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Improving the Energy Diagnosis of Steam Power Plants Using the Lost Work Impact Formula

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Abstract

In this paper, the energy diagnosis improvement of an existing steam power plant is faced on the basis of the Lost work Impact Formula, developed in the ambit of thermo-economics and presented in a previous paper. Three strategies for improving diagnostic accuracy are discussed and exemplified. Some cases of simultaneous malfunctioning of two components are introduced, to test the accuracy of energy recovery evaluation when intrinsic malfunction affects more than one component. The improved results show that the effect of the functional decay can be quantified with sufficient approximation also in that case where the first diagnostic attempt did not give meaningful answers.

Key words: exergy losses, diagnosis, malfunction thermoeconomics, productive structure

1. Introduction

In a previous paper (Reini and Taccani 2002) a simulation model of a real 320 MW steam power plant has been introduced. The functional decay of different components of the plant has been simulated using the model. Then different diagnostic formulations are applied, to test the accuracy in malfunctioning component identification and energy recovery quantification, if design conditions were restored in that component.

The results show that in most cases meaningful answers can be obtained by using the Lost work Impact Formula (LIF), developed in the ambit of thermoeconomics and presented in the same paper. When the first diagnostic attempt does not show a single main contribution to the additional global losses, so that the component affected by intrinsic malfunction cannot be clearly identified, further improvements in the diagnostic accuracy can be achieved through this additional losses formulation.

An improvement in diagnostic accuracy can be obtained on the basis of LIF by manipulating the productive structure (Reini and Giadrossi 1996), or by eliminating the ambient condition effects through a proper definition of the reference state for the plant (Torres et al. 1999, Valero et al. 2002).

Two cases introduced in a previous paper (Reini and Taccani 2002) are first considered in the following: they can be faced modifying flows, or variables, respectively, inside the productive structure:

- the steam air preheater identification as intrinsically malfunctioning component, when its global heat transfer coefficient is reduced;
- the improved allocation of additional global losses on the turbine actually affected by a decrease in its isentropic efficiency. This is obtained through the reallocation, on the actually malfunctioning component, of the shaft power junction (J27) term in the Lost work Impact Formula.

Then an alternative strategy for eliminating the modified ambient condition effects is presented and an example is shown. Finally some cases of simultaneous malfunctioning of two components are introduced to test the accuracy of energy recovery evaluation when intrinsic malfunction affects more than one component.

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2. Improving Energy Diagnosis

Productive Structure definition

The productive structure of the plant has been defined starting from the exergy flows connecting the considered control volumes, or "component units", and following the concepts of "Fuel" and "Product" (Valero et al. 1986, Tsatsaronis et al. 1990). Junctions and branches of flows (Frangopoulos 1987) have been introduced to isolate flows defined in the productive structure. Considered control volumes are shown in Reini, Taccani (2002), while the adopted productive structure is shown in *Figure 1* and the mathematical expressions of the main component units fuel and products are reported in the Appendix.

To describe in detail the procedure to pass from the physical flows to the productive structure is not the scope of the paper (see, for instance, Lozano et al. 1994; Torres et al. 1999). To fix ideas, let's think to a very simple steam power plant, made up with only four components: a steam generator, a steam turbine, a condenser and a pump. In this case the same working fluid flow passes through all components.

- Condenser: the main fuel is the physical exergy decrease of the working fluid passing through the component; an additional fuel can be the mechanical exergy decrease of the cooling water inside the tubes of the condenser. The product is defined as the neg-entropy flow (Spakovsky and Evans 1990; index "s" in *Figure 1*) supplied to the working fluid. The neg-entropy flow is then consumed as a fuel by the other components, each one consuming an amount of neg-entropy proportional to the entropy increase of the working fluid passing through that component.
- Pump: the fuel is the electrical (or mechanical) power driving the pump. The main product is defined as the mechanical exergy increase obtained for the working fluid. The corresponding thermal exergy increase can be regarded as a sub-product (Lozano et al., 1994).
- Steam Generator: the product is defined as the thermal exergy increase of the working fluid passing through the component. This flow is joined to the pump sub-product, the latter being evaluated at the same cost of the former. The fuel is the chemical exergy of the consumed fuel.
- Turbine: the thermal and mechanical exergy obtained by exergy-donor components join together, to obtain the physical exergy consumed as a fuel by the condenser and the turbine. The obtained shaft power output is the turbine product.

In the steam power plant considered in the paper, the productive structure has been obtained taking account of three main working fluid flows, each of them subdivided into various extractions and leakage: flows finally converging into the deareator, into the condenser and virtually converging into the water integration system (actually lost in the environment).

Modifying flows in the productive structure

The considered functional decay of the Steam Air Preheater (SAP) is a 13% reduction in the global heat transfer coefficient, while the preheated air temperature is kept constant by increasing the mass flow rate of the steam extracted from the turbine as a fuel of the SAP.

The results of the first diagnostic attempt, developed on the basis of the three global losses formulations considered in Reini and Taccani (2002), are reported in TABLE I. DEB shows that additional losses arise inside various control volumes, while also LIF and GFE do not allow the component affected by intrinsic malfunctions to be identified. Nevertheless, the LIF column clearly shows that this is because of the condenser induced malfunction.

In fact, because of the SAP functional decay, an additional amount of exergy is withdrawn from the medium pressure turbine. But it is not completely exhausted in the SAP, so that the temperature and the mass flow rate of the exiting stream from the SAP to the condenser increase. The not-exhausted fuel is then destroyed in a throttling process, bringing the flow to the condensation pressure and physically located inside the condenser control volume.

On the basis of these observations, a re-examination of the productive structure allows a more accurate allotment of additional global losses to the SAP.

The SAP fuels definition is modified, including into the physical exergy fuel (flow 25^b in *Figure 1*) the exergy destroyed in the throttling process of the exiting stream from the SAP to the condenser. The same amount of exergy has to be subtracted from the physical exergy fuel of the condenser.

In this way the condenser is still forced to dissipate an additional heat amount, but we expect the additional losses to be reallocated on the SAP through neg-entropy flows.

Results obtained on the basis of the improved fuels definition for SAP and condenser are compared with the previous ones in TABLE I.

Adopting the diagnostic error definition considered in Reini and Taccani (2002), the LIF error reduces from 92% to 23%, while GFE error passes from 103% to 43%. Such a result suggests that further improvement in the diagnostic accuracy may be achieved with a further revision of adopted fuel and products definitions, particularly for feedwater heater and deareator.

TABLE I. ADDITIONAL LOSSES (AND CORRESPONDING PERCENTAGES) ALLOTTED TO THE MAIN COMPONENT OF THE STEAM POWER PLANT, FOLLOWING THE THREE GLOBAL LOSSES FORMULATIONS, WHEN A SINGLE PERFORMANCE PARAMETER IS AFFECTED BY FUNCTIONAL DECAY. RESULTS FOR THE DIRECTLY RELATED COMPONENTS ARE IN BOLD CHARACTER. FOR THE GFE, ONLY THE PERCENTAGES OF ADDITIONAL LOSSES ARE CALCULATED. MINOR COMPONENTS ARE 1-WATER INTEGRATION, 2-EXTRACTION PUMP AND 3-PRESSURE DROP.

Components affected by intrinsic malfunctions		**Steam Air Preheater**					**Steam Air Preheater improved**				
		DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]
123	**minor components**	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0
4	**Low pressure FH**	1	7	0.4	3.1	-0.9	1	7	0.4	3.1	-0.9
5	**Deareator**	-14	-34	-6.2	-15.0	-15.3	-14	-34	-6.2	-15.0	-15.3
6	**Feed Pump**	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0
7	**High pressure FH**	16	29	7.1	12.8	14.3	16	29	7.1	12.8	14.3
8	**Steam Generator**	46	-10	20.4	-4.4	-7.2	46	-7	20.4	-3.1	-7.2
9	**High Pressure T**	5	0	2.2	0.0	-0.5	5	0	2.2	0.0	-0.5
10	**Middle Pressure T**	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0
11	**Steam Leakage**	0	0	0.0	0.0	-0.1	0	0	0.0	0.0	0.0
12	**Low Pressure T**	-12	1	-5.3	0.4	-22.7	-12	0	-5.3	0.0	-22.7
13	**Condenser**	85	151	37.6	66.8	80.8	4	-1	1.8	-0.4	-2.8
14	**Blower**	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0
15	**Steam Air Preheat.**	**44**	**89**	**19.5**	**39.4**	**44.3**	**125**	**242**	**55.3**	**107.1**	**127.8**
16	**Air PreHeater**	5	4	2.2	1.8	2.2	5	4	2.2	1.8	2.2
17	**Comb. Chamber**	52	8	23.0	3.5	6.7	51	8	22.6	3.5	6.7
18	**Alternator**	0	0	0.0	0.0	-1.5	0	0	0.0	0.0	-1.5
J27	**Shaft Power Junc.**	0	-17	0.0	-7.5	0.0	0	-17	0.0	-7.5	0.0
	Components	228	226	100.9	100.0	100.0	228	226	100.9	100.0	100.0
	ΔP_T	-2	-	-0.9	-	-	-2	-	-0.9	-	-
	Add. Losses	**226**	**226**	**100.0**	**100.0**	**100.0**	**226**	**226**	**100.0**	**100.0**	**100.0**

TABLE II. IMPROVED ALLOTMENT OF ADDITIONAL LOSSES AS IN TABLE I

Components affected by intrinsic malfunctions		**High Pressure Turbine**					**Low Pressure Turbine**				
		DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]
123	**minor components**	1	0	0.0	0.0	0.0	3	0	0.0	0.0	0.0
4	**Low pressure FH**	28	42	3.2	2.7	3.2	28	12	0.8	0.4	0.1
5	**Deareator**	10	11	0.8	0.8	1.4	3	-8	0.0	-0.2	-0.2
6	**Feed Pump**	2	0	0.2	0.0	0.1	4	0	0.1	0.0	0.0
7	**High pressure FH**	52	72	3.9	5.5	7.3	80	116	2.4	3.5	3.7
8	**Steam Generator**	197	-166	14.9	-12.6	-18.4	747	-52	22.2	-1.6	-3.4
9	**High Pressure T**	**535**	**1283**	**40.5**	**97.1**	**88.8**	74	-3	2.2	-0.1	-0.3
10	**Middle Pressure T**	4	-5	0.3	-0.4	0.2	6	-3	0.2	-0.1	0.0
11	**Steam Leakage**	0	-1	0.0	-0.0	-0.1	0	0	0.0	0.0	-0.1
12	**Low Pressure T**	88	-34	6.7	-2.6	5.8	**1473**	**3237**	**43.8**	**96.3**	**91.6**
13	**Condenser**	60	-4	4.5	-0.3	3.9	160	-23	4.8	-0.7	4.2
14	**Blower**	1	0	0.0	0.0	0.0	3	0	0.0	0.0	0.0
15	**Steam Air Preheat.**	8	-3	0.6	-0.2	0.6	13	1	0.4	0.0	0.0
16	**Air PreHeater**	31	14	2.3	1.1	2.3	69	25	2.1	0.7	1.5
17	**Comb. Chamber**	290	58	22.0	4.4	6.4	734	75	21.8	2.3	4.4
18	**Alternator**	0	0	0.0	0.0	-1.5	1	0	0.0	0.0	-1.5
	α_1, α_2	0	52	0.0	4.0	0.0	0	-10	0.0	-0.3	0.0

	Components	1308	1321	99.0	100.0	100.0	3397	3362	101.0	100.0	100.0
	ΔP_T	13	-	1.0	-	-	-35	-	-1.0	-	-
	Add. Losses	**1321**	**1321**	**100.0**	**100.0**	**100.0**	**3362**	**3362**	**100.0**	**100.0**	**100.0**

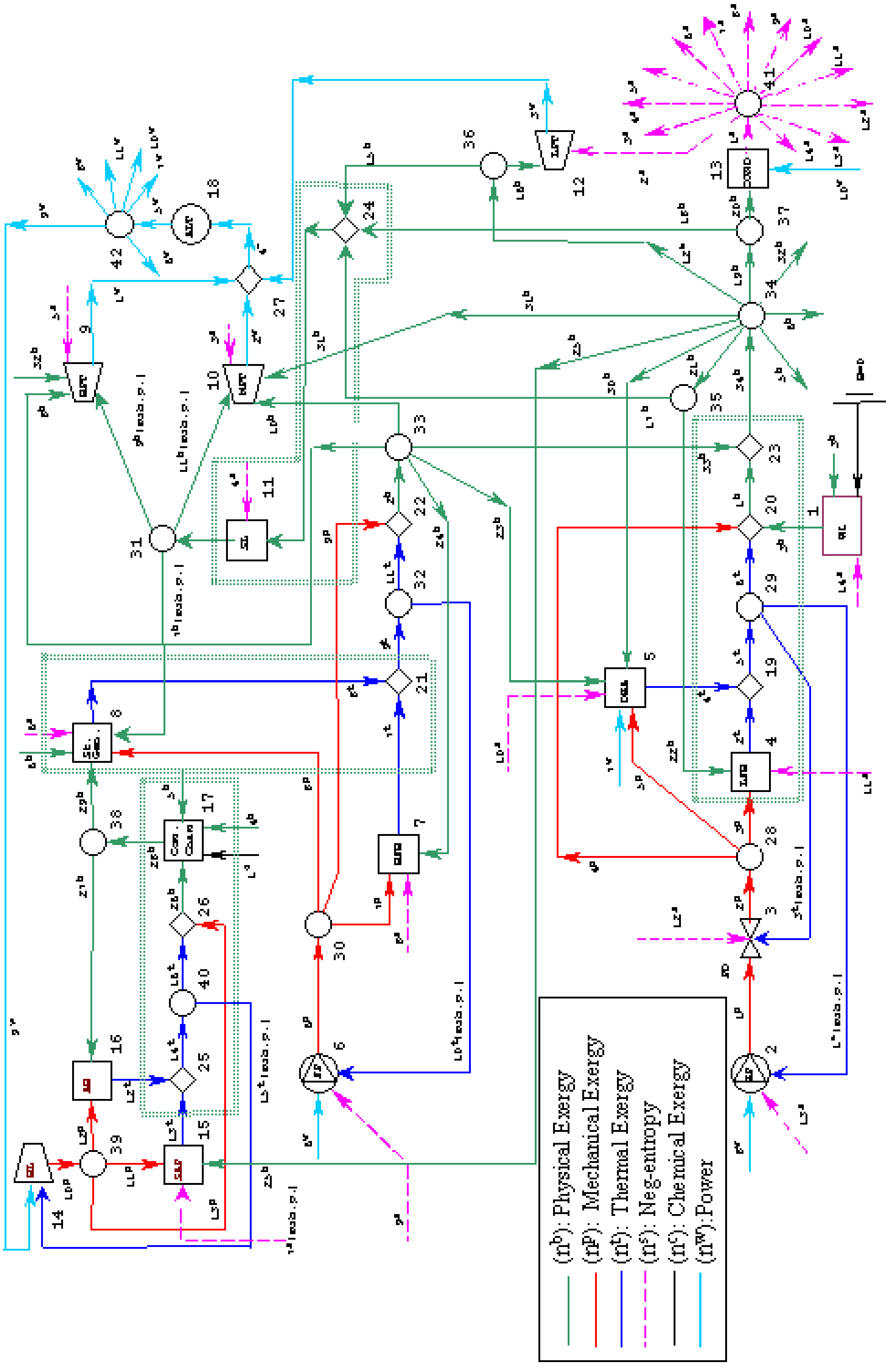

Figure 1. Productive structure

Modifying variables in the productive structure

In the shaft power junction (J27 in *Figure 2*) three power flows merge.

Taking account of the exergy balance of the junction, two independent unit consumptions (κ_{ij}) can be defined, whose variations originate the shaft power junction impact term, agreeing with equation (14) in Reini and Taccani (2002).

Applying the LIF, a non-zero impact term is obtained for the shaft power junction (J27) when the total load is distributed to the turbines in a proportion different from the reference one. It should be noted that this impact term can in principle arise even if turbine unit consumptions (κ_{ij}) are completely independent of one another. Moreover, the fuel supplied to one turbine cannot be independently varied from the fuels of the others, because the interventions to restore the reference power output imply a flowrate variation in all the turbines, not only in the perturbed one.

Taking these two remarks into account, a sub-system has been isolated in the productive structure, made of the three turbines, branches 31, 33, 34, and J27.

To obtain a reallocation of the J27 impact term on the actually perturbed turbine, in the sub-system the variable describing the state of the plant has been changed, introducing the bifurcation coefficients of flows 32^b (main high pressure turbine fuel) and 16^b (main low pressure turbine fuel):

$$\alpha_1 \equiv \frac{32^b}{16^b + 31^b + 32^b}; \alpha_2 \equiv \frac{16^b}{16^b + 31^b + 32^b} \qquad (1)$$

In such a way the J27 unit consumptions may be considered a function of the defined bifurcation coefficients (α_1, α_2) and of the unit consumptions (κ_{ij}) of the three turbines. The J27 unit consumptions variations may be shared with good approximation, through a first order Taylor expansion, in various terms, each of them related to a turbine κ_{ij} variation, or to a bifurcation coefficient (α_1, α_2) variation, so that the same can be done for the J27 impact term.

When applying this concept to the High Pressure Turbine (HPT) functional decay analyzed in the previous work, it follows that about a half of the J27 impact term (108 kW, see TABLE II in Reini and Taccani, 2002) is due to the perturbed turbine itself. The diagnostic error is reduced from 18.4% to 15.8%, while the remaining half of the J27 impact term is related to the bifurcation coefficient variations (see TABLE II).

The same concept, when applied to the Low Pressure Turbine (LPT) functional decay analyzed in the previous work, leads to an almost complete re-allocation of the J27 impact term (-296 kW), while the diagnostic error is reduced from 11% to 6%.

From these two cases, it can be inferred that bifurcation coefficients contain information on the state of the plant, complementary to that contained in junctions unit consumptions, and useful for an accurate diagnosis.

This revision strategy may be extended to other sub-systems, in order to make the productive structure more consistent with the actions actually performed to restore reference power output, in case of components malfunction.

Eliminating the boundary condition effects

A modification in the boundary condition affecting the operation of energy systems often generates additional losses in all their components. In these cases also the LIF shows that various components are malfunctioning.

As an example, a typical case of variation in boundary condition is considered in the following: the cooling water temperature in the condenser of the steam power plant; this temperature is used also as reference ambient temperature (T_0) in the exergy analysis. Inside the seasonal variation interval, four values of temperature T_0 have been considered for the plant and the values of the impact term, agreeing with LIF, are shown in *Figure 2* vs. temperature T_0.

It can be inferred that these malfunctions cannot be regarded as "small perturbations" of the state of the system, because few degree variations generate some MWs of additional losses. It can be also inferred that the relation is approximately linear, up to an increment of 8 - 9°C more than the reference value (impact terms having a magnitude of only 1-10 kW are not considered).

To improve the diagnostic accuracy of the analysis of the state of a plant, malfunctions induced by modification in the boundary conditions have to be eliminated from the impact term of each component. The main strategy is to define a new reference condition for the plant, introducing the actual values of the parameters describing ambient conditions (as well as all other boundary conditions: see Torres et al.

1999, Verda et al. 2001, Valero et al. 2002). But this strategy may be applied only if simulation software is available, allowing the new "artificial" reference condition to be identified in detail.

At least for ambient temperature (T_0) modification, an alternative strategy can be defined on the basis of the historical data of the ambient temperature and of the corresponding thermodynamic state of the plant, operating without any intrinsic malfunction of components.

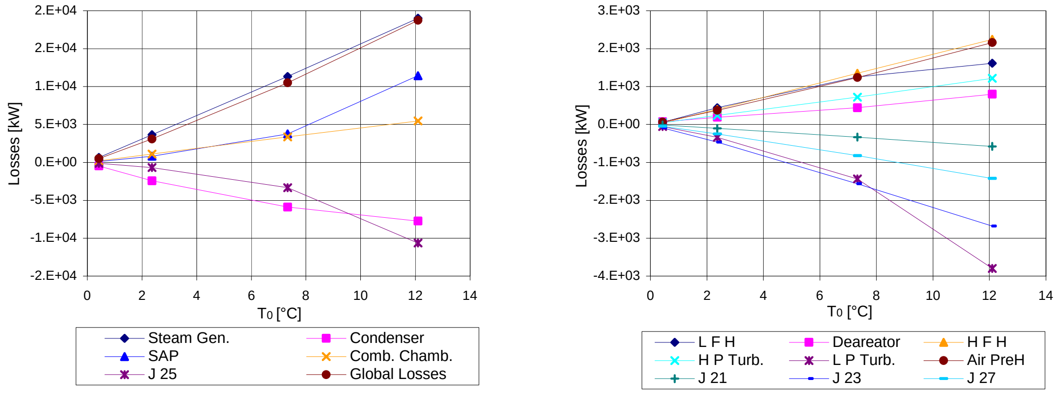

Figure 2. Impact term, agreeing with LIF of the main component unit and junction vs. temperature T_0

TABLE III. IMPROVED ADDITIONAL LOSSES AS IN TABLE I. AMBIENT TEMPERATURE REFERENCE VALUE IS T_0=20.3°C, WHILE NEW MODIFIED VALUE IS T_0=27.6°C

	Components affected by intrinsic malfunctions (in addition to T_0):	**High pressure Feedwater Heaters (HFH) n. 3**					
		Total		**subtracting the impact terms of modification of T_0 lone**			
		DEB [kW]	LIF [kW]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]
123	**minor components**	11	64	0	0	0.0	0.0
4	**Low pressure FH**	-90	-310	3	2	1.2	0.8
5	**Deareator**	108	525	38	80	15.2	32.0
6	**Feed Pump**	28	33	0	0	0.0	0.0
7	**High pressure FH**	**395**	**1538**	**80**	**184**	**32.0**	**73.6**
8	**Steam Generator**	6719	846	67	-20	26.8	-8.0
9	**High Pressure T**	584	725	0	0	0.0	0.0
10	**Middle Pressure T**	37	8	0	0	0.0	0.0
11	**Steam Leakage**	10	60	0	0	0.0	0.0
12	**Low Pressure T**	-1285	-1434	0	-1	0.0	-0.4
13	**Condenser**	-2331	-5892	-3	-6	-1.2	-2.4
14	**Blower**	20	22	0	0	0.0	0.0
15	**Steam Air Preheat.**	111	3778	0	5	0.0	2.0
16	**Air PreHeater**	509	1244	4	6	1.6	2.4
17	**Comb. Chamber**	5916	136	62	0	24.8	0.0
18	**Alternator**	2	0	0	0	0.0	0.0
J27	**Shaft Power Junc.**	0	-825	0	-1	0.0	-0.4
	Components	10745	10752	251	250	100.4	100.0
	ΔP_T	7	-	-1	-	-0.4	-
	Add. Losses	**10752**	**10752**	**250**	**250**	**100.0**	**100.0**

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By applying the LIF to a state of the plant where the ambient temperature (T_0) is the only modified parameter, the impact terms of this modification alone can be obtained, and diagrams like *Figure 2* can be drawn. At this point the impact terms related to component malfunction can be evaluated by applying superimposition of the effects, i.e. by subtracting, term by term, the ambient temperature fuel impact from the fuel impact calculated for the simultaneous variation of temperature T_0 and a malfunction of some component.

Due to error propagation, a decrease in diagnostic accuracy has to be often expected.

As an example, the impact terms of ambient temperature alone have been calculated through the steam power plant model. The evaluation obtained for the impact terms of malfunctioning components alone is shown in

TABLE III for a functional decay of the High pressure Feedwater Heaters (HFH) and a simultaneous increase of temperature T_0.

Numerical results suggest that the diagnostic accuracy of LIF is not strongly affected by this alternative strategy. The bigger part of additional losses is nonrecoverable, because related to ambient condition, while 250 kW only can be recovered restoring reference condition inside the HFH. Agreeing with the results obtained in a previous work, less than a half of recoverable additional losses arise inside the malfunctioning component control volume.

TABLE IV. ADDITIONAL LOSSES (AND CORRESPONDING PERCENTAGES) ALLOTTED TO THE MAIN COMPONENT OF THE STEAM POWER PLANT, FOLLOWING THE THREE GLOBAL LOSSES FORMULATIONS, FOR SIMULTANEOUS COMPONENTS MALFUNCTION.

Components affected by intrinsic malfunctions		**High Pressure Turbine + Low Pressure Turbine**						**Feed Pump (η_m) + HFH** n.3						**Low Pressure Turbine + Condenser**					
		DEB [kW]	LIF [kW]	Ref. [kW]	DEB [%]	LIF [%]	Ref. [%]	DEB [kW]	LIF [kW]	Ref. [kW]	DEB [%]	LIF [%]	Ref. [%]	DEB [kW]	LIF [kW]	Ref. [kW]	DEB [%]	LIF [%]	Ref. [%]
123	**minor components**	4	0	0	0.0	0.0	0.0	0	0	0	0.0	0.0	0.0	3	-1	0	0.1	0	0.0
4	**Low pressure FH**	50	45	0	1.0	1.0	0.0	6	5	0	0.7	0.5	0.0	20	-21	0	0.5	-0.5	0.0
5	**Deareator**	12	0	0	0.3	0.0	0.0	-2	-8	0	-0.2	-0.9	0.0	27	43	0	0.7	1.1	0.0
6	**Feed Pump**	7	0	0	0.1	0.0	0.0	**279**	**647**	**676**	**32.4**	**74.3**	**77.6**	4	0	0	0.1	0	0.0
7	**High pressure FH**	102	121	0	2.1	2.5	0.0	**99**	**200**	**195**	**11.4**	**22.9**	**22.4**	28	1	0	0.7	0	0.0
8	**Steam Generator**	1020	-72	0	21.0	-1.5	0.0	203	-11	0	23.3	-1.3	0.0	859	-12	0	22.5	-0.3	0.0
9	**High Pressure T**	**623**	**1244**	**1321**	**12.8**	**25.6**	**27.2**	15	0	0	1.7	0.0	0.0	85	-2	0	2.2	-0.1	0.0
10	**Middle Pressure T**	10	-4	0	0.2	-0.1	0.0	1	-1	0	0.1	-0.1	0.0	6	-3	0	0.2	-0.1	0.0
11	**Steam Leakage**	0	-1	0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0	0	0	0.0	0	0.0
12	**Low Pressure T**	**1575**	**3518**	**3539**	**32.4**	**72.4**	**72.8**	28	0	0	3.2	0.0	0.0	**1361**	**3360**	**3362**	**35.6**	**87.8**	**87.9**
13	**Condenser**	222	-34	0	4.6	-0.7	0.0	21	3	0	2.5	0.3	0.0	**523**	**685**	**463**	**13.7**	**17.9**	**12.1**
14	**Blower**	5	0	0	0.1	0.0	0.0	1	0	0	0.1	0.0	0.0	4	0	0	0.1	0	0.0
15	**Steam Air Preheat.**	21	-4	0	0.4	0.1	0.0	3	1	0	0.3	0.1	0.0	14	1	0	0.4	0	0.0
16	**Air PreHeater**	119	62	0	2.5	1.3	0.0	18	14	0	2.1	1.6	0.0	82	30	0	2.1	0.8	0.0
17	**Comb. Chamber**	1072	164	0	22.1	3.4	0.0	197	23	0	22.7	2.6	0.0	826	84	0	21.6	2.2	0.0
18	**Alternator**	1	0	0	0.0	0.0	0.0	4	0	0	0.5	0.0	0.0	1	1	0	0.0	0	0.0
J27	**Shaft Power Junc.**	0	-177	0	0.0	-3.6	0.0	0	0	0	0	0.0	0.0	0	-342	0	0.0	-8.9	0.0
	Components	4840	4860	4860	99.6	100	100	872	871	871	100	100	100	3845	3825	3825	100	100	100
	ΔP_T	20	-	-	0.4	-	-	-1	-	-	-0.1	-	-	-20	-	-	-0.5	-	-
	Add. Losses	**4860**	**4860**	**4860**	**100**	**100**	**100**	**871**	**871**	**871**	**100**	**100**	**100**	**3824**	**3825**	**3825**	**100**	**100**	**100**

The expectation is that the principle of superimposition of the effects can be applied also to another kind of plant, to eliminate the ambient temperature effect from the diagnosis, at least in case of small temperature variations.

3. Simultaneous Components Malfunctions

In real plant operation, components do not malfunction one at a time, so that diagnostic accuracy should be tested using simultaneous components malfunctions, too.

As an example, the results obtained by applying the DEB and the LIF to the simultaneous functional decays of two components at the same time are shown in TABLE IV. The functional decay simulated for each component is the same considered in the previous work as a single malfunction. The first column contains the additional losses arising inside each control volume (accordingly to the DEB). The second contains the impact terms allotted to each component, by applying the LIF (equation (14) in Reini and Taccani, 2002). The third contains the recoverable additional losses arising all over the plant, when each component is malfunctioning, obtained through a numerical simulator.

The remaining three columns show the same results, as a percentage of total additional losses.

The table shows that two components only are perturbed at the same time. Note that if the results were equal to those presented in the reference columns (Ref. in TABLE IV), the maximum diagnostic accuracy would be reached.

The diagnostic accuracy of the results is similar to that obtained for single malfunctions.

In most cases the diagnostic error of LIF is from 6% to 11% of total additional losses. DEB shows that less than a half of these losses arise inside the control volumes of the two components actually affected by intrinsic malfunctions.

Note that, in the case of condenser functional decay, about 18% of total additional losses is allotted to the component, but the simulator shows that only 12% of that losses is due to condenser malfunction.

This happens because the condenser and the low pressure turbine have been perturbed at the same time. In this case each malfunction affects the other component. Nevertheless the diagnostic error of LIF is less than 11% and the summation of the three impact terms related to the condenser, the low pressure turbine and the shaft power junction gives, the 96.8% of the total additional losses.

4. Conclusions and Perspectives

Through the Lost work Impact Formula improvements in the diagnosis accuracy can be obtained. As shown in the discussed examples the productive structure can be manipulated to reduce errors. Moreover, boundary condition effects can be eliminated through a proper definition of the reference state for the plant, or taking advantages of the effects superimposition.

In particular the turbine functional decay tests suggest a revision strategy for the parameters describing components behavior, inside the Lost work Impact Formula. A set of “bifurcation coefficients” is introduced in order to make the formula more consistent with the actions actually performed to restore the reference power output, in case of components malfunction during plant operation.

While it can be concluded that the methodology can be usefully applied in the presented form, some points may be objects of further investigations:

- The optimized productive structure, to analyze a plant operating in malfunctioning conditions, can be obtained only “a posteriori” by means of successive approximations. But the theory does not allow to judge “a priori” if a productive structure is suitable or not.
- The bifurcation coefficients have been used to allocate additional losses on the actually malfunctioning turbines and it is expected that in a further analysis they will provide useful diagnostic additional information.
- The methodology gives useful information in the actual operation of the plant, but accurate measurements of operating variables, sometimes difficult to obtain, are required.

Nomenclature

α_1, α_2	Biforcation coeficients in eq. (1)
B	Exergy
DEB	Differential Exergy Balance
GFE	General Formula for the Efficiency
LIF	Lost work Impact Formula
sub. p.	Subproduct

Plant components

AH	Air heater
ALT	Alternator
AUX	Auxiliaries
BL	Blower
Com. Cham.	Combustion chamber and stack
COND	Condenser
DEA	Deareator control volume
EP	Extraction pump
FH	Fuel heater
FP	Feed water pump
HFH	High pressure feed water heater
HPT	High and medium pressure turbine
LFH	Low pressure feed water heater
LPT	Low pressure turbine
MPT	Medium and low pressure turbine
PD	Pressure drop
SAP	Air-steam heater
SL	Steam leagakes collector
St. Gen.	Steam generator
WI	Water integration system

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Appendix

Equations used in the productive structure

Exergy terms

Physical Specific Exergy $b = (h - h_0) - T_0 \cdot (s - s_0)$

Thermal Specific Exergy $b^t = b - b^p$

Mechanical Specific Exergy $b^p = v_0 \cdot (p - p_0)$

Specific Neg-entropy $b^s = T_0 \cdot (s - s_0)$

Coefficients used in streams definition

Condensing fraction of steam leakages $$fcf = \frac{(\dot{m}_{GVSL} + \dot{m}_{HSL} + \dot{m}_{MSL}) - \dot{m}_{SSL}}{\dot{m}_{GVSL} + \dot{m}_{HSL} + \dot{m}_{MSL}}$$

Control valves steam leakages $$fas = \frac{\dot{m}_{GVSL}}{\dot{m}_{GVSL} + \dot{m}_{HSL} + \dot{m}_{MSL}}$$

High pressure steam leakages $$fap = \frac{\dot{m}_{HSL}}{\dot{m}_{GVSL} + \dot{m}_{HSL} + \dot{m}_{MSL}}$$

Low pressure steam leakages $$fmp = \frac{\dot{m}_{MSL}}{\dot{m}_{GVSL} + \dot{m}_{HSL} + \dot{m}_{MSL}}$$

Steam leakages total fraction $$ffg = \frac{\dot{m}_{TSL}}{\dot{m}_{TSL} + \dot{m}_{RH-O}}$$

Fuels (F) and Products (P) for main functional components

Subscripts refer to physical flows in *Figure 1 appendix.* minor components (1, 2, 3) omitted.

4 **LFH**	**F**	$3^{p} = (\dot{m}_{LFH\text{-}IN} \cdot b^{p}_{LFH\text{-}IN}) - (\dot{m}_{L\text{-}O} \cdot b^{p}_{L\text{-}O})$ $22^{b} = 17^{b} - 21^{b} = (\dot{m}_{SL\text{-}O} \cdot b_{SL\text{-}O}) + (\dot{m}_{EX6} \cdot b_{EX6}) + (\dot{m}_{EX7} \cdot b_{EX7}) + (\dot{m}_{EX8} \cdot b_{EX8}) - (\dot{m}_{C\text{-}IN} \cdot b_{C\text{-}IN})$ $11^{s} = (\dot{m}_{SL\text{-}O} \cdot b^{s}_{SL\text{-}O}) - (\dot{m}_{C\text{-}IN} \cdot b^{s}_{C\text{-}IN}) + (\dot{m}_{LPS} + \dot{m}_{LPT\text{-}O} + \dot{m}_{C\text{-}IN} + \dot{m}_{SAPC\text{-}O}) \cdot$ $\cdot (b^{s}_{LFH\text{-}IN} - b^{s}_{L\text{-}O}) + (\dot{m}_{EX6} \cdot b^{s}_{EX6}) + (\dot{m}_{EX7} \cdot b^{s}_{EX7}) + (\dot{m}_{EX8} \cdot b^{s}_{EX8})$
	P	$2^{t} = (\dot{m}_{L\text{-}O} \cdot b^{t}_{L\text{-}O}) - (\dot{m}_{LFH-IN} \cdot b^{t}_{LFH-IN})$
5 **DEA**	**F**	$7^{w} = W_{RP} \qquad 5^{p} = (\dot{m}_{L\text{-}O} \cdot b^{p}_{L\text{-}O}) - (\dot{m}_{L\text{-}O} \cdot b^{p}_{FWP\text{-}IN})$ $23^{b} = (\dot{m}_{EX5\text{-}BIS} \cdot b_{EX5\text{-}BIS}) + ((\dot{m}_{EX5} - \dot{m}_{D\text{-}O}) \cdot b_{EX5}) + (\dot{m}_{D\text{-}IN} \cdot b_{D\text{-}IN}) - ((\dot{m}_{FWP\text{-}IN} - \dot{m}_{L\text{-}O}) \cdot b_{FWP\text{-}IN})$ $30^{b} = (\dot{m}_{D\text{-}O} \cdot b_{EX5}) - 0 \qquad 10^{s} = (\dot{m}_{LPS} + \dot{m}_{LPT\text{-}O} + \dot{m}_{C\text{-}IN} + \dot{m}_{SAPC\text{-}O}) \cdot (b^{s}_{L\text{-}O} - b^{s}_{FWP\text{-}IN})$
	P	P: $4^{t} = (\dot{m}_{L\text{-}O} \cdot b^{t}_{FWP-IN}) - (\dot{m}_{L-O} \cdot b^{t}_{L-O})$

6 **FP**	**F**	$6^{w} = W_{FP} \qquad 9^{s} = (\dot{m}_{LPS} + \dot{m}_{LPT\text{-}O} + \dot{m}_{C\text{-}IN} + \dot{m}_{SAPC\text{-}O}) \cdot (b^{s}_{FWP\text{-}IN} - b^{s}_{FWP\text{-}O})$
	P	P: $6^{p} = (\dot{m}_{FWP\text{-}O} \cdot b^{p}_{FWP\text{-}O}) - (\dot{m}_{FWP\text{-}IN} \cdot b^{p}_{FWP\text{-}IN})$ S-P: $10^{t} = -(\dot{m}_{FWP\text{-}O} \cdot b^{t}_{FWP\text{-}O}) + (\dot{m}_{FWP\text{-}IN} \cdot b^{t}_{FWP\text{-}IN})$
7 **HFH**	**F**	$7^{p} = (\dot{m}_{FWP\text{-}O} \cdot b^{p}_{FWP\text{-}O}) - (\dot{m}_{FW} \cdot b^{p}_{FW})$ $8^{s} = (\dot{m}_{LPS} + \dot{m}_{LPT\text{-}O} + \dot{m}_{C\text{-}IN} + \dot{m}_{SAPC\text{-}O}) \cdot \left(b^{s}_{FWP\text{-}O} - b^{s}_{FW}\right)$ $24^{b} = (\dot{m}_{EX1} \cdot b_{EX1}) + (\dot{m}_{EX2\text{-}4} \cdot b_{EX2\text{-}4}) + (\dot{m}_{EX3} \cdot b_{EX3}) + ((\dot{m}_{EX4} - \dot{m}_{AUX1}) \cdot b_{EX4})$
	P	P: $7^{t} = (\dot{m}_{FW} \cdot b^{t}_{FW}) - (\dot{m}_{FWP\text{-}O} \cdot b^{t}_{FWP\text{-}O})$

8 St. Gen.	**F**	$8^p = ((\dot{m}_{FW} - \dot{m}_{SGL} - \dot{m}_{GVSL})\cdot b^p_{FW}) - (\dot{m}_{HPT-IN}\cdot b^p_{HPT-IN}) + (\dot{m}_{RH-IN}\cdot b^p_{RH-IN}) - (\dot{m}_{RH-O}\cdot b^p_{RH-O})$ $6^b = ((\dot{m}_{SGL} + \dot{m}_{GVSL})\cdot b_{FW}) - fcf\cdot(\dot{m}_{GVSL}\cdot b_{CON-O}) - 0$ $29^b = 28^b - 27^b = \dot{m}_{CC-O}\cdot b_{CC-O} - \dot{m}_{AH-IN}\cdot b_{AH-IN}$ $6^s = fas\cdot(\dot{m}_{LPS} + \dot{m}_{SL-O})\cdot(b^s_{FW} - b^s_{GVSL}) + fap\cdot(\dot{m}_{LPS} + \dot{m}_{SL-O})\cdot(b^s_{FW} - b^s_{HPT-IN}) +$ $+ fmp\cdot(\dot{m}_{LPS} + \dot{m}_{SL-O})\cdot(b^s_{FW} - b^s_{HPT-IN} + b^s_{RH-IN} - b^s_{RH-O}) +$ $+ (\dot{m}_{LPT-O} + \dot{m}_{C-IN} - \dot{m}_{SL-O} + \dot{m}_{SAPC-O})\cdot(b^s_{FW} - b^s_{HPT-IN} + b^s_{RH-IN} - b^s_{RH-O})$
	P	P: $8^t = (\dot{m}_{HPT-IN}\cdot b^t_{HPT-IN}) - ((\dot{m}_{FW} - \dot{m}_{SGL} - \dot{m}_{GVSL})\cdot b^t_{FW}) + (\dot{m}_{RH-O}\cdot b^t_{RH-O}) - (\dot{m}_{RH-IN}\cdot b^t_{RH-IN})$ S-P: $7^b = -(\dot{m}_{GVSL}\cdot b_{GVSL}) + fcf\cdot(\dot{m}_{GVSL}\cdot b_{CON-O})$
9 HPT	**F**	$8^b = ((\dot{m}_{EX1} + \dot{m}_{EX2-4} + \dot{m}_{EX3} + \dot{m}_{EX4} - \dot{m}_{AUX1} + \dot{m}_{EX5-BIS} + \dot{m}_{EX5})\cdot b_{HPT-IN}) +$ $-(\dot{m}_{EX1}\cdot b_{EX1}) - (\dot{m}_{EX2-4}\cdot b_{EX2-4}) - (1 - ffg)\cdot(\dot{m}_{EX3} + \dot{m}_{EX4} - \dot{m}_{AUX1} + \dot{m}_{EX5})\cdot(b_{RH-IN} - b_{RH-O})$ $-(\dot{m}_{EX3}\cdot b_{EX3}) - ((\dot{m}_{EX4} - \dot{m}_{AUX1})\cdot b_{EX4}) - (\dot{m}_{EX5-BIS}\cdot b_{EX5-BIS}) - (\dot{m}_{EX5}\cdot b_{MPT-IN})$ $32^b = ((\dot{m}_{HPTL} + \dot{m}_{HSL} + \dot{m}_{AUX2} + \dot{m}_{AUX1} + \dot{m}_{MPT-IN} - \dot{m}_{EX5})\cdot b_{HPT-IN}) +$ $-(\dot{m}_{AUX2}\cdot b_{AUX2}) + (1 - ffg)\cdot(\dot{m}_{AUX1} + \dot{m}_{MPT-IN} - \dot{m}_{EX5})\cdot(b_{RH-IN} - b_{RH-O}) +$ $-(\dot{m}_{AUX1}\cdot b_{EX4}) - ((\dot{m}_{MPT-IN} - \dot{m}_{EX5})\cdot b_{MPT-IN}) - fcf\cdot(\dot{m}_{HSL}\cdot b_{CON-O})$ $5^s = fmp\cdot(\dot{m}_{LPS} + \dot{m}_{SL-O})\cdot(b^s_{HPT-IN} - b^s_{RH-IN} + b^s_{RH-O} - b^s_{MPT-IN}) +$ $+ fap\cdot(\dot{m}_{LPS} + \dot{m}_{SL-O})\cdot(b^s_{HPT-IN} - b^s_{HSL}) + (\dot{m}_{LPT-O} + \dot{m}_{C-IN} - \dot{m}_{SL-O} + \dot{m}_{SAPC-O})\cdot$ $\cdot(b^s_{HPT-IN} - b^s_{RH-IN} + b^s_{RH-O} - b^s_{MPT-IN})$
	P	P: $1^W = W_{HPT}$ S-P: $9^b = -(\dot{m}_{HSL}\cdot b_{HSL}) + fcf\cdot(\dot{m}_{HSL}\cdot b_{CON-O})$
10 MPT	**F**	$10^b = (\dot{m}_{EX5}\cdot b_{MPT-IN}) - (\dot{m}_{EX5}\cdot b_{EX5})$ $31^b = ((\dot{m}_{MPT-IN} - \dot{m}_{EX5})\cdot b_{MPT-IN}) - (\dot{m}_{LPT-IN}\cdot b_{LPT-IN}) - (\dot{m}_{S-IN}\cdot b_{S-IN}) - fcf(\dot{m}_{MSL}\cdot b_{CON-O})$ $3^s = fmp\cdot(\dot{m}_{LPS} + \dot{m}_{SL-O})\cdot(b^s_{MPT-IN} - b^s_{MPT-IN}) + (\dot{m}_{LPT-O} + \dot{m}_{C-IN} - \dot{m}_{SL-O} + \dot{m}_{SAPC-O})\cdot b^s_{MPT-IN} +$ $-(\dot{m}_{LPT-O} + \dot{m}_{C-IN} - \dot{m}_{SL-O})\cdot b^s_{LPT-IN} - (\dot{m}_{S-IN}\cdot b^s_{S-IN})$
	P	P: $2^W = W_{MPT}$ S-P: $11^b = -(\dot{m}_{MSL}\cdot b_{MSL}) + fcf\cdot(\dot{m}_{MSL}\cdot b_{CON-O})$

11 **SL**	**F**	$13^{b} = 7^{b} + 9^{b} + 11^{b} = -(\dot{m}_{GVSL} \cdot b_{GVSL}) - (\dot{m}_{HSL} \cdot b_{HSL}) - (\dot{m}_{MSL} \cdot b_{MSL}) + $ $+ fcf \cdot ((\dot{m}_{GVSL} + \dot{m}_{HSL} + \dot{m}_{MSL}) \cdot b_{CON\text{-}O})$ $4^{s} = fap \cdot ((\dot{m}_{LPS} + \dot{m}_{SL\text{-}O}) \cdot b^{s}_{HSL}) + fmp \cdot ((\dot{m}_{LPS} + \dot{m}_{SL\text{-}O}) \cdot b^{s}_{MSL}) +$ $+ fas \cdot ((\dot{m}_{LPS} + \dot{m}_{SL\text{-}O}) \cdot b^{s}_{GVSL}) - ((\dot{m}_{LPS} + \dot{m}_{SL\text{-}O}) \cdot b^{s}_{SL\text{-}O})$
	P	P: $14^{b} = -(\dot{m}_{GVSL} + \dot{m}_{HSL} + \dot{m}_{MSL}) \cdot (b_{SL-O} - fcf \cdot b_{CON-O})$
12 **LPT**	**F**	$16^{b} = 12^{b} - 15^{b} = (\dot{m}_{LPT\text{-}IN} \cdot b_{LPT\text{-}IN}) - (\dot{m}_{LPT\text{-}O} \cdot b_{LPT\text{-}O}) - (\dot{m}_{EX6} \cdot b_{EX6}) - (\dot{m}_{EX7} \cdot b_{EX7}) +$ $-(\dot{m}_{EX8} \cdot b_{EX8}) - (\dot{m}_{LPS} \cdot b_{LPS}) + (\dot{m}_{SS} \cdot b_{SL\text{-}O})$ $2^{s} = (\dot{m}_{LPS} \cdot b^{s}_{SL\text{-}O}) - (\dot{m}_{LPS} \cdot b^{s}_{LPS}) + (\dot{m}_{LPT\text{-}IN} \cdot b^{s}_{LPT\text{-}IN}) +$ $-(\dot{m}_{LPT\text{-}O} \cdot b^{s}_{LPT\text{-}O}) - (\dot{m}_{EX6} \cdot b^{s}_{EX6}) - (\dot{m}_{EX7} \cdot b^{s}_{RX7}) - (\dot{m}_{EX8} \cdot b^{s}_{EX8})$
	P	P: $3^{W} = W_{LPT}$
13 **CON.**	**F**	$10^{W} = W_{CP}$ $20^{b} = (\dot{m}_{LPT\text{-}O} \cdot b_{LPT\text{-}O}) + (\dot{m}_{SAPC\text{-}O} \cdot b_{SAPC\text{-}O}) + (\dot{m}_{C\text{-}IN} \cdot b_{C\text{-}IN}) + (\dot{m}_{LPS} \cdot b_{LPS}) - (\dot{m}_{CON\text{-}O} \cdot b_{CON\text{-}O})$
	P	$1^{s} = (\dot{m}_{CON-O} \cdot b^{s}_{CON-O}) - (\dot{m}_{LPS} \cdot b^{s}_{LSP}) - (\dot{m}_{LPT-O} \cdot b^{s}_{LPT-O}) - (\dot{m}_{C-IN} \cdot b^{s}_{C-IN}) - (\dot{m}_{SAPC-O} \cdot b^{s}_{SAPC-O})$
14 **BL**	**F**	$9^{W} = W_{BL}$ $\quad 10^{p} = (\dot{m}_{BL\text{-}O} \cdot b^{p}_{BL\text{-}O}) - (\dot{m}_{AIR} \cdot b^{p}_{AIR})$
	P	P: $10^{p} = (\dot{m}_{BL-O} \cdot b^{p}_{BL-O}) - (\dot{m}_{AIR} \cdot b^{p}_{AIR})$ $\quad 15^{t} = -(\dot{m}_{BL\text{-}O} \cdot b^{t}_{BL\text{-}O}) + (\dot{m}_{AIR} \cdot b^{t}_{AIR})$
15 **SAP**	**F**	$11^{p} = (\dot{m}_{BL\text{-}O} \cdot b^{p}_{BL\text{-}O}) - (\dot{m}_{SAPA\text{-}O} \cdot b^{p}_{SAPA\text{-}O})$ $\quad 25^{b} = (\dot{m}_{S\text{-}IN} \cdot b_{S\text{-}IN}) - (\dot{m}_{SAPC\text{-}O} \cdot b_{SAPC\text{-}O})$ $7^{s} = -(\dot{m}_{SAPC\text{-}O} \cdot b^{s}_{S\text{-}IN}) + (\dot{m}_{SAPC\text{-}O} \cdot b^{s}_{SAPC\text{-}O})$
	P	P: $13^{t} = (\dot{m}_{SAPA-O} \cdot b^{t}_{SAPA-O}) - (\dot{m}_{BL-O} \cdot b^{t}_{BL-O})$
16 **AH**	**F**	$12^{p} = (\dot{m}_{SAPA\text{-}O} \cdot b^{p}_{SAPA\text{-}O}) - (\dot{m}_{AH\text{-}O} \cdot b^{p}_{AH\text{-}O})$ $\quad 27^{b} = (\dot{m}_{AH\text{-}IN} \cdot b_{AH\text{-}IN}) - (\dot{m}_{ST} \cdot b_{ST})$
	P	P: $12^{t} = (\dot{m}_{AH-O} \cdot b^{t}_{AH-O}) - (\dot{m}_{SAPA-O} \cdot b^{t}_{SAPA-O})$
17 **Com. Cha.**	**F**	$1^{c} = \dot{m}_{FUEL} \cdot LHI$ $\quad 4^{b} = \dot{m}_{FUEL} \cdot b_{FUEL}$ $\quad 5^{b} = (\dot{m}_{AUX2} \cdot b_{AUX2} + (\dot{m}_{AUX1} \cdot b_{EX4}) - 0$ $26^{b} = 16^{t} + 13^{p} = (\dot{m}_{AH\text{-}O} \cdot b_{AH\text{-}O}) - (\dot{m}_{AIR} \cdot b_{AIR})$
	P	P: $28^{b} = (\dot{m}_{CC-O} \cdot b_{CC-O}) - (\dot{m}_{ST} \cdot b_{ST})$
18 **ALT**	**F**	$4^{W} = W_{HPT} + W_{MPT} + W_{HPT}$
	P	P: $5^{W} = W_{E}$

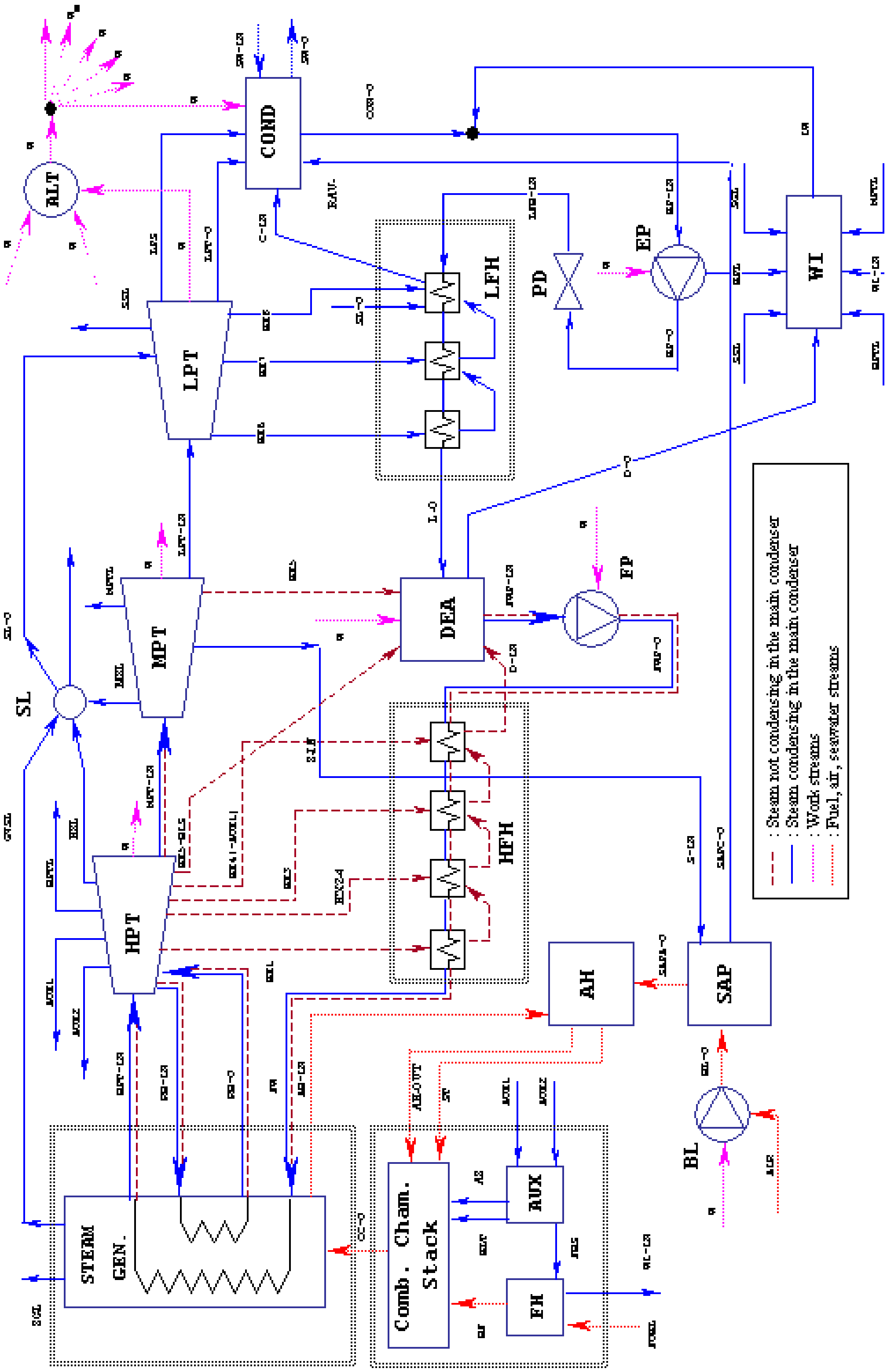

Figure 1 App. Control volumes and physical flows in the plant

Appendix nomenclature

1…m	Streams number
b	Specific exergy
h	Enthalpy
T	Temperature
s	Entropy
$\dot{m}$	Mass flowrate

Superscripts

p	Mechanical exergy
t	Thermal exergy
s	Neg-entropy
W	Work

Subscripts

0	Reference conditions
AH-O	Air heater outlet
AH-IN	Air heater inlet
AIR	Ambient air
AS	Fuel atomization steam
AUX1	Auxiliary steam
AUX2	Auxiliary steam
BL-O	Blower outlet
CC-O	Combustion outlet
C-IN	Condenser inlet
CON-O	Condenser outlet
D-IN	DEA inlet
D-O	Deareator outlet
ELT	Steam to gas cleaning unit
EP-0	Extraction pump outlet
EP-IN	Extraction pump inlet
EPL	Extraction pump losses
EX1…	Extraction steam
EX2-4	Extraction steam
EX5-BIS	Integration to extraction steam n. 5
FHS	Fuel heating steam
FUEL	Fuel
FW	Feedwater
FWP-IN	Feedwater pump inlet
FWP-O	Feedwater pump outlet
GVSL	Governor valves steam leakages
HF	Heated fuel
HSL	High pressure steam leakages
HPT-IN	High pressure turbine steam inlet
HPTL	High pressure turbine losses
IW	Integration water
LFH-IN	Low pressure heater inlet
LHV	Lower heating value
L-O	LFH outlet
LPS	Low pressure seals steam
LPT-IN	Low pressure turbine inlet
LPT-O	Low pressure steam outlet
MPT-IN	Medium pressure inlet
MPTL	Medium pressure turbine losses
MSL	Medium pressure steam leakages
RH-IN	Reheater steam inlet
RH-O	Reheater steam outlet
SAPA-O	Steam-air preheater outlet (air)
SAPC-O	Steam-air preheater outlet (conden.)
SGL	Boiler losses
S-IN	SAP inlet
SL-O	Steam leakages collector outlet
SS	Steam seals
SSL	Seals steam leakages
ST	Flue gas to stack
SW-IN	Seawater inlet
SW-O	Seawater outlet
TSL	Total steam leaks
WI-IN	Integration water inlet
W_{BL}	Blower power consumption
W_{CP}	Condenser pump power consumption
W_{E}	Total electrical power output
W_{EP}	Extraction pump power consumption
W_{FP}	Feedwater pump power consumption
W_{HPT}	Medium and high pres. turb. p. output
W_{LPT}	Low pressure turbine power output
W_{MPT}	Medium pres. turbine power output
W_{NET}	Net electrical power output
W_{RP}	Recirculation pump power consump