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A MODEL FOR THERMO-ECONOMIC ANALYSIS AND OPTIMIZATION OF STEAM POWER PLANTS FOR POWER AND COGENERATION

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ABSTRACT

The paper presents a model for thermoeconomic analysis and optimal design of steam power plants, for power generation and cogeneration use. The model, including both thermodynamic and economic description of a general steam power plant with regeneration, reheating and cogeneration, can be used for simulations, parametric analysis and optimization, with mathematical programming techniques.

The variability of components performance and efficiency versus costs can be also analyzed, and optimal trade-off between costs and performace obtained by optimization analysis. Significant applications to cogeneration are presented in the paper, discussing the effects of electrical and thermal loads, fuel price and changes in technology. The computer code, built in Matlab®, allows to perform complex optimization analyses with very limited computational time.

INTRODUCTION

The liberalization of energy markets and the aims of climate protection promote an increasing use of cogeneration (CHP), intended as simultaneous production of two energy forms (electrical or mechanical, and heat in the form of steam and/or hot water) from one energy source (fossil, biomass or nuclear). With CHP, the waste energy from electricity production is cascaded and used in the production of District Heating (DH) or to satisfy the industrial heat and/or steam demand. As it is known, with conventional production methods, where the waste thermal energy is dumped directly into the local ecosystem, the fuel efficiency is approximately from 40 to 45%, while in a CHP plant a global efficiency of 85–90% can be achieved (Cogen, 1987), with obvious benefits on the reduction of pollutant emissions and of the greenhouse effect.

Steam plants are largely used for CHP applications, mainly for medium and large scale applications, while reciprocating engines are usually preferred for small scale applications (Micro-Cogeneration) and Gas Turbines are adopted in the cases where heat at higher temperature is needed (El Wakil, 1984, Horlock, 1987). The use of steam plants makes it possible to use different and inhomogeneous fuels such as biomass, wood waste and fuels derived from refuse that could be considered as CO_2 neutral, so allowing additional environmental benefits. On the other hand, steam plants are characterized by larger initial investments and by higher inertia and lower operational flexibility with respect to the other solutions. Therefore, the economic benefits of the application of a steam plant for CHP must be carefully assessed, both in order to compare it with conventional or alternative solutions and to determine optimal plant structure and management strategies.

Several mathematical models for the study of steam power plants and cogeneration are available in literature. A simulation model for commercial cogeneration plants, written in ASPEN, has been developed by Zheng and Furimsky (2003). A general model (COGEN) for assessing the economic potential of cogeneration venture in Brasil has been applied by Salem Szklo et al. (2000), using simulation and sensitivity analysis.

Optimization techniques have also been applied to the design and the management of cogeneration plants. Evolutionary programming approach has been adopted to determine the optimal plant operation under variable electrical and thermal loads (Tsai et al., 2001). A multi-objective programming approach for the pre-feasibility analysis has been proposed by Balestrieri and De Barros Correia (1998). Mixed integer linear programming techniques have been used by Arivalagan (1995). Optimal operation of CHP plants with thermal storage for District Heating (DH) via non-linear programming has been investigated by Zhao et al. (1998).

A computer code (VAPOTT) for the study of steam power plants has been developed by the authors (Rizzo, 1987). The code, formerly written in Quick Basic®, has been used in some

Italian universities and at the University of Halifax, mainly for educational purposes. The model allows to perform simulation, parametric analysis and optimization of steam power plants for power generation, with powerful graphical capabilities. The computed code has been re-written and converted in Matlab®, due to large diffusion of this tool in the engineering framework and to the availability of powerful scientific libraries. The model has been substantially extended and improved to include cogeneration and to describe economic aspects. The main features of the model are described in the next chapter, and some significant applications presented.

NOMENCLATURE

Symbol	*Description*	*Unit*
CB	Base Plant Cost	K€
CI	Total Plant Cost	K€
Ee	Net Electrical Energy	kJ
Ep	Primary Energy	kJ
Et	Thermal Energy to the User	kJ
FC	Global Perturbation Factor for the Plant	/
f_i	Perturbation Function expressing the effect of technology on the component cost	/
h	Enthalpy	kJ/kg
IEN	National Energy Index (for Italian Legislation)	/
IRR	Internal Redditivity Ratio	%
NPV	Net Present Value	K€
p	Pressure	bar
P_i	Weight of the i-th component on plant cost	/
s	Entropy	kJ/kg·K
T	Temperature	K

Pedices	*Description*
CR	Critical Point
F	Saturated Liquid
G	Saturated Steam
s	Saturation
TP	Triple Point

STEAM PROPERTIES MODEL

Steam properties are computed by the relationships proposed by Irvin and Liley (1984). The main features of the model are summarized in the following.

Saturation temperature is expressed as function of saturation pressure by the relationship:

$$\text{(1)} \qquad Ts=A+B/[\log(ps)+C]$$

where the coefficients A, B e C assume different values according to the pressure range. Conversely, saturation pressure can be computed from temperature by the equation:

$$\text{(2)} \qquad \log(ps)=\sum_{i=1}^{10} A_i \cdot (Ts)^{i-1} + A_{11}/(Ts-A_{12})$$

Other thermodynamic properties (specific volume, enthalpy, and entropy for saturated liquid and for saturated steam) are computed by equations with the following structure:

$$\text{(3)} \qquad h_F = YS \cdot h_{F,CR}$$

The property (in this case enthalphy for saturated liquid) is expressed as a function of the property value at critical point (or at the triple point, in case of evaporation enthalpy). YS is expressed as:

$$\text{(4)} \quad YS=B_1+B_2 \cdot TC^{1/3}+B_3 \cdot TC^{5/6}+B_4 \cdot TC^{7/8}+\sum_{i=1}^{7} B_i \cdot TC^i \quad ,$$

where the coefficients B's are assigned and term TC expresses the relative distance of saturation temperature T_S from critical temperature T_{CR}:

$$\text{(5)} \qquad TC = (T_{CR} - Ts) / T_{CR}$$

The properties in the superheated region are computed as function of temperature and pressure.

For specific enthalpy, the following equation is used:

$$\text{(6)} \qquad h = h_1 + h_2 \cdot t + h_3 \cdot t^2 - h_4 \cdot e^{(ts-t)/45}$$

where:

$$\text{(7)} \qquad h_i = rk_{i,1} + rk_{i,2} \cdot p + rk_{i,3} \cdot p^2 \qquad \mathbf{i=1,3}$$

$$h_4 = rk_{4,1} + rk_{4,2} \cdot p + rk_{4,3} \cdot p^2 + rk_{4,4} \cdot p^3 + rk_{4,5} \cdot p^4$$

Similarly, specific entropy is evaluated as:

$$\text{(8)} \qquad s = S_1 + c_{11} \cdot \log(10 \cdot p + c_{12}) - S_2 \cdot e^{(ts-t)/85}$$

where

$$\text{(9)} \qquad S_1 = c_1 + c_2 \cdot t + c_3 \cdot t^2 + c_4 \cdot t^3 + c_5 \cdot t^4;$$

$$S_2 = c_6 + c_7 \cdot ts + c_8 \cdot ts^2 + c_9 \cdot ts^3 + c_{10} \cdot ts^4$$

while coefficients c's are assigned.

The error in properties evaluation is less than 1%, except in the region near the critical point. For further details on steam properties model, the reader is addressed to the original textbook of Irvin and Liley (1984).

POWER PLANT MODEL

The model describes a general steam power for power generation and cogeneration. The following hypotheses are adopted:

- Constant pressure heat addition and heat subtraction.
- Constant values for turbine adiabatic efficiency along expansion lines.
- Liquid properties are computed by the saturated liquid ones.
- Pump work computed considering non-ideal process.
- Real steam generator operation considering heat and combustion losses.

- In case of reheating, the exit temperature is equal to the maximum cycle temperature.
- In case of regeneration, surface heat exchangers are adopted, with assigned efficiency.
- Variable electrical and thermal load assigned by the user.
- Independent (design) variables: minimum and maximum pressure, maximum temperature, steam mass flow rate, number and pressure of steam extraction, number and pressure of reheats, minimum temperature of thermal (for cogeneration).

The model can be used for simulations and parametric analysis with respect to all the design variables, with powerful graphical output. Thermodynamic cycles can be represented, on planes (T,s) (Fig. 1) and (h,s) (Fig. 2).

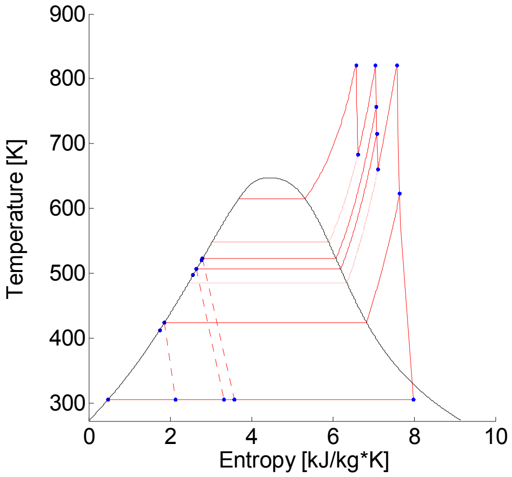

Fig. 1 – Thermodynamic cycle on (T,s) plane

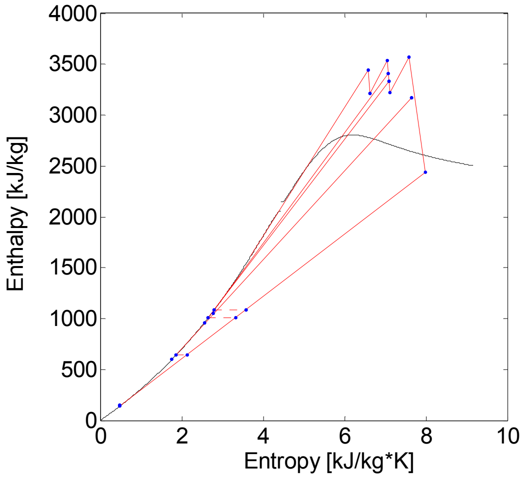

Fig. 2 – Thermodynamic cycle on (h,s) plane

Plant schemes can be also drawn, with values of pressure, temperature and enthalpy. An example, referred to a plant with two reheats and three stages of regeneration, is reported below (Fig. 3):

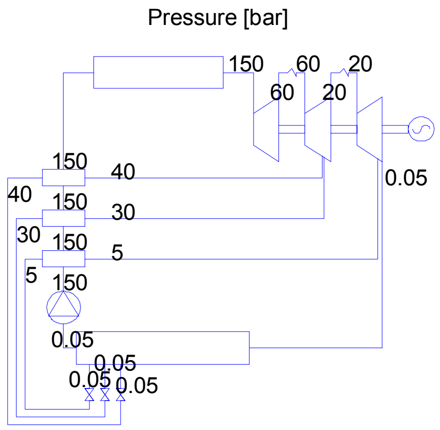

Fig. 3 – Power plant scheme with pressure values (bar)

THE ECONOMIC MODEL

The model can be used to evaluate the operation costs for both power generation and cogeneration applications. In this case, variable electrical and thermal loads can be considered, with cases describing the differences between seasons and days (winter/summer – weekday/holyday).

Operation costs are computed considering the need of possible integration of thermal and/or electrical energy, and also taking into account possible revenues due to sale of electrical energy surplus. Electrical costs and prices are computed starting from time slots and energy index, according to the Italian legislation.

Total cost includes operational, maintenance and investment costs. Regard to investment costs, a reference unit cost CB for a "base" plant is assigned as function of net electrical power (Fig. 4), starting from literature data (Mastrullo et al., 1992).

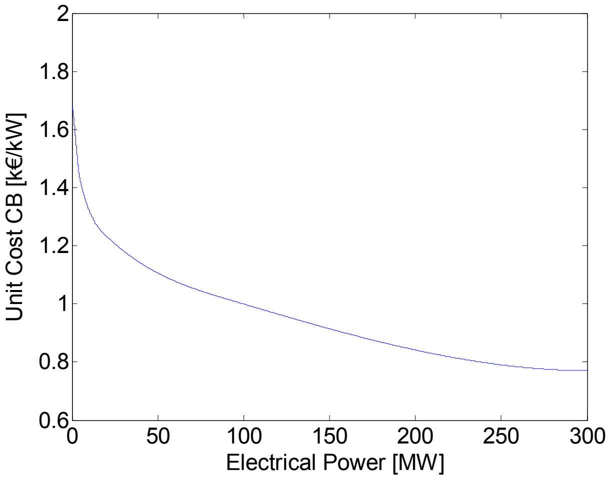

Fig. 4 – Base Plant Cost vs. Electrical Power

The actual plant cost CI is then computed introducing a perturbation factor FC:

(10) $$CI = CB \cdot FC$$

FC accounts for the influence of the incidence plant sub-systems, and of their technology. Seven components have been considered: pump, turbine, steam generator, condenser, electrical generator, reheats, stages of regeneration. For each component, a suitable reference variable, representative of cost, is considered.: efficiency is adopted for turbine, steam generator, electric generator and pump; the cost due to reheats and regeneration is instead expressed as a function of number of reheats and of steam extractions, respectively; in this application the variability of the cost of condenser has not been considered.

The relationships between efficiencies and cost for each component are expressed by means of suitable perturbation functions f_i. A typical trend is reported in Fig. 5, for the turbine. The perturbation function is 1 (dashed line) when the reference variable (turbine efficiency) is equal to the assigned base value 0.90 (Tab. 1), and tends to very high values when the turbine efficiency approaches 1.

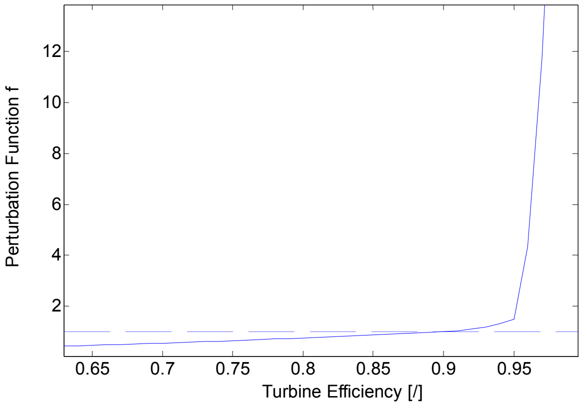

Fig. 5 – Relationship between efficiency and cost for turbine.

The factor FC is then computed according to:

(11)
$$FC=\sum_{i=1}^{7} P_i \cdot f_i$$

where P_i is a weight factor describing the influence of each sub-system on plant cost, that can be assigned by the user (Tab. 1). For future applications, more precise descriptions could be implemented in the code, starting from data of cost and efficiency provided by the producers.

With this approach, the variability of components performance and efficiency versus costs can be analyzed, and optimal trade-off between costs and performace can be obtained by optimization analysis, as shown in following chapters.

Finally, the economic feasibility of the investment is evaluated by comparing the proposed plant with the conventional one, where electrical energy is buyed by the provider and thermal energy is obtained by a conventional boiler. NPV, Pay-Back and IRR (Internal Redditivity Rate) can be computed for each solution. The optimal contract with the energy provider (according to the Italian legislation) and the optimal plant work load are also computed by the model. Sensitivity analysis of the optimal solutions can be also performed, in order to check the technical feasibility of the proposed solutions. Some significant applications to practical cases are presented and discussed in the following chapters.

Component		*Weigth (%)*	*Reference Variable*	*Base Value*
1	Steam Generator	28	Efficiency	0.92
2	Turbine	17	Efficiency	0.90
3	Pump	4	Efficiency	0.95
4	Condenser	13	-	-
5	Electrical Generator	18	Efficiency	0.95
6	Reheating	10	No.of reheating	2
7	Regeneration	10	No.of extractions	5
		100		

Tab. 1 – Relative contributions to plant cost

PARAMETRIC ANALYSIS RESULTS

Some typical results obtained by the model using parametric analysis are described. In the following. example, the effect of regeneration pressure has been investigated, for a plant with three stages of reheating, characterized by the data reported in Tab. 2.

Minimum pressure	bar	0.05
Maximum Pressure	bar	150
Maximum Temperature	K	820
Turbine Efficiency	/	0.90
Steam Generator Efficiency	/	0.92
Pump Efficiency	/	0.95
Heat Exchanger Efficiency	/	0.89
Number of Reheating	-	3
Reheating Pressure	bar	70 30 3
Number of Steam Extractions	-	1

Tab. 2 – Parametric Analysis - Base plant data.

It can be observed that, even if the adducted heat is a continuous function of regeneration pressure (Fig. 6), discontinuities occur when the extraction point pressure corresponds to a reheating pressure (3, 30 and 70 bar, in the example). In this case, there is a drop in efficiency when the extraction point shifts to the higher pressure turbine (Fig. 7). This discontinuity is of course present also in the operation costs (Fig. 8), related to specific fuel consumption.

The presence of possible discontinuities in efficiency and costs may result in computational problems during optimization analysis, particularly when classical techniques, based on the hypothesis of continuity of the optimized function, are adopted (Gill et al., 1981).

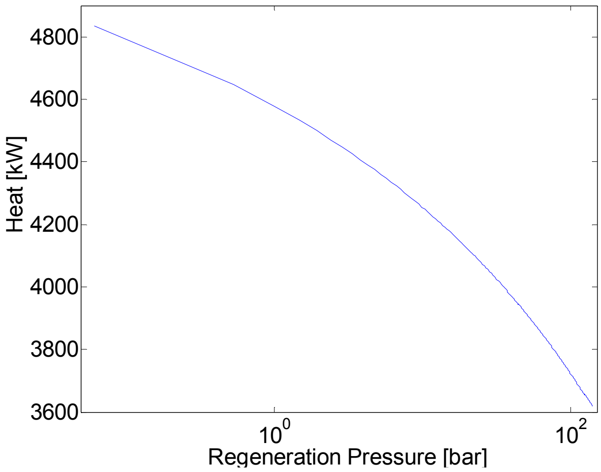

Fig. 6 – Adduced heat vs. regeneration pressure

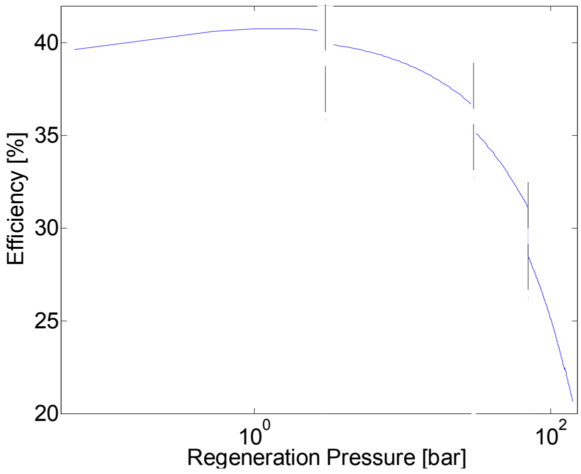

Fig. 7 – Thermodynamic Efficiency vs. Regeneration Pressure

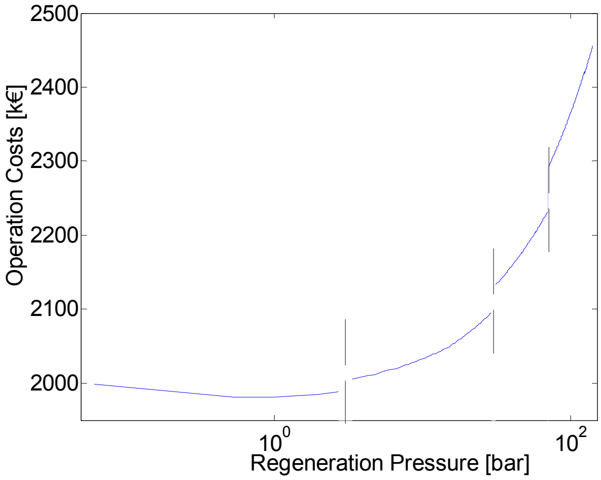

Fig. 8 – Operation cost vs. regeneration pressure

OPTIMAL PLANT DESIGN

Although simulation and parametric analysis are powerful tools for studying the effects of design variables on plant performance and costs, the optimal plant design and/or the determination of optimal management strategy could not be effectively accomplished by an exclusive recourse to these approaches. In fact, the presence of complex non-linear interactions between the input and the output variables would require a prohibitive number of model evaluations to completely characterize the system, when a significant number of design variables and of their levels, representative of real power plants, is considered (Gill at al, 1981). For such applications, optimization techniques represent the best choice.

The proposed model allows to perform optimal design analysis considering both technical and economic aspects in the objective function. Three different cases can be considered:

- Maximum thermodynamic efficiency (12);
- Maximum value of the energy index IEN (13), considering electrical and thermal output of cogeneration plant (Mastrullo et al., 1992);
- Maximum Net Present Value (NPV) (Horlock, 1987).

(12) $$\eta = \frac{W}{Ep}$$

(13) $$IEN = \frac{Ee}{Ep} + \frac{Et}{0.9 \cdot Ep} - \left[\left(\frac{1}{0.51} - 1 \right) \left(0.51 - \frac{Ee}{Ep} \right) \right]$$

where *W* is net mechanical work, *Ep* is primary energy, *Ee* is electrical energy and *Et* is thermal energy to the user.

Classical mathematical programming techniques, implemented in the routine FMINCON of Matlab®, have been used.

The problem formulation is:

(14) $\min\limits_{X} f(x)$ [non-linear objective function]

(15) $C(x) \leq 0$ [non-linear inequality constraint]

(16) $C_{eq}(x) = 0$ [non-linear equality constraint]

(17) $A \cdot x \leq B$ [linear inequality constraint]

(18) $A_{eq} \cdot x = B_{eq}$ [non-linear equality constraint]

(19) $L_b \leq x \leq U_b$ [lower and upper bounds]

where x is the vector of the design variables.

The optimum problem (14)÷(19) is solved by a second-order Sequential Quadrating Programming approach. The recursive Hessian matrix estimate is performed by the BFGS method (Gill et al., 1981).

Furthermore, several constraints (15)÷(19) can be considered, taking into account of:

- Minimum pressure at the condenser.

- Maximum temperature at turbine inlet.
- Maximum allowable moisture content of the steam at turbine outlet (usually 0.85).
- Maximum capital investment.
- Maximum allowable pay-back.
- Minimum allowable energetic index (in order to access to financial benefits provided by the Italian governement for energy saving).

Sensitivity analysis of the optimal solutions can be also performed, in order to check the feasibility of the proposed solutions.

This classical approach leads to a very efficient optimum search, but it is assumes that the design variables and the output function should be continuous. Therefore, it does not allow to study simultaneously the effects of continuous (e.g. pressure and temperatures) and discrete (e.g. number of reheats and of regeneration stages) variables (Mixed Optimization). Furthermore, this approach could be unsuccessful in the determination of the global optimum, due to the possible presence of discontinuities in the optimized function, as illustrated in Fig. 7 and Fig. 8. For future developments, the adopted optimization approach will be integrated or substituted for the use of Genetic Algorithms (GA).

THERMODYNAMIC VS. ECONOMIC OPTIMIZATION

In the following example the differences between a thermodynamic approach, where thermodynamic efficiency (Case A) or energy index IEN (13) (Case B) are maximized, and a thermo-economic approach, where the maximum NPV is searched for (Case C), are illustrated.

The base plant is characterized by the data reported in Tab. 3. In all cases, two variables are optimized (minimum pressure and reheat pressure).

Maximum Pressure	bar	170
Maximum Temperature	K	810
Turbine Efficiency	/	0.80
Steam Generator Efficiency	/	0.92
Pump Efficiency	/	0.90
Temperature of Thermal User	K	380
Number of reheats	-	1
Optimized Variables		*Minimum Press.* *Reheat Press.*

Tab. 3 – Base plant data for thermodynamic and economic optimization.

The results are summarized in Tab. 4, while the corresponding thermodynamic cycles are reported in Fig. 9 and Fig. 10, respectively for cases A and C.

It can be observed that, as expected, when the maximum thermodynamic (i.e. electrical) efficiency is maximized (Case A) a very low value of minimum pressure is proposed (Fig. 9), that corresponds to a much higher values in efficiency with respect to Cases B and C. The pay-back, however, is much higher than in Cases B and C, due to the fact that the temperature at turbine discharge is lower than the value required by the user (380 K), and therefore the recourse to auxiliary generation is needed, with additional fuel costs.

	Case A – Opt. Therm. Eff.	Case B – Opt. IEN	Case C – Opt. NPV
Minimum Pressure (bar)	*0.007*	*1.4557*	*1.2829*
Reheating Pressure (bar)	*14.82*	*40.32*	*37.96*
Moisture content at turb.outlet (/)	0.959	Superheated	Superheated
Net Power (kW)	1126.35	662.8	677.59
Adduced Heat (kW)	3113.71	2595.20	2617.58
Efficiency (%)	**36.17**	25.54	25.89
Energy Index (/)	0.16255	**0.68695**	0.68645
Investment (k€)	1162	692	708
Savings (k€/year)	118	117	121
Pay-Back (years)	12.9	6.8	6.7
NPV (k€)	66	525	**552**
Profit Index (/)	1.0572	1.75896	1.7791
IRR (%)	5.2	13.9	14.1

Tab. 4 – Optimization Results – Thermodynamic vs. Economic

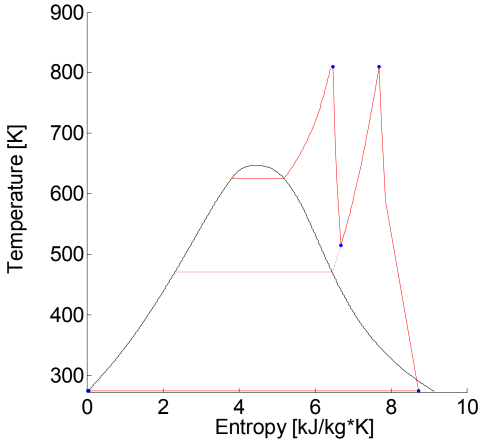

Fig. 9 – Optimal solution – Case A

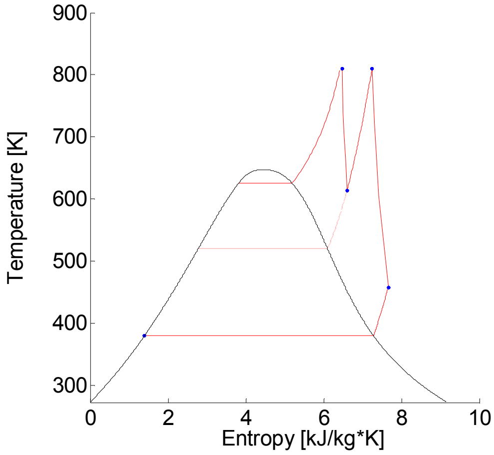

Fig. 10 – Optimal solution – Case B

In cases B and C a higher value of minimum pressure is selected (Fig. 10), allowing to satisfy the required thermal load without recourse to auxiliary generation. Further, it can be observed that higher values also for reheat pressure are proposed with respect to case A, due to the non-linear interaction between these variables. The solutions proposed for cases B and C are quite similar: the energy index appears in this case well representative of the optimum economic operation. Anyway, some small but significant differences can be detected in the optimized variables (minimum pressure and reheat pressure): for case C, an increase in electrical power of about 2.4% is achieved, with an improvement of NPV of about 5% with respect to case B.

CHANGES IN COMPONENT COSTS

In the following example the influence of the relative costs of components is analyzed. In the case 1, the most expensive component is steam generator, while in case 2 the cost of the turbine is assumed the highest (Tab. 6).

The base data for the plants are summarized in Tab. 5. For both cases, three variables have been optimized: extraction pressure, turbine efficiency, steam generator efficiency.

The results (Tab. 7) show that in the case 2, where the cost of turbine is assumed prevailing, a less efficient turbine has been proposed, with a drop in efficiency of about 1.2%. Conversely, a more efficient steam generator is proposed, with an increase of its efficiency of about 1.2%. Net power and thermal efficiency are almost unchanged. The case 2 is however characterized by higher investment (about 11%) and worse economic outcomes.

Min.Pressure	Bar	1.5
Max.Pressure	Bar	170
Max.Temperature	K	780
Steam Mass Flow Rate	Kg/s	20
Pump Efficiency	/	0.9
No.of extractions		1
No.of reheats	-	1
Heat Exchangers Eff.	-	0.89
Reheat Pressure	Bar	30
Elec.Gener.Efficiency	/	0.92
Temp.Thermal User	K	380
Optimized Variables	*Extraction Pressure* *Turbine Efficiency* *Steam Generator Efficiency*	

Tab. 5 – Study of the Effects of Component Costs - Base Plant Data

Component	*Reference Variable*	*Base Value*	*Weigth Case 1*	*Weigth Case 2*
Steam Gener.	Efficiency	0.92	28	17
Turbine	Efficiency	0.90	17	28
Pump	Efficiency	0.95	4	4
Condenser	-	-	13	13
Elec.Generator	Efficiency	0.95	18	18
Reheating	N.reheating	2	10	10
Regeneration	N.extract.	5	10	10

Tab. 6 – Relative Cost and Base Values for Plant Components

	CASE 1	CASE 2
Extraction Pressure (bar)	*13.59*	*11.69*
Turbine efficiency	*0.911052*	*0.900391*
Steam Generator Efficiency	*0.930726*	*0.94247*
Moisture Content at Turb.Out.	Superheated	Superheated
Mechanical Power (kW)	19841.33	19760.16
Heat Flow (kW)	65714.43	65341.49
Thermodynamic Effic. (%)	30.15	30.24
Investment (k€)	18965	21072
Savings (k€/year)	5384	5359
Pay-Back (years)	3.8	4.3
NPV (k€)	36924	34553
Profit Index (/)	2.947	2.6397
IRR (%)	26.3	23.2

Tab. 7 – Optimization Results – Effects of Component Cost Variations

EFFECTS OF THERMAL AND ELECTRICAL LOAD

This example shows the effects of changes in thermal and electrical load on the optimal design of the cogeneration plant. Three different cases are considered, where the ratio between the global thermal and electrical load changes from 2 to 0.5 (Tab. 9, Cases 1,2,3). The hourly distribution of the required electrical and thermal power are reported in solid lines in Fig. 11 and Fig. 12, for Case 1, and in Fig. 13 and Fig. 14, for Case 3, while the corresponding optimal power provided by the cogeneration plant is plotted in dashed lines.

The optimal configurations differ substantially in steam mass flow rate. The highest values are selected when thermal load is prevailing (Case 1), where the thermal and electrical power plant cover about the average values of the external loads. A much small plant is adopted when the ratio between electrical and thermal load is increased (Case 2 and 3). In the latter case, the proposed solution tends to satisfy thermal load (Fig. 14), with recourse an external provider for electricity (Fig. 13). Thermodynamic efficiency is almost unchanged in the three cases. Case 1 is characterized by higher values in savings and in investment, while the reduction in plant size allows to achieve good values of economic indices in the cases B and C, with lower initial investments.

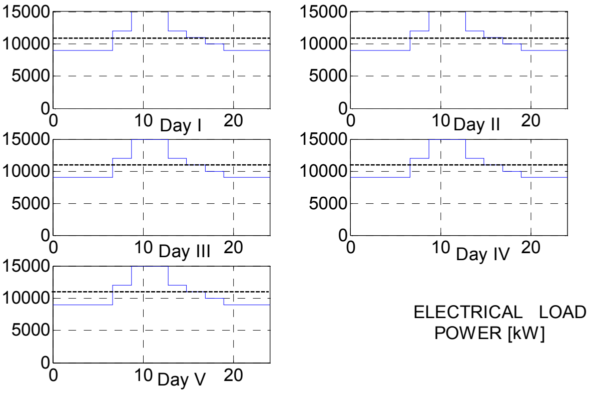

Fig. 11 – Case 1 – Required (solid) and Optimal (dashed) Electrical Load

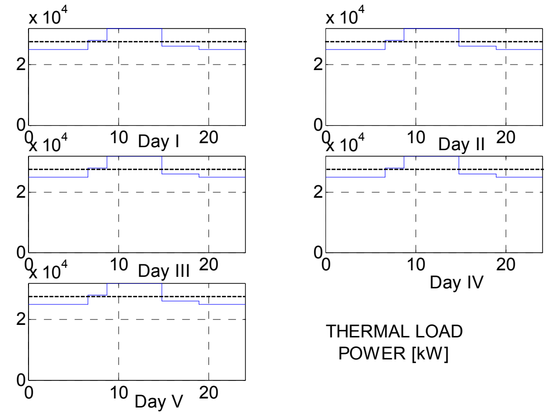

Fig. 12 - Case 1 – Required (solid) and Optimal (dashed) Thermal Load

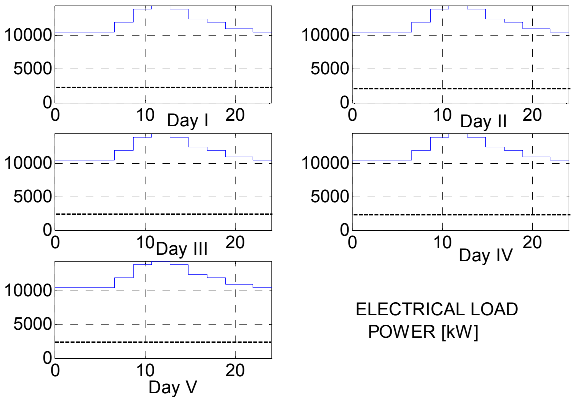

Fig. 13 - Case 3 – Required (solid) and Optimal (dashed) Electrical Load

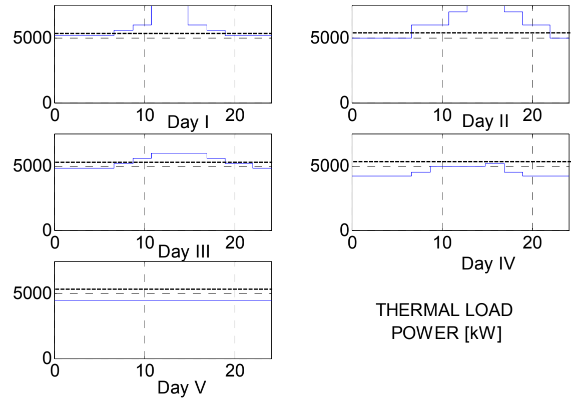

Fig. 14 - Case 3 – Required (solid) and Optimal (dashed) Thermal Load

Min.pressure	bar	1.5
Max.pressure	bar	150
Max.temperature	K	800
Turbine Efficiency	/	0.89
Steam Gen.Eff.	/	0.9
Pump Eff.	/	0.92
No.of reheats	-	1
No. of steam extr.	-	2 pressure: 30 – 10
Elec.Gen.Eff.	/	0.89
Temp.of Thermal User	K	380
Optimized Variables	*Steam Mass Flow Rate* *Reheat Pressure*	

Tab. 8 - Base data – Variations of Thermal and Electrical Loads

	CASE 1 H/E=2	CASE 2 H/E=1	CASE 3 H/E=0.5
Steam Mass Flow Rate	*15.18*	*5.99*	*2.998*
Reheat Pressure (bar)	*87.15*	*79.50*	*78.58*
Moisture Content	0.973	0.981	0.982
Net Power (kW)	12811.09	5129.68	2569.34
Adduced Heat (kW)	44419.73	17736.83	8881.23
Thermodynamic Eff.(%)	28.84	28.92	28.93
Investimento (k€)	12503	5514	3004
Risparmio annuo (k€)	3587	1596	889
Pay-Back (years)	3.8	3.7	3.6
NPV (k€)	27432	11049	6225
Profit Index (/)	2.98	3.004	3.07
IRR (%)	26.6	26.8	27.5

Tab. 9 – Optimization Results – Effects of Thermal and Electrical Loads

FUEL PRICE EFFECTS

The last application analyzes the effects on the optimal plant configuration of variations in fuel price. The base data and the list of the optimized variables are described in Tab. 10, while the optimal solutions are reported in Tab. 11. In the second case, where the fuel price has the half value, steam mass flow rate is increased of about 13%, with almost the same raise on the net power. A slight reduction in steam generator efficiency (about 1%) has also been proposed, to reduce the corresponding investment cost. Although the global investment is increased of about 6%, a relevant improvement in all the economic indices can be detected.

Min.pressure	Bar	1.5
Max.pressure	Bar	120
Max.temperature	K	598.65 (Rankine)
Turbine Efficiency	/	0.89
Pump Eff.	/	0.92
No. of steam extr.	-	2 1st extraction press.: 20 bar
eff scambiatori		0.85
Elec.Gen.Eff.	/	0.92
Temp.of Thermal User	K	380
Optimized Variables	*Steam Mass Flow Rate* *Steam Generator Efficiency* *2nd extr.pressure*	

Tab. 10 – Base data – Study of Fuel Price Variations.

	CASE 1	CASE 2
Fuel Price	Full	Half
Steam Mass Flow Rate	*22.675*	*25.6271*
2nd Reheat Pressure (bar)	*6.42*	*6.45*
Steam Gen.Efficiency (/)	*0.9445*	*0.9315*
Net Power (kW)	11541.68	13043.57
Adduced Heat (kW)	43673.96	50045.09
Thermodynamic Eff.(%)	26.43	26.06
Investment (k€)	12339	13070
Savings (k€/year)	3826	4879
Pay-Back (years)	3.5	2.8
NPV (k€)	27371	37570
Profit Index (/)	3.2182	3.8745
IRR (%)	28.9	35.2

Tab. 11 – Optimization Results – Effects of Fuel Price

MODEL COMPUTATIONAL REQUIREMENTS

The model has been implemented on a PC Pentium III 800 MHz, with 128 MB RAM. The computational time is reported in the table below, as a function of the plant structure (in terms of Thermodynamic Cycle, Number of Reheats, Number of Regeneration Stages). Although the base computational time is quite limited, it may increase up to two orders of magnitude when a very complex plant is considered, particularly when superheated properties have to been computed, due to the necessity of solving many non-linear equations. Further code optimization seems necessary to reduce computational time in such conditions.

The optimization analyses shown in this paper have required a computational time ranging from 10 and 40 minutes, depending on number of variables, model structure, initial values and assigned tolerance. This result is compatible with the computational exigencies in the industrial and professional framework, considering that further improvements could be achieved with a proper optimization of numerical and computational aspects.

Plant Options(*)	*Average Time (s)*	*Normalized Time*
R_0_0	0.0151	1
R_0_2	0.0238	1.5762
R_0_4	0.0280	1.8543
R_0_6	0.0352	2.3467
R_0_8	0.0412	2.7285
R_0_10	0.0509	3.3709
H_0_0	0.0164	1.0861
H_0_3	0.4889	32.3775
H_0_6	0.9567	63.3576
H_0_9	1.2505	82.8146
H_2_0	1.1614	76.9139
H_2_3	1.5419	102.1126
H_2_6	2.0813	137.8344
H_2_9	2.4033	159.1589
H_4_0	2.0706	137.1258
H_4_3	2.5414	168.3046
H_4_6	3.0057	199.0530
H_4_9	3.5215	233.2119

Tab. 12 – Model Computational Time

(*) <**R**ankine-**H**irn>-<#reheats>-<#regeneration stages>

CONCLUSIONS AND FUTURE DEVELOPMENTS

The presented model allows to analyze the effects of the main design variables on the energetic and economic aspects of a steam power plant for power generation and cogeneration use. It allows also to analyze the effects of the incidence of each component on the overall plant cost, also considering the effects of the technological level of the single component over energetic and economic outcomes. Some results, obtained by optimization analysis, have demonstrated the capability of the model to adapt the optimal plant size and its structure to variations in external loads, in fuel price and in the cost of components. The results evidence also that the proposed solutions are in many cases non trivial, and hardly predictable without recourse to complex methodologies.

Further work is needed to improve the precision of the economic model on the basis of data provided by the industry, to extend the capability of the model to include thermal storage and to better describe variable operation and off-design conditions. Specific attention will be paid toward the integration of steam power plant with renewable sources (hybrid power plants). Genetic algorithms will be implemented into the code, in order to extend the capabilities of the program, allowing to consider both continuous and discrete variables representative of real cases.

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