i}=\frac{abs\left(z_{1_i}-z_{2_i}\right)}{z_{i_{up}}-z_{i_{low}}} \in [0,..1] \qquad (23)$$

$$\Delta_b(\mathbf{z_1},\mathbf{z_2})=\frac{\Delta_{d_i}+\gamma_b\Delta_r}{1+\gamma_b} \in [0,..1] \qquad (24)$$

$$\Delta(\mathbf{z_1},\mathbf{z_2})=\sqrt{\frac{\sum_m \beta_m\left(\Delta_{b_m}\right)^2}{\sum_m \beta_m}} \in [0,..1] \qquad (25)$$

with Δ_r, Δ_{d_i} and Δ_b the normalized distances between real variables of the same bunch, between two integer or binary variables, and between two bunches, respectively. The parameters α, γ, β are weighting coefficients $\in [0,..,1]$ (see *Fig. 3*).

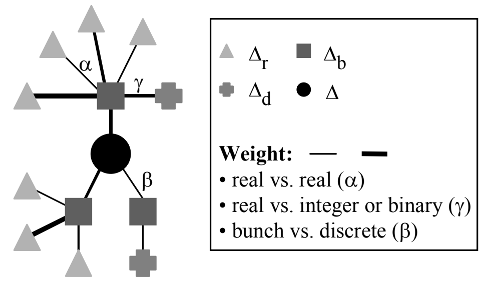


Figure 3. Schematic representation of the distance function ($\Delta(z_1, z_2)$) based on a bunched tree representation.

The coefficients α, γ, β are not limited to constant values, however, during the optimization procedure, permitting an exploration in more detail of one or several particular niche(s) of the overall feasible domain. Their values can be found in several ways (Olsommer, 1998), including calculation of the marginal costs involved or the performance of sensitivity studies on the objective function. The latter approach was used to determine the values summarized in TABLE VI.

TABLE VI. Weighting Coefficients α, γ, β for the Calculation of the Bunched-tree Based Distance Function ($\Delta(\mathbf{z_1}, \mathbf{z_2})$).

Bunch	Int. & bin variable	Real variable	α (-)	γ (-)	β (-)
1	δ_{F1}			0	1
2	δ_{F2}			0	1
3	δ_{F3}			0	1
4	δ_{GT}	$\dot{m}_{B_{GT}}$	1	0.3	1
		Π_{GT}	1		
		$\eta_{t_{K_{GT}}}$	1		
		$\eta_{t_{T_{GT}}}$	1		
5	δ_{RH}	ΔT_{RH}	1	0.3	0.8
6	δ_{AB}	$\dot{m}_{B_{AB}}$	1	0.3	0.4
		η_{AB}	1		
7	δ_{T1}	$\eta_{t_{T1}}$	1	0.3	1
		$p_{cond_{T1}}$	1		
		ΔT_{C1}	1		
8	δ_{T2}	$\eta_{t_{T2HP}}$	1	0.3	1
		p_{extr}	1		
		$\eta_{t_{T2LP}}$	1		
		$p_{cond_{T2}}$	1		
		ΔT_{C2}	1		
9	δ_{inj}	$x_{dil_{F1}}$	1	0.3	1
		$x_{dil_{F2}}$	1		
		$x_{dil_{F3}}$	1		

[18] Note that the extraction costs of the fuel and the environmental costs are not considered in this study.

10	1	x_{sout}	1	1	1
11	1	x_{T2HP}	1	1	1
12	1	ΔT_{DH}	1	0.3	0.8

Another principal modification of the original "Struggle" GA revolves around the choice of parents. For each offspring, the "father" is chosen randomly from the current generation, whereas the "mother" is randomly chosen part of the time (as in the original "Struggle" GA) while the rest of the time she is choosen as the nearest individual to the "father" (see TABLE VIIa). In this way, one can focus the search in the current niches or extend the search to the overall feasible domain.

At level L2, the K=12 subproblems are simpler than that at level L1, having 12 independent variables per subproblem of which only 3 are binary. At this level, a more conventional "Steady State" GA (GALIB, 1998), with fewer generations n_{gen} and fewer individuals n_{ind} was found to be sufficiently powerful. TABLES VIIa and VIIb summarize the parameters chosen for both the "Struggle" and "Steady State" GAs used here.

TABLE VIIa. Parameters for the "Struggle" GA (level L1).

Generations number	n_{gen}	1000
Individuals number	n_{ind}	120
Crossover probability	p_c	1.0 (-)
Mutation probability	p_m	0.0 (-)[19]
Father's choice		- random
Mother's choice		- random: 15 % of the time - nearest individual: 85 % of the time

TABLE VIIb. Parameters for the "Steady State" GA (level L2).

Number of bit for coding		10
Generations number	n_{gen}	20
Individuals number	n_{ind}	40
Crossover probability	p_c	0.8 (-)
Mutation probability	p_m	0.01 (-)

7. Application Results

This problem was solved with a total of 174 variables: 30 independent variables at level L1 and 12 per time interval for the 12 intervals belonging to four groups at level L2 (see TABLE I).

7.1 Synthesis aspects of the optimal solutions

As an illustration of the synthesis aspects of the optimal solutions, *Fig. 4a* shows the formation and evolution of niches while *Fig. 4c* shows the defining synthesis characteristics of each niche[20]. During the first couple of hundred generations, there are no clearly defined niches. By the 200th generation, however, the first niches appear and begin to evolve. What is evident is that the 52 best individuals (configurations) all include the GT and RH while for individuals 53 to 120 these components are not present. The optimal GT when chosen is the largest and the most efficient permitted while the optimal pinch temperature difference for the RH when present is the smallest allowed so that as much energy as possible can be recovered and this despite the added costs incurred by the larger heat transfer surfaces required.

Another interesting thing illustrated by *Fig. 4* is that for individuals 1 to 7 (niche 1) and 53 to 68 (niche 5) a single furnace is chosen as optimal and this despite the fact that availability considerations were taken into account in our model. This means that the cost reductions for consecutive operational sequences are insufficient to offset the additional investment costs incurred with the presence of additonal furnaces. This result is interesting in that for the most part existing waste incineration plants of comparable size are equiped with multiple furnaces.

Figure 4 also indicates that the principal role given to the AB during the optimization is that of backup system for the furnace(s) and the GT when present (e.g., see niche 5). This results in an increase in the overall availability of the waste incineration system.

One final point of interest which *Fig. 4* illustrates is that all of the best solutions are equiped with the extraction steam turbine (T2). Furthermore, the two different steam turbines (T1 and T2) are never chosen simultaneously. This is explained by the fact that the added redundance which results from both turbines being present leads to an increase in investment costs which are not sufficiently offset by the increased revenues resulting from the sale of electricity.

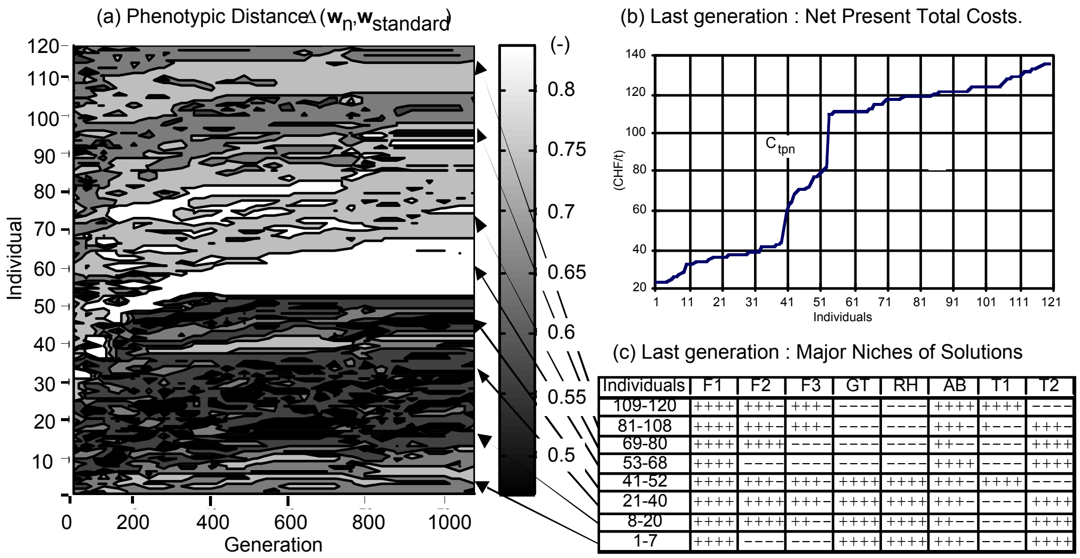
7.2 Design and operations aspects of the global optimum

Figure 5 provides the principal operational characteristics (cycle and electric efficiency as well as a breakdown of electric power production) for the optimal cycle. TABLES VIII and IX

[19] Note that the mutation rate can be set to p_m=0.0 thanks to the "blend crossover" which allows for enlarging the search outside of the interval between both parents (see Grüninger and Wallace, 1996).

[20] Note that individuals are ranked in ascending order of their corresponding objective function value, i.e. the 1st individual represents the global optimum.

give the global optimum values for the independent synthesis-design (level L1) and synthesis-operation (level L2) variables. TABLE VIII is divided into binary / integer variables and real variables. The former indicate that the configuration



Individuals	F1	F2	F3	GT	RH	AB	T1	T2
109-120	++++	+++-	+++-	----	----	++++	++++	----
81-108	++++	+++-	+++-	----	----	+++-	+---	+++-
69-80	++++	++++	----	----	----	++--	----	++++
53-68	++++	----	----	----	----	++++	----	++++
41-52	++++	+++-	+++-	++++	++++	+++-	++++	----
21-40	++++	++++	+++-	++++	++++	+++-	----	++++
8-20	++++	++++	++--	++++	++++	++--	----	++++
1-7	++++	----	----	++++	++++	+++-	----	++++

Figure 4. (a) Formation and evolution of solution niches during the optimization procedure; (b) total net present costs; and (c) characteristics of the principal niches ("+"=present; "-"=absent; "++++"=always present; "----"=always absent.

for the global optimum (individual 1) consists of a single furnace (F1), gas turbine (GT) and heat recovery heat exchanger (RH), auxiliary boiler (AB), extraction steam turbine (T2), and auxiliary equipment. Each piece of equipment was purchased at the time of the plants construction (i.e. at the start of period 1). The option of injecting all or a portion of the GT's exhaust gases into the F1 was rejected.

As already mentioned, the optimal GT chosen was the largest and most efficient permitted. In addition, for all operational sequences, the GT operates at its maximum output, thus, maximizing its return on investment.

The F1, on the other hand, is sized to meet the maximum rate of wastes that the plant will eliminate during its economic lifetime. On an operational level this means that during the first three groups of sequences (through 2010), the F1 will always operate at partial load.

The next major piece of equipment, the AB, although much smaller than either the F1 or the GT, plays, nonetheless, an important role and is sized in order to guarantee: i) that the district heating demand for heat is met when the F1 and/or GT are down and ii) that when conditions permit, the T2 operates at full load. The latter impacts the operational sequences during the Winters of 1996-2000, 2006-2010 and 2011-2015.

TABLE VIII. Optimal Independent Structural (synthesis-design) Variable Values at Level L1.

Binary and integer variables								
δ_{F1}	δ_{F2}	δ_{F3}	δ_{GT}	δ_{RH}	δ_{AB}	δ_{T1}	δ_{T2}	δ_{inj}
1	0	0	1	1	1	0	1	0

Real variables						
$\dot{m}_{B_{GT}}$ (kg/s)	Π_{GT} (-)	$\eta_{t_{K_{GT}}}$ (-)	$\eta_{t_{T_{GT}}}$ (-)	ΔT_{RH} (K)	$\dot{m}_{B_{AB}}$ (kg/s)	η_{AB} (-)
2.98	13.35	0.8979	0.9279	10.5	0.205	0.86
$x_{dil_{F1}}$ (-)	$x_{dil_{F2}}$ (-)	$x_{dil_{F3}}$ (-)	x_{sout} (-)	ΔT_{DH} (K)	x_{T2HP} (-)	$\eta_{t_{T1}}$ (-)
-	-	-	0.2315	13.6	-	-

p_{condT1} (bar)	ΔT_{C1} (K)	η_{tT2HP} (-)	p_{extr} (bar)	η_{tT2LP} (-)	p_{condT2} (bar)	ΔT_{C2} (K)
-	-	0.806	4.95	0.7901	0.144	14.7

TABLE IX. Optimal Independent Synthesis-Operation Variable Values at Level L2.

Group (gr)	1			2			3			4		
Period	1996 - 2000			2001 - 2005			2006 - 2010			2011 - 2015		
Sequence (k)	1	2	3	4	5	6	7	8	9	10	11	12
Season	W	M	S	W	M	S	W	M	S	W	M	S
δ_{GT}	1	1	1	1	1	1	1	1	1	1	1	1
δ_{RH}	1	1	1	1	1	1	1	1	1	1	1	1
δ_{AB}	1	0	0	0	0	0	1	0	0	1	0	0
x_{GT} (-)	1	1	1	1	1	1	1	1	1	1	1	1
x_{F1} (-)	1	1	1	1	1	1	1	1	1	1	1	1
x_{F2} (-)	-	-	-	-	-	-	-	-	-	-	-	-
x_{AB} (-)	0.378	0	0	0	0	0	0.047	0	0	0.189	0	0
x_{sout} (-)	0.004	0	0	0	0	0	0.03	0.06	0.03	0.07	0.05	0.05
x_{T2HP} (-)	-	-	-	-	-	-	-	-	-	-	-	-
p_{condT1} (bar)	-	-	-	-	-	-	-	-	-	-	-	-
p_{extr}(bar)	3	3	3	3	3	3.12	3	3.09	3.2	3.02	3.25	3.5
p_{condT2} (bar)	0.075	0.079	0.09	0.069	0.078	0.12	0.071	0.081	0.101	0.073	0.083	0.104

As to the T2, its optimal capacity is chosen to be somewhat smaller than what is possible with the optimal F1 chosen. This, of course, is due to the fact that the F1 operates at partial load for three quarters of its lifetime. It is also due to the fact that the T2 will eventually operate at more than 100% of load, resulting in an improved performance for this piece of equipment at the operational level.

The aero-condenser (C2) is sized in order to minimize its investment which is directly proportional to the pinch point temperature difference (ΔT_{C2}) for the ventilator part and inversely so for the heat exchanger part. Its size also results from minimizing its operational costs which are directly proportional to the ΔT_{C2} since the smaller this difference, the less energy the ventilators need to expend. The compromise at which one arrives is a C2 slightly oversized with respect to its heat exchange surface so that the ventilator can operate with less air than would otherwise be possible with the different pinch point differences (ΔT_{C2}) which occur at the operational level.

Finally, a constraint on optimally sizing the DH is that it must be dimensioned for the coldest day (the largest heat demand). With this constraint and a given network temperature as well as the fact that the mass flow rate of steam through the DH is inversely proportional to the ΔT_{DH}, the DH is sized for a relatively large ΔT_{DH}. This results in a reduced investment for the heat exchanger, reduced investment and operating costs for the extraction pump (P3), and increased revenues from the sale of electricity due to the reduced amount of steam extracted from the T2.

7.3 Analysis of the total present net costs at the global optimum

Figures 6 and *7* give a breakdown of the total present net costs for the optimal cycle. *Figure 6* presents a decomposition of these costs globally over the entire economic lifetime of the plant whereas *Fig. 7* is reported per each of the four periods over which the optimal cycle operates.

Figure 6 indicates that the financial costs associated with equipment investment (annuities, own funds and depreciation) represent about 33% of the total outlays while the costs for resources (almost exclusively for natural gas – 99%) represent about 55% of outlays. The remainder (12%) comprises things such as taxes, insurance, maintenance, the export of wastes, and fixed charges.

As to revenues (see TABLE X), the sale of heat to the district heating system is marginal at best (about 2% of the total) since 98% of all revenues results from the production and then sale of electricity to the exterior grid. Of this, about 10% is due to the expansion of steam generated by the F1 while 90% is either directly (via the GT) or indirectly (via the RH) a result of the topping cycle. In fact, the difference between the solutions represented by niche 1 (cogeneration cycle with topping cycle) and niche 5 (cogeneration cycle without topping cycle) is almost entirely due to the difference in revenues generated by the addition of the topping cycle.

In looking at *Fig. 7*, it is interesting to note that the system produces a net gain during the last group of sequences (2011-2015). This can be mainly attributed to the thermoeconomic scenario chosen for this application (TABLE I).

TABLE X. Details of the Different Operating Cost Contributions (Objective Functions at Optimization Level L2) for the Various Sequences[21].

Group (gr)	1			2			3			4		
Period	1996 - 2000			2001 - 2005			2006 - 2010			2011 - 2015		
Sequence (k)	1	2	3	4	5	6	7	8	9	10	11	12
Season	W	M	E	W	M	E	W	M	E	W	M	E
Operating costs[22]	-3501	-1992	-513	-3832	-2228	-648	-4284	-2520	-858	-5411	-3443	-1479
Sale of electricity	-6965	-5407	-3957	-7275	-5733	-4200	-7791	-6102	-4506	-8990	-7065	-5180
Sales from the DH	-80	-42	-12	-129	-68	-20	-181	-94	-28	-213	-112	-33
GT fuel	3344	3344	3344	3449	3449	3449	3542	3542	3542	3596	3586	3586
BA fuel	88	0.55	0.55	0.57	0.57	0.57	11.6	0.58	0.58	48	0.59	0.59
Export of wastes	112	112	112	122	122	122	133	133	133	148	148	148
DH availability	0	0	0	0	0	0	0	0	0	0	0	0

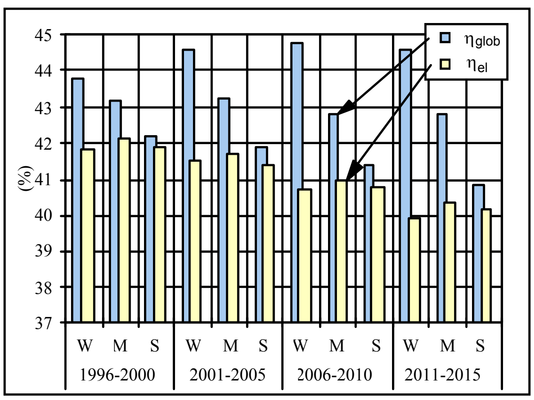


Figure 5a. Optimal values at level L2 of the cycle and electric 1st law efficiencies.

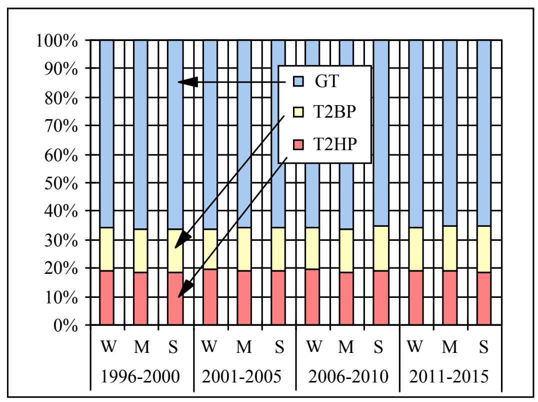


Figure 5b. Optimal distributions at level L2 of the electricity produced.

21 All operational costs are in CHF/h.

22 The objective function at the operation level (L2) (see Eq. (21)): $\dot{C}_k$, k ∈ [1,..12], in CHF/h. A negative cost in fact represents a gain for the plant.

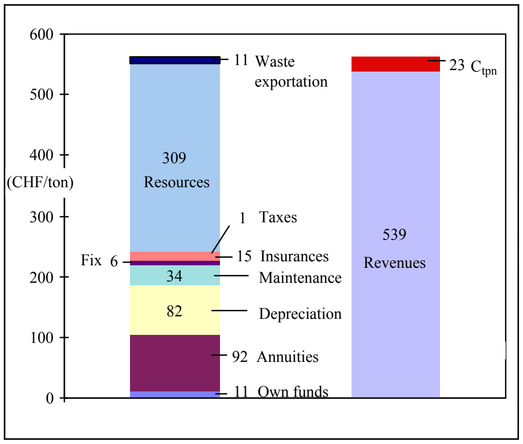


Figure 6. Composition of the optimal values of the total present net costs in CHF/ton (vertical axis); the left column represents costs while the right revenues.

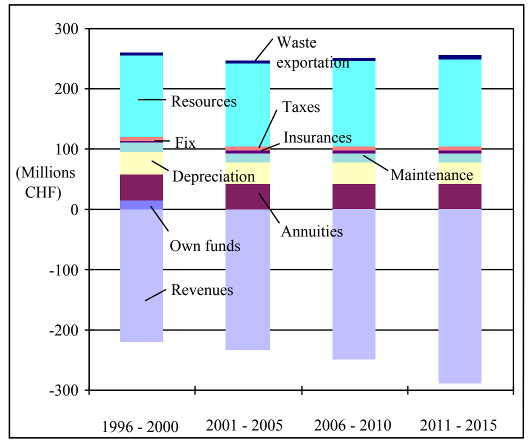


Figure 7. Composition of the optimal values of the total present net costs in millions of CHF (vertical axis) for each group of sequences.

8. Conclusions

Due to some key time-dependent parameters such as the amount of wastes or the district heating demand, to name just two, waste incineration plants (energy conversion systems, in general) should not simply be designed around some nominal point as is the current practice in industry today. Furthermore, reliability and availability considerations can play an important role in the decision process. To address these problems, this paper has presented a thermoeconomic methodology for modeling and optimizing such systems in order that proper answers can be given to fundamental questions such as when to invest and reinvest and which technology, configuration, component capacity and performance, and modes of operation to adopt.

Thermoeconomics which deals simultaneously with both economic and energy based criteria permits one to formulate a specific goal (objective function) which in our case represents the specific present total net costs of waste treatment integrated over the entire economic lifetime of a plant. Although the objective function in this paper is purely thermoeconomic, it can be extended to an environomic objective by including environmental and life cycle aspects.

To deal with the global problem of simultaneously optimizing the synthesis, the design and the operating modes over the entire economic lifetime of the plant, a general approach was presented here. It is based on a two-level decomposition optimization procedure in which the operating modes influence the structure (synthesis and design) and vice versa by going back and forth between the two levels, optimizing for each selected set of structural variable values at the upper level the operating modes at the lower level. To solve this two-level decomposition procedure for the highly complex optimization problem tackled here, genetic algorithms were developed and implemented. The associated code was parallelized for use on a (massively) parallel computer.

The inclusion of reliability and availability analysis in the thermoeconomic model required the development of a comprehensive method which was both new and original. It was implemented for a flexible structure of equipment in active and/or passive redundancy and connected in series and/or parallel.

Results show that the two levels of optimization are strongly linked and that it is not possible to make sensible decisions on one level without taking into account the other. Results also indicate that a comprehensive availability analysis should not be neglected and that it can greatly affect the decision process. In addition, for the case of a cogeneration plant without a topping cycle results show that the potential savings in costs of waste treatment, based on a comparison with an existing plant, are on the order of 11% (Olsommer et al., 1997). Results, furthermore, indicate that these savings can be improved much further, notably by the judicious integration of a relatively large, high efficiency gas turbine or by assuring a minimum system availability with back-up equipment.

Finally, perspectives for the use of such a general thermoeconomic or environomic methodology are growing. The method proposed in this paper is of particular interest for the development of systems within the context of a global sustainability. However, a thermoeconomic industrial application of the methodology has already been carried out for a future waste incineration plant in Switzerland. The results have been determinant in the decision process for the future plant. Results will be published in a future paper.

For more details on the development and incorporation of reliability and availability considerations into a thermoeconomic model, the reader is referred to Part II (Olsommer et al., 1999) of our series of two articles.

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Nomenclature

AB	auxiliary boiler	
C	aero-condenser	
C, $\dot{C}$	cost, cost rate	(CHF, CHF/s)
c	unit cost rate	(CHF/kg, CHF/kWh)
CHF	Swiss francs	
CRF	Capital Recovery Factor	
D	deaerator	
DH	heat exchanger for district heating	
$\dot{E}_{el}$	electric power	(W)
F	furnace plus steam generator	
G	generator	
g	inequality constraint set	
GA	Genetic Algorithm	
Gr, gr	number, index of groups of sequences	
GT	gas turbine	
h	equality constraint set	
h	loan	
HP	high pressure	
I, i	sequence number, number of corresponding groups of sequences	
J, j	number, number of one year periods of corresponding groups of sequences	
K, k	number, index of sequences	
L	logical expression set	
LP	low pressure	
M	motor	
M	mid-season	
$\dot{m}$	mass flow rate	(kg/s)
MINLP	Mixed Integer Non-Linear Programming	
N	lifetime	(yr)
P	pump	
P	penalty function	
p	pressure	(bar)
$\dot{Q}$	thermal power	(W)
PWF	Present Worth Factor	(-)
RH	heat recovery heat exchanger	
S	summer	
s	subsidy	
T	turbine	
T	temperature	(K)
t	time	(s)
W	winter	
w	structural (synthesis-design) independent variable set	
x	synthesis-operation independent variable set	
y	dependent variable set	
z	independent variable set which contains the sets **x** and **w**	

Greek Symbols

α	weighting coefficient	(-)
β	weighting coefficient	(-)
Δ	distance function	(-)
δ	binary or discrete variable	
Δh_0	heating value	(J/kg)
ΔT	pinch point temperature difference	(K)
Δt	time interval	(s)
$\dot{\Phi}$	resource or revenue rate	(W, kg/s)
γ	weighting coefficient	(-)
η	1^{st} law efficiency	(-)
η_t	thermal efficiency	(-)
Π	pressure ratio	(-)

Subscripts and Superscripts

AE	equipment purchase
b	bunch
c	crossover
CL	civil engineering and land (facilities construction, land purchase and preparation)
cond	condensation
d	integer or binary variable
dep	depreciation
dil	dilution
el	electricity
e	economic
export	waste exportation
extr	extraction
fix	fixed
gas	natural gas
gen	generation
glob	global
H	fees
i	index of a binary/integer variable in variable set **z**
ind	individual
inj	direct injection of exhaust gas of GT into the furnace
ins	insurance
j	index of a real variable in variable set **z**
K	compressor

L1	structural level
L2	operational level
low	lower bound
m	mutation
m	oil
m	market
maint	maintenance
n	inflation
r	real variable
res	resource
rev	revenues
s	salvage value
sout	high pressure steam extraction
tpn	total present net
T	turbine
TCI	total investment cost
tax	taxes
up	upper bound
w	waste

References

Benelmir, R., von Spakovsky, M.R., Lallemand, M. and Lallemand, A., 1991, "Exergetic and Economic Optimization of a Heat Pump Cycle: Primary Iteration", *Analysis of Thermal and Energy Systems*, 1, 321, ASME, Greece.

Curti, V., von Spakovsky, M.R., Favrat, D., 1998, "An Approach for the Environomic Modeling and Optimization of a District Heating Network Based on Centralized and Decentralized Heat Pumps (Parts I and II)", *International Conference on Energy and the Environment (ICEE'98),* Shanghai, China.

da Silva, R. J. and Nebra, S., 1996, "Thermoeconomic Comparative Analysis of Different Processes of Cement Production", *Proceedings of the 1996 International Symposium on Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems: ECOS'96*, ASME, Stockholm.

El-Sayed Y., 1996, "A Second-Law-Based Optimization: Part I Methodology & Part 2 Application", *Journal of Energy Resources Technology*, ASME, v. 118, pp. 693-703.

El-Sayed, Y.M. and Evans, R.B., 1970, "Thermoeconomics and the Design of Heat Systems", *J. of Eng. for Power*, 92, 27, Jan..

Evans, R.B., 1961, *A Contribution to the Theory of Thermo-Economics*, Master's Thesis, Dep. of Eng., Univ. of Calif. at L.A., Dec. 1961.

Floudas, C.A., 1995, *Nonlinear and Mixed-Integer Optimization. Fundamentals and Applications*, Oxord University Press, N.Y..

Frangopoulos, C.A., 1994, "Application of Thermoeconomic Optimization Methods to the CGAM Problem", *Energy: The International Journal*, special edition, Vol. 19, No. 3, pp. 323-342, Pergamon Press, Great Britain.

Frangopoulos, C.A., and von Spakovsky, M.R., 1993, "The Environomic Analysis and Optimization of Energy Systems (Parts I and II)", *Proceedings of the International Conference on Energy Systems and Ecology: ENSEC'93*, Vol. I, pp. 123-132, ASME, Cracow, Poland, July.

Frangopoulos, C.A., 1989, "Optimal Synthesis and Operation of Thermal Systems by the Thermoeconomic Functional Approach", *ASME Winter Annual Meeting*, AES 10-3, 49.

Gaggioli R.A., 1977, "Proper Evaluation and Pricing of Energy", *International Conference on Energy Use Management*, II, 31, Pergamon.

GALIB, 1998, "Genetic Algorithms Libraries", MIT.

Goldberg, D.E., 1989, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison Wesley, Reading, MA.

Grüninger, T, Wallace, D.R., 1996, "Multimodal Optimization using Genetic Algorithms", MIT CADlab-Tech. Rept.: 96.02.

Kehlhofer, R., 1991, *Combined-Cycle Gas & Steam Turbine Power Plants*, Fairmont Press Inc., Lilburn, GA, USA.

Lazzaretto, A. and Andreatta, R., 1995, "Algebraic Formulation of a Process-Based Exergoeconomic Method", *Thermodynamics and the Design, Analysis and Improvement of Energy Systems*, AES-Vol. 35.

Mahfoud, S.W., 1995, "A Comparison of Parallel and Sequential Niching Methods", *Sixth Int. Conf. on Genetic Algo-rithms*, pp 136-143.

Olsommer, B., von Spakovsky, M.R., Favrat, D., 1997, "An Approach for the Time-dependent Thermoeconomic Modeling and Optimization of Energy System Synthesis, Design and Operation", *International Conference on Thermodynamic Analysis and Improvement of Energy Systems (TAIES'97)*, Beijing, ASME, June.

Olsommer, B., 1998, *Development and Application of a Thermoeconomic Optimization Method to a Waste Incineration Plant with Cogeneration and a Topping Cycle*, Ph.D. Dissertation, Swiss Federal Institute of Technology of Lausanne, Lausanne.

Olsommer, B., von Spakovsky, M.R., Favrat, D., 1999, "An Approach for the Time-dependent

Thermoeconomic Modeling and Optimization of Energy System Synthesis, Design and Operation (Part II: Reliability and Availability)", *International Journal of Applied Thermo-dynamics*, Vol. 2, No. 4.

Pelster, S., 1998, *Environomic Modeling and Optimization of Advanced Combined Cycle Cogeneration Power Plants including CO_2 Separation*, Ph. D Dissertation, Swiss Institute of Technology of Lausanne, Lausanne.

Reklaitis G.V., Ravindran A., Ragsdell K.M., 1983, *Engineering Optimization. Methods and Applications*, John Wiley and Sons.

Tribus, M., 1956, "Thermodynamic and Economic Considerations in the Preparation of Fresh Water from Sea Water", *Eng. Dept. Rept. No. 56-16*, Univ. of Calif., Los Angeles.

Tsatsaronis, G., Pisa, J., 1994, "Exergoeconomic Evaluation and Optimization of Energy Systems: Application to the CGAM Problem", *Energy: The International Journal*, Vol. 19, No. 3, pp. 287-321, Pergamon, Great Britain.

Valero, A., Serra, L., Lozano, M.A., and Torres, C., 1994, "Application of the Exergetic Cost Theory to the CGAM Problem", *Energy: The International Journal*, Vol. 19, No. 3, pp. 365-381, Pergamon, Great Britain.

von Spakovsky, M.R., 1998, "The Thermodynamic, Thermoeconomic and Environomic Modeling and Optimization of Energy Systems – Discussion and Applications", *Entropie*, no. 205, France.

von Spakovsky, M.R., 1994, "Application of Engineering Functional Analysis to the Analysis and Optimization of the CGAM Problem", *Energy: The International Journal*, Vol. 19, No. 3, pp. 343-364, Pergamon, Great Britain.

von Spakovsky, M.R., Frangopoulos, C.A., 1994, "The Environomic Analysis and Optimization of a Gas Turbine Cycle with Cogeneration", *Thermodynamics and Design, Analysis and Improvement of Energy Systems, ASME*, AES-Vol.-33.

von Spakovsky, M.R., and Evans, R.B., 1993, "Engineering Functional Analysis (Parts I and II)", *Journal of Energy Resources Technology*, ASME, Vol. 115, No. 2, N.Y., June.

Wallace, D.R., 1996, "Design Search under Probabilistic Specifications using Genetic Algorithms", *Computer Aided Design*, Vol. 28, No. 5, pp. 405-421.

Yokoyama, R. and Ito, K., 1995, "Multi-Objective Optimization in Unit Sizing of a Gas Turbine Cogeneration Plant", *Journal of Engineering for Gas Turbines and Power*, ASME, N.Y., Vol. 117, No. 1.