A COMBINED EXPERT SYSTEM/CASE-BASED REASONING APPROACH FOR COGENERATION PLANT DESIGN

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Abstract. *The paper deals with the design problem of natural gas cogeneration systems. Despite its complexity, this design problem subjected to several constraints is properly solved by humans, which suggests the use of artificial intelligence (AI). Moreover, the design process is strongly based on knowledge that experts have in a domain, so that the AI techniques known as knowledge-based systems (KBS) are a well-suited approach for the cogeneration plant design. Expert systems (ES) and case-based reasoning (CBR) are two of the most important KBS techniques. An ES prototype for natural gas cogeneration systems design and optimization has been developed by the authors and reported in previous articles. In this work, the basic concepts of CBR technique and a preliminar CBR prototype for cogeneration plant design are presented. The incorporation of CBR technique in the ES prototype is discussed as well. This combined approach allows the ES prototype to retain a solution in a case-base for future references, i.e., the prototype learns from its previous experiences. Quite advantageously the CBR technique can be implemented in the same shell used to develop the ES prototype, through the object-oriented language available in the shell.*

Keywords*: Cogeneration, Design, Natural Gas, Expert Systems, Case-based Reasoning*

1. INTRODUCTION

The design of a cogeneration plant is a synthesis problem subjected to thermodynamics constraints which includes location and sizing of components – heat exchangers, reciprocating internal combustion engines, gas turbines, chillers, Heat Recovering Steam Generators (HRSG), etc – in order to meet power and thermal energy loads. Despite its complexity, the design of a cogeneration plant subjected to several constraints is a well established problem, which suggests the use of artificial intelligence (AI, computational techniques that codify and emulate the reasoning patterns of human mind) to automate part of this task.

Since the design process is highly based on knowledge that experts have in a particular domain, the AI techniques known as knowledge-based systems (KBS) are an adequate approach for the cogeneration plant design. One of the most important KBS techniques is the expert system (ES), which has been successfully applied to energy systems design. Akagi *et al.* (1988) developed an ES for marine-power plant design, where the knowledge is described in the form of an object-oriented representation. Melli and Sciubba (1997) presented a prototype ES called COLOMBO for the conceptual synthesis of thermal processes. COLOMBO works backwards, considering the design goal as an effect, and trying to find its causes. Melli *at al.* (1992) presented the SYSLAM, an interactive expert system for power plant design and optimization, which is capable of "assembling" a plant starting from a list of available components stored in a database. Manolas and Efthimeros (2001) presented a genetic-algorithm-based expert system shell that, when combined with a proper database comprising the available energy-savings technologies for the process industry, is able to identify the best available technologies and calculates their optimal design parameters. Matelli and Bazzo (2006) presented an expert system for cogeneration plant design that differs from the aforementioned works in at least three ways: first, the domain is restricted to natural gas cogeneration plants; second, it is developed in an available ES shell instead of programming it; and third, the ES presents more than one solution, providing more design alternatives to the user.

However, the typical ES approach presents some limitations, especially regarding maintenance of the knowledge-base and learning from previous experiences (Vargas and Raj, 1993). Case-based reasoning (CBR) is a KBS technique that can overcome some of the ES limitations, particularly those mentioned before. Over the last years, CBR has become one of the most attractive IA method, so attractive that in 1991 Marvin Minsk, cited in Wangenheim and Wangenheim (2003), predicted that *"… 20 years from now CBR will be the most important application of Artificial Intelligence*". Basically, CBR solves a new problem by retrieving a solution from a similar situation. More specifically, CBR uses *cases* previously known so that a new problem is solved based on the assumption that similar problems have similar solutions. The similar solution can be either totally or partially applied to the new problem. It can also be modified according to the requirements of the new problem. The new solution is then reviewed and corrected (if necessary), it also can be stored in the case-base for future use, characterizing the system's learning.

The need to build a case-base is a limitation in CBR that is studied by Finnie and Sun (2003). Another potential limitation is the need of general knowledge about the domain (opposed to specific knowledge embodied by cases) supporting all the CBR cycle (Fig. 1). This support may range from very weak (or none) to very strong, depending on the type of CBR method. A set of rules may have the same role (Aamodt and Plaza, 1994).

By combining both ES and CBR one can have a strongly synergetic system, because the limitations of the ES are compensated by the CBR and vice-versa. For instance, the ES part can be used to create cases for the case-base and the CBR part can make the system learn from its previous experience. The application of CBR in cogeneration plant design is an original and important contribution of this work, although CBR has been applied to somewhat similar problems like process engineering design (Avramenko and Kraslawski, 2006), synthesis of separation processes (Seuranen *et al.*, 2005) and selection of reactive distillation column (Avramenko *et al.*, 2004). The objective of this article is to discuss some aspects of this ES/CBR approach for cogeneration plant design, as well as presenting a preliminary CBR prototype implemented.

2. CASE-BASED REASONING

In Fig.1 is presented the CBR cycle proposed by Aamodt and Plaza (1994). The authors described the cycle as follows: an initial description of a problem (top of figure) defines a new case. This new case is used to *retrieve* a case from the collection of previous cases. The retrieved case is combined with the new case – through *reuse* – into a solved case, i.e. a proposed solution to the initial problem. Through the *revise* process this solution is tested for success, e.g. by being applied to the real world environment or evaluated by a teacher or expert, and repaired if failed. During *retain*, useful experience is retained for future reuse, and the case base is updated by a new learned case, or by modification of some existing cases.

Since the objective of CBR is to reuse known solutions in the context of the new problem, the choice of the cases in the case-base that can be potentially used to provide an effective solution is a major issue in this AI technique (Wangenheim and Wangenheim 2003). Consequently, a quantitative measure of how much a case is similar to the new problem is required. This measure is known as similarity and in order to be calculated the cases must be properly represented. Typically, a case represents the description of a situation (the problem) and the experience retained (the solution) during its resolution. Thus, a case is an association of two sets of information: one set is the problem description and the other is its solution (Wangenheim and Wangenheim 2003). In Fig. 2 examples of a case and a case-base are depicted.

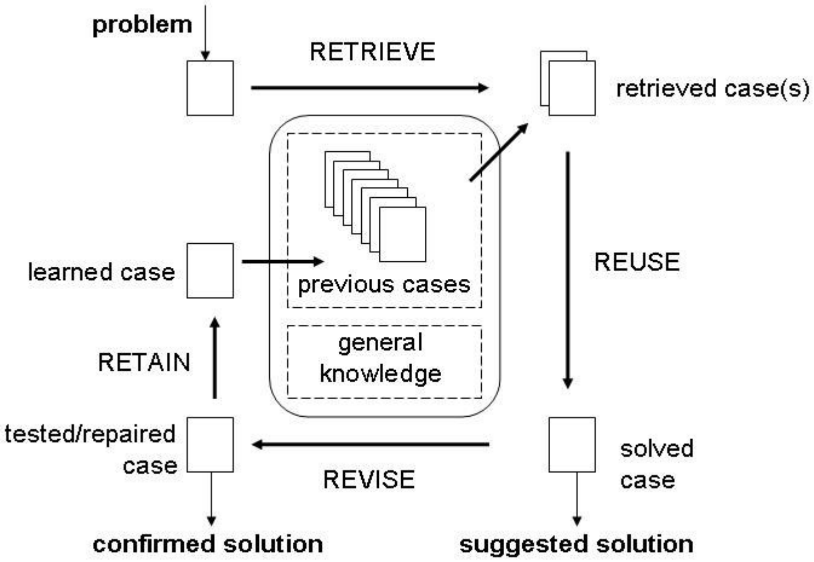
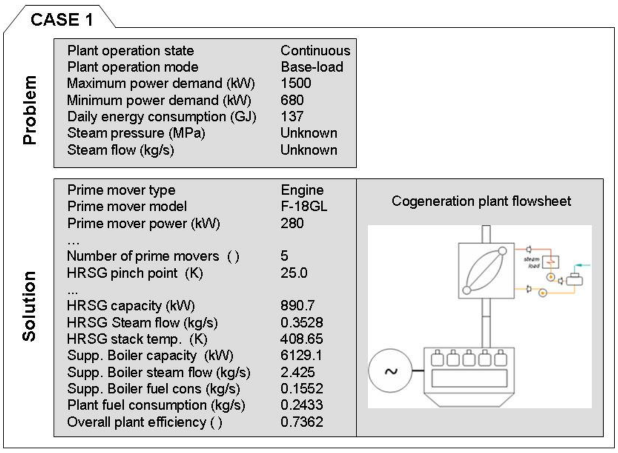
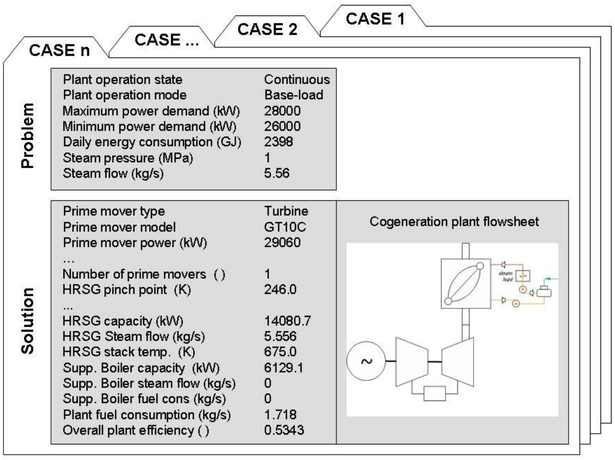


Figure 1. The CBR cycle (adapted from Aamodt and Plaza, 1994).



Problem	Plant operation state	Continuous
	Plant operation mode	Base-load
	Maximum power demand (kW)	1500
	Minimum power demand (kW)	680
	Daily energy consumption (GJ)	137
	Steam pressure (MPa)	Unknown
	Steam flow (kg/s)	Unknown
Solution	Prime mover type	Engine
	Prime mover model	F-18GL
	Prime mover power (kW)	280
	...	
	Number of prime movers ( )	5
	HRSG pinch point (K)	25.0
	...	
	HRSG capacity (kW)	890.7
	HRSG Steam flow (kg/s)	0.3528
	HRSG stack temp. (K)	408.65
	Supp. Boiler capacity (kW)	6129.1
	Supp. Boiler steam flow (kg/s)	2.425
	Supp. Boiler fuel cons (kg/s)	0.1552
	Plant fuel consumption (kg/s)	0.2433
	Overall plant efficiency ( )	0.7362

Figure 2a. Example of a case containing the problem and its solution



Problem	Plant operation state	Continuous
	Plant operation mode	Base-load
	Maximum power demand (kW)	28000
	Minimum power demand (kW)	26000
	Daily energy consumption (GJ)	2398
	Steam pressure (MPa)	1
	Steam flow (kg/s)	5.56
Solution	Prime mover type	Turbine
	Prime mover model	GT10C
	Prime mover power (kW)	29060
	...	
	Number of prime movers ( )	1
	HRSG pinch point (K)	246.0
	...	
	HRSG capacity (kW)	14080.7
	HRSG Steam flow (kg/s)	5.556
	HRSG stack temp. (K)	675.0
	Supp. Boiler capacity (kW)	6129.1
	Supp. Boiler steam flow (kg/s)	0
	Supp. Boiler fuel cons (kg/s)	0
	Plant fuel consumption (kg/s)	1.718
	Overall plant efficiency ( )	0.5343

Figure 2b. Example of a case-base composed of n cases.

The following definitions are found in the work of Kraslawsky *et al.* (1993). A case is an instance I_i of a database, where i = 1,n is a particular case. Every instance I_i is characterized by X_j attributes, where j = 1,m is a particular attribute. The new problem P is also characterized by X_j attributes, but here j = 1,p and generally $m \neq p$. The CBR system must then find a set of cases I_i nearest to P in the sense of the defined metric in the n-dimensional space: the lower the distance between I_i and P, the higher the similarity between them. For a given X_j attribute, the measure of the distance of the new problem P and a case I_i is based on the Minkowski r-metric d:

$$d(P, I_i)_j = \left(\int_{-\infty}^{+\infty} \left| P(X_j) - I_i(X_j) \right|^r dX_j \right)^{\frac{1}{r}} \tag{1}$$

Depending on the r value, well-known distance functions are created, such as Hamming (r = 1), Euclidean (r = 2) or Chebyshev (r = ∞). The Hamming and Euclidean distances are wide-spread in many CBR applications (Wangenheim and Wangenheim 2003; Avramenko and Kraslawski, 2006). However, the distance is an absolute measure of similarity. It is more convenient to normalize it in a range from 0 to 1, where 0 means total dissimilarity and 1 means total similarity. For numeric attributes the linear function of similarity, Eq. (2), is a proper normalized measure of similarity between $P(X_j)$ and $I_i(X_j)$. Note that Eq. (2) is based on the Hamming distance. For attributes that no partial match is allowed, the similarity is either 1, if $P(X_j)$ exactly matches $I_i(X_j)$,or 0 otherwise, as shown in Eq. (3).

$$\text{locsim}\left[P(X_j), I_i(X_j) \right] = 1 - \frac{\left| P(X_j) - I_i(X_j) \right|}{\max(X_j) - \min(X_j)} \tag{2}$$

$$\text{locsim}\left[P(X_j), I_i(X_j) \right] = \begin{cases} 1, & P(X_j) = I_i(X_j) \\ 0, & P(X_j) \neq I_i(X_j) \end{cases} \tag{3}$$

Both Eqs. (2) and (3) refers to local similarity, i.e., the similarity between a i-case attribute $I_i(X_j)$ and the same attribute $P(X_j)$ of the problem. In order to calculate the similarity between the cases (known as global similarity) all the local similarities are considered. Generally the attribute have weights: the higher the weight of an attribute, the higher its contribution on the global similarity. In other words, the global similarity is a weighted average of the local similarities, as shown in Eq. (4).

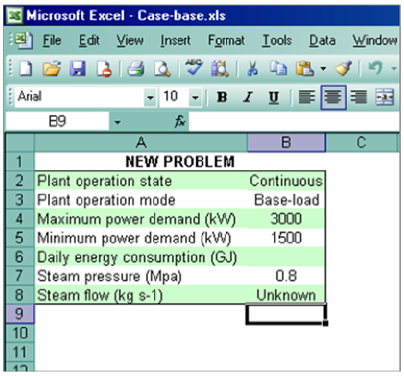
$$\text{sim}(P, I_i) = \frac{\sum_{j=1}^{n} w_j \cdot \text{locsim}\left[P(X_j), I_i(X_j) \right]}{\sum_{j=1}^{n} w_j} \tag{4}$$

The case with the higher value of sim(P,I_i) is the one that is reused to generate a solution. According Watson (1997), in many circumstances this is sufficient to have a solution to the problem. Unfortunately this is not the case in engineering design. The CBR system must adapt the retrieved case to the needs of the problem. Among several adaptation techniques (presented in Watson, 1997), the *parameter adjustment technique* seems to be the most appropriated to the cogeneration plant design problem, because it compares specified parameters of the retrieved case and the problem, applying adaptation rules or formulas directly to the retrieved case in order to generate the final solution. As usual in any KBS methodology, the solution must be validated and, if no correction is required, the solution is stored in the case-base.

3. CBR PROTOTYPE FOR COGENERATION PLANT DESIGN

3.1. Problem presentation and similarity calculation

The previously presented concepts are applied to build a preliminary CBR prototype for cogeneration plant design. The utilities considered are limited to power and saturated steam. Basically, a cogeneration plant that meets such utilities has a prime mover (engine or gas turbine) to produce power and a HRSG to produce steam. HRSG are unfired boilers that use the prime mover exhaust gases to produce steam. They tend to be larger, with more heat exchange surface than a fired boiler with the same capacity. The heat recovery is limited by the temperature of the gases leaving the HRSG stack: the lower this temperature, the higher the heat recovered. However, temperatures lower than 393 K are not recommended in order to avoid formation and condensation of acids in the stack. A supplemental fired boiler is required if the stem demand is higher than the available exhaust gases heat. The CBR prototype is implemented in a data-sheet and is divided in three parts. In the first part the user informs the cogeneration plant requirements (Fig. 3). These requirements are the attributes that are compared between the problem and the cases. Here one can note one of the main characteristic of KBS techniques: the ability to deal with incomplete or unknown data. This is desirable because the designer of a cogeneration plant faces quite often this situation.

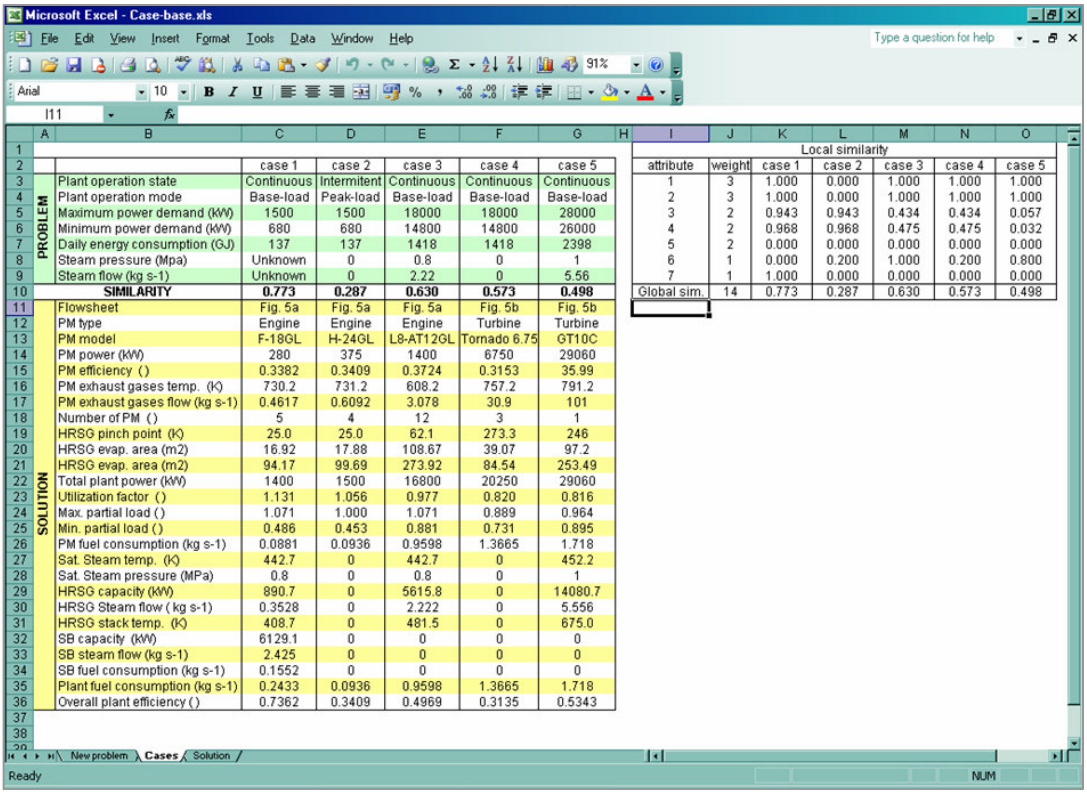


NEW PROBLEM	
Plant operation state	Continuous
Plant operation mode	Base-load
Maximum power demand (kW)	3000
Minimum power demand (kW)	1500
Daily energy consumption (GJ)	
Steam pressure (Mpa)	0.8
Steam flow (kg s-1)	Unknown

Fig. 3. Design requirements.

In the second part of the prototype the problem attributes are compared to the attributes of five cases (Fig. 3), all of them generated by the ES developed by the authors and reported in Matelli and Bazzo (2006). It is an obviously small case-base, and this can lead to an inappropriate solution if the cases are not similar enough to the problem (Avramenko and Kraslawski, 2006). However, the aforementioned case-base is sufficient for the purposes of this work.

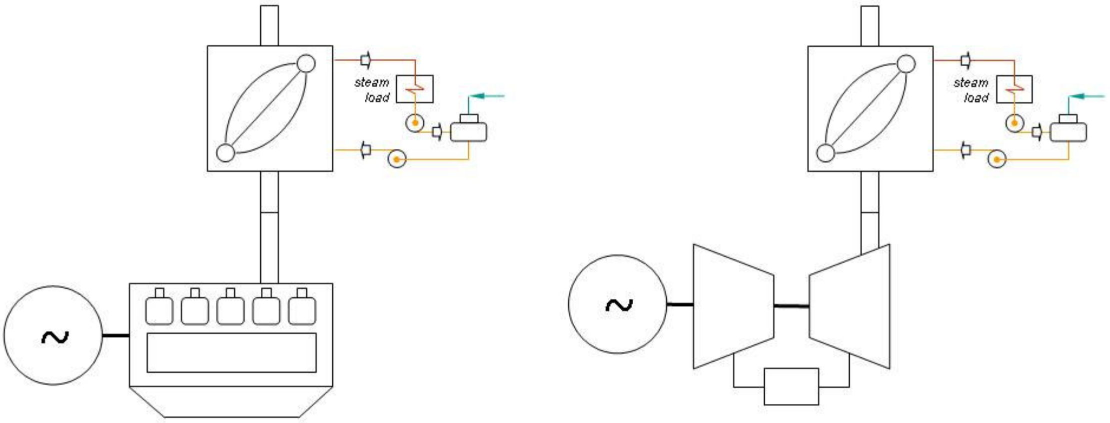
Note that the plant scheme is part of the solution for every case (see first line of the solution part in Fig. 4). The schemes are depicted in Fig. 5. As shown in Fig. 4, one can see that the most similar case is the case 1, presenting a global similarity equal to 0.773. The most dissimilar case is case 2, which presents a global similarity equal to 0.287. The local similarity of the attributes 1 and 2 are calculated according Eq. (3). All others local similarities are calculated through Eq. (2). So case 1 is the case retrieved to generate the problem solution in the third part of the prototype (Fig. 6). It is interesting to note that the steam flow is unknown in both the problem and the retrieved case. However the CBR is able to size the steam generating subsystem based on the expert knowledge that steam flow in the range from 0.9722 to 2.778 kg/s is adequate for most of applications.



		case 1	case 2	case 3	case 4	case 5
PROBLEM	Plant operation state	Continuous	Intermitent	Continuous	Continuous	Continuous
	Plant operation mode	Base-load	Peak-load	Base-load	Base-load	Base-load
	Maximum power demand (kW)	1500	1500	18000	18000	28000
	Minimum power demand (kW)	680	680	14800	14800	26000
	Daily energy consumption (GJ)	137	137	1418	1418	2398
	Steam pressure (Mpa)	Unknown	0	0.8	0	1
	Steam flow (kg s-1)	Unknown	0	2.22	0	5.56
	SIMILARITY	**0.773**	**0.287**	**0.630**	**0.573**	**0.498**
SOLUTION	Flowsheet	Fig. 5a	Fig. 5a	Fig. 5a	Fig. 5b	Fig. 5b
	PM type	Engine	Engine	Engine	Turbine	Turbine
	PM model	F-18GL	H-24GL	L8-AT12GL	Tornado 6.75	GT10C
	PM power (kW)	280	375	1400	6750	29060
	PM efficiency ()	0.3382	0.3409	0.3724	0.3153	35.99
	PM exhaust gases temp. (K)	730.2	731.2	608.2	757.2	791.2
	PM exhaust gases flow (kg s-1)	0.4617	0.6092	3.078	30.9	101
	Number of PM ()	5	4	12	3	1
	HRSG pinch point (K)	25.0	25.0	62.1	273.3	246
	HRSG evap. area (m2)	16.92	17.88	108.67	39.07	97.2
	HRSG evap. area (m2)	94.17	99.69	273.92	84.54	253.49
	Total plant power (kW)	1400	1500	16800	20250	29060
	Utilization factor ()	1.131	1.056	0.977	0.820	0.816
	Max. partial load ()	1.071	1.000	1.071	0.889	0.964
	Min. partial load ()	0.486	0.453	0.881	0.731	0.895
	PM fuel consumption (kg s-1)	0.0881	0.0936	0.9598	1.3665	1.718
	Sat. Steam temp. (K)	442.7	0	442.7	0	452.2
	Sat. Steam pressure (MPa)	0.8	0	0.8	0	1
	HRSG capacity (kW)	890.7	0	5615.8	0	14080.7
	HRSG Steam flow (kg s-1)	0.3528	0	2.222	0	5.556
	HRSG stack temp. (K)	408.7	0	481.5	0	675.0
	SB capacity (kW)	6129.1	0	0	0	0
	SB steam flow (kg s-1)	2.425	0	0	0	0
	SB fuel consumption (kg s-1)	0.1552	0	0	0	0
	Plant fuel consumption (kg s-1)	0.2433	0.0936	0.9598	1.3665	1.718
	Overall plant efficiency ()	0.7362	0.3409	0.4969	0.3135	0.5343

Local similarity						
attribute	weight	case 1	case 2	case 3	case 4	case 5
1	3	1.000	0.000	1.000	1.000	1.000
2	3	1.000	0.000	1.000	1.000	1.000
3	2	0.943	0.943	0.434	0.434	0.057
4	2	0.968	0.968	0.475	0.475	0.032
5	2	0.000	0.000	0.000	0.000	0.000
6	1	0.000	0.200	1.000	0.200	0.800
7	1	1.000	0.000	0.000	0.000	0.000
Global sim.	14	0.773	0.287	0.630	0.573	0.498

Fig. 4. Case-base and similarity calculation.

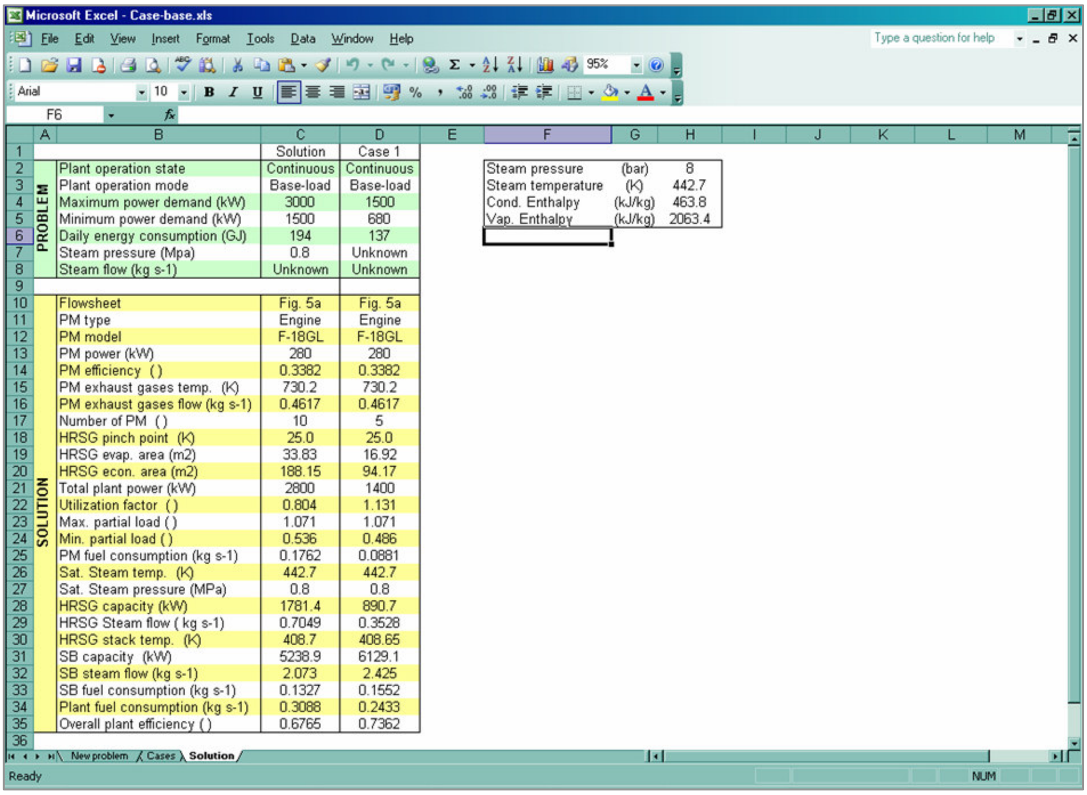


(a) (b)

Figure 5. Plant schemes based on engine (a) and turbine (b).

3.2. Adaptation of the retrieved solution

The third part of the process is related to the adaptation. Basically adaptation requires the recalculation of the number of prime movers, which allows determining the amount of exhaust gases heat available for recovering. Consequently all the design parameters of a HRSG are calculated, indicating if a supplemental boiler is necessary. This is in accordance with the *parameter adjustment adaptation technique* previously described, where adaptation rules and/or formulas are directly applied to the retrieved case in order to generate the final solution. These rules and formulas are used in the ES developed by the authors and presented in Matelli and Bazzo (2006) and can be used in the CBR part. The detailed description of such procedure is presented as follows.



	A	B	C	D
1			Solution	Case 1
2	PROBLEM	Plant operation state	Continuous	Continuous
3		Plant operation mode	Base-load	Base-load
4		Maximum power demand (kW)	3000	1500
5		Minimum power demand (kW)	1500	680
6		Daily energy consumption (GJ)	194	137
7		Steam pressure (Mpa)	0.8	Unknown
8		Steam flow (kg s-1)	Unknown	Unknown
9				
10	SOLUTION	Flowsheet	Fig. 5a	Fig. 5a
11		PM type	Engine	Engine
12		PM model	F-18GL	F-18GL
13		PM power (kW)	280	280
14		PM efficiency ( )	0.3382	0.3382
15		PM exhaust gases temp. (K)	730.2	730.2
16		PM exhaust gases flow (kg s-1)	0.4617	0.4617
17		Number of PM ( )	10	5
18		HRSG pinch point (K)	25.0	25.0
19		HRSG evap. area (m2)	33.83	16.92
20		HRSG econ. area (m2)	188.15	94.17
21		Total plant power (kW)	2800	1400
22		Utilization factor ( )	0.804	1.131
23		Max. partial load ( )	1.071	1.071
24		Min. partial load ( )	0.536	0.486
25		PM fuel consumption (kg s-1)	0.1762	0.0881
26		Sat. Steam temp. (K)	442.7	442.7
27		Sat. Steam pressure (MPa)	0.8	0.8
28		HRSG capacity (kW)	1781.4	890.7
29		HRSG Steam flow (kg s-1)	0.7049	0.3528
30		HRSG stack temp. (K)	408.7	408.65
31		SB capacity (kW)	5238.9	6129.1
32		SB steam flow (kg s-1)	2.073	2.425
33		SB fuel consumption (kg s-1)	0.1327	0.1552
34		Plant fuel consumption (kg s-1)	0.3088	0.2433
35		Overall plant efficiency ( )	0.6765	0.7362
36				

F	G	H
Steam pressure	(bar)	8
Steam temperature	(K)	442.7
Cond. Enthalpy	(kJ/kg)	463.8
Vap. Enthalpy	(kJ/kg)	2063.4

Figure 6. Adaptation of the case retrieved and final solution.

According to the expert knowledge, the prime mover should be sized to meet 90% of the maximum power demand (D_{max}), because in most cases the power demand is greater than this value only for short periods of time, and the movers generally can operate overloaded for a moment. Thus the number of prime movers n_{PM} that have a nominal power W_{PM} suggested by the retrieved case is given by Eq. (5), so that the cogeneration plant available power (W_{plant}) is given by Eq. (6):

$$n_{PM} = \text{greater integer}\left(\frac{0.9D_{max}}{W_{PM}}\right) \tag{5}$$

$$W_{plant} = n_{PM} W_{PM} \tag{6}$$

The prime mover utilization factor μ is defined as the ratio between the daily energy E_d (in GJ) and the energy that can be delivered by the cogeneration plant during 24 h (also in GJ), as seen in Eq. (7).

$$\mu = \frac{E_d}{0.0864 W_{plant}} \tag{7}$$

The prime mover's maximum and minimum partial load (L_{max} and L_{min}, respectively) operation are calculated by Eqs. (8) and (9), respectively.

$$L_{max} = \frac{D_{max}}{W_{plant}} \tag{8}$$

$$L_{min} = \frac{D_{min}}{W_{plant}} \tag{9}$$

Finally, the fuel consumption of the movers ($\dot{m}_{ng,PM}$) is given by Eq. (10), where η_{PM} is the prime mover's efficiency and LHV is the lower heating value of natural gas:

$$\dot{m}_{ng,PM} = \frac{W_{plant}}{\eta_{PM} LHV} \tag{10}$$

Regarding the steam demand, the pinch point PP (Eq. 11) and the stack gases temperature T_{sk} (Eq. 12) are the key parameter in the HRSG sizing. They are calculated considering the heat recovery from the prime mover exhaust gases.

$$PP = T_g - T_{st}^{P_{st}} - \frac{\dot{m}_{st} h_{lv}^{P_{st}}}{n_{PM} \dot{m}_g c_{P,g}} \tag{11}$$

$$T_{sk} = T_g - \frac{\dot{m}_{st}}{n_{PM} \dot{m}_g c_{P,g}} \left[h_{lv}^{P_{st}} - c_{P,w} \left(T_{st}^{P_{st}} - T_{rc} \right) \right], \tag{12}$$

where Tg is the prime mover exhaust gases temperature; $\dot{m}_g$ is the exhaust gases flow; $c_{P,g}$ is the specific heat of the exhaust gases; $T_{st}^{P_{st}}$ is the saturated steam temperature at pressure P_{st}; $\dot{m}_{st}$ is the steam flow; $h_{lv}^{P_{st}}$ is the enthalpy of vaporization of the water at pressure P_{st}; $c_{P,w}$ is the specific heat of water; and T_{rc} is the temperature of the condensate.

Once defined the HRSG steam mass flow, its capacity Q_{HRSG} is given by Eq. (13), and the HRSG heat exchange surfaces A are calculated according Eqs (14) and (15) for the evaporator section (U = 0.4 kW m^{-2} K^{-1}) and economizer section (U = 0.038 kW m^{-2} K^{-1}) [19], respectively.

$$Q_{HRSG} = \dot{m}_{st,HRSG} \left[h_{lv}^{P_{st}} + c_{P,w} \left(T_{st}^{P_{st}} - T_{rc} \right) \right] \tag{13}$$

$$A_{ev} = \frac{n_{PM} \dot{m}_g c_{P,g} \left[T_g - \left(T_{st}^{P_{st}} + PP \right) \right]}{U \left[\left(T_g - T_{st}^{P_{st}} - PP \right) \right]} \ln \left(\frac{T_g - T_{st}^{P_{st}}}{PP} \right) \tag{14}$$

$$A_{ec} = \frac{n_{PM} \dot{m}_g c_{P,g} \left[\left(T_{st}^{P_{st}} + PP \right) - T_{sk} \right]}{U \left[PP - \left(T_{sk} - T_{rc} \right) \right]} \ln \left(\frac{PP}{T_{sk} - T_{rc}} \right), \tag{15}$$

where U is the overall heat transfer coefficient.

The natural gas-fired boiler, if required, has its capacity Q_{SB} and steam mass flow $\dot{m}_{st,SB}$ calculated by Eq. (16) and (17), respectively. Its fuel consumption $\dot{m}_{ng,SB}$ is calculated by Eq. (18).

$$Q_{SB} = S - Q_{HRSG} \tag{16}$$

$$\dot{m}_{st,SB} = \dot{m}_{st} - \dot{m}_{st,HRSG} \tag{17}$$

$$\dot{m}_{ng,SB} = \frac{Q_{SB}}{\eta_{SB} LHV} \tag{18}$$

where S is the steam demand and η_{SB} is the boiler efficiency. Finally, the overall cogeneration plant efficiency is given by:

$$\eta_{pl} = \frac{W_{plant} + Q_{HRSG} + Q_{SB}}{\left(\dot{m}_{ng,PM} + \dot{m}_{ng,SB} \right) LHV} \tag{19}$$

The CBR cycle rarely occurs without human intervention. The case revision and adaptation is often undertaken by the user (Watson, 1997). In order to validate the adapted solution, the cogeneration plant designer must keep the following considerations in mind:

i. The utilization factor (Eq. 7) is a key parameter when selecting a prime mover: the higher the utilization factor, the lower the operation and installation costs;
ii. The maximum partial load operation (Eq. 8) of the prime mover should not exceed 1.1, because most of the engines and turbines commercially available do not operate more about such rate. The minimum partial load operation (Eq. 9) should not be lower than 0.5 for engines, because the efficiency decreases and the operation costs will be very high. For turbines, the minimum partial load should not be lower than 0.7, for two reasons: first, because the efficiency would decrease significantly; second, because turbines have in general slow load response;
iii. Eventually the prime movers exhaust gases heat is not enough to produce the required steam demand. This is the case when one of the following situations occurs:

    a. the pinch point is lower than 15 K, which implies in high heat exchange surface and high initial cost (note that a pinch point lower than zero is a violation of the second law of thermodynamics). So the pinch point is set to 25 K and Eq. (11) is used to calculate the HRSG steam mass flow $\dot{m}_{st,HRSG}$. Equation (12) is then evaluated by $\dot{m}_{st} = \dot{m}_{st,HRSG}$;
    b. the stack gases temperature is lower than 393.2 K, which is not recommended in order to avoid formation and condensation of acids in the stack. So the stack gases temperature is set to 393.2 K. Eq. (12) is used to calculate the HRSG steam mass flow $\dot{m}_{st,HRSG}$. Equation (11) is then evaluated by $\dot{m}_{st} = \dot{m}_{st,HRSG}$;

Since the solution is validated it can be stored as the sixth case of the CBR prototype case-base, being available for future use. The solution of the proposed problem represented a new experience to the system, and by storing this experience it can be said that the system has learned from its previous experience.

4. COMBINING ES AND CBR FOR COGENERATION PLANT DESIGN

The combination of ES and CBR techniques results in a very synergetic system, as one can see in Tab. 1. However, the most attractive aspect of such combination is the possibility of implementation in the same shell used to implement the ES reported in Matelli and Bazzo (2006). This shell is the CLIPS, originally developed by NASA. Nowadays it is public domain software that is maintained independently. CLIPS is a forward chaining shell based on pattern-matching architecture (Gonzales and Dankel, 1993), where the knowledge can be represented in the form of rules, functions and Object-Oriented Design. CLIPS has a module named COOL (from CLIPS Object-Oriented Language) which allows the implementation of the fundamental principles of OOD – abstraction, inheritance, encapsulation and polymorphism.

Table 1. Synergy between ES and CBR techniques.

Characteristic	ES	CBR	ES/CBR
System learning?	No	**Yes**	**Yes**
Easy knowledge base maintenance?	No	**Yes**	**Yes**
Easy knowledge representation?	No	**Yes**	**Yes**
Reasoning from scratch?	**Yes**	No	**Yes**
Solution needs adaptation?	**No**	Yes	**No**
Needs human intervention?	**No**	Yes	**No**

Through OOD the cases can be modeled as objects; the object's attributes would store the information regarding the problem description and the problem solution. These objects can be manipulated by the inference machine of the ES through rules that calculates the similarity between the objects. Rules for adapting the retrieved solution can be considered as well. Indeed these rules are the same that the ES uses to infer a solution from the scratch. This can be possible because the cogeneration is a domain where the parameter adjustments are well-understood and relatively simple, as one can see from Eq. (5) to Eq. (19). However, the possibility of user interference in the adaptation phase cannot be neglected, because as Watson (1997) states, "case adaptation is in many ways the Achilles' heel of CBR".

Another possibility is the system learning, giving the user the choice to export the solutions proposed by the ES to a case-base. Thus, in the next ES Prototype session, the user could either start an inference from scratch or search the case-base in order to find and adapt a similar solution. This could be an advantage when the component database becomes too large, because in this case the inference process from stratch consumes an amount of computational time larger than that observed in case retrieving.

5. CONCLUSION

In this paper the design problem of natural gas cogeneration systems is modeled through AI techniques known as knowledge-based systems (KBS). Expert systems (ES) and case-based reasoning (CBR) are two of the most important KBS techniques. In this work, the basic concepts of the CBR technique and a preliminary CBR prototype for cogeneration plant design are presented. The prototype is able to find a solution from previous cases through the similarity calculation, but the adaptation and case storing is undertaken by the user. The incorporation of the CBR technique in the ES prototype is discussed as well, and this approach indicates to be a very synergetic way to solve the cogeneration plant design problem. Furthermore, this combined approach allows the prototype to retain a solution in a case-base for future references, i.e., the prototype learns from its previous experiences. Quite advantageously the CBR technique can be implemented in the same shell used to develop the ES prototype, through the object-oriented language available in the shell.

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