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Thermoeconomic Diagnosis of an Urban District Heating System based on Cogenerative Steam and Gas Turbines

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RIASSUNTO

La *diagnosi* è una tecnica di indagine fondata su metodi sperimentali e di calcolo, la cui applicazione ha lo scopo di verificare la presenza di eventuali anomalie di funzionamento nei sistemi energetici e determinare i volumi di controllo nei quali hanno avuto luogo. Per ottenere queste informazioni si confrontano i valori assunti da opportune variabili in una condizione di funzionamento con i corrispondenti valori di riferimento.

In questa tesi si propone una procedura di diagnosi basata sull'impiego di variabili termodinamiche, elaborate utilizzando i metodi della analisi termoeconomica. La principale novità, rispetto ad altre procedure di diagnosi termoeconomica, consiste nel fatto che la procedura proposta consente di tenere in considerazione l'effetto del sistema di regolazione sul funzionamento dell'impianto; tale effetto può quindi essere isolato ai fini della ricerca dei malfunzionamenti. L'utilità di questa operazione è mostrata attraverso l'applicazione ad alcuni casi di anomalie, di funzionamento di due impianti termoelettrici reali, situati nel comune di Moncalieri (Torino). Le condizioni di funzionamento corrispondenti ai casi analizzati sono state ottenute attraverso un modello matematico del sistema, dal momento che nella pratica non è possibile disporre di altrettanti dati misurati.

La termoeconomia è una disciplina dell'ingegneria, nata negli anni sessanta, che consiste nell'utilizzo contemporaneo dei principi della termodinamica e di considerazioni di natura economica. Questo consente di attribuire un costo a tutti i processi produttivi che avvengono all'interno di un sistema ed in particolare ai loro prodotti. Tale costo può essere misurato in unità monetarie e, all'occorrenza, in unità puramente termodinamiche, quali flussi di energia o exergia.

La chiave delle procedure di analisi termoeconomica è costituita dalla creazione di un modello produttivo del sistema, chiamato struttura produttiva, il quale in generale è differente dal suo modello fisico. Ogni trasformazione energetica è rappresentata e quantificata in termini di prodotto fornito, cioè dell'effetto utile ottenuto, delle risorse utilizzate e di eventuali residui rilasciati in ambiente. Tali grandezze nella moderna temoeconomia sono espresse in termini di flussi di exergia.

A questo scopo il sistema è scomposto in una serie di sottosistemi o componenti, in ciascuno dei quali ha luogo una trasformazione energetica significativa. Il grado di dettaglio con il quale si compie la scomposizione dipende dalle informazioni disponibili e dalle finalità dell'analisi. Le variabili termodinamiche (flussi di massa e di energia, temperature, pressioni ecc.) necessarie per caratterizzare tutti i flussi entranti e uscenti dai componenti devono essere note, pertanto da una analisi fatta con un grado di dettaglio più spinto corrispondono da un lato maggiori informazioni e dall'altro la necessità di misurare un numero maggiore di variabili fisiche.

Il rapporto tra ciascuna risorsa utilizzata da un componente e il prodotto da esso fornito prende il nome di consumo unitario di exergia. Il modello termoeconomico del sistema è completamente espresso dai valori assunti da queste grandezze. Questo significa che la descrizione del sistema attraverso il suo modello produttivo risulta notevolmente semplificata

rispetto a quella fatta attraverso il modello fisico. Le informazioni sono infatti condensate in una serie di parametri termoeconomici che sostituiscono le variabili termodinamiche misurate in corrispondenza dei flussi che attraversano i confini di ciascun volume di controllo. La diagnosi termoeconomica si effettua attraverso lo studio della variazione nel tempo dei valori assunti dai consumi specifici di exergia, mentre, per quanto riguarda le metodologie di diagnosi normalmente impiegate negli impianti, occorre seguire l'evoluzione di una serie di grandezze estremamente diverse tra loro, quali vibrazioni, pressioni, temperature.

Con le procedure di diagnosi termoeconomica si trattano allo stesso modo tutti i tipi di anomalie, in pratica cioè si acquista generalità nella trattazione. Altre procedure sono invece diversificate a seconda delle anomalie che si intendono diagnosticare e i dati disponibili devono essere di volta in volta organizzati perché possano fornire le informazioni necessarie. Per contro la diagnosi termoeconomica è in grado di evidenziare unicamente la presenza di malfunzionamenti che abbiano ripercussioni apprezzabili sul comportamento termodinamico del sistema. Inoltre il passaggio dalla struttura fisica alla struttura produttiva fa perdere informazioni sul sistema, cosa che potrebbe significare l'impossibilità di localizzare correttamente determinate anomalie. La diagnosi termoeconomica pertanto non è in grado di sostituire completamente le tecniche normalmente utilizzate, semmai di affiancarle in modo da fornire ulteriori informazioni. In particolare le tecniche di diagnosi sono normalmente concepite per prevenire quei tipi di anomalie che, se non venissero riparate, porterebbero a rotture e quindi alla fermata dell'impianto. Al contrario l'obiettivo della diagnosi termoeconomica è quello di rilevare tutte quelle anomalie che determinano un abbassamento delle prestazioni del sistema e quindi una riduzione del rendimento. Inoltre per sua natura l'analisi termoeconomica consente di valutare i costi delle trasformazioni che avvengono in un sistema, e quindi anche i costi legati alla variazione delle condizioni di funzionamento. A ciascun malfunzionamento può essere attribuito un costo, per esempio in termini di consumo addizionale di combustibile, il che consente di classificarli in funzione del loro impatto e quindi decidere quando sia più conveniente operare la manutenzione. La semplice valutazione della diminuzione di efficienza di un componente non è infatti indicativa dei suoi effetti economici, tenuto presente che la stessa variazione di efficienza in due componenti diversi può incide in modo differente sul consumo di combustibile. Questa considerazione è nota in letteratura come principio di non uguaglianza delle irreversibilità.

Le procedure di diagnosi termoeconomica consistono nel confronto dei valori assunti dai consumi unitari di exergia relativi a una condizione di funzionamento e una di riferimento e nel calcolo di opportuni indici a partire da queste grandezze. Le due condizioni devono essere caratterizzate dalle stesse condizioni al contorno. Questo vuole dire che l'ambiente esterno deve essere nelle stesse condizioni di temperatura, pressione e umidità, che la produzione dell'impianto deve essere la stessa quantitativamente e qualitativamente (stessa potenza elettrica e, nel caso di cogenerazione, stessi valori di potenza termica, temperatura, pressione e eventualmente titolo termodinamico del flusso uscente) e infine che la qualità del combustibile deve essere la stessa. A causa di questi vincoli, la condizione di riferimento è normalmente determinata attraverso l'utilizzo di un simulatore del sistema.

La corretta localizzazione dell'anomalia è possibile nei casi in cui l'effetto provocato dalla sua presenza sia in maggioranza concentrato nel componente all'interno del quale l'anomalia si è manifestata, cosa che non sempre accade.

Il primo effetto di una anomalia è quello di causare una riduzione dell'efficienza del componente in cui essa ha luogo (malfunzionamento intrinseco). Se la risorsa del componente è rimasta inalterata l'anomalia si traduce in una diminuzione del suo prodotto. Essendo il prodotto del componente in generale risorsa di altri componenti, anch'essi si troveranno a funzionare in condizioni diverse da quelle di riferimento. In particolare la loro produzione sarà variata, vista la diminuzione di risorse. Questo effetto, di per sé non negativo, si definisce disfunzione. L'efficienza di questi componenti in generale varierà per effetto delle mutate condizioni di funzionamento, pertanto anche in questi avrà luogo un malfunzionamento. Tale malfunzionamento si definisce indotto, essendo stato provocato da un'anomalia in un altro componente.

Un'altra conseguenza della variazione delle condizioni di funzionamento è costituita dal cambiamento di alcuni dei parametri di controllo, tra i quali sicuramente la produzione dell'impianto, ed eventualmente anche i set-points in alcuni punti critici. La condizione di funzionamento che ne deriva è inaccettabile, pertanto determina l'intervento del sistema di controllo, il quale riporterà quei parametri al valore di taratura. Questo intervento modifica la propagazione naturale degli effetti dell'anomalia, generando altri malfunzionamenti indotti e disfunzioni. La localizzazione di quale sia il malfunzionamento intrinseco pertanto si complica una volta che il sistema di regolazione è intervenuto.

La procedura di diagnosi termoeconomica qui proposta consiste nel determinare a calcolo la condizione di funzionamento del sistema che avrebbe luogo se il sistema di regolazione non fosse intervenuto. Tale condizione è chiaramente fittizia, dal momento che i vincoli imposti dal sistema di controllo non sarebbero rispettati, pertanto deve essere determinata mediante un procedimento matematico. Nel caso in cui il malfunzionamento sia sufficientemente piccolo, l'effetto del sistema di controllo su ciascuna delle grandezze che caratterizzano la struttura produttiva (i flussi della struttura stessa o i consumi specifici di exergia) può essere determinato con uno sviluppo di Taylor di ordine uno. Le variabili indipendenti nello sviluppo sono costituite dalle variabili indipendenti del sistema di regolazione, pertanto l'applicazione della procedura richiede di individuare un set di grandezze che ne caratterizzino completamente la posizione.

Questa condizione di funzionamento artificiale, qui chiamata condizione di funzionamento libero, è caratterizzata dalla stessa regolazione della condizione di riferimento, però ne differisce per il fatto che essa include gli effetti del malfunzionamento. La diagnosi viene fatta per confronto tra i valori dei consumi specifici di exergia in condizione di funzionamento libero e in condizione di riferimento. Le tecniche di diagnosi termoeconomica descritte in letteratura sono invece basate sul confronto tra la condizione di funzionamento reale e la condizione di riferimento. La differenza tra i consumi unitari di exergia in queste due condizioni include anche il contributo del sistema di regolazione, cosa che in certi casi impedisce di determinare correttamente la localizzazione del malfunzionamento, come mostrato dalle applicazioni proposte.

La procedura di diagnosi proposta è stata applicata a due impianti: un impianto a vapore e un turbogas, entrambi in grado anche di cedere calore a una rete di teleriscaldamento urbano. Di tali impianti è stato costruito un modello matematico per simularne il comportamento, descritto nel primo capitolo della tesi. Attraverso questo modello sono state provocate anche alcune anomalie, in forma di riduzione di rendimenti, variazione di coefficienti di scambio termico e variazioni di perdite di pressione. Nel modello degli impianti è stato considerato anche il sistema di regolazione degli stessi, individuandone le variabili caratteristiche. In particolare per la turbina a gas le variabili di regolazione sono la portata di combustibile, il grado di apertura delle pale statoriche del compressore, la portata di acqua inviata al recuperatore di calore e l'apertura della valvola di by-pass del recuperatore stesso. Per l'impianto a vapore invece le variabili del sistema di regolazione sono la portata di combustibile, l'apertura delle valvole di parzializzazione del primo stadio della turbina di alta pressione e la portata di vapore inviata allo scambiatore per la cogenerazione. L'effetto di queste variabili sui flussi della struttura produttiva è stato valutato in modo differente per i due impianti: in forma analitica a partire dal modello fisico per la turbina a gas e in forma numerica a partire da condizioni reali di funzionamento per la turbina a vapore.

Nel caso dello sviluppo analitico l'effetto del sistema di regolazione sui flussi della struttura produttiva è stato formalizzato come un problema di ottimizzazione vincolata, descritto matematicamente attraverso una funzione Lagrangiana. Tale espressione è particolarmente significativa, considerando che i moltiplicatori di Lagrange coincidono con i costi marginali associati a ciascuna variabile. In questo modo è possibile anche associare un costo a ciascuna variabile del sistema di regolazione.

La procedura è stata applicata a malfunzionamenti singoli e multipli e in tutti i casi ha permesso di evidenziare correttamente il componente nel quale erano presenti le anomalie. Essa si è rivelata particolarmente utile, rispetto a quella di diagnosi termoeconomica normalmente utilizzata, nel caso della turbina a gas, per la quale il sistema di regolazione incide fortemente sulla propagazione degli effetti dei malfunzionamenti. In particolare la regolazione può generare malfunzionamenti indotti paragonabili e talvolta superiori al malfunzionamento intrinseco, rendendo impossibile la corretta localizzazione dell'anomalia. Per quanto riguarda invece l'impianto a vapore, normalmente gli effetti dei malfunzionamenti sono abbastanza localizzati e il sistema di regolazione non induce importanti malfunzionamenti nel sistema, pertanto i risultati forniti dai due approcci sono molto prossimi.

Un ulteriore sviluppo della tecnica di diagnosi riguarda l'eliminazione del contributo legato agli effetti indotti dovuti al comportamento specifico dei componenti, cioè legato alla variazione di efficienza dovuta alla variazione delle condizioni delle risorse utilizzate. Per tenere in considerazione questo contributo il sistema può essere scomposto nei vari componenti, ciascuno dei quali è considerato separatamente. La conoscenza di vari stati di funzionamento, corrispondenti ad altrettante regolazioni del sistema, permette di costruire, per ogni componente del sistema, un modello termoeconomico lineare. In questo modo il prodotto di ciascuno può essere determinato al variare di ciascuna delle risorse. Questa dipendenza è accettabile quando lo scostamento di ciascun flusso rispetto al valore assunto in condizioni di riferimento è sufficientemente piccolo.

Il modello consente di calcolare i consumi specifici di exergia di ciascun componente in una condizione di funzionamento nella quale le risorse assumono lo stesso valore che caratterizza la condizione di funzionamento libero. I componenti però non presentano alcuna anomalia, dal momento che questa condizione è determinata a partire dallo stato di riferimento. Una differenza nel valore del consumo specifico di exergia è pertanto legata al comportamento specifico dei componenti.

Il malfunzionamento indotto dalla dipendenza del comportamento di ogni componente dalla quantità e qualità delle sue risorse può essere in questo modo eliminata. La tecnica funziona tanto meglio quanto più è disaggregata la struttura produttiva; a tal fine ad esempio è raccomandata la separazione dell'exergia nelle sue componenti al fine della definizione della struttura produttiva. Essa è stata applicata all'impianto di turbina a gas ed in particolare ai casi di malfunzionamento singolo e ad un esempio di malfunzionamento combinato, nel quale è stata simulata la presenza di tre anomalie nell'impianto. In tutti i casi la procedura ha permesso di evidenziare in una sola volta quanti e quali fossero gli effetti intrinseci presenti nei componenti. Si tratta di un apporto decisamente importante nelle applicazioni reali, dal momento che il numero di componenti malfunzionanti è incognito a priori. Inoltre alcuni degli effetti indotti possono diventare preponderanti rispetto ad effetti intrinseci. In questi casi la sola alternativa è rappresentata dall'applicazione della procedura di localizzazione dell'anomalia più importante, seguita da un intervento manutentivo allo scopo di rimuoverla. Nel caso in cui sia presente più di una anomalia è necessario ripetere le due operazioni, pertanto non è possibile la contemporanea localizzazione di più anomalie.

La procedura completa di diagnosi termoeconomica è presentata nel quarto capitolo, mentre l'applicazione ai casi di malfunzionamento simulati relativi ai due impianti è esposta nei capitoli 5 e 6. In quest'ultimo capitolo è anche proposta una applicazione ottenuta a partire dai dati misurati relativi all'impianto di turbina a vapore.

I risultati ottenuti non costituiscono una dimostrazione della validità assoluta della metodologia ai fini della diagnosi dei sistemi energetici, tuttavia un risultato importante è stato conseguito: nella diagnosi termoeconomica, al contrario di quanto avviene per le altre applicazioni della termoeconomia, è indispensabile considerare anche il sistema di regolazione e controllo. Questo risultato non costituisce certamente un punto di arrivo, ma un punto di partenza per ulteriori studi in questo campo. In particolare, nel caso in cui nel sistema siano presenti più anomalie, la tecnica di diagnosi proposta non consente di prevedere in modo corretto la quantità di combustibile teoricamente risparmiabile correggendo ciascuna di esse. Questo tipo di informazione richiede infatti l'utilizzo di un modello fisico del sistema.

Un secondo aspetto studiato in dettaglio in questa tesi è l'effetto della scelta della struttura produttiva sui risultati forniti dalla diagnosi. La definizione di risorse e prodotti non è univoca, infatti, sebbene i numerosi studi ed applicazioni abbiano consentito di raggiungere un certo accordo, soprattutto per alcune tipologie impiantistiche, l'analista è libero operare la scelta che ritiene più opportuna. Nel caso del calcolo dei costi dei flussi interni di un sistema tale scelta incide in modo sensibile sui risultati. In particolare i costi calcolati con l'analisi termoeconomica dipendono fortemente dall'assegnazione dei residui, cioè di quei flussi, caratterizzati da una exergia non nulla, che escono dall'impianto, disperdendosi in ambiente. Nel modello produttivo tali flussi non possono uscire dal sistema, dal momento che non sono dei prodotti, pertanto devono essere trattati come irreversibilità e assegnati ai vari componenti. Esistono diversi criteri per effettuare questa operazione, a ciascuno dei quali corrisponde una diversa struttura produttiva e una diversa ripartizione dei costi dei flussi. Nel terzo capitolo sono descritti alcuni di questi criteri ed è proposta la loro applicazione agli impianti esaminati. Un particolare risalto è dato all'analisi termoeconomica del gruppo turbogas, per il quale la scelta del modello produttivo incide fortemente sui costi calcolati.

Nel caso della procedura di diagnosi proposta, tutte le strutture produttive utilizzate forniscono indicazioni tra loro in accordo sul componente ritenuto principale responsabile del malfunzionamento. Inoltre una struttura produttiva più dettagliata, nella quale la definizione di risorse e prodotti si avvalga della separazione dell'exergia nelle componenti meccanica e termica (ed eventualmente anche chimica) consente di ottenere informazioni più precise. Nel caso della turbina a gas, in particolare, quando il malfunzionamento è di origine puramente meccanica o termica, l'utilizzo di una struttura più dettagliata consente anche di individuarne la causa. Per contro nel caso in cui il malfunzionamento non sia di questo tipo, la struttura ne rende più complessa la localizzazione, dal momento che i suoi effetti si distribuiscono su due termini della matrice dei consumi unitari di exergia, invece che su uno. Tuttavia le informazioni non sono in contraddizione, ma si completano, pertanto è raccomandato l'utilizzo contemporaneo di più strutture produttive.

Un ultimo contributo di novità apportato da questa tesi è costituito dalla valutazione del costo su base exergetica da attribuire all'intervento del sistema di regolazione. Tale grandezza è ottenuta considerando il consumo di combustibile e il prodotto fornito dall'impianto nelle condizioni di funzionamento e di funzionamento libero; in particolare il costo unitario è definito come il rapporto tra la variazione complessiva delle risorse utilizzate e la corrispondente variazione del prodotto totale. L'utilità di questo parametro consiste nel fatto che permette di valutare l'incidenza dei vincoli presenti nell'impianto e, in modo particolare i set-points, sull'efficienza dei processi produttivi. Questa indicazione è valida sia che nell'impianto siano presenti malfunzionamenti, sia che esso stia funzionando correttamente. In questo secondo caso tale costo coincide con il costo marginale del prodotto.

Un alto valore del costo significa che l'intervento del sistema di controllo comporta un incremento del costo dei prodotti del sistema, mentre un valore basso (inferiore al costo del prodotto) ne determina una riduzione. Valori negativi del costo sono invece associati a una contemporanea riduzione dell'efficienza dell'impianto e della quantità di prodotto complessivamente fornito (oppure un contemporaneo aumento degli stessi).

Dal punto di vista dell'analisi dei malfunzionamenti un valore del costo della regolazione superiore al costo dei prodotti forniti significa che il sistema di regolazione induce dei malfunzionamenti nel sistema, che ne determinano l'abbassamento dell'efficienza. In questi casi la procedura di diagnosi proposta migliora notevolmente la situazione, dal momento che evita il sorgere di questi malfunzionamenti, o meglio, li elimina dalla condizione di funzionamento reale.

ABSTRACT

The energy system diagnosis is a experimental technique applied for the detection and the location of possible anomalies. These information are obtained by comparing the values assumed by opportune variables in a operation condition with the corresponding reference values. In this thesis a procedure based on the use of thermodynamic variables, elaborated using the thermoeconomic methods, is proposed. The main originality, in comparison with other thermoeconomic diagnosis procedures, consists on the evaluation of the regulation system effects on the plant working condition; these effects can be then isolated to achieve the purpose of the malfunction location. The usefulness of such an operation is shown by applying the procedure to some cases of anomalies, obtained using a mathematical model of two thermal power plants, located in Moncalieri (Turin).

Thermoeconomics is an engineering discipline born in sixties, consisting in the contemporary use of thermodynamic principles and economic concepts. It allows to associate a cost to all the productive processes taking place inside a system and in particular their products. This cost can be measured in monetary units and eventually in pure thermodynamic units.

The key of the thermoeconomic analysis procedures consists on a productive model of the system, called productive structure, generally different from its physical model. Every energy transformation is represented and quantified in terms of supplied product, i.e. the useful effect obtained, resources required and possible losses. Such quantities in modern thermoeconomics are expressed using exergy fluxes.

The system is first divided in some subsystems or components, in each one a significant energy transformation takes place. The grade of detail depends on the available information and on the aim of the analysis. The thermodynamic variables (mass and energy flows, temperatures, pressures etc.) required to characterize the fluxes entering and exiting the component must be known. In this way a more detailed analysis furnish more information, but it requires the measures of a larger number of physical variables.

The ratio between every resource used by a component and its product is called unit exergy consumption. The values assumed by the whole of the unit exergy consumptions completely describes the thermoeconomic model of the system. This means that the description of the system based on its productive model is a simplification of the physical model. The information are summarized in the thermoeconomic parameters, which substitute the thermodynamic variables measured in correspondence of the fluxes crossing the boundaries of the control volumes. The thermoeconomic diagnosis is made by studying the temporal variation of the unit exergy consumptions, while, the methodologies usually applied in the energy systems, the variation of a whole of different quantities is analysed.

The thermoeconomic diagnosis allows the use of the same procedure for all the anomalies, so it is a general methodology. On the contrary the other methodologies use a different procedure, depending on the kind of anomaly wants to be detected; the available data must be chosen and organized so that they could furnish the required information. Nevertheless the

thermoeconomic diagnosis only allows to detect anomalies having sensible repercussions on the thermodynamic behaviour of the system. Moreover some information are lost when the physical structure is substitute with the productive structure, which could make the procedure unable to locate some kind of malfunctions. These considerations suggest the contemporary use of the thermoeconomic diagnosis together with other methodologies, as they are often complementary. In particular the other techniques are normally devised to prevent the anomalies which can cause, if not repaired, failures. On the contrary the aim of the thermoeconomic diagnosis consists on the detection and the location of the anomalies causing the reduction of the system efficiency. Moreover it also allows to evaluate the costs associated to the variation of the working condition, which is more significant than the simple variation of the efficiency of a single process. The same efficiency variation can in fact involves a different fuel impact depending on where it takes place. This consideration is known as principle of non equivalence of the irreversibilities.

The procedures of thermoeconomic diagnosis consist on the determination of the values assumed by the unit exergy consumptions in a operation condition and a reference condition, on the calculation of opportune evaluation indices based on these quantities and on their comparison. The two states must be characterized by the boundary conditions: the environment must be characterized by the same temperature, pressure and humidity, the plant production must be the same in quality and quantity (the same electric power and, in case of thermal production, the exiting flow must be characterized by the same energy flow, temperature, pressure and thermodynamic quality) and finally the fuel quality must be the same. Due to these constraints, the reference condition is usually determined by means of a simulator.

The correct anomaly location is only possible in the cases where its effect is largely concentrated in the component where it has taken place. This does not happens always.

The first effect of an anomaly is the reduction of the efficiency of the component where it has occurred (intrinsic malfunction). If the component resource has been maintained constant, the anomaly causes the reduction of its product. As this product is generally resource of other components, their production is affected too and in particular it decreases. This effect is not negative, but can have a negative consequence: the efficiency of the components generally depends on the working condition, so the variation of their resources involve a variation of their efficiency too. A malfunction, called induced malfunction, takes so place in the other components, although any anomalies have occurred in them.

A second consequence of the variation of the working condition consists on the variation of some control parameters. In particular the total production of the plant has varied and some set-points can have varied. The working condition originated as direct effect of the anomaly is unacceptable, so the control system intervenes to operate a regulation in order to restore the setting values of these parameters. The intervention modifies the natural effects of the anomaly, so other malfunctions and dysfunctions are induced. The location of the intrinsic malfunctions becomes more difficult once the regulation system has intervened.

The thermoeconomic diagnosis procedure here proposed is based on the determination of the working condition that would have taken place if the regulation system did not intervene. This condition is fictitious, as the constraints imposed by the control system are not complied, so it must be mathematically calculated.

If the anomaly is sufficiently little, the effect of the regulation parameters on the unit exergy consumptions can be calculated using a Taylor's development. The independent variables are represented by the characteristic variables of the regulation system, i.e. a set of variables which completely individuated its positioning. In this way an artificial working condition can be built, where the effects of the regulation system are not present but the effects of the anomaly are. This condition is here called *free condition*.

The diagnosis is made by comparison of the values assumed by the unit exergy consumptions in free and reference conditions. The thermoeconomic diagnosis procedures proposed in literature are based on the comparison between operation and reference conditions. In this comparison the contribution of the regulation system is hidden and sometimes makes impossible the correct location of the anomalies, as shown in the proposed applications.

The proposed procedure is here applied to two energy systems: a steam turbine and a gas turbine plants, both able to also provide thermal power to an urban district heating network. A mathematical model of the plants, described in the first chapter, has been built in order to simulate their behaviour. Some anomalies have been simulated by varying the values of the characteristic parameters of the components, like efficiencies, heat transfer coefficients and pressure drops. The model also takes into account the regulation system. In particular its characteristic parameters in the gas turbine plant are the fuel mass flow, the opening grades of the inlet guided vanes and of the by-pass valve and the water mass flow passing through the recuperator. The regulation parameters of the steam turbine are the fuel mass flow, the opening grade of the throttles and the mass flow of the steam extraction for the cogeneration.

The effect of these variables on the productive structure fluxes has been differently evaluated for the two plants: an analytical calculation, using the mathematical model of the plant, is proposed for the gas turbine plant, while a numerical calculation, using some working conditions, is proposed for the steam turbine plant.

The analytical development has been expressed in form of a constrained optimization problem, mathematically described using a Lagrangian function. Such expression is particular significant as the Lagrange multipliers coincide with the marginal costs associated to every variable. In this way a cost can be associated to the regulation parameters.

The procedure is applied to some cases of single and multiple malfunctions. In all the cases it allows to locate where the anomalies have taken place. The procedure is particularly helpful in the application to the gas turbine plant, where the effects induced by the regulation system are sometimes larger than the intrinsic malfunction, so that the correct location is impossible using the ordinary thermoeconomic procedures. On the contrary, in the steam power plant the effect of the malfunctions are mainly intrinsic, so that the correct location is in most of the cases possible using both the procedures.

A further develop of the diagnosis technique consists on the erasure of the contribution of the effects induced by the specific components behaviour, i.e due to the efficiency variations caused by the variation of the resources. To take into account this contribution the system can be split into its components, each one considered separately. The knowledge of different working conditions, corresponding to as many regulations, allows to build a linear thermoeconomic model of the components. The each product can be calculated as resources vary. This dependence is acceptable only if the difference between the fluxes in free and reference conditions is sufficiently low.

The unit exergy consumptions of every component in a condition characterized by the same resources as in free condition can be calculated. In this condition any anomaly is present in the system, as it is built starting from the reference state. A difference between the unit exergy consumptions respect to the reference values is due to the behaviour of the components.

The induced malfunctions caused by the dependence of the efficiencies on the quality and amount of resources can be so erased. The more desegregate is the productive structure and the better works this technique. The use of structures defined by splitting exergy into its components is recommended. The procedure has been applied to some gas turbine operation conditions, where single malfunctions and a triple malfunction have been simulated. In all cases it has allowed to find at the same time how many were the intrinsic effects and where they had occurred. This is an important improvement in the application to the real systems, as the number of malfunctioning components is a priori unknown.

The procedure is described in the forth chapter, while the applications to the power plants is shown in chapters 5 and 6. In this last chapter an application obtained using measured data relative to the steam power plant is proposed.

These results do not constitute a demonstration of the absolute validity of the methodology for the energy system diagnosis. Nevertheless an important result has been obtained: a correct thermoeconomic diagnosis is impossible without considering the regulation system. It is not a finish line, but the starting point for future studies in this field. In particular, when if more than one anomaly are present in the system, the proposed diagnosis procedure does not allow to correctly predict the technical energy saving obtained by completely removing each one. In fact, this information requires the use of a mathematical model of the system.

A second aspect of the thermoeconomic analysis here studied in deep is the effect of the choice of the productive structure on the results. The definition of fuels and products is not universally accepted, although many studies and applications have allowed to achieve a certain agreement. Some grade of freedom are so available for the analyst.

The choice of the productive structure has a sensible impact on the cost calculation, in particular when some losses occur in the system, i.e. some fluxes characterized by a non zero exergy exit the system without being provided (and sold) to the users. These fluxes are not products, as they do not have any usefulness, so they can not exit the system in the productive model. The components of the system must be charged for them. Different criteria allow to make this operation. A different productive structure, an so a different cost accounting, corresponds to each criterion.

In the third chapter some criteria are described and applied to the Moncalieri plants. A particular emphasis is given to the choice of the productive models for the gas turbine plant.

The diagnosis procedure is not sensitive to the choice of the productive structure: all the examined cases give information in coherent to indicate the components responsible for the malfunctions. Moreover a detailed structure, obtained splitting exergy into mechanical and thermal (and if necessary chemical) components to define fuels and products, also allows to obtain a more detailed information. In particular, if the gas turbine plant is considered, a more detailed structure allows to individuate the causes of pure mechanical or thermal malfunctions. On the contrary if other kinds of malfunctions occur, the location becomes more difficult, as the effects are split on terms of the unit exergy consumption matrix. Nevertheless the information does not contradict the one given by a simpler structure, so the contemporary use of both of them is suggested.

The last contribution of this thesis is the evaluation of the exergy cost to be associated to the regulation system intervention. This quantity is obtained considering the fuel consumption and the total product in operation and free conditions. The unit cost is defined as the ratio between the variation of the resources and the corresponding variation of the products.

This parameter allows to evaluate the incidence of internal constraints, like set-points, on the plant efficiency. If the plant does not present any anomaly this parameter is equal to the marginal cost calculated in reference condition, otherwise it assumes a different value. An higher value means that the regulation system intervention causes an increase in the cost of the products, while a lower value causes a cost decrease. negative values are associated the contemporary decrease (or increase) of the plant efficiency and the total production.

From the malfunction analysis point of view, a value of the unit cost of the regulation higher than the unit cost of the plant products means that the regulation system induces malfunctions in the system. In that case the use of the proposed procedure is particularly suitable, as it allows to eliminate those malfunctions from the system.

INTRODUCTION

A look on the Thermoeconomic Analysis

A condition for the realisation of a productive process is its economic convenience. This consideration makes interesting an analysis of the energy systems also taking into account the economic aspects. To achieve this objective a discipline, called Thermoeconomics, was introduced in sixties by Tribus [Tribus 1956], Evans [Tribus, Evans 1962] El Sayed and Gaggioli [Gaggioli 1999], joining the thermodynamic laws to the economic concept of cost, as a natural evolution of second law analysis. The objective of these first studies was the costing of the energy products of systems characterized by more than one product, such as cogenerative power plant. In particularly the case of interest were systems like desalination plants, paper makers and oil distillation columns. The techniques were based on the assumption of specific exergy as quality index of the flows. The exergy base allows to take into account the inefficiencies of the processes in the assignment of the costs to the products. This assumption was confirmed by real cases where the application of a simple energy costing proved to be a mistaken procedure. In the same years another field of Thermoeconomics was opened by El-Sayed and Evans: the thermoeconomic optimization (see for example [El Sayed, Aplenc 1970]). Its objective is the evaluation of the best design condition of a system, taking into account at the same time economic and thermodynamic aspects. The mathematical problem is formulated as a constrained optimization problem, where the independent variables are the design parameters of the plant. The first applications have demonstrated that the information about costs are contained in the Lagrange multipliers [El-Sayed, Evans 1970].

Successive developments in Thermoeconomics were made by the contribution of different authors, who proposed new calculation procedures. In particular the purposes were the definition of standard rules for the computer implementation. All the procedures guarantee the economic cost balance of the overall system and of all its components, which means that it is possible to write, for the system or every component:

$$\sum_i \Pi_{in_i} + Z_c = \sum_j \Pi_{out_j} ,$$

where:

Π_{in_i} is the cost rate associated to the i^{th} input;
Z_c is the cost rate of the component (or of the system);
Π_{out_j} is the cost rate associated to the j^{th} output.

If *n* is the number of flows and *m* the number of components *(n-m)* more equations must be written. These equations are called auxiliary equations. The way to find the auxiliary equations constitues a first difference between the methodologies.

The algebric procedures [Petit, Gaggioli 1980, Gaggioli, Wepfer 1980] propose to impose the value of some costs of fluxes exiting the components or the equivalence of some of them. As an exemple if a steam turbine is considered, the unit cost[1] of the exiting steam flow can be put equal to the produced mechanical power, or to the entering stream. See also [Arena 1997].

A few years later Tsatsaronis proposed the concepts of fuel and product of a component, respectively the resources necessary to achieve its purposes and the useful flux make disposal [Tsatsaronis, Winhold 1985]. These ones are not necessarily associated to physical fluxes of exergy, but they can also be linear compositions of the fluxes, for example the difference of two fluxes. The definition of fuel and product of every component allows to build a representative structure of the system called *productive structure*.

In 1986 Valero et Al. developed an analysis and optimization methodology, called Theory of the Exergetic cost [Lozano, Valero 1993]. One of its characteristics is the 'automatic' procedure which is used for writing the auxiliary equations [Valero et al. 1989]. The procedure is based on the definition of a productive structure where the fluxes, i.e. the fuels and the products of the components, are exergy flows. Moreover the application of standard rules written in four propositions allows to write the auxiliary equations. This characteristic and the matricial representation of the system topology make the procedure particularly suitable for the computer implementation. The cost of every product is defined in economic units or in thermodynamic ones: as the cost of a flow is the amount of resourses necessary to obtain it, the *exergetic cost* of a flow is defined as the amount of exergy necessary to obtain it, while the thermoeconomic cost represents its expression in term of money.

The Theory of the Exergetic cost puts on evidence where are the critical points of the plant, i.e. where the cost has an high increase, and allows to verify the effect on the costs of improvement operations realized in that points [Lozano et Al. 1994]. This is known as process of cost formation. Another important point resulting from the application of the theory is the principle of not equivalence of irreversibilities, which represents an additional information respect to the exergetic analysis: the irreversibilities have a different impact on the cost of the products, depending on the localization of each tranformation in the process. Moreover if the plant production is constanct and the irreversibility in a component changes, its impact on the fuel consumption is different, depending on the component position. This contitutes a first idea which makes the thermoeconomic analysis suitable for the thermal system diagnosis.

In eigthies Frangopoulos developed the Thermoeconomic Functional Analysis [Frangopoulos 1983] and Evans and von Spakovsky developed the Engineering Functional Analysis [von Spakovsky 1992]. These techniques are characterized by the formal representation of the role played by every components in the thermodynamic cycle. The use of definition of fuel and product becomes here foundamental. Exergy is generally split into its components and a quantity, called negentropy, is used to define the product of dissipative units, like the condenser in a steam power plant. The auxiliary equations are obtained using fictitious reversible components, junctions and branching points, which functions are respectively to mix fluxes of the same nature (e.g. the junction of thermal exergy flows) and to supply them to the components. In this way every component takes one or more resources from the branching points and give its product (or its products) to the corresponding junction.

Another important contribution in the theoretical developments of Thermoeconomics has been also given by Tsatsaronis, mainly in the field of the thermoeconomic analysis and cost accounting [Tsatsaronis, Pisa 1994]. In particular its work has allowed the definition of some

1. The unit cost is defined as the ratio between the cost of a flux and its exergy flow

parameters, useful for the exergetic and economic system evaluation. Moreover he has developed some analysis methods, like the LIFO approach [Tsatsaronis, Lin 1990].

In 1992 a general theory was presented: Structural Theory of Thermoeconomics [Valero et Al. 1992]. This theory does not introduce any new procedure, but is a general approach which can be applied for cost accounting or optimization using any other thermoeconomic model. Some comparisons between the results obtained using the original procedure and applying the structural theory to the same representation can be found in literature [Serra 1994, Erlach 1998]. A detailed description of this theory is presented in chapter 2.

Nowadays the objectives of thermoeconomics are larger. The Thermoeconomic Optimization procedures have been extended in order to take into account the environmental problems connected with the energy systems operation. The environmental considerations have determined the development of a field of research called Environomics [Frangopoulos, von Spakovsky 1993]. In environomic procedures the costs of abatement units and procedures and the internalization of environmental externalities are considered. A particular attention has been dedicating to the reduction of emitted CO2 [Santarelli 1998], also examining the possible use of different methodologies. Modifications of the energy power plants (semi-closed gas cycles) have been also proposed, in order to improve the recovery efficiency [Langeland, Wilhelmsen 1993].

The liberalization of energy markets and the race for cost reduction have determined an increasing attention to the maintenance of power plants and the prevention of their failures. In this context the Thermoeconomic Theories give their contribution in building maintenance strategies, as well as they allows the evaluation of possible plant malfunctions and help their localization. The Thermoeconomic field developed to achive these purposes is called Thermoeconomic Diagnosis [Lozano et Al 1994], which is the main objective of this thesis.

The energy system diagnosis

The importance of the system diagnosis is related to its economic implications: the presence of an anomaly in the working condition of a system means that a larger quantity of resources is required to obtain the same production, as its efficiency has reduced. Moreover the anomalies can cause failures and then additional costs.

For these reasons a purpose of the plant diagnosis is to check its correct operation condition and to calculate their economic impact. If this tool is at disposal, the best moment when the maintenance can be made is determined using the criterion of the economic convenience. This kind of diagnosis is made while the system is working and consists on the comparison between the fuel consumption in two different situations, characterized by the same external constraints: the same environmental conditions and the same production. The first is the *reference condition*, usually coinciding to the first hours of the plant operation, and the second is the actual working condition, called *operation condition*.

As it has been specified, reference and operation conditions must by characterized by the same external constraints, in fact the plant load and the environment condition have an impact on the fuel consumption. If the required data are not disposal they can be also obtained using a plant simulator, in order to calculate the fuel consumption in all the possible reference conditions.

The plant diagnosis system usually provides more information. In particular some parameters like rotor vibration, temperatures and pressures in critical zones and pressure drops are measured in order to avoid failures or immediately detect the cause of the anomalies.

A more accurate diagnosis can be made while the system maintenance has been doing. In this case the components are visually inspected by the staff and eventually some other parameters are measured, like erosions, wrinklednesses, etc. The application of particular diagnosis procedures [see for example Zaleta 1997] allows to obtain useful information about the plant condition.

The latest approach to the energy system diagnosis is the thermoeconomic one. The thermoeconomic model of the system is described by the fuels and products of every component and in particular by the ratio between every component fuel and its product, called unit exergy consumption. This model is much simpler than the physical model, in fact the information contained in the thermodynamic quantities, measured in correspondence of the boundaries of the control volumes, are joined together into the values of the unit exergy consumptions. The thermoeconomic diagnosis consists on the comparison between the values assumed by these quantities in operation and reference conditions. The procedure is the same for all the possible malfunctions, while in the case of the diagnosis normally applied to the power plants the procedure and the data to be considered depend on the kind of malfunction analysed.

Nevertheless the thermeoconomic diagnosis only allows to detect anomalies having sensible consequences on the thermodynamic behaviour of the system. Moreover the use of the productive structure makes miss information about the system, what would make the procedure not able to locate some kind of malfunctions. All these considerations suggest the use of thermoeconomic diagnosis together with the other methodologies, also taking into account their general different purpose. The diagnosis techniques normally used in the plants were born to allow avoiding their failures, while the thermoeconomic diagnosis was born to detect and locate the anomalies involving a reduction of the plant efficiency. Moreover the thermoeconomic diagnosis allows the assignment of a cost to the malfunctions, for example in term of additional fuel consumption. This represents a possible criterion for the classification of the effects of the anomalies, which helps to decide if the maintenance is opportune.

Aims of the thesis

When an anomaly takes place in a component, it causes a variation of the efficiency in the component itself (intrinsic malfunction), and a variation of the production (dysfunction) and the efficiency (induced malfunction) of the other components. The overall production and some other controlled quantities vary too, which causes the intervention of the regulation system. This one restores the values of the set-points and the required production, but also induces other malfuncions and dysfunctions in the plant. These last induced effects sometimes are comparable with the intrinsic malfunction so its correct location becomes difficult or impossible.

The main objective of this thesis is to propose a new thermoeconomic diagnosis procedure, which allows to take into account the effects of the regulation system intervention on the malfunction propagation

The proposed procedure is applied to two existing plants: a gas turbine and a steam plant, which are located in Moncalieri, near Turin. Both the plants also provide thermal power to the Turin district heating network. The application to the gas turbine plant is particularly interesting as the characteristics of this kind of technology make difficult the thermoeconomic diagnosis, due to the high impact of the regulation system intervention. In all the cases examined the procedure allows to correctly locate where the malfuncions have occurred. This result does not means that the procedure has an absolute validity and always allows to achieve the diagnosis purposes. Nevertheless it has demonstrated that it is impossible to do it without considering the effects of the regulation system.

The effect of the choice of the productive structure on the diagnosis results is also analysed in deep. No rules are universally accepted for the definition of fuels and products, so it is interesting to know if all the productive structures furnish the same results on the malfunction location or if some of them have better performances.

Finally the cost to be associated to the regulation system intervention is also defined and calculated. Such parameter constitutes an evaluation of the impact of this system on the efficiency of the productive processes happening in the plant. A value of this parameter higher than the unit cost of the plant products means that the regulation system causes the decrease of the plant efficiency, so it induces malfunctions in the system. In those cases the use of the proposed diagnosis procedure is particularly suitable, as it allows to avoid the contribution of the malfunctions induced by the regulation.

CHAPTER 1

The model of the plants

In spite of power plants are designed to work in a particular condition, called design condition, in the reality they generally work in off-design conditions. This can be caused by four groups of factors:

- variation of the external requirement (electric load, thermal load, etc.);
- variation of the environment conditions (temperature, pressure, humidity);
- variation of the fuel quality;
- anomalies.

The efficiency of a plant and then the cost of its products strongly depend on these factors, so that a system simulator represents an useful tool for the plant management, as it allows to quantify the effects of all this quantities on the plant behaviour.

The use of a mathematical model in this thesis is particularly helpful, in fact the operation conditions of the plant, corresponding to malfunctions located in different components and characterized by different values can be simulated. This allows to check the performances of the proposed diagnosis procedure, which would be impossible to do without. Measured data corresponding to as many working conditions are not available in the reality. A second use is the determination of the appropriate reference condition corresponding to every operation condition. For this purpose the possibility to vary the environmental conditions and the plant production of the reference condition is required, in order to made them equal to the values assumed in operation condition.

A mathematical model of a thermal system is constituted by the characteristic equations of the components and the fluid equation of state. Moreover the values assumed by some independent variables must be imposed in order to determine a working condition. The independent variables are the environment conditions, the characteristic parameters of the component, i.e. the constants appearing in their characteristic equations, and the variables which allow to determine the working condition. Two different approaches can be distinguished, depending on the kind of these last variables: in an analytical approach the external loads and the set points values are usually fixed, while in an approach close to the reality the values assumed by the regulation variables are fixed. In the first case the aim is the knowledge of the plant behaviour as the product request assumes a particular value. On the other hand the set point constraints must be always respected. On the contrary, in the reality the regulation parameters are the free variables of the plant and the control system operates on them in order to obtain a particular productions, respecting, at the same time, the set point constraints.

In this thesis a diagnosis procedure is developed and applied to two cogenerative plants, a gas turbine and a steam turbine, located in Moncalieri, near Turin (Italy). These plants produce electric power, respectively 33 MW and 101 MW, and supply thermal power, respectively 63 MW and 163 MW, to the Turin district heating network. A mathematical model of these two plants is described in this chapter.

The urban heating system is also supplied by boilers and two cogenerative diesel engines. All these thermal power producers are located in three stations: the above indicated Moncalieri station, the B.I.T station and the Mirafiori Nord station. The boilers are used only in the most cold days or in case of breakdown of a plant, as the maximum thermal request of the users is about 300 MW[1]. The district heating network is composed by the outward piping, where flows superheating water temperature is about 120 °C, the return piping, where the water temperature is about 70 °C, and pumping stations, located on the outward piping, in order to compensate the pressure drops. The users of this system are civil and public buildings and hospitals.

The urban heating system map is represented in figure 1.1. The total area served by the urban heating has been divided into 44 areas corresponding to big users or groups of users. In the figure the barycenters of these areas (thermal barycenters) are represented.

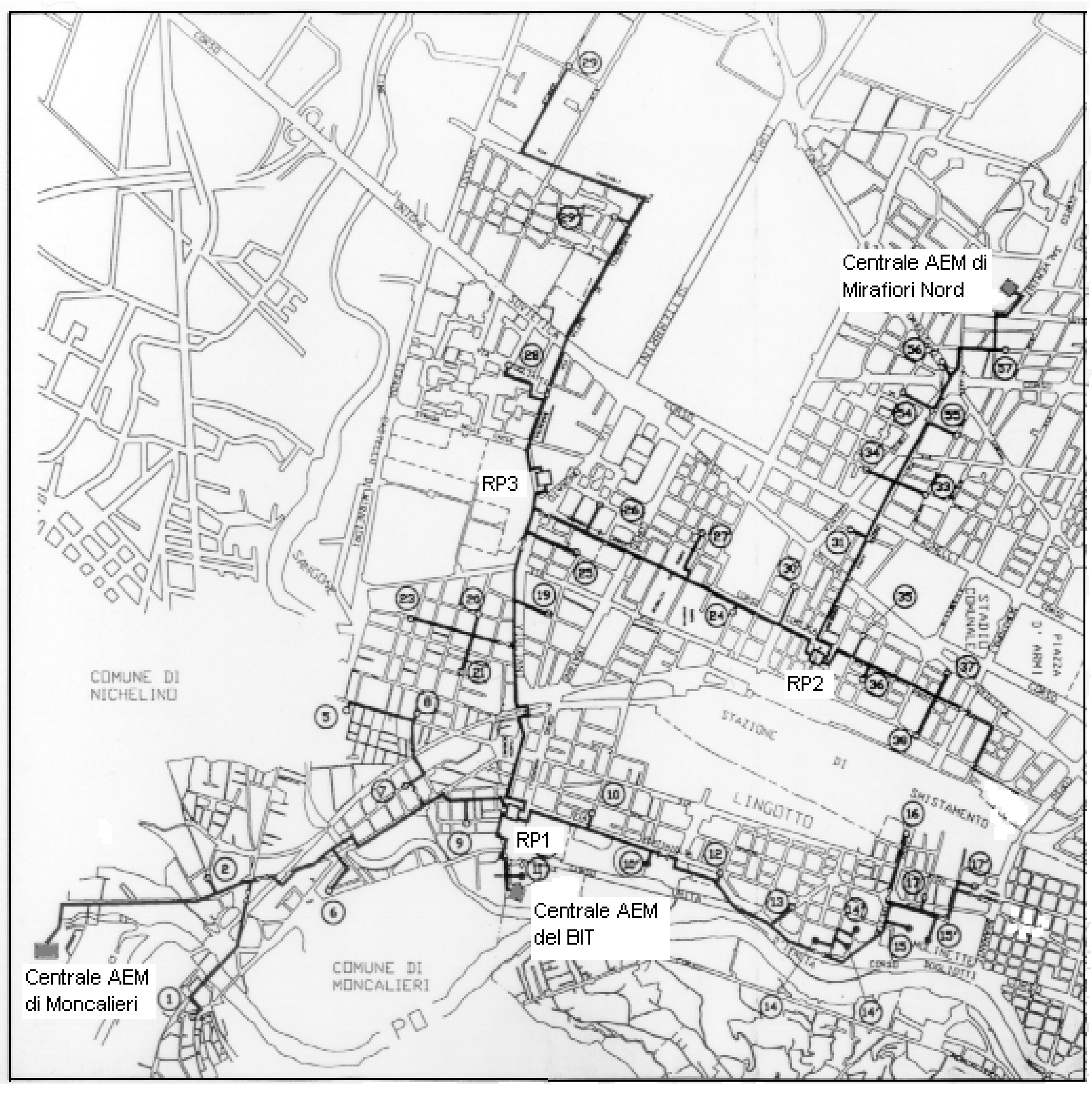


Figure 1.1 - Urban heating system topology

1. All the data are relative to the heating season 1997-1998.

1.1 The steam power plant

The steam power plant was designed in 1962 by De Pretto-Escher Wyss and started working in 1966. In the original project the plant could supply 137 MW to the electric network. A second project was made in 1988 in order to modify the plant and make it able to also work in cogeneration mode. The plant produces 163 MW of thermal power and 101 MW of electric power when is working at the maximum thermal load condition. A scheme of the plant is depicted in figure 1.2.

The boiler actually burns natural gas and produces superheated steam and reheated steam. A part of the enthalpy containt of the exhausted combustion gas is recuperated in a Ljungstrom heat exchanger, which allows the combustion air preheating. The water entering the boiler is preheated in two sections of feed water heaters, by mean of eight steam extractions.

Steam exits the generator (SG) at a fixed pressure, about 120 bar maintained by a regulation valve, and enters the high pressure turbine (HPT) at a temperature of 540 °C. This turbine consists of 14 stages, being the first one is a one-row governing stage. The steam mass flow is regulated by means of four partialization valves, located upstream this stage. In this way, at the highest electric loads, the steam goes through all the turbine annular sectors only, while at lower loads the sectors are partialized. The outlet streams of the first stage are mixed and then distributed to all the sectors of the next stages. At the exiting of the high pressure turbine the flow enters the reheater and then expands in the intermediate pressure turbine (IPT), which consists of 14 stages, characterised by a low degree of reaction. At the exit of this turbine it is located the extraction that feeds the heat exchanger, called *hot condenser* (HC), which transfers heat to the district heating network. A valve (CGRV) allows to regulate the mass flow extracted. The remaining steam enters the low pressure turbine (LPT), which is characterised by a triple flow and 5 reaction stages. The flow enters then a water condenser (C), in which there is a pressure of about 0.032 bar, maintained by two ejection pumps. The extracted water stream enters the low pressure section of the feed water heater, at the exit of which it is joined to the water exiting the *hot condenser*. The water completes the cycle entering the deareator (D), the circulation pump (CP) and the high pressure section of the feed water heater. [A.E.M. 1966, A.E.M. 1983, A.E.M. 1989]

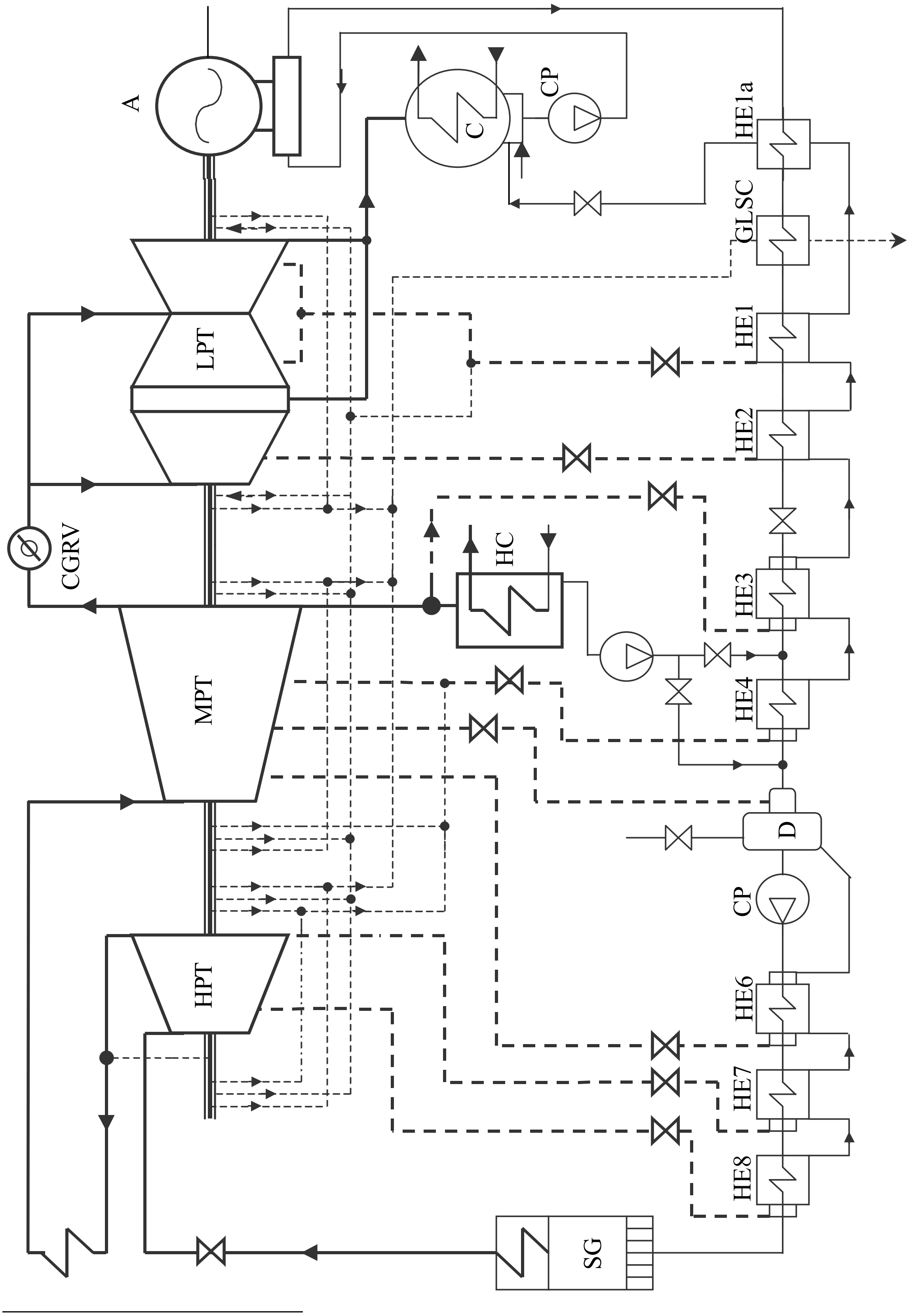


Figure 1.2 - Scheme of Moncalieri steam power plant

1.1.1 Steam generator

The steam generator is a Franco Tosi pressurized generator with natural circulation. The combustion chamber is characterised by 12 tangential burners, burning natural gas. The boiler tubes are vertical and disposed on the walls of the combustion chamber, where there are also three groups of superheater tubes, two reheater tubes and two Ljungstrom air preheaters. The main characteristics are:

nominal steam production	420 t/h of superheated steam at 535°C and 130 bar and 370 t/h of reheated steam at 530°C and 30 bar;
combustion chamber volume	2100 m^3;
heat transfer areas	boiler tubes 3750 m^2 ; superheater tubes 4450 m^2; reheater 1461 m^2; Ljungstrom 7000 m^2.

The model of this component has been made simply considering the measured values of the efficiency. Its value is practically constant in a large range of working conditions and equal to 0.953.

The efficiency is defined:

$$\eta_g = \frac{G_s \cdot (h_s - h_f) + G_r \cdot (h_r - h_v)}{G_c \cdot H_i} \tag{1.1}$$

where:

- G_s is the superheated steam mass flow;
- h_s is the superheated steam enthalpy;
- h_f is the feed water enthalpy;
- G_r is the reheated steam mass flow;
- h_r is the reheated steam enthalpy;
- h_v is the enthalpy of the steam exiting the high pressure turbine;
- G_c is the fuel mass flow;
- H_i is the fuel lower heating power.

The pressure drops in the reheater have been calculated in different working conditions using the design data. A linear dependence on the inlet pressure has been put on evidence, so that the pressure drops can be calculated as:

$$\Delta p = pp_{rh} \cdot p \tag{1.2}$$

where the per cent pressure drop pp_{rh} is constant, assuming a value of 0.1 and p is the reheater inlet pressure.

1.1.2 Turbine

The turbine is a Escher Wyss 3TZ 3066[2], characterized by a nominal electric power of 136 MW at 3000 rpm.

The behaviour of the turbines has been modelled using the hypothesis of nozzle analogy.

2. The turbine has been substituted in 1999. These data refers to 1997-1998.

This means that a group of stages characterised by the same mass flow can be treated as a single nozzle [Cooke 1985]. The high pressure turbine has been divided into three groups of stages: the first one corresponds to the governing stage, while the other two are represented by the groups of stages respectively upstream and downstream the first steam extraction. The second extraction is located at the end of the expansion in the high pressure turbine. The middle pressure turbine has been divided in four group of stages, as it is characterized by four steam extractions, but the last one is located at the end of the expansion. Finally the low pressure turbine has been divided in three group of stages as there are two extractions in the turbine.

All the nozzles are non chocked, so that the mass flow can be calculated applying the law of the Stodola's ellipse to every group of stages [Catania 1979]:

$$G = (G)_d \cdot \frac{p_o^t}{(p_o^t)_d} \cdot \sqrt{\frac{(p_o^t)_d \cdot (v_o^t)_d}{p_o^t \cdot v_o^t}} \sqrt{\frac{1-(p_k/p_o^t)^2}{1-((p_k)_d/(p_o^t)_d)^2}} \tag{1.3}$$

where the subscripts respectively indicate:

d the design condition

o the upstream cross section

k the downstream cross section

while the superscript *t* indicates the total quantities.

The mass flow entering the next group of stages is calculated applying the continuity equation to an appropriate control volume in the extraction zones, as it is shown in figure 1.3.

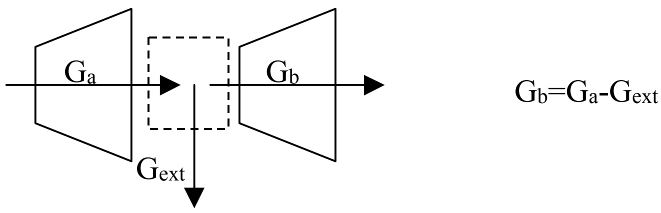


Figure 1.3 - Control volume to consider for the mass flow calculation

The mass flow extractions are initially calculated as an interpolation of known values. The exact value of every flow is determined by the regulation system of the feed water heaters, so that its calculation requires an iterative procedure.

The knowledge of mass flow and pressures relative to the governing stage in design condition allows to determine the exiting area A_u, using the equation:

$$G = (1-\varepsilon) \cdot A_u \cdot \frac{p_o^t}{\sqrt{p_o^t \cdot v_o^t}} \sqrt{\frac{2k}{k-1}\left[\left(\frac{p_k}{p_o^t}\right)^{\frac{2}{m}} - \left(\frac{p_k}{p_o^t}\right)^{\frac{m+1}{m}}\right]} \tag{1.4}$$

The partialization grade ε is null in design condition, as the sectors are completely open.

Equation 1.4 is strictly valid for a politropic transformation of a perfect gas in a nozzle. Nevertheless its use is acceptable to determine the steam mass flowing in the turbine for every non-choked condition [Cooke 1985]; it needs the knowledge of the degree of partial admission and the outlet pressure.

For a choked turbine it is necessary to consider, in equation 1.4, that pressure ratio equals to the critical pressure ratio:

$$\frac{p_k}{p_o^t} = \left(\frac{2}{m+1}\right)^{\frac{m}{m-1}} \tag{1.5}$$

In these conditions of the outlet pressure decrease does not produce any variation in the mass flow.

The expansion in a turbine stage occurs in the nozzle and in the bucket if the reaction grade is upper than zero, while it occurs in the nozzle only if the reaction grade is zero. Figure 1.4 shows a general expansion. If the expansion only happens in the nozzle, points 1 and 2 would be on the same isobar, but they would not coincide because in the bucket a part of the kinetic specific energy is transformed in enthalpy. Nevertheless the point 1is and 2is would coincide.

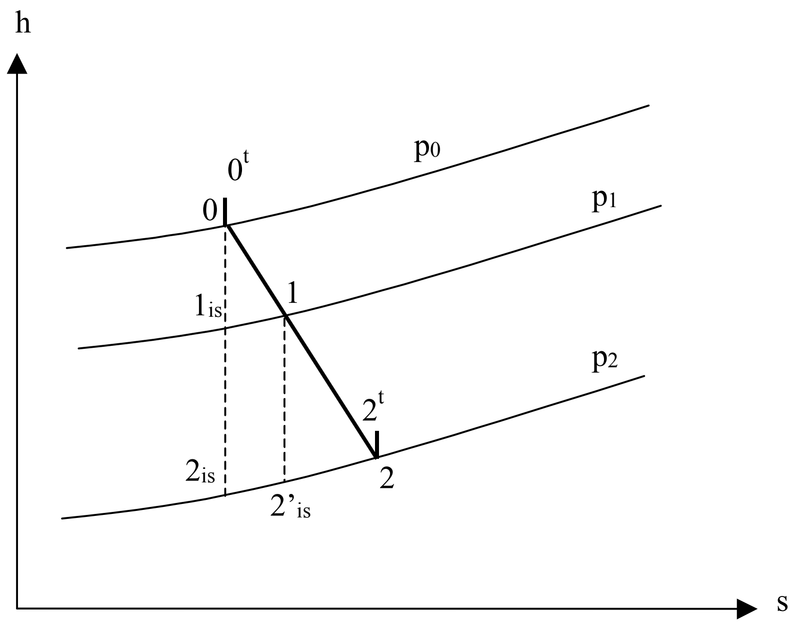


Figure 1.4 - Expansion in a turbine stage

If the flow exiting from a turbine stage enters in another stage or if its kinetic energy is totally recuperated the stage efficiency (total to total efficiency) can be defined:

$$\eta_\Theta = \frac{h_o + \frac{c_o^2}{2} - h_2 - \frac{c_2^2}{2}}{h_o + \frac{c_o^2}{2} - h_{2is} - \frac{c_2^2}{2}} \tag{1.6}$$

while, if the kinetic energy of the exiting fluid is not recuperate, the stage efficiency (total to static efficiency) is:

$$\eta_\theta = \frac{h_o + \frac{c_o^2}{2} - h_2 - \frac{c_2^2}{2}}{h_o + \frac{c_o^2}{2} - h_{2is}} \quad (1.7)$$

In the case of a plant analysis, the kinetic energy variation is usually neglected, so that the efficiency definition can be assumed as:

$$\eta_t = \frac{h_o - h_2}{h_o - h_{2is}} \quad (1.8)$$

The procedure proposed by Spencer, Cotton and Cannon can be applied to predict the efficiency of a steam turbine [Spencer et al. 1974]. In the case of the Moncalieri power plant the data of the efficiency of every group of stage were available in design and in three partial load conditions [A.E.M. 1966, Macor et al. 1997] so that a simpler equation for the efficiency variation has been here adopted [Catania 1979].

$$\eta_t = (\eta_t)_d \cdot \left[1 - \alpha\left(\frac{((p_k)_d/(p_o^t)_d)}{p_k/p_o^t} - 1\right)^2\right] \quad (1.9)$$

where the coefficient α has been assumed 0.2, as proposed in literature. The values assumed by the efficiency of the stages in design condition are shown in table 1.1.

Turbine stages					
High pressure		Middle pressure		Low pressure	
η_{is0}	0.7	η_{is1}	0.859	η_{is1}	0.872
η_{is1}	0.789	η_{is2}	0.886	η_{is2}	0.911
η_{is2}	0.817	η_{is3}	0.873	η_{is3}	0.730
		η_{is4}	0.875		

Table. 1.1 - Isentropic efficiencies in design condition

A model of the packing leakage represents a particular aspect that has been taken into account in this work. The system used to reduce the leakage is a labyrinth seal. It is constituted by a series of lamellae disposed alternatively on the rotor and on the stationary part of the turbine, in order to create a succession of cells, as shown in figure 1.5. In this way two effects are obtained: the escape area is reduced and the pressure drop is divided into more falls.

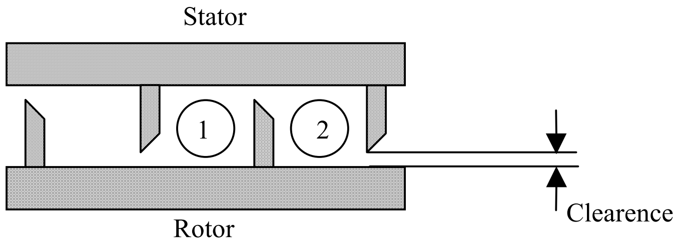


Figure 1.5 - A labyrinth seal

Labyrinth seals characterised by different number of cells are located upstream and downstream every turbine, in order to limit the non-controlled mass flows exiting. A certain number of pipelines are located among the cells, in order to gather the escaped fluid and to allow reusing it in the process. The enthalpy of these streams is recuperated in different ways, depending on the fluid pressure. A complete scheme of the packing system of the plant is represented in figure 1.6.

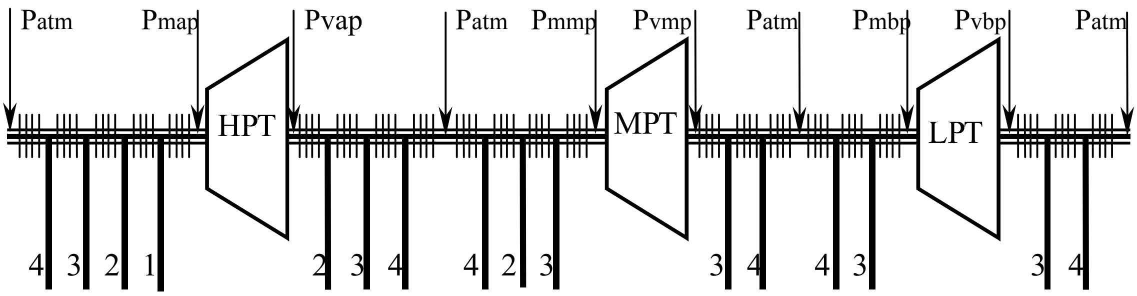


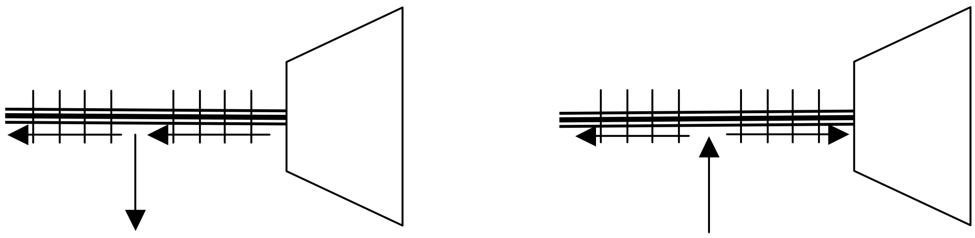
Figure 1.6 - Scheme of the labyrinth seals in the 136 MW turbine

where:

p_{atm} is the atmospheric pressure;
p_{map} is the pressure downstream the governing stage;
p_{vap} is the pressure downstream the high pressure turbine;
p_{mmp} is the pressure upstream the middle pressure turbine;
p_{vmp} is the pressure downstream the middle pressure turbine;
p_{mbp} is the pressure upstream the low pressure turbine;
p_{vbp} is the pressure downstream the low pressure turbine.

The stream characterized by the higher pressure is extracted only from the packing located upstream the high pressure turbine; this is indicated as *1* in figure 1.6. This flux is mixed with the main stream exiting the high pressure turbine, so its pressure is close to the value p_{vap}. Another flux, indicated as 2, which is at a lower pressure is reused by mixing it with one of the extractions of the intermediate pressure turbine. The flux indicated as 3 is at a fixed pressure, maintained at a value higher than the atmospheric pressure, about 1.5 bar. The value is maintained by a system which provides for draw a bigger steam flow or for discharge the excess, respectively if the pressure tends to decrease or increase. This is made in order to avoid the defilement of air in the steam flowing in the sub-atmospheric pressure parts of the turbine, which would pollute it, i.e. it ensures the turbine airtight sealing. To maintain the pressure value the steam necessary for the valves piloting is used, moreover an opportune extraction downstream the high pressure turbine can be also used. The excess stream, called gland sealing system excess [see also Brown Boveri 1983], is mixed to an extraction of the low pressure turbine. The last leakage flow is at a sub-atmospheric pressure, about 0.95 bar; this is made in order to avoid steam escaping to the atmosphere. The enthalpy of this flow is partially recuperated in the gland leakage steam condenser and then wasted in the environment.

The pressure downstream the low pressure turbine is close to the value in the condenser, so that it is lower than the pressure of the stream 3. In this way a steam flow comes in the low pressure turbine from the pipe indicated as 3 and passes trough the labyrinth; another flow comes from this pipe toward the pipe 4. The same thing can also occur upstream the low pressure turbine when the steam flow passing trough this turbine is very small, which happens at the lowest loads or in case of very high thermal production. Figure 1.7 shows a scheme of the two different behaviours.



Case 1: high steam mass flow in LPT   Case 2: little steam mass flow in LPT

Figure 1.7 - Behaviour of the labyrinth seals upstream the low pressure turbine

The model used to simulate the behaviour of the leakage system is based on two hypotheses: 1) the number of cells in the packing is high; in this case the pressure drop between two cells is sufficiently low to consider the fluid incompressible and 2) the steam conditions are non critical.

The mass flow exiting from a cell can be calculate using the Stodola formula [Catania 1979]:

$$G = K \cdot \sqrt{\frac{p_1^2 - p_2^2}{p_1 \cdot v_1}} \tag{1.10}$$

where K is a constant depending on the geometric parameters of the labyrinth seal, like the number of cells and the clearance.

In correspondence of the leakage pipes a continuity equation must be applied in order to determine the total mass flow escaping through a labyrinth. In the case of the labyrinth upstream the high pressure turbine four equation must be written:

$$G_4 = K_D \cdot \sqrt{\frac{p_{erm}^2 - p_{low}^2}{p_{erm} \cdot v_{erm}}} \tag{1.11}$$

$$G_3 = K_C \cdot \sqrt{\frac{p_{E4}^2 - p_{erm}^2}{p_{E4} \cdot v_{E4}}} - G_4 \tag{1.12}$$

$$G_2 = K_B \cdot \sqrt{\frac{p_{vap}^2 - p_{E4}^2}{p_{vap} \cdot v_{vap}}} - G_4 - G_3 \tag{1.13}$$

$$G_1 = K_A \cdot \sqrt{\frac{p_{map}^2 - p_{vap}^2}{p_{map} \cdot v_{map}}} - G_4 - G_3 - G_2 \tag{1.14}$$

The values assumed by the constants K are shown in table 1.2

K_A kg/m^{2}s	K_B kg/m^{2}s	K_C kg/m^{2}s	K_D kg/m^{2}s
0.01621	0.02628	0.04504	0.03372

Table. 1.2 - Values of the labyrinth seal coefficients

these values are assumed the same for all the labyrinths.

1.1.3 Alternator

The Tecnomasio Brown Boveri alternator has these characteristics:

power	136 MW/170 MVA;
voltage	17 kV;
power factor	0.8;
efficiency	0.986;
refrigeration fluid	hydrogen.

Its model has been made considering its efficiency and the thermal flow exchanged between the refrigeration circuit and the feed water. Table 1.3 shows the thermal power exchanged in different conditions. In the table the inlet and outlet temperature of the feed water and its mass flow are also reported.

W	Φ	T_{in}	T_{out}	G
136	1.46	26.1	29.9	92.01
120	1.27	24	27.8	80.05
95	1.01	21.4	25.2	63.53
60	0.73	18.3	22.6	40.38

Table. 1.3 - Thermal recuperation of the alternator refrigeration system

No data are disposal about the hydrogen circuit characteristics, nevertheless the value of the hydrogen thermal conductivity is so high that its value can be assume independent to the feed water condition. This mean that thermal flow Φ recuperated by heating the feed water can be assumed as a fraction of the total thermal flow exiting the alternator, here indicated as Φ_T.

$$\Phi = \eta_{H2} \cdot \Phi_T \tag{1.15}$$

where η_{H2} is the recuperation system efficiency.

The total thermal flow can be calculated considering the energy flow balance of the alternator:

$$\Phi_T = W_t - W_{el} \tag{1.16}$$

where

$$W_{el} = \eta_{alt} \cdot W_t \tag{1.17}$$

According to the disposal data the recuperation system efficiency can be assumed 0.76.

1.1.4 Condenser

As the plant is located near the Po river, the cooling fluid of the condenser is the water of the river. It is a 1-2 shell and tube heat exchanger, which main characteristics are:

heat transfer area	6540 m^2
number of tubes	10350
tubes length	8050 mm
external and internal diameter	25/23 mm
tubes material	Albrass (77 Cu2A1004 AsZn)
water volume flow	175000 m^3/h

The condenser behaviour has been simulated in order to determine the operating pressure for every working condition. The vacuum degree is maintained by two ejection pumps. Its value depends on the temperature of the water and on the mass flow of the condensing steam, as shown in figure 1.8 [Escher Wyss 1962].

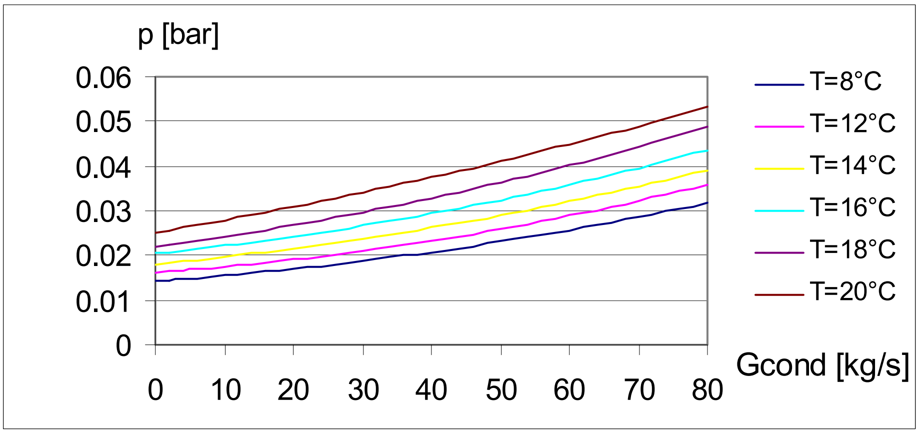


Figure 1.8 - Condenser pressure

The mass flow of the condensing steam includes the stream exiting the low pressure turbine and the exhausted steam extractions feeding the low pressure heat exchangers. The make up water enters the condenser too.

The equations of the curves modelling the pressure in the condenser are:

$$(T = 8°C) \quad p = 1.392 \cdot 10^{-6} \cdot G^2 + 1.069 \cdot 10^{-4} \cdot G + 1.43 \cdot 10^{-2} \tag{1.18}$$

$$(T = 12°C) \quad p = 1.688 \cdot 10^{-6} \cdot G^2 + 1.116 \cdot 10^{-4} \cdot G + 1.613 \cdot 10^{-2} \tag{1.19}$$

$$(T = 14°C) \quad p = 1.51 \cdot 10^{-6} \cdot G^2 + 1.424 \cdot 10^{-4} \cdot G + 1.81 \cdot 10^{-2} \tag{1.20}$$

$$(T = 16°C) \quad p = 1.655 \cdot 10^{-6} \cdot G^2 + 1.567 \cdot 10^{-4} \cdot G + 2.048 \cdot 10^{-2} \tag{1.21}$$

$$(T = 18°C) \quad p = 1.596 \cdot 10^{-6} \cdot G^2 + 2.07 \cdot 10^{-4} \cdot G + 2.2 \cdot 10^{-2} \tag{1.22}$$

$$(T = 20°C) \quad p = 1.066 \cdot 10^{-6} \cdot G^2 + 2.647 \cdot 10^{-4} \cdot G + 2.518 \cdot 10^{-2} \tag{1.23}$$

1.1.5 Feed water heaters

The water exits the condenser by mean of an extraction pump and enters the low pressure feed water heater, which is constituted by four heat exchangers, fed by four turbine extractions at the lowest pressures, and by the leakage steam condenser. At the exit, the water enters the deareator, where the fluid is maintained in saturated condition, by means of a turbine extraction, in order to allow the air separation. Successively the water is pumped and enters the two parallel high pressure feed water heaters, which are constituted by three heat exchangers, fed by the extractions at the highest pressures. The exhausted extractions are mixed with the main stream in the deareator.

The general structure of the heat exchangers presents three sections: where the superheated steam is cooled, condensed and, if the third section is present, subcooled. The hot fluid mass flow is regulated by mean of a float system controlling the water level in the heat exchanger: if too much water is extracted the level rises and the float goes up, operating to close more the valve on the extraction pipe. In this way the extracted steam mass flow decreases. Similarly if the water level falls the float goes down and operates to open more the valve. Such a system guarantees that the hot fluid exits the second heat exchanger section in saturated liquid condition. The same system is also used to control the mass flow extraction which feeds the deareator.

Heat exchangers constituting the feed water heater have been modelled using the effectiveness-NTU method. The model has built by mean of the knowledge of mass flow and enthalpy of the streams entering and exiting the heat exchangers in design condition. A value of the pressure drop in the component has also been considered. Finally three values of the heat transfer coefficient have been assumed in order to simplify the heat transfer problem, respectively corresponding to three conditions of the hot fluid: superheated vapour, saturated vapour and liquid [Bell 1978]. These data allow to calculate the heat transfer area of every heat exchanger, which is a necessary quantity for solving the off-design problem.

If mass and enthalpy of the streams entering the feed water heater, the heat transfer areas, and the values of heat transfer coefficient are known, the conditions of all the exiting flows can be calculated using effectiveness-NTU method. Every single heat exchanger has been analysed using the scheme proposed in figure 1.9, where it has been represented composed by two heat exchangers and one mixer.

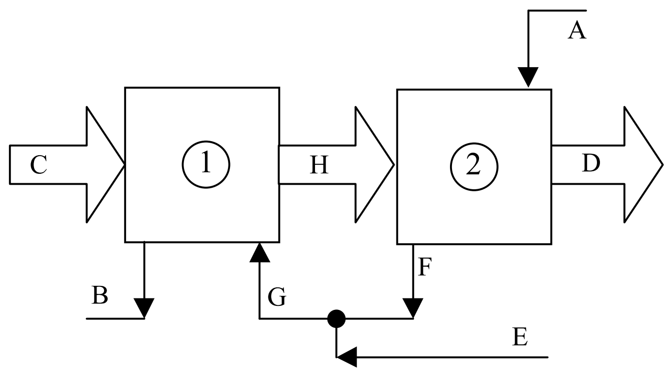


Figure 1.9 - Heat exchanger of a feed water heater

Points A and C represent the enters of hot and cold fluids, points B and C the relative exits; point E represents the enter of the hot fluid exiting the heat exchanger located downstream the point D.

The area of the two heat exchangers has been calculated supposing the fluid at point F as dry saturated steam in design conditions. The heat transfer process can be illustrated as shown in figure 1.10.

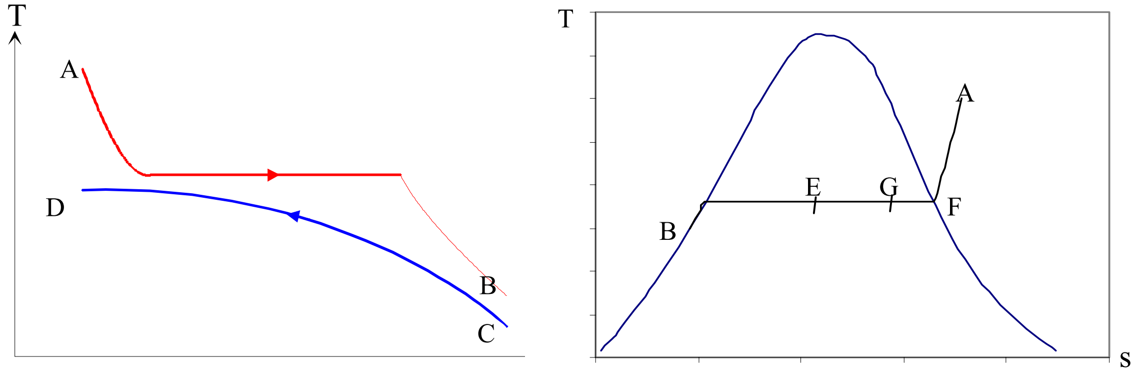


Figure 1.10 - Representation of the thermodynamic transformation in a heat exchanger

The calculus is made by applying an iterative procedure to the component. A value of the enthalpy of the water at the point B condition is supposed. As points B and C are known, the enthalpy of points H and G can be calculated using the equations written below, where the superscripts ' and " respectively refer to hot and cold fluid:

$$NTU = \frac{K \cdot A}{(G \cdot c_p)_{min}} \tag{1.24}$$

$$\varepsilon = \frac{G \cdot c_p \cdot (T_G - T_B)}{(G \cdot c_p)_{min} \cdot (T_G - T_C)} \tag{1.25}$$

$$r = \frac{(G \cdot c_p)_{min}}{(G \cdot c_p)_{max}} \tag{1.26}$$

$$h_G = \mathrm{h_G}(T_G, p_G) \tag{1.27}$$

$$\Phi = G' \cdot (h_G - h_B) = G'' \cdot (h_H - h_C)\,. \tag{1.28}$$

The heat exchanger effectiveness depends on the geometry of the heat exchanger: for counter-flow heat exchanger it can be written as

$$\varepsilon = \frac{1 - e^{-(NTU \cdot (1 - r))}}{1 - r \cdot e^{-(NTU \cdot (1 - r))}} \tag{1.29}$$

The enthalpy of the fluid in point G condition can not be calculated as indicated in equation 1.27 if the fluid is saturated. In this case the problem is solved using as independent quantities pressure and thermodynamic quality:

$$h_G = \mathrm{h_G}(x_G, p_G) \tag{1.30}$$

Heat transfer area A_1 necessary to the process starting from the conditions of point B to the saturated liquid condition is calculated. If A_1 is higher than the total heat transfer area A, the calculus is repeated using as a known quantity the value of the area, otherwise the area necessary to the complete evaporation A_2 is calculated. If this value is lower than A-A_1 the calculus is completed, by determining the conditions of exiting flows, as the remaining area is A-A_1-A_2. If this value is higher, the quality of point G is calculated by proportionality:

$$x_G = \frac{A - A_1}{A_2} \tag{1.31}$$

The application of energy flow balance to the mixer allows to calculate the enthalpy of point F. The enthalpy of points A and D is calculated as shown for G and H. If the calculated enthalpy of point A differs to the known value, the entire procedure must be repeated, using a different value for the assumed enthalpy of point B.

This procedure is particularly complicated, so an alternative model has been used. This model is based on the application of the concepts of terminal temperature difference (TTD) and temperature drain cooling advantage (TDCA). These two parameters are shown in figure 1.11: TTD is the difference between the condensation temperature of the hot fluid and the temperature of the exiting cold fluid; TDCA is the difference between the temperature of the exiting hot fluid and the entering cold fluid.

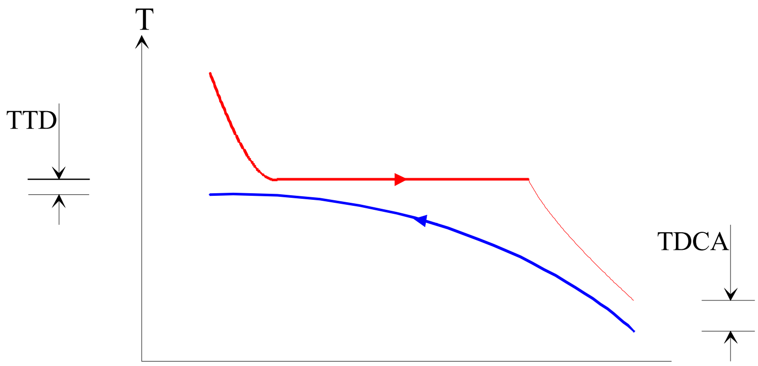


Figure 1.11 - Characteristic parameters of the heat exchangers model

The built plant model only uses the TTD parameter, as the subcooling zone is present only for two heat exchangers HE3 and HE6, moreover a separate subcooling heat exchanger is present in the plant HE1a2a, so that the efficiency-NTU method has been chosen to calculate all the liquid-liquid heat transfer processes. The TTD parameter is sufficient to resolve the thermal problem of a heat exchanger if the hot fluid exits in saturated liquid condition, in fact the only two unknown variables are the extraction mass flow and the cold fluid exiting temperature but two equations are disposal: the TTD definition and the overall energy flow balance.

The TTD values can be calculated by considering the disposal plant data in different working conditions [Escher Wyss 1966]. Graphs in figures 1.12 and 1.13 show the TTD values in the heat exchangers respectively relative to the low pressure and high pressure feedwater heaters as the mass flow of the main stream varies. The data refer to non cogenerative working conditions.

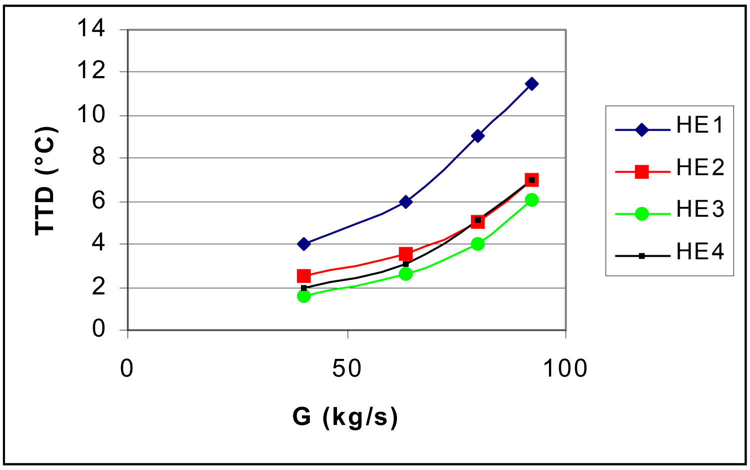


Figure 1.12 - TTD in the low pressure feed water heater

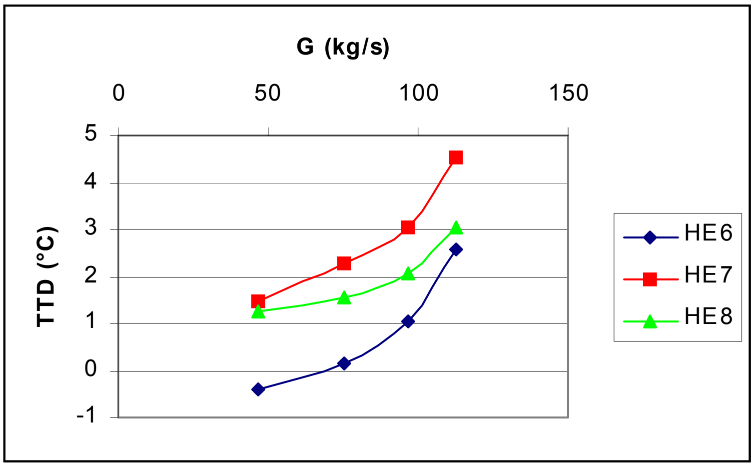


Figure 1.13 - TTD in the high pressure feed water heater

Numerical correlation can be alternatively used to calculate the variation of these parameters as the working condition varies [Erbes and Gay 1989]:

$$\frac{TTD}{(TTD)_d} = \left(\frac{G}{(G)_d}\right)^x \cdot \left(\frac{T}{(T)_d}\right)^y \cdot \left(\frac{p}{(p)_d}\right)^z \cdot \left(\frac{G_{ext}}{(G_{ext})_d}\right)^a \cdot \left(\frac{p_{ext}}{(p_{ext})_d}\right)^b \tag{1.32}$$

where the coefficients x, y, z, a, b for low pressure and high pressure feed water heaters tipically assume the values shown in table 1.4:

	x	y	z	a	b
LPFWH	-0.04	18.97	-0.12	1.11	4.33
HPFWH	-2.395	4.407	-0.713	0.584	0

Table. 1.4 - Typical values of the coefficient x, y, z, a, b

and

$$\frac{TDCA}{(TDCA)_d} = \left(\frac{G}{(G)_d}\right)^x \cdot \left(\frac{T}{(T)_d}\right)^y \cdot \left(\frac{p}{(p)_d}\right)^z \tag{1.33}$$

where the coefficients x, y, z tipically assume the values shown in table 1.5:

	x	y	z
LPFWH	0.43	-0.02	0.1
HPFWH	0.64	-0.29	0.52

Table. 1.5 - Typical values of the coefficient x, y, z

The evaluation of the pressure drops in the extraction pipes is possible using the data relative to the project of the Moncalieri plant modification [Brown Boveri 1985]. In all the disposal working conditions, corresponding to different thermal and electric loads, the ratio between the pressures downstream and upstream the extraction pipes is practically constant. The values assumed by this ratio is shown in table 1.6.

	$(G_{ext})_d$ kg/s	$(T_{ext})_d$ °C	$(p_{ext})_d$ bar	p_{down}/p_{up}
G_{ext1}	4.064	75.5	0.394	0.894
G_{ext2}	3.889	128.8	0.824	0.900
G_{ext3}	5.006	229.1	2.486	0.914
G_{ext4}	3.183	294.9	4.528	0.920
G_{ext5}	3.353	353.0	7.371	0.893
G_{ext6}	4.861	457.4	16.132	0.935
G_{ext7}	7.847	350.7	31.538	0.941
G_{ext8}	4.261	391.0	43.022	0.946

Table. 1.6 - Pressure drop in the extraction pipes

As no data were disposal, the pressure drop at the water side, in every heat exchanger, has been evaluated as a linear function of the inlet pressure:

$$\Delta p = pp_w \cdot p \tag{1.34}$$

were the constant pp_W has been assumed 0.02 and p is the inlet pressure.

1.1.6 Pumps

The model of the extraction and circulation pump has been made considering two parameters: the pressure increase and the isentropic efficiency.

The available design data [Escher Wyss 1966] make possible to calculate the pressure increase in four working conditions, corresponding to four different water mass flows. A parabola Δp=f(G) can be considered as characteristic behaviour of the component.

W MW	G kg/s	$p_{upstream}$ bar	$p_{downstream}$ bar	ΔP bar
60	40.38	0.02	3.15	3.12
95	63.53	0.03	5.07	5.05
120	80.05	0.03	5.93	5.90
136	92.01	0.03	7.31	7.28

Table. 1.7 - Data relative to the extraction pump behaviour

W MW	G kg/s	$p_{upstream}$ bar	$p_{downstream}$ bar	ΔP bar
60	46.88	2.92	156.77	153.8
95	75.53	4.41	161.06	156.6
120	96.72	5.54	166.42	160.9
136	112.33	6.57	177.17	170.6

Table. 1.8 - Data relative to the circulation pump behaviour

The characteristic equations of extraction and circulation pump are respectively

$$\Delta p = 0.0002 \cdot G^2 + 0.057 \cdot G + 0.62 \tag{1.35}$$

$$\Delta p = 0.0019 \cdot G^2 - 0.0479 \cdot G + 150 \tag{1.36}$$

The graphs in figures 1.14 and 1.15 show the curves and the available data.

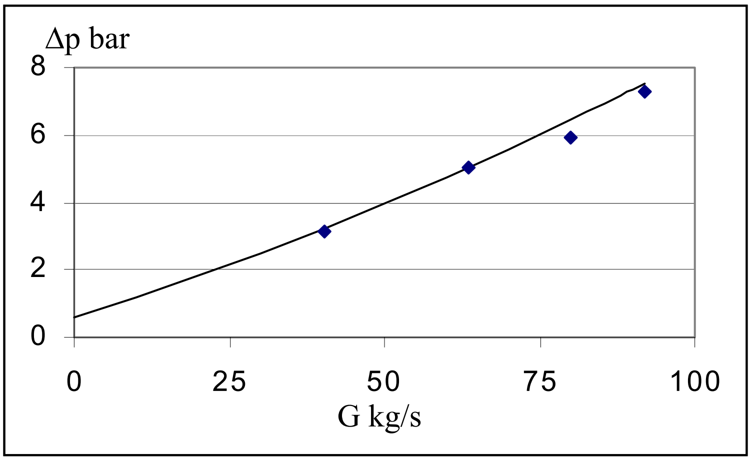


Figure 1.14 - Pressure increase in the extraction pump

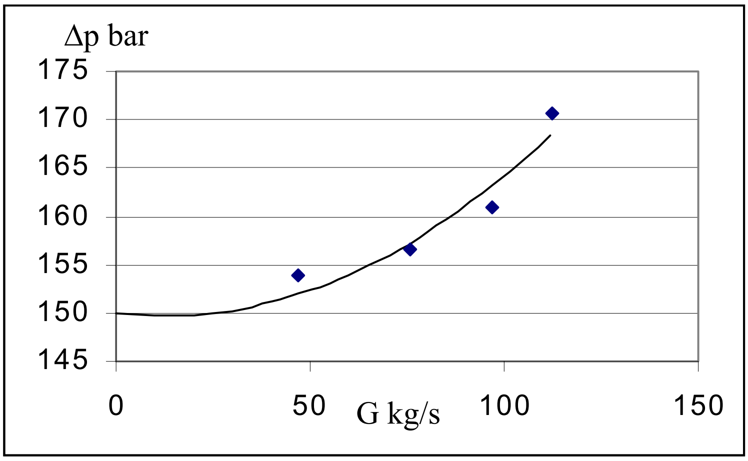


Figure 1.15 - Pressure increase in the circulation pump

The isentropic efficiency of a pump is defined:

$$\eta_p = \frac{h_{kis} - h_o}{h_k - h_o} \tag{1.37}$$

where:

h_o is the enthalpy of the inlet water;
h_k is the enthalpy of the outlet water;
h_{kis} is the enthalpy of the outlet water in a isentropic transformation (ideal pump).

These point are shown in figure 1.16:

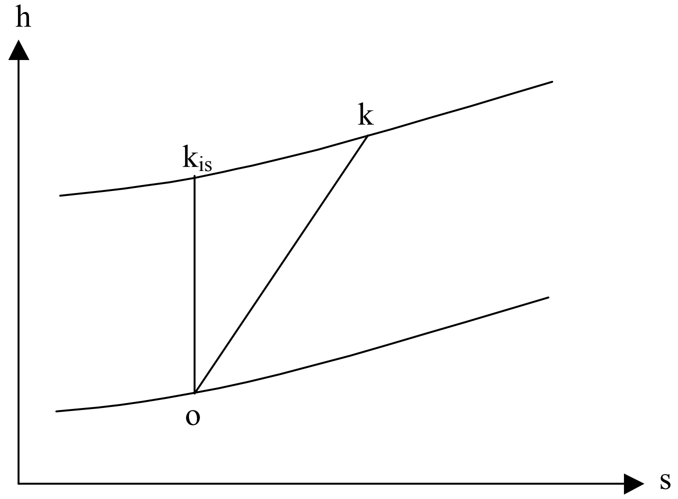


Figure 1.16 - Pumping transformation

1.1.7 Hot condenser

In 1988 the Moncalieri power plant was modified in order to supply heat to the Turin district heating network. Nowadays the main plant product is just the heat and the thermal requirement leads the plant regulation.

The cogenerative mode is obtain by a heat exchanger, called *hot condenser*, which is fed by an extraction located downstream the intermediate pressure turbine. A valve located on the crossover pipe allows to regulate the steam mass flow extracted.

The *hot condenser* is a shell and tubes heat exchanger and has the characteristics shown below:

- steam side	maximum mass flow	250 t/h
	maximum thermal load	163 MW
- water side	maximum mass flow	2400 m^3/h
	nominal inlet temperature	60 °C
	nominal outlet temperature	120 °C
	nominal pressure	16 bar

The outlet fluid at the steam side is in condition of saturated liquid.

1.1.8 Regulation system

Equation 1.4 can be assumed valid only for an infinite number of regulation valves (throttle), so that the partialization grade ε can vary continuously. If this hypothesis is verified each control valve is totally open or closed, and there is no lamination through the valves. If the number of control valves is high the effect of the lamination can be neglected and equation 1.4 is a good approximation of the real behaviour of the system. In the analysed case the flow entering the turbine is regulated by four valves; the scheme reported in figure 1.17 describes the opening sequence of the valves as the electric load varies, in a non-cogenerative mode.

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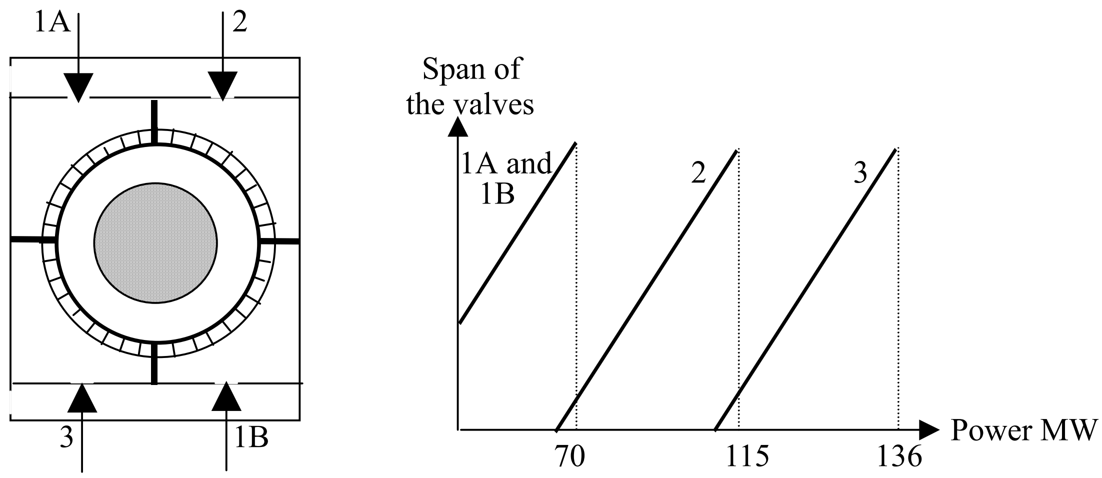

Figure 1.17 - Turbine regulation

In general a lamination occurs for one of the streams, so the behaviour of the governing stage can be better modelled than the equation 1.4 does. In figure 1.18 a general situation is represented: the valves 1A and 1B are totally open, the valve 3 is closed and the valve 2 is regulating. The corresponding expansion line is also reported. The steam expansion in the nozzles proceeds in different ways for the streams exiting the valves 1A and 1B and for the stream exiting the valve 2. The streams exiting the nozzles are then mixed before entering the moving buckets.

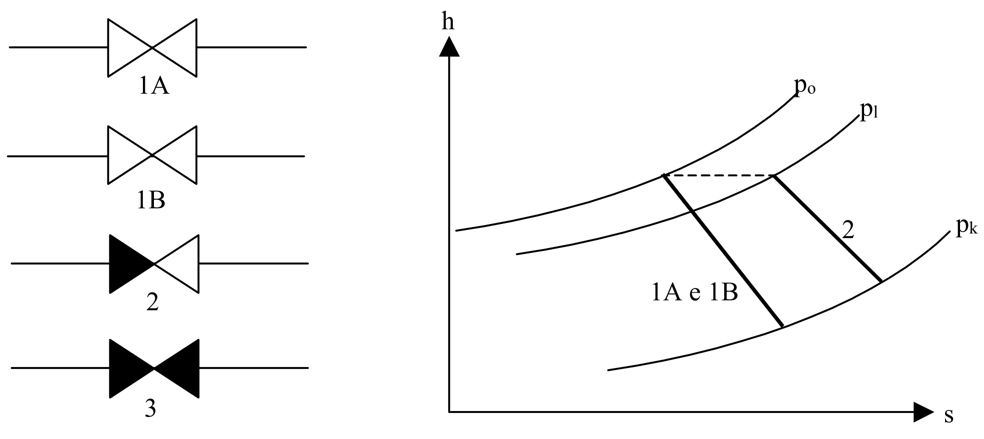

Figure 1.18 - Expansion in partalized annular sectors

In this work the governing stage behaviour has been modelled using three nozzles which expands the steam to the same outlet pressure, each one is regulated by a lamination valve. The efficiency of every single nozzle has been considered independent to the behaviour of the other ones, depending only on the pressure ratio at its ends.

The graph in figure 1.19 shows how the enthalpy downstream the governing stage varies as the steam mass flow varies, keeping constant the downstream pressure. The continue line represents the behaviour of a turbine regulated by three partialization sectors, while the dotted line represents the behaviour of a turbine regulated by an infinite number of sectors. This last model is clearly ideal but it can be considered in case of a great number of partialization sectors. The enthalpy is constant because the sectors are totally open or closed, so that the expansion always occurs between the same upstream and downstream states as no fluxes are laminated. The case where the number of regulation states is very little, as it happens in the Moncalieri steam turbine, can be examined starting from a working condition, characterized by a steam mass flow near zero. Such a working condition does not occur in the reality. Two of the regulation sectors are completely closed, while the third is partially open. The flow is laminated to the point that the pressure upstream the turbine (which coincides to the pressure downstream the valve, i.e. p_l in figure 1.18) is very close to the downstream pressure. This happens because the passage of a little mass flow requires a little pressure ratio, according to equation 1.3. In this case the expansion is so reduced that the downstream enthalpy is close to the upstream one; this last quantity is equal to the entering flow enthalpy, as the lamination can be considered an isenthalpic transformation. If the mass flow increases, the difference between the two pressures p_l and p_k increases too; in this way the expansion is larger and the downstream enthalpy decreases. The expansion in the turbine tends to last to lower entropy values, until the line coincides with *1A and 2A* line (see figure 1.18) when the first lamination valve is completely open. In such a condition, characterized by a valve completely open and the other two closed, the downstream enthalpy is equal to the value which would be obtained with an infinite number of partialization sectors. In the reality this condition can not be obtained because, before a valve is completely open, another valve start opening; nevertheless the downstream enthalpy conditions do not sensibly vary because the mass flow passing through the second valve is very little.

If the mass flow still increases, a valve is completely open and a second valve start regulating. In this condition two fluxes are expanding in the turbine in a different way. The two fluxes are mixed downstream the governing stage. The downstream enthalpy has a particular trend, characterized by a maximum value. If the mass flow still increases, the enthalpy decreases, until the point corresponding to the second valve completely open. This point is characterized by the same enthalpy of the infinite partialization sector case. This behaviour is caused by contemporary variation of enthalpy and mass flow passing through the second valve: the enthalpy of the laminated steam is larger than the enthalpy of the not laminated steam. As the mass flows increases its contribution becomes larger but, at the same time, the enthalpy becomes more and more lower. The same thing happens when the third valve is regulating.

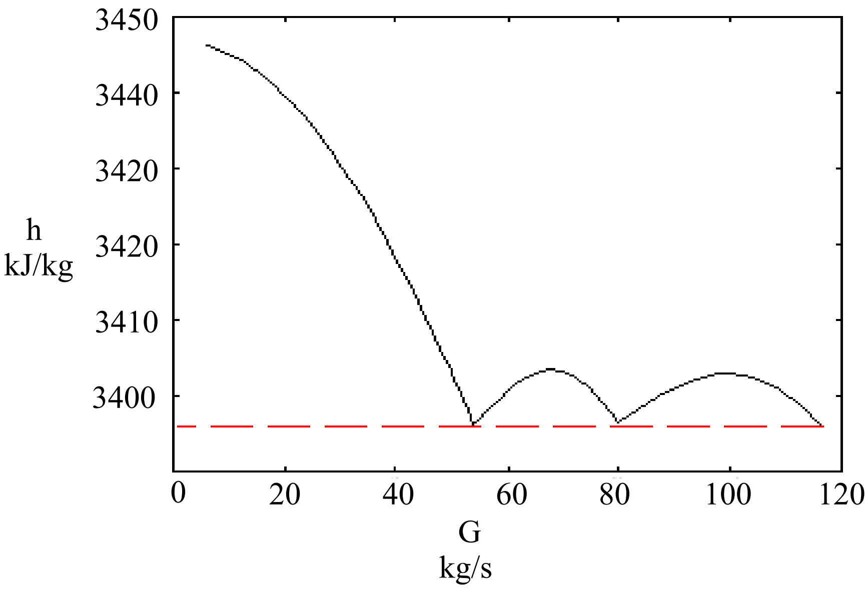

Figure 1.19 - Downstream enthalpy variation in the governing stage

The fluidodynamic behaviour of the high, middle and low pressure turbines can be obtained using the law of the ellipse 1.3. This equation is mathematically correct only for a turbine with a infinite number of stages, but can be used also for a turbine with a finite number of stages, provided all of these are non-choked [Cooke 1985]. The validity of this hypothesis has been verified for the analysed plant, assuming a reaction grade equals to zero for the high pressure and intermediate pressure turbines and equals to 0.5 for the low pressure turbine. Moreover the pressure ratio in all the nozzles of a single group of stages has been assumed equals. The hypothesis validity has been confirmed by confirmed by the A.E.M. technicians.

The valve regulating the steam mass flow extracted for cogeneration has been simulated considering that a regulation does not affect the fluidodynamic behaviour of the upstream component. In this way the mass flow entering the low pressure turbine is equal to the difference between the mass flow exiting the intermediate pressure turbine and the extraction feeding the hot condenser. This last datum is an independent variable of the simulator. The equation 1.3 needs to be applied to the low pressure turbine to determine the value of its upstream pressure. This value is assumed equal to the pressure downstream the valve.

1.1.9 Fluid

The water properties are calculated using a routine [Comino et al. 1996] based on the formulation proposed by the 1982 conference of the International Association for the Properties of Steam [Haar et al. 1994].

The formulation consists on a approximate definition of the Helmoltz function:

$$f(\rho, T) = f_{base}(\rho, T) + f_{residual}(\rho, T) + f_{ideal}(\rho, T) \tag{1.38}$$

where:

- f_{base} describes the behaviour of the Helmoltz function, at low temperature, for every value of the density and, at high density, for every value of the temperature;
- f_{residual} is a correction of the base function;
- f_{ideal} describes the behaviour of the Helmoltz function at the conditions where the fluid can be considered an ideal gas.

The expression of every single term can be found in [Comino et al. 1996].

The thermodynamic properties necessary for the model can be calculated using the Helmolts function:

$$p = \rho^2 \cdot \left(\frac{\partial f}{\partial \rho}\right)_T \tag{1.39}$$

$$s = -\left(\frac{\partial f}{\partial T}\right)_\rho \tag{1.40}$$

$$u = f + T \cdot s \tag{1.41}$$

$$h = u + \frac{p}{\rho} \tag{1.42}$$

$$c_v = -T \cdot \left(\frac{\partial^2 f}{\partial T^2}\right)_\rho \tag{1.43}$$

$$c_p = c_v + \frac{T}{\rho^2} \cdot \frac{\left(\frac{\partial p}{\partial T}\right)_\rho^2}{\left(\frac{\partial p}{\partial \rho}\right)_T} \tag{1.44}$$

The formulation 1.38 can be used in the following definition field:

$$0 \le T \le 1100 \quad °C$$

$$0 < p \le 1000 \quad bar$$

except an area around the critical point, where:

$$|T - T_{cr}| < 1 \quad °C$$

$$\left|\frac{\rho - \rho_{cr}}{\rho_{cr}}\right| < 0.1$$

1.1.10 Some results

In this paragraph the results corresponding to some plant simulation are proposed.

The first application has been made in order to represent the behaviour of the plant in different conditions. Figure 1.20 shows the thermodynamic cycle corresponding to four different electric loads, respectively 136 MW, 120 MW, 90 MW and 60 MW. It is possible to notice that the expansions in the turbines are characterized by a similar efficiency, in fact the lines are practically parallel, except the governing stage, where the efficiency is conditioned by the amount of flux laminated in the throttles. In the cases corresponding to a production of 120 and 90 MW the expansions are practically coinciding. In the last group of stages in the low pressure turbine the efficiency is lower than in the other stages due to the first drops of condensing liquid.

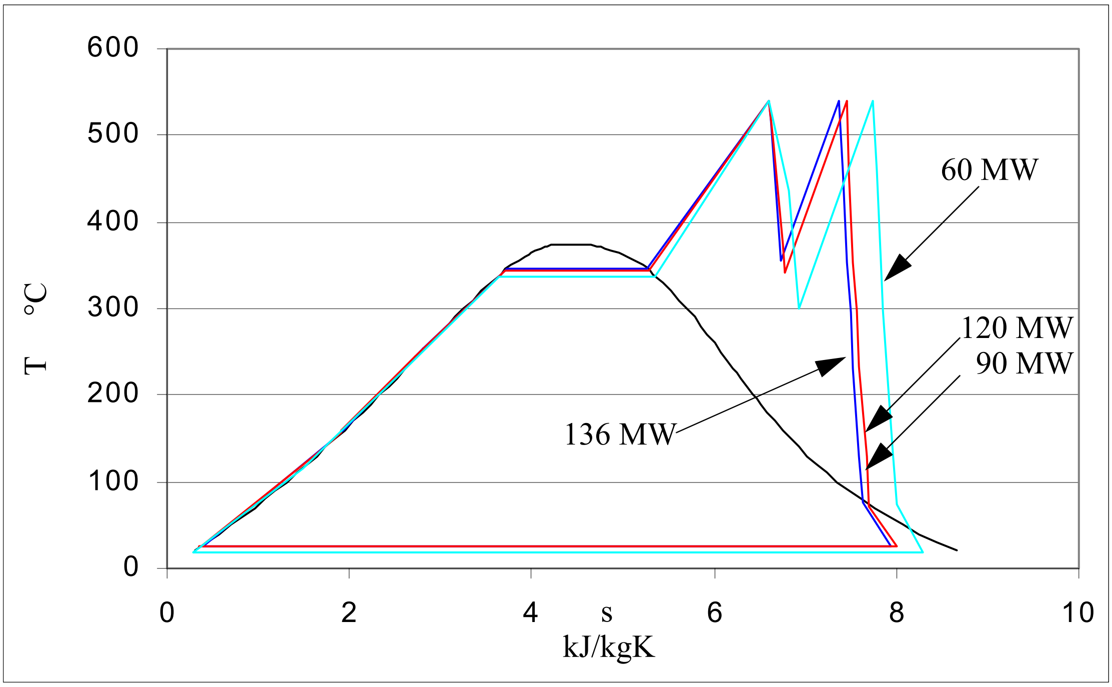

Figure 1.20 - Thermodynamic cycle corresponding to different electric loads (no thermal production)

The regulation of the thermal load is obtained by mean of a valve, which operates a lamination of the main steam flow. Figure 1.21 shows the effect of this regulation on the expansion line corresponding to the maximum throttle opening grade.

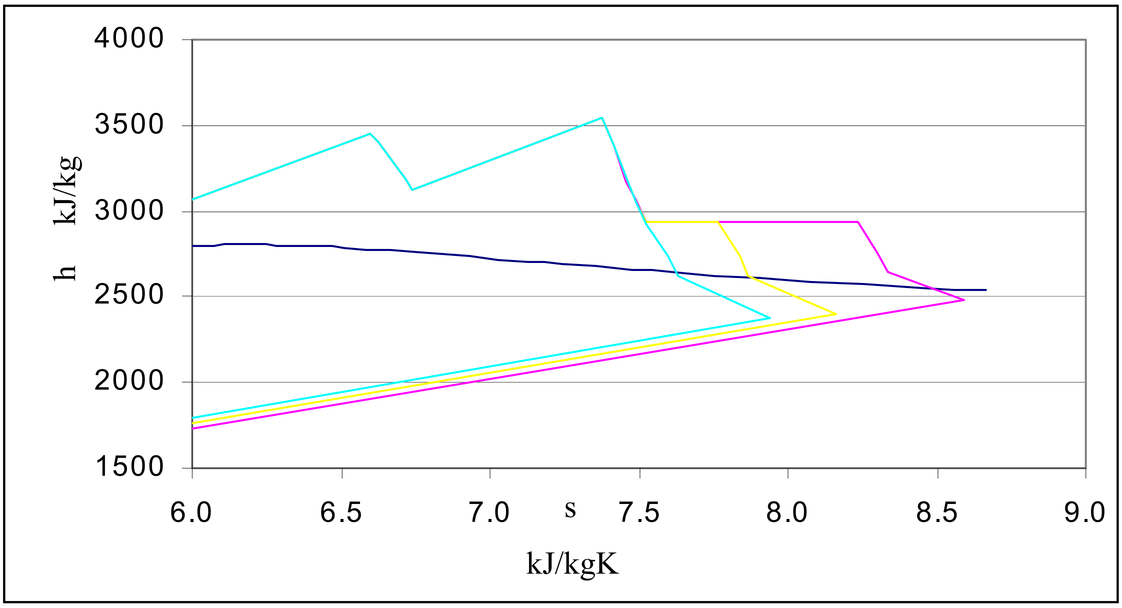

Figure 1.21 - Expansion lines in cogeneration functioning mode

Other results obtained by applying the model of the steam power plant can be found in annex 1 and in [Calì, Verda 1999].

1.2 The gas turbine plant

The Moncalieri gas turbine power plant is a Fiat TG20 B2. It started working in 1976 and in 1989 a Casinghini recuperator has been located downstream the turbine in order to provide a thermal power up to 63 MW to the Turin district heating network. The main characteristics of the plant in nominal condition are [A.E.M. 1997, GTW 1999]:

maximum electric power	33.1 MW
maximum production in cogeneration	32.7 MW electric
	63 MW thermal
fuel	natural gas
gas mass flow	160.4 kg/s
inlet turbine gas temperature	945 °C
outlet turbine gas temperature	485 °C
outlet chimney gas temperature	110 °C
pressure ratio	11

A plant scheme is shown in figure 1.22.

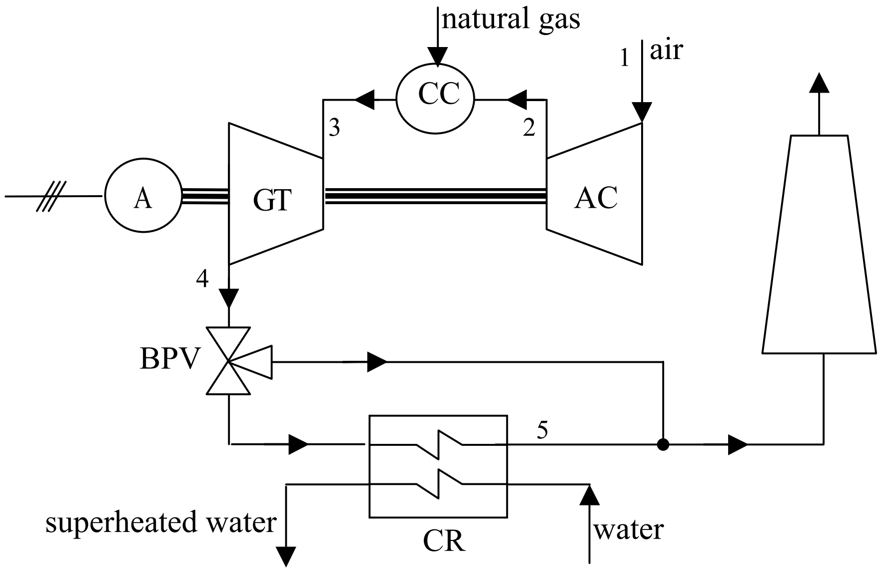

Figure 1.22 - Scheme of the Moncalieri gas turbine plant

The control system guarantees the fulfilment of four constraints: the electric and thermal loads, the turbine inlet temperature and the temperature of the water exiting the recuperator. To achieve these purposes the control system passes a signal to the regulation system, which operates on the opening grade of the inlet guided vanes and the fuel mass flow, the by pass valve opening and the water mass flow. In particular the two regulation parameters are changed together in order to obtain the control of the electric power and the inlet turbine temperature. The modification of the two other parameters is characterized by a longer reaction time. Moreover it is made taking into account the regulation characteristics of the overall system, i.e the thermal load is shared among the steam turbine plant, the gas turbine plant and the boilers [Becher et al. 1991,].

1.2.1 Compressor

The compressor is an axial turbomachine driven by the turbine shaft at 4918 rpm. It is constituted by 18 stages without inter-cooling system.

The air mass flow is regulated by mean of the inlet guide vanes system, so that its expression can be formulated as:

$$G_a = (G_a)_d \cdot igv \tag{1.45}$$

The component has been modelled considering it as a single stage. The pressure ratio is determined by the overall fluidodynamic equilibrium, so that only its definition is possible for the compressor:

$$\beta_c = \frac{p_2}{p_1 \cdot (1 - pp_f)} \tag{1.46}$$

where the pressure drop ratio in the filter assumes the value 0.01 [A.E.M 1989]. The outlet temperature can be calculated considering the compressor isentropic efficiency:

$$T_2 = T_1 \cdot \left(1 + \frac{1}{\eta_c} \cdot \left(\left(\beta_c^{\frac{R_a}{c_{p_{1-2}}}}\right) - 1\right)\right) \quad (1.47)$$

The isentropic efficiency in design condition has been calculated starting from the known quantities. Its value is 0.835. The off-design values can be calculated by mean of the equation 1.48:

$$\eta_c = (\eta_c)_d \cdot \left[a_2 \cdot \left(\frac{(G_a)_d \cdot igv}{\rho_1}\right)^2 + a_1 \cdot \frac{(G_a)_d \cdot igv}{\rho_1} + a_0\right] \quad (1.48)$$

where a_0, a_1 and a_2 are constants which assume the values:

a_0 0.7;

a_1 4.33 10^{-3} s/m^3;

a_2 1.54 10^{-5} (s/m^3)^2.

Finally the energy flow balance must be written:

$$W_c = G_a \cdot (h_2 - h_1) \quad (1.49)$$

1.2.2 Combustor

The combustor is characterized by eight radial burners, made in stainless steel. Every burner is independent in order to make easier its stripping down and its maintenance.

The balance of energy flow and mass flow can be written:

$$G_a \cdot (h_2 - h_0) + G_c \cdot H_i \cdot \eta_{cc} = G_g \cdot (h_3 - h_0) \quad (1.50)$$

$$G_a + G_c = G_g \quad (1.51)$$

The outlet pressure is calculated considering the pressure drop ratio in the combustor:

$$p_3 = p_2 \cdot (1 - pp_{cc}) \quad (1.52)$$

This parameter has been assumed 0.03.

1.2.3 Turbine

The combustion gas is expanded in the axial turbine, which is constituted by three stages. Its model has been made considering the Stodola law for the mass flow calculation in off design conditions [Catania 1979].

$$\frac{G_g}{(G_g)_d} = \sqrt{\frac{p_3 \cdot \rho_3}{(p_3 \cdot \rho_3)_d}} \cdot \sqrt{\frac{1 - \frac{1}{(\beta_t)^2}}{1 - \frac{1}{((\beta_t)_d)^2}}} \quad (1.53)$$

The pressure ratio is determined by the fluidodynamic equilibrium of the system, so that only its definition can be expressed:

$$\beta_t = \frac{p_3}{p_4} \tag{1.54}$$

its value in nominal condition is 10.3.

The use of the isentropic efficiency of the turbine allows to calculate the outlet temperature:

$$T_4 = T_3 \cdot \left(1 - \eta_t \cdot \left(\left(\beta_t^{\frac{R_a}{c_{p_{1-2}}}}\right) - 1\right)\right) \tag{1.55}$$

The isentropic efficiency in design condition has been calculated starting from the known quantities. Its value is 0.851. The off-design values can be calculated by mean of the equation 1.56:

$$\eta_t = (\eta_t)_d \cdot [b_2 \cdot (G_g)_d^2 + b_1 \cdot (G_g)_d + b_0] \tag{1.56}$$

where b_0, b_1 and b_2 are constants which assume the values:

- b_0 0.86;
- b_1 1.37 10^{-3} s/kg;
- b_2 -3.11 10^{-6} $(s/kg)^2$.

The last equation is constituted by the energy flow balance:

$$W_c + W_t = G_g \cdot (h_3 - h_4) \tag{1.57}$$

1.2.4 Alternator

The alternator, built by Marelli, is characterized by a nominal power of 43750 kVA and a voltage of 15kV. Its model has been made simply considering its efficiency, assumed 0.98. This parameter allows to calculate the electric power provided by the plant:

$$W_{el} = \eta_{alt} \cdot W_t \tag{1.58}$$

1.2.5 *Casinghini* recuperator

The modification on this plant made in 1989 consists on the implementation of a recuperator, here called Casinghini, downstream the turbine. The regulation of the thermal load is obtained by mean of a by pass valve, which makes possible to chose the gas mass flow passing through the recuperator. The rest of the gas by-passes the recuperator and exits the plant by the chimney. This modification has affected the working condition of all the components as a pressure drop occurs in the valve and in the heat exchanger. This is the cause of the different electric power obtained by the plant when it works in maximum cogenerative mode and in no cogenerative mode. The pressure drop has been modelled considering a linear dependence on the mass flow passing through the recuperator:

$$p_1 = p_4 \cdot (1 - pp_{he}) \tag{1.59}$$

$$pp_{he} = pp_{ch} + pp_{hem} \cdot bpg \tag{1.60}$$

$$bpg = \frac{G_{he}}{G_g} \tag{1.61}$$

where:

- pp_{ch} is the pressure drop ratio in the chimney, which is equal to 0.01 [A.E.M. 1989];
- pp_{hem} is the maximum pressure drop ratio in the recuperator, which is equal to 0.02 [A.E.M. 1989];
- bpg is the opening grade of the by-pass valve;
- G_{he} is the gas mass flow passing through the recuperator.

The model allows also to calculate the conditions of the outlet water, provided to the district heating network, and the exiting gas. The effectiveness NTU method has been used for this purpose.

No data were available about the heat transfer area, so that a value of the heat transfer coefficient has been assumed (constant in all the conditions) in order to determine it, considering the plant in the maximum thermal load condition.

- K 0.12 kW/m^{2}K [Bell 1978];
- T_{in} 70 °C;
- A 3125 m^2.

The equations of the effectiveness NTU method are:

$$r = \frac{C_{min}}{C_{max}} = \frac{G_{he} \cdot c_{p_{4-5}}}{G_w \cdot c_{p_w}} \tag{1.62}$$

$$NTU = \frac{K \cdot A}{G_{he} \cdot c_{p_{4-5}}} \tag{1.63}$$

$$\varepsilon = \frac{1 - e^{-NTU \cdot (1-r)}}{1 - r \cdot e^{-NTU \cdot (1-r)}} \tag{1.64}$$

$$\varepsilon = \frac{T_4 - T_5}{T_4 - T_{in}} \tag{1.65}$$

Moreover the balance of the thermal energy flows must be written:

$$G_{he} \cdot (h_4 - h_5) = G_w \cdot (h_{out} - h_{in}) \tag{1.66}$$

where the term at the right hand side represents the component product.

1.2.6 Fluid

The gases are modelled using the hypothesis of ideal gas, which means that the specific enthalpy is assumed independent on the pressure. The enthalpy expression is:

$$h - h_0 = \int_{T_0}^{T} c_p \cdot dT \tag{1.67}$$

The reference specific enthalpy of the pure substances is assumed zero at 25 °C.

The dependence of the specific heat capacity on the temperature is considered. This dependence has a polynomial expression [Lozza 1996]:

$$c_p = a_0 + a_1 \cdot T + a_2 \cdot T^2 + a_3 \cdot T^3 + a_4 \cdot T^4 \tag{1.68}$$

The values assumed by the coefficients a_0, a_1, a_2, a_3 and a_4 are shown in table 1.9 for different gases. The specific heat capacity is calculated in J/kgK and the temperature is expressed in °C.

	a_0	a_1	a_2	a_3	a_4
Ar	520.372	0	0	0	0
CO_2	821.495	1.02731	-8.872E-04	3.979E-07	-7.005E-11
H_2O	1849.28	0.351988	6.103E-04	-4.145E-07	7.828E-11
N_2	1043.26	-0.0825203	7.640E-04	-7.277E-07	2.146E-10
O_2	898.61	0.348098	-4.624E-05	-1.415E-07	6.448E-11

Table. 1.9 - Coefficient of the specific heat capacity expression

The expression of the entropy of a pure substance is:

$$s - s_0 = \int_{T_0}^{T} c_p \cdot \frac{dT}{T} - \int_{p_0}^{p} R \cdot \frac{dp}{p} \tag{1.69}$$

where the pressure of the reference environment p_0 is assumed 1.013 bar.

If the gas is a mixture of *n* pure substances its properties can be calculate using the following expressions:

$$h = \sum_{i=1}^{n} y_i \cdot h_i \tag{1.70}$$

$$s = \sum_{i=1}^{n} y_i \cdot s_i - R \cdot \sum_{i=1}^{n} x_i \cdot \ln(x_i) \tag{1.71}$$

where:

y_i is the mass fraction, which is defined:

$$y_i = \frac{x_i \cdot m_{mol_i}}{m_{mol}} \tag{1.72}$$

x_i is the mole fraction, which is defined:

$$y_i = \frac{n_{mol_i}}{n_{mol}} \tag{1.73}$$

m_{mol} is the molecular weight of the mixture, which is:

$$m_{mol} = \sum_{i=1}^{n} x_i \cdot m_{mol_i} \tag{1.74}$$

n_{mol} is the number of moles of the mixture.

Finally the perfect gas equation is used to calculate the density in every condition:

$$\rho = \frac{p}{R \cdot T} \tag{1.75}$$

1.2.7 Some results

In this paragraph some results relative to the application of the gas turbine model in different working conditions are discussed.

In figure 1.23 the T-s diagram of the gas turbine in condition of maximum thermal load is shown. The point 1 represents the air entering the compressor; the pressure in this point is lower than the environment pressure because of the pressure drop in the filter and its entropy is higher. The line 1-2 is the representation of the non isentropic compression. The main effect of this process is the pressure increasing, but it is clear a second positive effect, represented by the increasing of the temperature. The line 2-3 is the union of two processes: the combustion transformation and the mixture of the combustion gas with the air used to refrigerate the first turbine stage. In this way the point 3 does not represents the combustion temperature but the inlet turbine temperature. The outlet combustor temperature in the represented condition is about 1290 K. The line 2-3 also evidences the pressure drop in the component. The line 3-4 is the non isentropic expansion in the turbine. The pressure at the end of the expansion (point 4) is higher than the atmospheric pressure because of the pressure drop in the recuperator and in the chimney. Finally the line 4-5 represents the heat transfer, in the recuperator, between the hot gas exiting the turbine and the district heating water, which enters the recuperator at 70 °C and exits it at 120 °C. The pressure and the entropy of point 5 are higher than point 6, which represents the outlet of the plant. This is due to the pressure drop in the chimney.

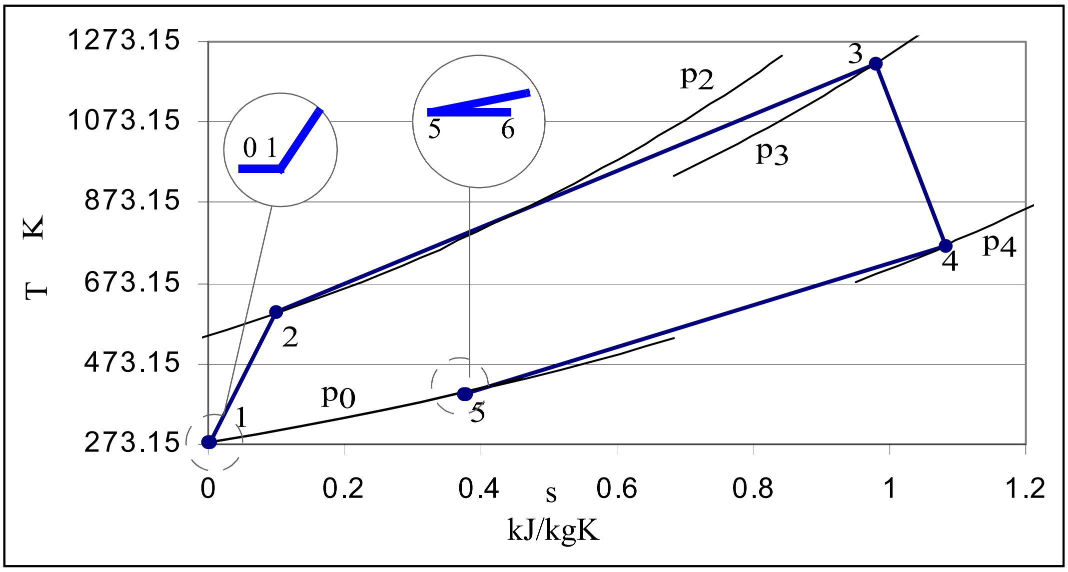

Figure 1.23 - T-s diagram of the gas turbine in condition of maximum thermal production

The first simulation refers to the effect of the environment temperature on the plant performances. The graph in figure 1.24 shows the variation of the electric power and the plant efficiency in the case of maximum electric production mode (no cogeneration). For temperature values lower than 5°C, which is the reference value, the plants works better. This is due to the increased density of the air, which means that, keeping constant the igv regulation at the maximum opening grade, the air mass flow increases as the temperature decreases. As the inlet turbine temperature must be kept constant, the control system regulates the increasing of the fuel mass flow, as a larger air mass flow would cause a decrease of the outlet combustor temperature. The turbine has to process a larger gas mass flow, what requires a higher pressure upstream, as the downstream value is determined by the environment. This effect causes the increase of the pressure ratio in the compressor. The specific useful work obtained by the turbine increases as the pressure ratio increases, which determine a higher efficiency. The percentual variation of the electric power is further higher because of the larger mass flow.

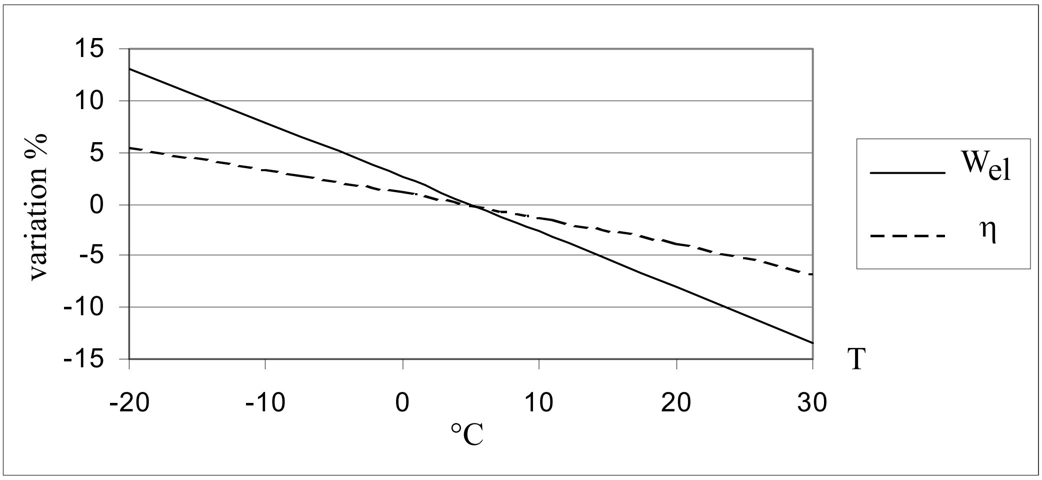

Figure 1.24 - Effect of the environment temperature variation

The effect of the plant regulation on the thermodynamic parameters can be analysed by varying the electric load. The effect of the thermal load regulation, i.e the gas mass flow rate passing through the recuperator, is in fact sensible only on the temperature of the exiting gas.

The graph in figure 1.25 shows the per cent variation of some parameters: the maximum thermal load, the compressor pressure ratio, the inlet and outlet turbine temperatures, the overall plant outlet temperature in case of maximum cogeneration grade and the gas mass flow.

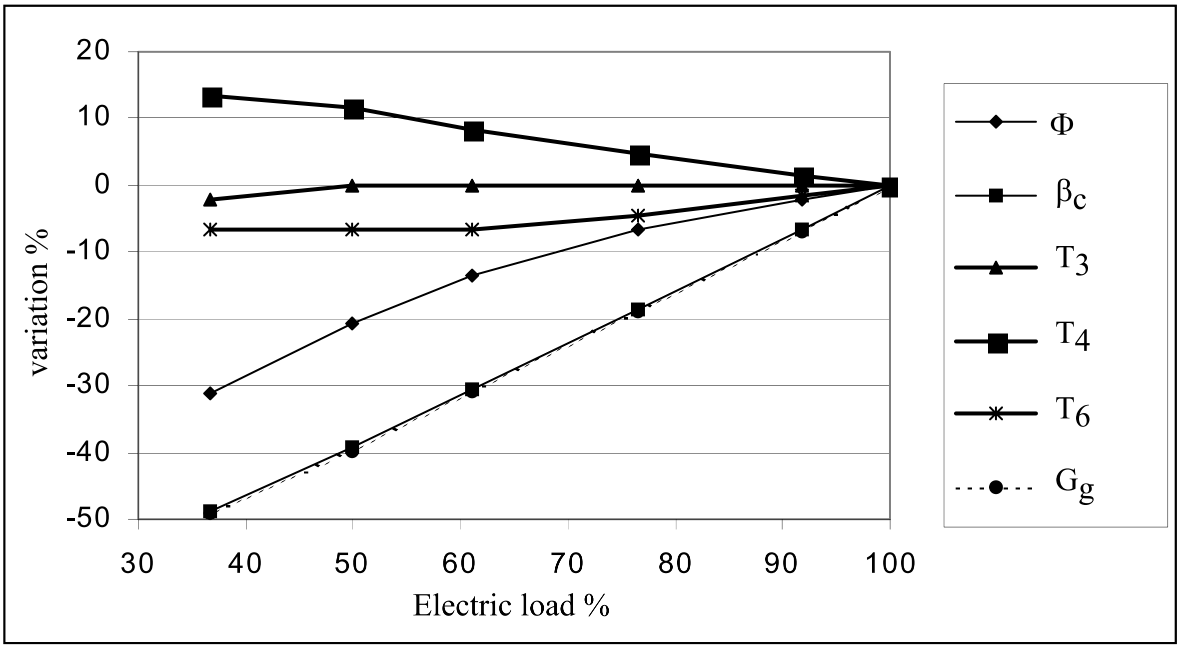

Figure 1.25 - Variation of some plant parameters depending on the electric load

The maximum thermal load decreases as the electric load decreases because the gas mass flow becomes less and less larger; this negative effect is by far preponderant respect to the positive effect represented by the increased outlet turbine temperature. The compressor pressure ratio decreases too, because of the mass flow variation. This dependence is clearly put on evidence by the Stodola law of the ellipse, reported in equation 1.53: the larger is the gas mass flow the higher must be the pressure ratio.

Another interesting curve is represented by the inlet turbine temperature. This value is kept constant by the control system until it is possible. If the electric load becomes less than the 50% of the nominal value the regulation can not be made by increasing the closing grade of the inlet guide vanes, because the minimum grade has been reached. The further electric load reduction can be made only reducing the fuel mass flow, but this cause the turbine inlet temperature decreasing.

Finally the electric efficiency of the plant has been calculated in some different electric load conditions. The results are shown in figure 1.26. This graph evidences way the gas turbine usually works at the maximum electric load, in fact its efficiency strongly decreases as the electric load decreases.

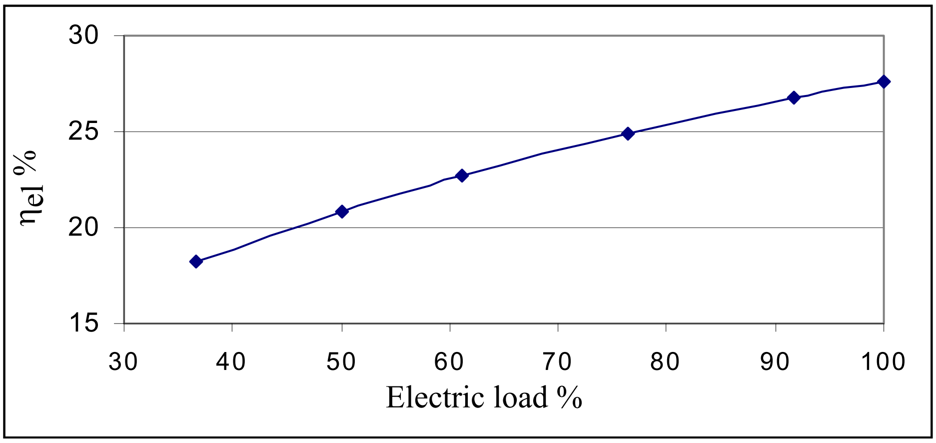

Figure 1.26 - Dependence of the electric efficiency to the electric load

Other results obtained by using the proposed model are shown in annex 1.

CHAPTER 2

Exergy and Thermoeconomic Analysis

In this chapter some tools necessary to achieve the diagnosis purposes are presented. First of all the exergy analysis is introduced. Its application to thermal power plants gives some information about how systems work: it allows to define an efficiency for the components, which is an index of the theoretical possible improvement. Moreover the concept of specific exergy includes the concept of energy quality, so that the degradation of an energy flow, i.e. the reduction of its quality, is associated to a reduction of its exergy. Nevertheless the application of the exergetic analysis does not give all the informations necessary for operation like design and analysis of energy systems: technical and economic constraints are usually not negligible; so the results of the exergetic analysis of the system components are not generally comparable among them. Finally the irreversibilities in the plant components are not equivalent, as the same exergy destruction corresponds to a different fuel impact.

The concept of exergy is then used joined with the economic concept of cost, as it is a better measure of the quality of a flow than the simple energy is. This second step has been called Thermoeconomics [Tribus, Evans 1962]. The application of thermoeconomic analysis is generally made to determine the cost of all the flows in a plant, which allows to make the cost accounting of its products or to calculate the optimum design, taking into account technical and economic considerations. In this thesis the calculation of the costs of flows and the knowledge of the structure of costs, i.e. how the transformations realized by the components affect the costs, are used for the thermoeconomic diagnosis. The general principles of Thermoeconomics are shown in this chapter, and a general theory of Thermoeconomics, called *Structural Analysis* [Valero et Al. 1993], is presented.

2.1 The exergy analysis

Thermal systems are designed to transform one or more kinds of energy into other more useful forms, like electricity, heat etc. The amount of energy entering the plant is equal to the exiting one, but not all the exiting energy is generally useful. The ratio between the useful energy exiting the plant and the total energy entering the plant is not a rational way to express the efficiency of the system because it requires the definition of what is useful and what is not. If the whole energy exiting the plant were useful, its efficiency would be unitary. In this way most of the energy converters constituting a thermal power plant could have unitary efficiency, or closed to this value, while the components having a high energy loss are told be characterised by a low efficiency. As an example it is possible to consider a steam power plant: if 100 MW of fuel are introduced, almost 42 MW of electric power can be obtained, 5 MW are loss by the exhausted gas exiting the boiler and 40 MW are loss by the condenser. The condenser is so the component where are localized the higher energy losses, so the first law put it on evidence as the component to be improved. The application of this definition of efficiency, based on the first law of thermodynamic, lacks information: no losses are associated to adiabatic processes like heat exchange or lamination; moreover no concept of utility is associated to energy flow, i.e. a 40 MW thermal flow exiting the steam power plant by the condenser (at about 20 °C) can be compared with a 40 MW thermal flow at 120 °C. First law does not tell that the last considered flow can be used for urban heating, while the first one does not have any engineering application. This is due to the absence of an important consideration: not all the kinds of energy are equals. The second law of thermodynamic give us the way to take it into account, so thermodynamic analysis will be based here on the *use* of *the second law, first*, as Gaggioli and Petit titled an article in 1977, [Gaggioli, Petit 1977].

The forms of energy can be divided into two groups: ordered energy and disordered energy [Brodyansky et al. 1994]. The first group includes the forms which can be transformed in any other forms of energy, while the second one includes the forms which are not characterized by this property. The part of energy which can be transformed in any other kind of energy is called exergy, the rest is defined anergy. The ordered energies (electrical, nuclear and work) are characterised by an amount of exergy equal to the amount of energy and by a null entropy. The disordered energies (molecular, chemical and heat) are characterised by value of entropy different to zero. As the second law of thermodynamic permits processes that altogether increase the entropy or maintain it constant, its application to a thermal system allows to verify the theoretical possible realisation of a process. The definition of the system efficiency using the concept of exergy gives a lot of information: a high efficiency means a good use of the resource quality [Wall 1999]. As an example it is possible consider an electric heater in a room: the first law efficiency of this system is unitary while the second law one is closed to zero. This is because the second law put on evidence the bad use of a high value energy, such as the electric energy, to obtain heat at the internal environment temperature.

Exergy is so the ‘potential energy’, i.e. the capacity to cause change for us [Gaggioli, Petit 1977], while energy alone does not tell anything about this capacity. In alternative exergy can be defined as the minimum work required to obtain a whole of substances in a particular state, starting from the substances available in the environment at its condition [Bejan et Al. 1996]. These definitions require the use of a reference state, which is a condition characterised by a known value of the exergy. This state is defined by a pressure, a temperature and a chemical composition. The exergy of the system in whatever condition is so a measure of the difference between the two states. When the system is in equilibrium with the environment it could not evolve spontaneously; this system condition is called dead state. The reference state, or reference environment, is a system characterised by thermodynamic properties which do not vary in spite of the interactions with other systems. This condition corresponds to consider the environment as a system characterised by an infinite mass. For engineering purpose this is realised when the environment is large enough to neglect the interation effect.
The exergy balance of a system can be expressed using a linear combination of first and second law of thermodynamic [Calì, Gregorio 1996]:

$$\sum_{j=1}^{J} \Phi_j + \Phi_0 - W_t - W_0 = \frac{dU^{(t)}}{dt} + \sum_{k=1}^{N} \pm G_k \cdot h_k^{(t)} \tag{2.1}$$

$$\sum_{j=1}^{J} \frac{\Phi_j}{T_j} + \frac{\Phi_0}{T_0} + \Sigma_i = \frac{dS}{dt} + \sum_{k=1}^{N} \pm G_k \cdot s_k . \tag{2.2}$$

Equation 2.1 and 2.2 are the first and the second law of thermodynamic written for an open system, i.e a system which can exchange mass and energy with other systems. The terms in them are:

- Φ_j thermal flow exchanged with a system at a temperature T_j (or with the environment in the case of Φ_0);
- J is the number of thermal sources, i.e. systems which the system exchanges thermal flows with;
- W_t mechanical shaft power;
- W_0 mechanical power obtained by the control volume variation;
- $U^{(t)}$ total internal energy of the system;
- G_k mass flow of the k^{th} flow;
- N number of mass flows entering or exiting the system
- h_k specific enthalpy of the k^{th} flow;
- Σ_i entropy generation;
- S entropy of the system
- s_k specific entropy of the k^{th} flow;

(Exergy equation) = (First law) - T_0 * (Second law)

$$\sum_{j=1}^{J} \Phi_j \cdot \left(1 - \frac{T_0}{T_j}\right) - W_t = \frac{d}{dt}(U^{(t)} + p_0 \cdot V - T_0 \cdot S) + \sum_{k=1}^{N} \pm G_k \cdot (h^{(t)} - T_0 \cdot s)_k + T_0 \cdot \Sigma_i. \quad (2.3)$$

This equation is the law of degradation of the energy, which is due to the irreversibilities of real processes. It can be written in a more compact form:

$$\Psi_q - W_t = \frac{dA^{(t)}}{dt} + G_b + \Psi_i \quad (2.4)$$

where:

- Ψ_q is the exergy flow associated to the thermal flows;
- $A^{(t)}$ is the total internal available energy. Its derivate is zero in steady state condition;
- G_b is the exergy flow associated to entering and exiting mass flows;
- Ψ_i is the destroyed exergy flow.

The equation 2.3 points out that the maximum theoretical work can be obtained from a system only if the process is reversible, which corresponds to a null value of the term of exergy destruction Ψ_i. The exergy destruction is due to the irreversibilities of real transformations. The main causes of exergy destructions in industrial processes are [Moran, Shapiro 1995]: free (non controlled) chemical reactions, free expansions of fluids, free mix of fluids, free heat transfer, inelastic deformation, electricity flow in a resistance, friction and magnetic hysteresis.

If no chemical reaction are involved in the process, the total exergy of the stream can be divided into physical, kinetic and potential components. Potential exergy is usually negligible in the analysis of thermal power plant, as its contribution is low. Kinetic exergy is not generally negligible, in particular if the control volume intersect a rotor, like a turbine stage, where important variations of the fluid velocity occur. Physical exergy can be ulteriorly split into two components: thermal and pressure components.

These two components can be founded for a stream of substance in the state 1, simply considering a reversible process starting from state 1, characterized by a temperature T_1 and a pressure p_1, and ending at the state corresponding to the environmental condition. As the exergy involved in a reversible process does not depend on the process itself, it can be considered composed by a first isobaric transformation, at pressure p_1, and a successive isothermal transformation, at the environment temperature T_0 [Kotas 1995]. The exergy obtained by the first transformation:

$$b_T = \left[-\int_{T_1}^{T_0} \frac{T - T_0}{T} dh \right]_{p_1} \tag{2.5}$$

is defined thermal component of physical exergy and it is due to a temperature difference between the stream and the environment. The pressure component of physical exergy, also called mechanical exergy, is defined:

$$b_M = T_0 \cdot (s_0 - s_i) - (h_0 - h_i) \tag{2.6}$$

where the subscript *i* refers to the state at the end of the first (isobaric) transformation. Mechanical exergy is due to a pressure difference between the stream and the environment. The separation of the components of physical exergy is an useful procedure in the thermoeconomic analysis, as it will be shown in the next parts, but unfortunately their exact calculation is possible only for ideal gases and incompressible liquid. This operation has been also discussed in literature for water, which can be present in different phases (liquid, saturated vapour or supersaturated vapour) in thermal engineering applications [Tsatsaronis et Al. 1990].

If chemical reaction are involved in the system, a fourth component of exergy must be considered: the chemical exergy. It represents the maximum technical work obtainable by a system, at the same temperature and pressure of the environment, brought into equilibrium with it. The chemical composition of the environment must be defined first. This step consists on the choice of a reference substance at least for any chemical element involved in the analysed process. The concentration of every reference substance must be specified too. Chemical exergy is sum of two terms: the reaction component (b^r_{ch}) and the concentration component (b^c_{ch}) [Brodyansky et al. 1994]. The first term represents the exergy required to obtain the substance, starting from substances contained in the reference environment. The second term is due to a different concentration of the reference substances in the system (really present or required for the reactions defining the term b^r_{ch}) and in the environment.

$$b_{ch} = b^r_{ch} + b^c_{ch}. \tag{2.7}$$

The reaction term is calculated considering a theoretical (reversible, isothermal and isobaric) oxidation reaction where the oxidizer and the products are substances of the reference environment [Tsatsaronis et Al. 1989]:

$$b^r_{ch} = -\Delta g_0 - \nu_{ox} \cdot b^r_{ch_{ox}} + \sum_l \nu_l \cdot b^r_{ch_l} \tag{2.8}$$

where:

Δg_0 is the molar Gibbs function for the reaction;

υ is the stoichiometric coefficient of the considered reference substance (oxidizer or products);

ox refers to the oxidizer;
l refers to the reaction products.

The concentration term is differently evaluated according on the mixture is between liquids, solids or gases, i.e. if the substances belong to hydrosphere, lithosphere or atmosphere [Morris, Szargut. 1986]. If a gas mixture is considered the term can be evaluated as:

$$b^c_{ch} = \sum_m x_m \cdot b^c_{ch_m} + R \cdot T_0 \cdot \sum_m x_m \cdot \ln x_m \tag{2.9}$$

where:
m indicates the gas composing the mixture;
x is the mole fraction of the m^{th} substance.

The definition of the environment conditions is an important step of the exergy analysis. Usually the pressure is assumed 1 atm, while temperature is assumed between 0°C and 25°C, but those values can be chosen by the analyst, depending on the case studied. The really delicate part is the choice of the environment chemical composition. Many authors have proposed different possibilities: some of them are global environment, i.e. are the same for the whole world, built considering portions of oceans, Earth's crust and atmosphear [see for example Szargut, Dziedzieniewicz 1970; Ahrends 1980], while other ones are local [Wepfer, Gaggioli 1980; Guallar, Valero 1988; Lozano, Valero 1988]. This last type allows to consider the effect on the plant of the different concentration of substances in the environment, which can mark the difference between, for instance, the exergy (and successively the cost) of water in the Sahara desert or at the North Pole [Rodriguez 1980]. The choice of the environment chemical composition can have repercussion on the results of the analysis [Arena 1997]. As the only chemical reaction in the analysed plant is a complete combustion involving air (considered as a mixture of oxigen and nitrogen) and natural gas, a possible choice is to consider zero the exergy of molecular oxigen, molecular nitrogen, carbon dioxide and liquid water at temperature and pressure of the environment.

The exergetic evaluation of systems is usually made by using the efficiency as an index, which can assume different expressions. Here is reported the rational efficiency [Kotas 1995], defined as the ratio beween the exiting and the entering exergy flows:

$$\varepsilon = \frac{\sum \Psi_{out}}{\sum \Psi_{in}} \tag{2.10}$$

2.2 Fuel, Product and Exergetic Efficiency

Every component in a system plays a role, giving its contribution so that the system could supply its products. The mathematical expression of this role, made using the exergetic analysis, allows the definition and the calculation of the process efficiency, according to the following considerations.

The energy transformation carried out by a component is driven by one ore more resources, which can be expressed in terms of exergy fluxes. These ones are the component *fuel*, F. Similarly, the exergy fluxes which are identified as the contribution of the component to the system production are the component *product*, P. Other fluxes can exit a component, but their usefulness is null or their use in the process is not convenient. These fluxes are called *losses*, L. The sum of the exergy losses and the exergy destructions represents the total irreversibilities of the components, here indicated as I:

$$I = L - \Psi_i \tag{2.11}$$

The definition of fuels and products has a certain grade of arbitrary, as no rules are universally accepted, so that the experience of the analyst is usually helpful. The definition can involve exergy fluxes identified with physical fluxes or a composition of them. As an example the boiler of a steam power plant represented in figure 2.1 can be considered.

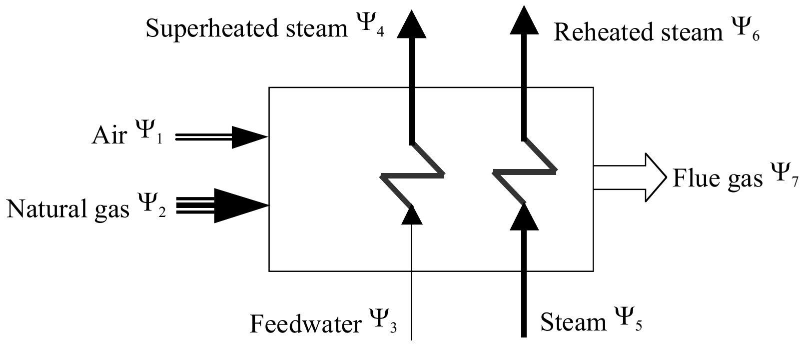

Figure 2.1 - Exergy flows in a steam power plant boiler

The fuel of the plant can be considered as the sum of exergy fluxes associated to natural gas ($\Psi 2$) and to air ($\Psi 1$). The system is characterised by two products: the exergy flow transferred to the feedwater to obtain superheated steam ($\Psi 4$-$\Psi 3$) and the exergy flow necessary to reheat the steam ($\Psi 6$-Ψ_5). Finally the losses are represented by the exergy flow of flue gas ($\Psi 7$). Alternatively the fuel can be assumed as the sum of the exergy fluxes entering the component, while the product will be the sum of the exiting fluxes, except the flue gas, which is usually considered as a loss if no component can recuperate its exergy contents.

The definition of fuel and product can also involve the mechanical, thermal and chemical components of exergy. If the pipes of the boiler, trough water flows, are characterized by pressure drops, as in the reality happens, mechanical exergy decreases between the entering and the exiting fluxes. This needs a pump to compensate the pressure drop. In this way the variation of mechanical exergy between the entering and exiting steam flows are fuel of the component:

$$F = \Psi_1 + \Psi_2 + (\Psi_{3M} - \Psi_{4M}) + (\Psi_{5M} - \Psi_{6M}).$$

The product of the component becomes the increase of thermal exergy flow in the heater and reheater:

$$P = (\Psi_{4T} - \Psi_{3T}) + (\Psi_{6T} - \Psi_{5T}).$$

Sometimes a component plays more than one role: the main role and the secondary roles. This means that the process provides, besides the main product, other fluxes which can be useful in other parts of the plant or outside it. These fluxes are called *by-products*. As an example the role of the compressor in a gas turbine plant is to increase the pressure of the entering air, nevertheles also the temperature increases. The increase of the mechanical exergy flow represents the product of the compressor, while the increase of thermal exergy flow represents its by-product. Fuel of the component is the mechanical exergy flow entering by the shaft.

The ratio between product and fuel is the component efficiency. The efficiency is always lower than 1, in fact the exergy of product is lower than the fuel one, according to the second law of thermodynamic, because of the irreversibilities in the real processes. Moreover losses can further contribute to make the efficiency lower.

Using these concepts the expression of the exergetic efficiency is:

$$\varepsilon = \frac{P}{F} \tag{2.12}$$

and considering the exergy flows balance:

$$P = F - I \tag{2.13}$$

it is also possible to write:

$$\varepsilon = \frac{F - I}{F} = 1 - \frac{I}{F} \tag{2.14}$$

which shows that efficiency is a quantity lower than 1 in the real processes.

Exergy analysis gives interesting information to engineering designers and analysts. Exergy destructions and efficiency are in fact powerful quantities to understand where a process can be theoretically improved and to check how a system is working too. Nevertheless this tool is not sufficient: what is thermodynamically feasible can be not technically or economically feasible. For this and other reasons, reported forward in this chapter, some economic concepts are introduced in the approach, in particular the concept of cost.

2.3 Thermoeconomic analysis. Exergetic and thermoeconomic cost

Thermoeconomics is a powerful tool for the analysis of the energy systems which has been developed keeping together the principles of thermodynamics and economic concepts. In this way the theoretical improving of the system are also evaluated from the economic point of view.

The concept of cost involves what is necessary to spend in order to obtain a good, which means not only money, but resources in general, like energy, materials, fuel, people, knowledge. A cost can express the amount of money for a process, but also, for example, the amount of energy, or, using the concepts expressed above, the amount of exergy. As exergy flow is a quantitative and qualitative evaluation of a flow in a power plant, the cost is the amount of external resources, measured in exergetic units, necessary to dispose of it. This definition of cost is known in scientific literature as *exergetic cost* [Lozano, Valero 1993].

The cost is a property fulfilling a balance equation, i.e. if a system is considered, the sum of the costs corresponding to the entering fluxes must be equal to the sum of the costs of the exiting fluxes. The cost rate corresponding to the system must be included too, but its value can be assumed zero, depending on the objective of the analysis.

The goods in a energy system are its products: electricity, heat, water, etc. which are identified by some of the output fluxes. The inputs are physical fluxes of materials or energy entering the plant. The cost can be written in a general form $G_X{}^*$ as product of the flow G of an extensive property X (to which corresponds the intensive property x), assumed as quantitative measure of the flux, and the unit cost c:

$$G_x{}^* = c \cdot G_x . \qquad (2.15)$$

Table 2.1 reports some examples of cost expressions.

Kind of cost Unit of measurement	Kind of extensive property Unit of measurement of the flow (G)	Unit of measurement of the unit cost
Money - \$/s	Mass - kg/s	\$/kg
Money - \$/s	Energy - kW	\$/kJ
Money - \$/s	Exergy - kW	\$/kJ
Energy - kW	Mass - kg/s	kJ/kg
Energy - kW	Energy - kW	kJ/kJ
Energy - kW	Exergy - kW	kJ/kJ
Exergy - kW	Mass - kg/s	kJ/kg
Exergy - kW	Energy - kW	kJ/kJ
Exergy - kW	Exergy - kW	kJ/kJ

Table. 2.1 - Some measures for the cost of flows.

The first step of a thermoeconomic analysis procedure consists on the assignment of a cost to the exergy flows entering the plant from outside the system. These flows can be easily evaluated if they enter the plant directly from the environment, in fact the exergetic cost can be assumed equal to the exergy of the flow. If the flows enter the plant from another system their cost must be evaluated taking into account the process that makes it disposal, e.g. a fossil fuel like oil is the result of a process of extraction and distillation of petroleum, so the exergetic cost this process should be evaluated. Nevertheless the cost of fossil fuel is usually assumed equal to the exergy flow, neglecting the previous processes.

As shown in paragraph 2.2 a component uses resources to supply its product to another component or to the environment, so it can be represented as shown in figure 2.2. Such a scheme, where fuels and products of the components of a system are reported, is called productive structure.

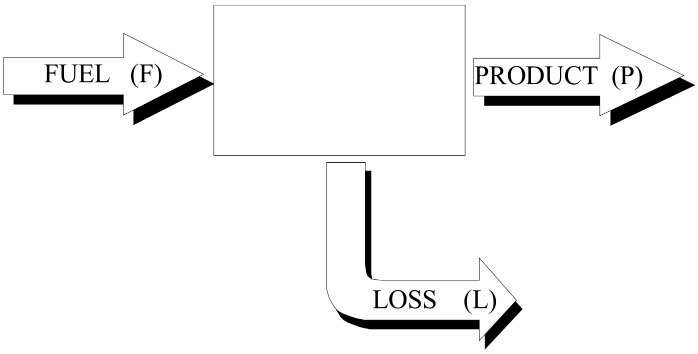

Figure 2.2 - Productive structure of a general system

If F* is the exergetic cost of the resources of the system, however it is evaluated, and F* and L* are the exergetic costs of product and losses, the cost balance of the system is:

$$F^* = P^* + L^* + \Psi^*_S . \tag{2.16}$$

where Ψ^*_S is the exergetic cost rate associated to the system, which represents the amount of exergy, distributed on the its period of useful life, that has been necessary to build the system and made it able to work. This cost is not considered if the aim of the exergetic cost analysis is the process diagnosis, but it provides useful information if a complete environmental impact judgement is required.

As the losses have not any utilities in other system processes, their cost must be assumed zero. In this way the cost of their production is charged on the plant products. In this case the equation 2.16 becomes:

$$F^* = P^* . \tag{2.17}$$

Unit exergetic costs are obtained dividing each cost for the respective exergy flow:

$$k^*_F = \frac{F^*}{F} \tag{2.18}$$

$$k^*_P = \frac{P^*}{P} . \tag{2.19}$$

Joining the equations 2.17, 2.18 and 2.19 it is possible to obtain a relation between fuel cost and product cost:

$$k^*_P = \frac{P^*}{P} = \frac{F^*}{P} = \frac{1}{\varepsilon} \cdot \frac{F^*}{F} = \frac{1}{\varepsilon} \cdot k^*_F \tag{2.20}$$

So:

$$k^*_F = \varepsilon \cdot k^*_P . \tag{2.21}$$

The exergetic efficiency is a quantity lower the 1, so the unit cost of the product of a component is higher than the cost of its fuel, due to exergy losses and irreversibilities; if the component carried on a reversible transformation and no losses occur, the two cost will be equal, but this is not a real case.

A quantity, called unit exergy consumption, defined as the fuel necessary to obtain a unit of product in a component can be introduced:

$$k = \frac{F}{P} = \frac{1}{\varepsilon} \tag{2.22}$$

the equations 2.20 and 2.21 can be written:

$$k^*_P = k \cdot k^*_F \tag{2.23}$$

$$k^*_F = \frac{1}{k} \cdot k^*_P . \tag{2.24}$$

How it has been said before, the first and main applications of Thermoeconomics are connected to the economic aspects of the energy systems, like the cost accounting or the design optimization. In these applications costs are expressed in a economic scale and represent the amount of money necessary to obtain the flows. These costs, called thermoeconomic costs, take into account the appropriate contribution of the capital cost rate of the components too. In this way the balance of a component is:

$$\Pi_F = \Pi_P + \Pi_L + Z \tag{2.25}$$

where:

Π is the thermoeconomic cost associate to a flux in the productive structure;

Z is the 'appropriate' contribution of the capital cost rate of the component.

The word 'appropriate' means that the components of the capital cost that must be considered depends on the purposes of the analysis [Tsatsaronis, Winhold 1985]. For example if the costs of the products of every components of the system have to be calculated it is necessary to consider the levelized costs of the capital investment, operation and mainteinance. A method to do split these costs on the components can be found in literature [Bejan et Al 1996].

The capital cost rate is a quantity dimensionally coherent with the cost of the fluxes and represents the amount of money which is necessary to pay in every time unit for the component. Its expression is:

$$Z = C \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \cdot \frac{1}{h \cdot 3600} \tag{2.26}$$

where:

C is the cost of the system at the present;

i is the effective rate of return;

n is the economic life of the system expressed in years;

h is the number of hours which the system works in a year;

As described ahead, the term C, and therefore the term Z, can include different contributions depending on its use: equipment cost investment, total cost investment including also land, buildings, staff, engineering, etc. and operation and maintenance. When the thermoeconomic costs of all the fluxes must be calculated, the cost rate corresponding to every components is needed. A good procedure to achieve this objective consist on splitting the total cost of the plant into all the components by mean of empirical formulae, which define the cost of a component in function of some characteristic parameters. This kind of procedure is particularly useful in the optimization problems, when the sizes of the components are generally unknown data [Frangopoulos 1983, Santarelli 1998]. In these cases cost estimating charts can be used too [Bejan et al. 1995]. These ones reports the cost of an equipment in function of the size parameter which best represents the function of the component, like the heat transfer area for a heat exchanger or the pressure ratio for a compressor. The curves reported on these charts can be designed using an expression like:

$$C = C_k \cdot \left(\frac{X}{X_k}\right)^{\alpha} \tag{2.27}$$

where:

C_k	is the known cost of the equipment of a particular size X_k;
X	is the size of the equipment which cost is unknown;
α	is a coefficient depending on the kind of equipment.

The unit thermoeconomic costs can be evaluated as shown for the exergetic costs:

$$c_F = \frac{\Pi_F}{F} \tag{2.28}$$

$$c_P = \frac{\Pi_P}{P} \tag{2.29}$$

while the cost of the losses is usually assumed zero.

The unit costs defined in this paragraph are average costs as they are calculated dividing the total cost of a flow for the exergy associated with the flow itself. Another kind of unit cost can be also defined: the marginal cost. It represents the production cost of the successive unit of product. In this way the marginal cost expressed in exergetic units is the amount of fuel necessary to increase the product obtaining one unit more, mathematically defined as:

$$k^* = \frac{\partial E_0}{\partial P_i} \tag{2.30}$$

where E_0 is the total fuel of the plant and P_i the product of the i^{th} component.

The use of this cost is usually for optimization purpose, while the average cost is helpful in the system analysis (see for example [Reini et al 1995]). The average cost is determined once the amount of resources necessary to obtain the product is known. It is not possible to calculate the resource necessary to obtain a different amount of product $P_i+\Delta P_i$ using the average unit cost, but it is necessary the use of the marginal cost.

2.4 Some parameters for the thermoeconomic evaluation

The equations written above show that the bigger is the difference (or the ratio) between the exergy flows of fuel and product, the bigger is the difference between the unit costs of product and resources. This also means that the irreversibilities and the exergy losses make the unit cost of the products bigger than the unit cost of the fuel. The difference between the unit cost of product and fuel is a powerful index, depending, for an isolated component, on the transformation efficiency:

$$\Delta k^* = k^*_P - k^*_F = \frac{P^*}{P} - \frac{F^*}{F} = \frac{P^*}{P} - \frac{\varepsilon \cdot F^*}{P} = \frac{P^*}{P} - \frac{\varepsilon \cdot P^*}{P} = k^*_P \cdot (1-\varepsilon) \tag{2.31}$$

otherwise:

$$\Delta k^* = k^*_P - k^*_F = \frac{P^*}{P} - \frac{F^*}{F} = \frac{1}{\varepsilon} \cdot \frac{P^*}{F} - \frac{F^*}{F} = \frac{1}{\varepsilon} \cdot \frac{F^*}{F} - \frac{F^*}{F} = k^*_F \cdot \frac{1-\varepsilon}{\varepsilon}. \tag{2.32}$$

The definition of this parameter also contains the unit cost of fuel or product: this means that its value is higher for the components characterised by a higher cost of fuel (or product), what not necessarily occur at the end of the physical processes. In this way the parameter indicates how a component uses its resources, in fact a penalty is assigned to the component not only depending on the inefficient use of the resources, but also proportionally to their unit cost.

The difference between the unit costs of product and fuel can be also expressed using monetary units :

$$\Delta c = c_P - c_F = \frac{\Pi_P}{P} - \frac{\Pi_F}{F} = \frac{\Pi_P}{P} - \frac{\varepsilon \cdot \Pi_F}{P} = \frac{\Pi_P}{P} - \frac{\varepsilon \cdot (\Pi_P - Z)}{P} = c_P \cdot (1-\varepsilon) + \frac{\varepsilon \cdot Z}{P} \tag{2.33}$$

otherwise:

$$\Delta c = c_P - c_F = \frac{\Pi_P}{P} - \frac{\Pi_F}{F} = \frac{1}{\varepsilon} \cdot \frac{\Pi_P}{F} - \frac{\Pi_F}{F} = \frac{1}{\varepsilon} \cdot \frac{\Pi_F + Z}{F} - \frac{\Pi_F}{F} = c_F \cdot \frac{1-\varepsilon}{\varepsilon} + \frac{1}{\varepsilon} \cdot \frac{Z}{F}. \tag{2.34}$$

This parameter, usually divided for the unit cost of the fuel, is one of the most used, in the optimization procedure [Tsatsaronis 1995].

Another important parameter, suggested by Tsatsaronis [Tsatsaronis, Winhold 1985], is the exergoeconomic factor:

$$f_P = \frac{Z}{Z + c_F \cdot I} \tag{2.35}$$

which can be also written:

$$f_P = \frac{Z}{Z + c_F \cdot (F - P)} = \frac{Z}{Z + c_F \cdot F - c_F \cdot P} = \frac{Z}{c_P \cdot P - c_F \cdot P} = \frac{Z}{\Delta c \cdot P}. \tag{2.36}$$

The exergoeconomic factor of a component is so the ratio between the investment cost of the component and the total impact of the component on the cost, which is represented by the increment of cost due to irreversibilities and losses and to the investment cost of the component. If a component is characterized by a small value of the exergoeconomic factor it is theoretically convenient improve its efficiency, investing on it a larger capital.

The use of this parameter in the plant design is usually made together with other thermoeconomic parameters (see [Arena 1997]). In particular a procedure for the plant effectiveness cost improving is described in literature [Bejan et al 1996]. This procedure is based on the use of the exergoeconomic factor together with the capital cost rate Z and the cost rate of exergy destruction, in order to determine the best order of the components to which the analysis. This last parameter is defined as the product of the flux of exergy destruction in a component and the unit cost of the component fuel:

$$\Pi_I = c_F \cdot \Psi_i \tag{2.37}$$

2.5 Matrix Approach for System Analysis

The complex system analysis is usually made using computers, which make useful matrix representations and calculations. The introduction of this technique was made in the fluidodynamic calculation for pipe network [Shamir, Howard 1968]. The whole network is described using the concepts of *branch*, which represents a pipe, and *node*, which represents the joining point of two or more pipes. Every pipe is delimited by two nodes. The whole system topology is then described by mean of a matrix, called incidence matrix, having as many rows as the nodes are and as many columns as the branches are. Once a conventional verse is assumed for every branch, not necessarily coinciding with the real verse, the element i, j of the incidence matrix is 1 if the branch *i* exits the node *j*, -1 if it enters or 0 if it does not interact the node (see for example [Calì, Borchiellini 1987]).

This approach was introduced to evaluate the pressure in every node and the mass flow in every pipe and successively applied to the heat transfer problem too [Chandrashekar, Chinneck 1984], but using a complex model, which makes difficult the application to the power plant analysis.

Every component in a power plant can be identified with a branch. It is usually connected to other components in more than two points, so it can be delimited by more than two nodes. Moreover the aims of a power plant analysis generally require the knowledge of mass flow, pressure and temperature, of the all flows entering and exiting each control volume and the energy flows not associated to fluid too, like mechanical power, heat flows exchanged etc. This means that the fluidodynamic definition of node is not available, because it does not guarantee a univocal identification of the temperature. As an example it is possible consider the mix of two flows at different temperatures. The fluidodynamic node does not permit to consider different values for the two entering flows and for the exiting one.

The same problem arises in the fluidodynamic and thermal analysis (and thermodynamic too) of district heating network [Borchiellini et al. 1999].

For all these reasons the ideas of branch and node is quite different in the energy system applications, where thermal component of energy is not negligible. A branch identifies a component and a node identifies the cross section joining two components, so that in every node it is possible define values of mass flow, pressure and temperature if a fluid flows through the cross section, otherwise a value of energy flow can be defined in the other cases. The incidence matrix, usually indicated as ***A***, is characterised by as many rows as the components are and as many columns as the flows are. The element A_{ij} of the matrix is 1 if the flow *j* enters the component *i*, -1 if it exits or 0 if it does not interact the component (see for example [Valero et Al. 1986]).

If the Moncalieri gas turbine power plant, represented in figure 2.3, is considered

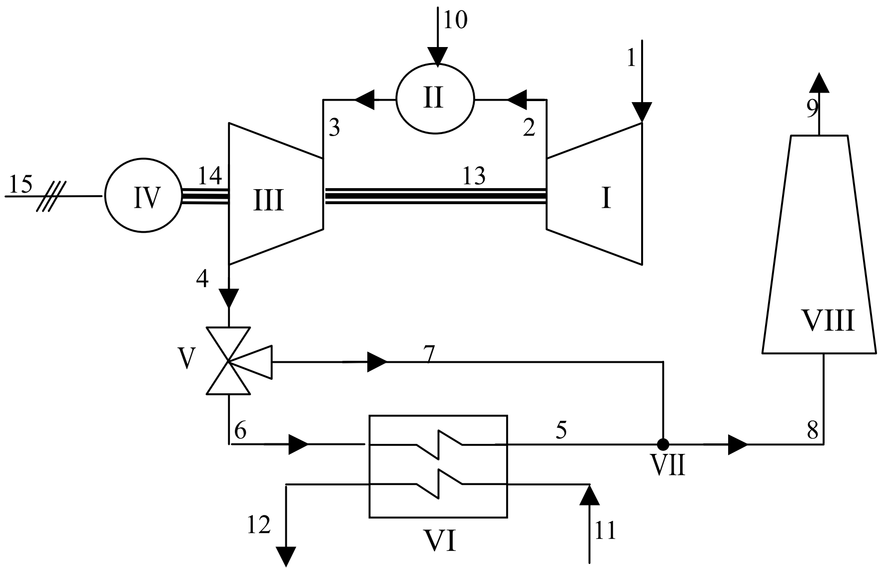

Figure 2.3 - Scheme of the Moncalieri gas turbine plant

the incidence matrix is:

$$\mathbf{A} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

A property of the incidence matrix is that the sum of every column is different to zero only in the cases of flows entering or exiting the system.

The incidence matrix directly allows to write the balances of mass, energy and exergy flows:

$$\mathbf{A} \cdot \mathbf{G} = \mathbf{0} \tag{2.38}$$

$$\mathbf{A} \cdot \mathbf{G_h} = \mathbf{0} \tag{2.39}$$

$$\mathbf{A} \cdot \mathbf{G_b} = \Psi_\mathbf{i} \tag{2.40}$$

where:

G is the vector of mass flows (zero for the nodes not crossed by fluids);
$\mathbf{G_h}$ is the vector of energy flows;
$\mathbf{G_b}$ is the vector of exergy flows;
$\Psi_\mathbf{i}$ is the vector of destroyed exergy flows in each component;

which means that the same incidence matrix is available for whatever system balance is needed.

The incidence matrix here used is relative to the physical structure of the plant, i.e. the structure which describes the real connection of the components. In the case of thermoeconomic analysis the incidence matrix can be use too, but it must refer to the productive structure. The productive structure is then designed considering all the components and the productive fluxes connecting them: the product of a component is the fuel of other components or one of the products of the plant; similarly the fuel of a component is product of another component or a flow entering the plant from the environment. In this way the balances of costs can be written for the whole system as:

$$\mathbf{A} \cdot \mathbf{G}_{\mathbf{B}*} = \mathbf{0} \tag{2.41}$$

$$\mathbf{A} \cdot \mathbf{G}_{\Pi} = -\mathbf{Z} \tag{2.42}$$

where:

- $\mathbf{G}_{\mathbf{B}*}$ is the vector of the exergetic costs of the flows (Fuels, Products and Losses);
- $\mathbf{G}_{\Pi}$ is the vector of the thermoeconomic costs of flows;
- $\mathbf{Z}$ is the vector of the capital cost rate of the components.

2.6 Implications of the use of thermoeconomics

The exergy analysis lacks some information, which can be taken into account, in operations like design and analysis of energy systems, using thermoeconomics. A first consideration is that not all the irreversibilities can be avoided in the real plants, due to technical and economic constraints, so not necessarily the component characterized by the higher exergy destruction is the first to improve to conveniently increase the plant efficiency. A second consideration is that the same variation of the irreversibility in the components, made one by one, has different effects on the plant behaviour and fuel consumption, depending on the position of the component in the whole process. This information has important implications in system optimization and diagnosis:

1) the improving of a component efficiency causes a different global efficiency improving, depending on the position of a component;
2) the effect of an anomaly, i.e. the worsening of a component efficiency, causes a different fuel impact, depending on the position of a component.

2.6.1 Avoidable and Unavoidable Inefficiencies

As exergy analysis does not include any technological or economic constraints, the evaluation of the irreversibilities, for example, in a steam turbine plant underlines that the steam generator is by far the component responsible of the larger amount of exergy destruction (approximately 80% of the total plant amount). A sensible reduction of this value, unless an heat recovery steam generator is used, requires the increase of the steam temperature, which is generally limited by technological constraints.

As external constraints differently operate on the plant components, the simple exergetic efficiencies are not generally comparable among them, so the evaluation of irreversibilities in a power plant so is not a sufficient criterion to represent the potential of improvement for the system components. Kotas has proposed the calculation first of the intrinsic irreversibilities, which are defined as the minimum value of irreversibilities imposed by economical, physical and technical constraints. The avoidable irreversibilities in the system components are the difference between their irreversibilities and intrinsic irreversibilities. This constitute an index of the potential of improvement of the components [Kotas 1995].

A tool to split exergy destruction into the avoidable and unavoidable components has been also proposed by Tsatsaronis [Tsatsaronis, Park 1999]. Every system is characterised by two parameters: its investment cost Z and the exergy destruction in the process, both here divided for the exergy flow constituting the system product. It is possible to presume that system improves as much as the investment cost rises, nevertheless it is not possible to bring its efficiency above a physical limit, which is lower than 1. The exergy destruction corresponding to this condition are unavoidable (*u*). The difference between the exergy destruction in the actual system condition (*F* in figure 2.4) and the unavoidable exergy destruction represents the avoidable exergy destruction (*a*).

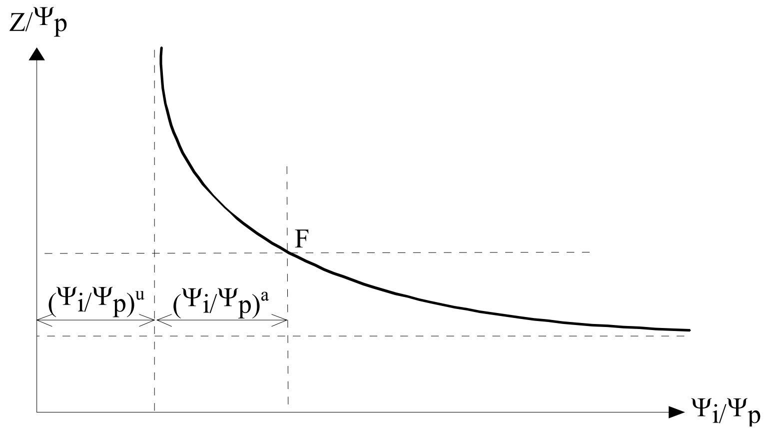

Figure 2.4 - Graphical representation of avoidable and unavoidable exergy destruction.

For the reasons above reported Tsatsaronis proposes the use of a modified efficiency, defined:

$$\hat{\varepsilon} = \frac{\Psi_P}{\Psi_F - (\Psi_i)^u} \tag{2.43}$$

which takes into account the technical impossibility to eliminate the irreversibilities in a real process.

2.6.2 The process of cost formation

The equations 2.31-2.34 show the close relation between cost variation and efficiency of a component. This relation is easy to understand for a single component, but if a complete system is considered, it becomes more complex to put on evidence the incidence of the efficiency of a particular process on the cost of the products. In this paragraph a sequential process is considered in order to explain a difference between the use of exergy and thermoeconomic methods for the plant analysis [Lozano, Valero 1993].

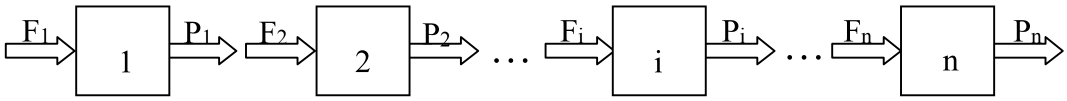

Figure 2.5 - A sequential process

The characteristic of this process is that the fuel of the component *i* is produced by the previous component *i-1*. This means that the exergy flow of the two fluxes is the same (piping exergy destructions are included in the components):

$$F_i = P_{i-1} \tag{2.44}$$

moreover, the fuel exergetic cost of the i^{th} component is equal to the product exergetic cost of the $i\text{-}1^{th}$ component:

$$F^*_i = P^*_{i-1}\,. \tag{2.45}$$

For every component the exergetic cost balance can be written:

$$F^*_i = P^*_i\,. \tag{2.46}$$

If the equations 2.45 and 2.46 are considered for all the components a cost chain can be written:

$$F^*_1 = P^*_1 = F^*_2 = P^*_2 = \ldots = F^*_i = P^*_i = \ldots = F^*_n = P^*_n \tag{2.47}$$

so the cost of all the fluxes is the same. This is not as well true for the exergetic unit cost, because of the irreversibilities; the sequential process makes the unit cost of the fuel of component *i* equal to the unit cost of the product of component *i-1*:

$$k^*_{F_i} = \frac{F^*_i}{F_i} = \frac{P^*_{i-1}}{F_i} = \frac{P^*_{i-1}}{P_{i-1}} = k^*_{P_{i-1}} \tag{2.48}$$

but for the component i the relation between the unit costs of product and fuel is represented by the equation 2.23; this one joined to the 2.48 allows to write:

$$k^*_{P_i} = k_i \cdot k^*_{P_{i-1}} \tag{2.49}$$

where k_i is the unit exergy consumption of the component *i*. If the same procedure is repeated for the components upstream, a relation between the product unit costs of the first and the i^{th} component can be written:

$$k^*_{P_i} = k^*_{P_1} \cdot \prod_{j=2}^{i} k_j \tag{2.50}$$

which can also written, applying the equation 2.23 to the first component:

$$k^*_{P_i} = k^*_{F_1} \cdot \prod_{j=1}^{i} k_j\,. \tag{2.51}$$

If the exergetic unit cost of the fuel of the first component, which enters the plant from the environment, is assumed unitary, the equation 2.51 becomes:

$$k^*_{P_i} = \prod_{j=1}^{i} k_j . \tag{2.52}$$

This equation can be used to obtain a relation between the cost of the product of a component and the product itself:

$$P^*_i = k^*_{P_i} \cdot P_i = P_i \cdot \prod_{j=1}^{i} k_j = P_i \cdot \prod_{j=1}^{i} \frac{F_j}{P_j} = P_i \cdot \prod_{j=1}^{i} \frac{P_j + I_j}{P_j} = P_i + \sum_{j=1}^{i} I_j . \tag{2.53}$$

2.6.3 Law of non equivalence of irreversibilities

Now a modification in the efficiency in a component is considered. The irreversibility in the component *i* will be:

$$I_i + \Delta I_i$$

If the total product of the plant P_n is kept constant, an increase in the irreversibility of the component *i* does not affect the components downstream *i*, but the fuel of this component varies, as well as the total fuel of the plant. The increase in the fuel of component *i* is:

$$\Delta F_i = \Delta I_i ; \tag{2.54}$$

the increase in the product of the component *i-1* is equal to the variation in the fuel of component *i*. As the efficiency of the components does not depend on the amount of entering flow, the corresponding increase in the fuel of the component *i-1* is:

$$\Delta F_{i-1} = k_{i-1} \cdot \Delta P_{i-1} = k_{i-1} \cdot \Delta F_i = k_{i-1} \cdot \Delta I_i . \tag{2.55}$$

Proceeding so on, the increase in the total fuel of the plant is:

$$\Delta F_1 = \Delta I_i \cdot \prod_{j=1}^{i-1} k_j = \Delta I_i \cdot k^*_{P_{i-1}} = \Delta I_i \cdot k^*_{F_i} . \tag{2.56}$$

Equation 2.56 is an important theoretical result: the impact of a variation of the irreversibility on the total plant fuel depends on the position of the component where it has happened, i.e. the irreversibility of the plant are not equivalent. In particular, the closer is the component where the irreversibility has increased to the plant product and the higher is the impact on the overall fuel consumption. This principle is known as principle of technical non-equivalence of the local irreversibilities [Lozano, Valero 1993]. It constitutes an important conclusion because the simple exergetic analysis does not allow to classify the irreversibilities in relation to their impact. As the thermoeconomic theories take into account this fact their use is justified in the power plant diagnosis.

Moreover, it is possible to notice that the total variation of the irreversibility in the plant is different to the local variation in component *i*. The total variation is in fact equal to the additional fuel consumption, because the total product of the plant has been supposed constant, so the application of exergy flow balance to the whole system is:

$$\Delta I = \Delta F_1 = \Delta I_i \cdot k^*_{F_i} \tag{2.57}$$

This result shows that a variation in a component efficiency affects the whole system, so that the irreversibilities vary not only in the component itself, but also in the others, in spite of their efficiency is constant. This is another important consideration at the base of thermoeconomic diagnosis and concepts like dysfunctions and malfunction [Torres et Al. 1999].

2.7 A unified procedure of thermoeconomic analysis

The thermoeconomic procedures lean on the definition of the fuel and the product of the plant components. The mathematical formulation of these assumptions, made, in modern thermoeconomics, using the second law joined with its graphical representation is called productive structure. Every thermoeconomic theory makes use of a different formalism and, above all, a different model. This means that the choice of a particular productive structure imposes to renounce to the application of some thermoeconomic methodologies and sometimes only one is possible. This can cause confusion and impedes the development of thermoeconomics in general [Tsatsaronis 1994]. The Structural Theory of thermoeconomics [Valero et al 1994] provides a general formulation, which allows the use of the same procedure whatever is the chosen productive structure, provided it fulfils some mathematical conditions analysed in this chapter. In this way the cost of the fluxes calculated using whatever thermoeconomic theory can be reproduced applying the structural theory to the same productive structure [Erlach 1998; Erlach et al. 1999].

The productive structure in the structural analysis formulation is characterized by a graphical representation, where every flux E_{ij}, entering the component j and exiting the component i, represents the fuel of the component j produced by the component i.

The application of some productive structures to the Moncalieri steam power plant and gas turbine is proposed, while a complete analysis is made in the next chapter. All of them are based on exergy as quantitative and qualitative measure of the fluxes. The separation of exergy into mechanical, thermal and chemical components and the implications of the use of negentropy to evaluate the product of dissipative units is also examined.

2.8 The productive structure

The first decision to be taken building the productive structure is which quantity to use as measure of the fluxes. In thermoeconomic disciplines it is universally accepted exergy as the scale which best represents the quality of a good in a energy system. Nevertheless the analyst can decide to split exergy into chemical, mechanical and thermal components. In the resulting structure every component of the same physical flux can have a different cost from the others. This is a first difference between the possible productive structures.

In figure 2.1 two possible productive structures of a simple gas turbine power plant are represented. The first, (a), is quite similar to the physical structure, as the fluxes are not split into components.

E_1 is the exergy flow of the natural gas;

E_2 is the exergy flow associated to the air exiting the compressor (the exergy of the air entering the compressor is assumed null);

E_3 is the exergy of the gas exiting the combustor;
E_4 and E_5 are the mechanical power produced by the turbine and
E_6 is the electric power produced by the alternator.

This kind of structure is very close to the physical one, in fact the product of every component coincide with the flux exiting the component in the physical structure. The only exception is represented by the flue gas exiting the turbine. This flux is rejected in the atmosphere at a temperature higher than the environment temperature, so its exergy is positive. This flux is not used in the productive process or made disposal for an external process, so it represents a loss. It can not exits the plant in the productive structure, because it would be considered as a product.

Such a structure corresponds to have assumed the loss as it would be an irreversibility of the last component, i.e. the turbine is charged for the loss. This is a questionable assumption, because not only the turbine is responsible for the not used resource, in fact also an isentropic turbine could not allow the complete use of the exergy contained in the gas, rejecting it at the environment temperature. The only way to obtain it in a non cogenerative plant requires the use of an air pre-heater characterized by an infinite heat transfer area. Some criteria to charge the components for the loss are shown below.

In the second productive structure, (b), the exergy of the streams is split into mechanical and thermal component. This allows to better characterize the role played by the components, in particular the compressor now supplies thermal and mechanical exergy to the combustor (E_{2T} and E_{2M}) and mechanical exergy to the turbine (E_{3M}). In this scheme the cost of mechanical exergy is so determined by the compressor, which seems to be physically correct, while in the scheme (a) the cost of mechanical exergy is hidden in the total exergy.

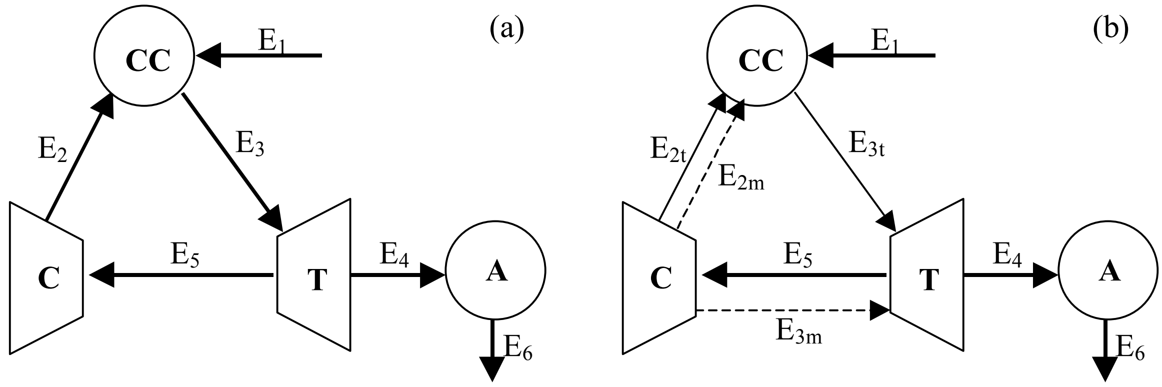

Figure 2.1 - Two productive structures for a simple gas turbine power plant

A second important difference between the possible productive structures refers to the subjective criteria to assign the cost of some fluxes. A general structure is composed by *m* components and *n* fluxes, under the condition

$$n > m; \tag{2.58}$$

as *m* cost balances must be accomplished, *n-m* auxiliary equations must be written to calculate the *n* costs, which constitutes as many degrees of freedom for the analyst. The exergetic cost of the fluxes entering the plant must be evaluated; usually this cost is assumed equal their exergy if they are associated to mass flows, like hydrocarbon fuels, water, air etc. On the contrary if the fluxes are not associated to a fluid entering the plant, e.g. a flux of electric power, an evaluation of the cost is required.

Other assumptions are generally needed, in particular there are three aspects to be taken into account:

1) the components having more than one product,
2) the use of fictitious components or fluxes and
3) the effect of the losses in the process of the cost formation.

If a component produces more than one product, i.e. a product and one ore more by-products, the usual procedure consists on equalling the unit cost of the by-products to the unit cost the flux produced by another component. This flux is required to be as similar as possible to the by-product. Other alternatives are the assumption of the same unit cost for all the products of the component, or a subjective evaluation. As an example it is possible to consider a compressor in a gas turbine power plant. An usual procedure (see for example [Lozano, Valero 1993 b]) is to assume the obtained increase of the mechanical exergy as product of the compressor while the increase in thermal exergy is considered as a by-product. In this scenery the unit cost of the by-product can be made equal to the unit cost of another thermal exergy flux produced in the plant, like the one produced by the combustion chamber. Alternatively it can be assumed equal to the mechanical exergy flux produced by the compressor. This choice mainly depends on the analyst and it can be based on his experience or sensitivity.

The product of a component can constitute one of the plant products or a fuel of other components of the system, so that a resource can become directly available for the users or be ulteriorly transformed in the plant. In this second case one or more subsystems have this flux as input. There are two possible representation of the general case: 1) the product of the component enters the downstream component and it is partially (or completely, or not at all) used by it. The remaining amount enters the successive components and so on. This first solution corresponds to a productive structure very close to the physical structure, like the one represented in figure 2.1a. 2) The product enters a fictitious component, called branching point, which splits it among the component according to their needs. This component is characterized by a null irreversibility so that the entering exergy flow equals the sum of the exiting ones; moreover the same unit cost is assumed for all the exiting flows.

An example of this kind of structures is presented in figure 2.2a. In this case mechanical exergy produced by the compressor enters a splitter ***S*** to be shared between the combustion chamber and the turbine. The branching point is not really necessary here. The same cost accounting can be obtained by representing the three fluxes directly exiting from the compressor, which implies having assumed the same unit cost for all. The component would become similar to the turbine, which provides mechanical power to compressor and alternator. The structure is so practically equal to the one represented in figure 2.1b. The branching point becomes necessary when the flux to be shared is originate by different contributions, characterised by different costs.

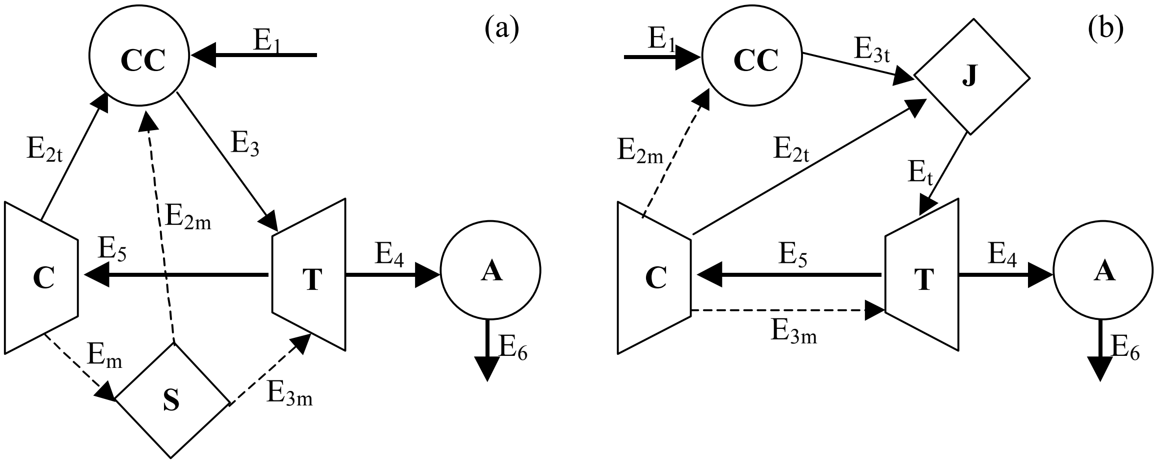

Figure 2.2 - Productive structures using fictitious components.

A similar problem arises when the same type of flux is produced by two or more components, as it happens, for example, in a gas turbine power plant, where thermal exergy flows are produced by the combustor, the compressor and, in case there are, the heat exchangers. A fictitious component, called junction, can be used for this purposes. Figure 2.2b represents an example of use of this component.

In other words, the real components make use and produce resources; the fictitious components join the resources and share them among the components, according to their needs, and without causing any variation of these quantities. This concept is well express by the engineering functional analysis approach [von Spakovsky, 1994].

Junctions are so ideal components too, which mix the entering fluxes into one without producing any irreversibilities. The impact on the assignment of costs is clear: the product of a junction is characterized by a unit cost equal to the average cost of the entering fluxes:

$$c_{out} = \frac{\sum E_{in_i} \cdot c_{in_i}}{\sum E_{in_i}} \tag{2.59}$$

where c_{in} and c_{out} respectively are the cost of the entering and exiting fluxes.

As an alternative, the direct assignment of the produced fluxes to the components is also possible. For example the LIFO procedure [Tsatsaronis 1990 and Lazzaretto, Tsatsaronis 1997] is based on the idea that the cost at which exergy is added to a stream or removed from it depends on the temperature and pressure conditions at which it happens. In this way the thermal exergy flows produced by the compressor and the combustor have a different cost. Moreover the last resource produced is the first used. In the case of the gas turbine, first the thermal exergy produced by the combustor and then the thermal exergy produced by the compressor are used.

Another feature which originate differences among the productive structures is the use of fictitious fluxes, like negentropy fluxes. Negentropy is defined as the variation of the entropy flow in a component, taken with the opposite sign and made dimensionally equivalent to an exergy flow. For the j^{th} component it is:

$$N_j = -T_0 \cdot \sum_{i=1}^{n} \mathbf{A}_{ji} \cdot G_i \cdot s_i \qquad (2.60)$$

where:

- n is the number of fluxes in the system;
- **A** is the incidence matrix;
- G is the mass flow;
- s is the specific entropy.

The use of negentropy in literature is well known [Frangopoulos 1983] (see also [Arena, Borchiellini 1999]). This concept has been introduced to define a product for the dissipative components: in a steam power plant a condenser allows to close the thermodynamic cycle, making the water up for the process. It is difficult to express a correct product only using exergy flows, in fact as the condensing fluid (water or air) is not useful, it is a loss and the only steams available for the definition of fuel and product are the entering steam and the exiting water, so the only possibility is to assign the first as fuel and the second as product. This choice has a direct and incorrect impact on the cost distributions: the exergetic cost balance of the condenser is:

$$P^* = F^* \qquad (2.61)$$

and the exergetic unit cost of the product is:

$$k^*_P = \frac{P^*}{P} = \frac{F^*}{P} = \frac{F}{P} \cdot k^*_F \, . \qquad (2.62)$$

The exergy flow entering the component is much bigger than the exiting one, so the unit cost of the product is much bigger than the unit cost of the fuel.

The use of negentropy, on the contrary, allows to define a different product for the component, expressing in a thermodynamic quantity its role in the cycle: in a very simple representation of a steam power plant the boiler, the turbines, the pumps and the pre-heaters all increase the entropy of the water, while the condenser closes the cycle, reducing it until the lowest value, as shown in figure 2.3.

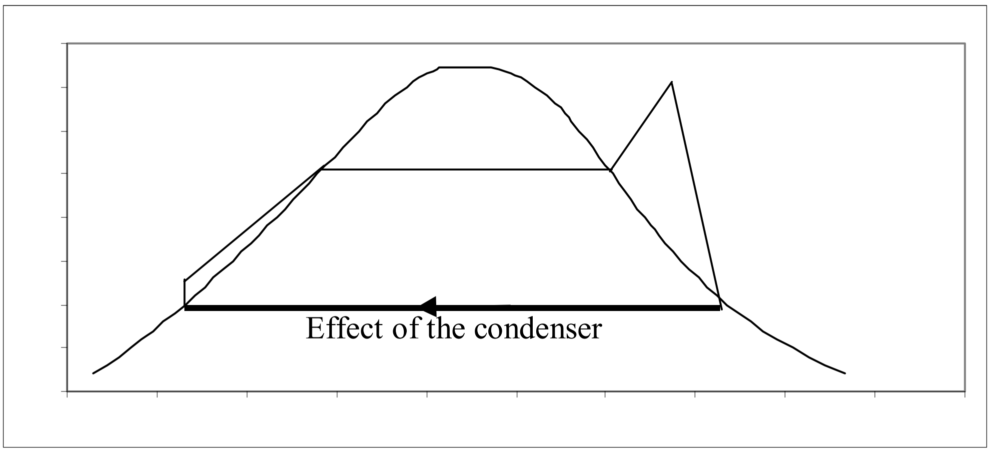

Figure 2.3 - Role of the condenser in a steam power plant

If this model is accepted, the function of the condenser is so to make the negentropy flow disposal for the other components and its fuel is the difference between the entering and the exiting exergy flows. Figure 2.4b shows the use of negentropy for a productive structure built for a simple steam turbine cycle, represented in figure 2.4a. Negentropy (dotted lines) is produced by the condenser (C) and provided by means of a branching point (B) to the steam generator (SR), the turbine (T) and the pump (P), which uses it, as they increase the entropy of the fluid. In this productive structure the exergy of the fluid produced by the boiler and the pump is not split into mechanical and thermal component. A fictitious component (JB), playing the role of junction first and branching point then, is used to provide exergy to the turbine and the condenser at its average cost.

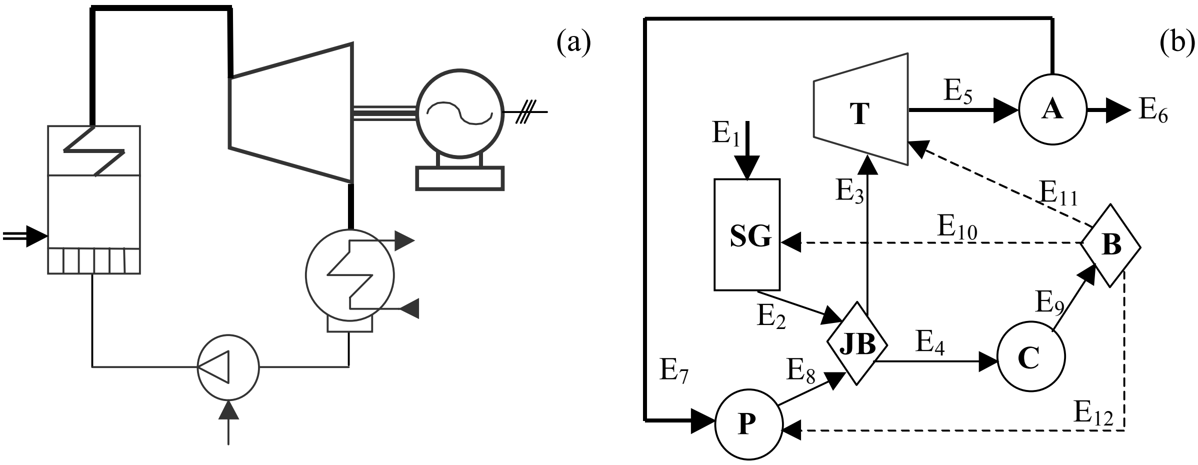

Figure 2.4 - Simple steam turbine power plant and a possible structure using negentropy

The application of the negentropy concept in the productive structure must be made very carefully, in fact its indiscriminate use can cause some anomalous costs of the fluxes. As an example it can be considered a simple combined cycle power plant. The heat recovery steam generator transfers a thermal exergy flow to the steam power plant but also reduces the entropy of the gases. If negentropy flows are used for both the steam and the gas cycles, the cost of the thermal exergy produced by the HRSG becomes lower than expected, because of the two products of the component. The final decision must be taken by the analyst, considering all the consequences of the assumptions.

Another effect generated by the use of the negentropy is the non validity of the second law expression, made in terms of fuel and product (eq 2.13), applied to every component, so:

$$P \neq F - L - \Psi_i . \tag{2.63}$$

The last aspect which can cause differences in the productive structures is represented by the impact of the losses on the costs. This problem stems from the desire of correctly charge the components for their contribution to the losses, avoiding to charge for every loss only the closest component, i.e. the component from which the stream goes out to the environment. This charge must be made because the exergetic cost of a loss flux is zero, in fact some other outputs of the system have to pay for it, as this flux is not useful.

Negentropy represents a possible solution of the problem, in fact the not useful fluids exiting the plant are characterized by an entropy higher than the entering fluxes. This means that the environment must 'close' the thermodynamic cycle, reducing the entropy of these fluxes to the value assumed at the entrance condition. In this way the environment represents a dissipative unit which produces negentropy by using the exergy contents of the losses. The application of this concept to a simple gas turbine plant is shown in figure 2.5.

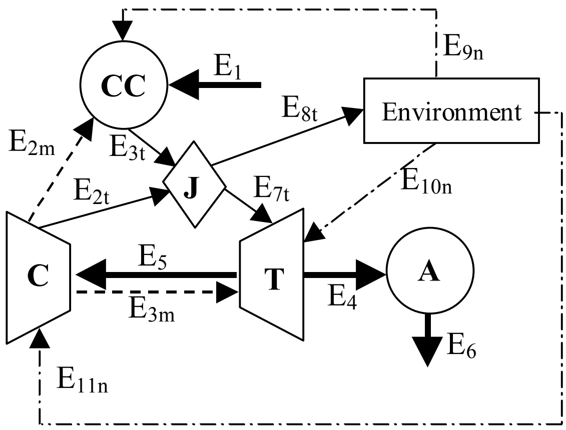

Figure 2.5 - Productive structure of a simple gas turbine using negentropy

Another possibility is represented by the direct assignment of the losses to the components, i.e. in the productive structure every component is also characterized by a loss (which can be zero for some of them). The criterion to make this assignment can be based for example on the entropy variation in every components, but can be also different depending on the analyst decision. The model fuel-product-loss [Torres 1999], allows the use of this kind of procedure in the structural analysis, and is an alternative to the use of negentropy for the analysis of dissipative units too.

2.9 Structural Analysis

2.9.1 Characteristic behaviour of the components

The thermodynamic behaviour of the components can be defined using characteristic equations. For every entering exergy flow a characteristic equation imposes a relation between this flux, the exiting exergy flows and some thermodynamic internal parameters. In this way the characteristic equation relative to the ith exergy flow entering in the uth component can be written:

$$E_i = g_i(\mathbf{E}_j, \chi_u) \qquad i \in \mathbf{I}_u \qquad j \in \mathbf{O}_u \qquad u = 1, \ldots, n \tag{2.64}$$

where:

$\mathbf{E}_j$ is the vector containing the exergy flows exiting the components of the system;

χ_u is the vector containing the characteristic parameters of the component u;

$\mathbf{I}_u$ is the whole of the component inputs;

$\mathbf{O}_u$ is the whole of the component outputs and n is the number of the system components.

In this way a characteristic equation can be written for every flux, except the *s* fluxes exiting the overall system, as they enter the environment. A external variable ω can be assigned to these fluxes, representing the amount of each system product required by the users:

$$E_i = \omega_i \qquad i \in \mathbf{I}_0 \tag{2.65}$$

where $\mathbf{I}_0$ is the whole of the environment inputs.

2.9.2 General equation of the marginal exergetic costs

According to the proposed mathematical model, the total cost of resources necessary to the system in order to obtain the required production can be expressed:

$$\Pi_0 = \sum_{i \in \mathbf{O}_0} c_i \cdot E_i + \sum_{u \in \mathbf{N}} Z_u, \tag{2.66}$$

where $\mathbf{O}_0$ is the whole of the environment outputs (i.e. the system inputs) and **N** is the whole of components. This expression is completely general, so the cost can be also expressed using thermodynamic units, such exergy.

The cost rate of the components can be modelled as an entering flux, so an equation similar to the characteristic equations can be written:

$$Z_u = Z_u(\mathbf{E}_j, \chi) \qquad j \in \mathbf{O}_u \qquad u = 1, \ldots, n \tag{2.67}$$

The total cost of the external resources is so function of the internal parameters, the plant fluxes and the required production:

$$\Pi_0 = \Pi_0(\mathbf{E}, \chi, \omega) \tag{2.68}$$

so the variation of the system resources, as an internal flux varies, can be obtained using the derivation chain rule:

$$\frac{\partial \Pi_0}{\partial E_i} = \frac{\partial Z_u}{\partial E_i} + \sum_{j \in \mathbf{O}_u} \frac{\partial \Pi_0}{\partial E_j} \cdot \frac{\partial g_j}{\partial E_i} \qquad j \in \mathbf{O}_u \qquad u \in \mathbf{N} \quad . \tag{2.69}$$

The term $\frac{\partial \Pi_0}{\partial E_i}$ is the marginal cost, i.e. the additional consumption of resources required by the system to obtain the next unit of the i^{th} flux. In the following the cost is expressed in term of exergy, so the unit cost is indicated as k^*_i.

The term $\frac{\partial g_j}{\partial E_i}$ is the marginal exergy consumption, i.e. the additional consumption of the flux E_j required by the system to obtain the next unit of the i^{th} flux. This quantity is indicated in the following as k_{ji}.

The equation 2.69 can be written using a more compact notation:

$$(\mathbf{U}_D - \langle \mathbf{EG} \rangle^t) \cdot \mathbf{k}^* = \mathbf{z_e}, \tag{2.70}$$

where:

$\mathbf{U}_D$ is the identity matrix;

$\langle \mathbf{EG} \rangle$ is the Jacobian of the characteristic functions, so a $m \times m$ matrix which elements are the unit exergy consumptions k_{ji};

k* is a $m \times 1$ vector containing the marginal costs associated to every flux and

$\mathbf{z_e}$ is a $m \times 1$ vector containing the unit costs of the entering resources and the component costs.

The equation 2.70 allows the calculation of the unit costs of the fluxes, once the unit costs of the entering fluxes and the characteristic equations are known [Torres 2000].

The internal parameters have been supposed to be independent to the fluxes exiting the component, so that a variation of these fluxes does not involve a variation of the internal parameters. This assumption constitutes a limitation in the application of the marginal costs to the system diagnosis, in fact the variation of the internal parameters relating entering and exiting exergy flows is one of the effects of the malfunctions. For this reason the average costs and unit exergy consumptions calculated in every working condition are used for the diagnosis purposes. In the next two parts a relation between marginal and average costs is found.

2.9.3 Linear model of characteristic equations

If the characteristic equation of the components are linear functions of the exiting exergy flows, the entering exergy flows can be written:

$$E_i = \sum_{j \in \mathbf{O}_u} \alpha_{ij}(\chi) \cdot E_j \qquad i \in \mathbf{I}_u \tag{2.71}$$

As the internal parameters are independent from the outlet fluxes, the coefficients α of the characteristic equation coincide with the marginal exergy consumptions:

$$\alpha_{ij}(\chi) = \frac{\partial g_i}{\partial E_j}(\chi) = k_{ij}(\chi) \tag{2.72}$$

Once the coefficients of the characteristic equations are known, the marginal exergy consumption are defined too and so the unit costs of the fluxes can be calculated using the equation 2.70.

2.9.4 Average and marginal costs

If a general component of a system, which characteristic equation is a linear function, is considered, the i^{th} entering exergy flow can be written:

$$E_i = \sum_{j \in \mathbf{O}_u} k_{ij} \cdot E_j = \sum_{j \in \mathbf{O}_u} E_{ij} \qquad i \in \mathbf{I}_u \tag{2.73}$$

where E_{ij} represents the amount of exergy flows of the i^{th} flux necessary to obtain the j^{th}

flux. According to the definition of average exergy cost:

$$E_j^* = \sum_{i \in \mathbf{O}_u} E_{ij}^* = \sum_{i \in \mathbf{O}_u} \overline{k^*}_i \cdot k_{ij} \cdot E_j \tag{2.74}$$

where $\overline{k^*}_i$ is the average exergy unit cost of the ith flux. As the flux E_{ij} enters the component, the average unit cost $\overline{k^*}_i$ is supposed known.

The marginal cost associated to the characteristic equation 2.73 is:

$$k^*_i = \frac{\partial E_0}{\partial E_j} = \sum_{i \in \mathbf{O}_u} \frac{\partial E_0}{\partial E_i} \cdot \frac{\partial g_i}{\partial E_j} = \sum_{i \in \mathbf{O}_u} \overline{k^*}_i \cdot k_{ij} \tag{2.75}$$

So the behaviour of average and marginal costs is the same in the case of linear characteristic equations [Serra et al. 1995].

2.9.5 Assignment rules of the exergetic costs

In this paragraph the complete procedure required to calculate the exergetic costs using the Structural Theory is shown.

Once the productive structure of the system has been defined, the marginal cost can be calculated applying the derivation chain rule to the characteristic equations of the system. Four cases can occur:

1) Fluxes entering the system

   If a flux E_i of the productive structure enters the system from the environment it is a fuel of the process, so that the characteristic equation has the form:

$$E_0 = E_i \tag{2.76}$$

   where E_0 is the fuel of the plant produced by the environment. The marginal cost is unitary:

$$k_i^* = \left(\frac{\partial E_0}{\partial E_i}\right) = 1\,. \tag{2.77}$$

   If the flux entering the system is the product of another system, its unit cost must be calculated, or evaluated, applying the rules of the thermoeconomic analysis to the process which has produced it.

2) Component characterized by one fuel and one product

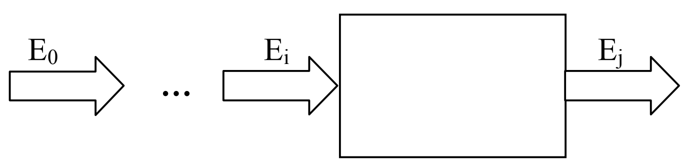

Figure 2.6 - Component characterized by one fuel and one product

The derivation chain rule for such a component (or system) is:

$$k_j^* = \left(\frac{\partial E_0}{\partial E_j}\right) = \left(\frac{\partial E_0}{\partial E_i}\right) \cdot \left(\frac{\partial E_i}{\partial E_j}\right) = k_i^* \cdot \left(\frac{\partial E_i}{\partial E_j}\right). \tag{2.78}$$

Using the notation introduced for the marginal fuel consumption:

$$k_{ij} = \left(\frac{\partial E_i}{\partial E_j}\right) \tag{2.79}$$

the equation 2.78 can be also written:

$$k_j^* = k_i^* \cdot k_{ij}. \tag{2.80}$$

3) Component characterized by one fuel and more than one product

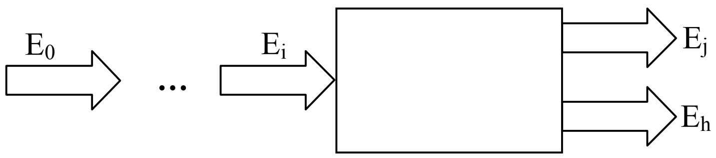

Figure 2.7 - Component characterized by one fuel and more than one product

Such a component can be represented as the one represented in case 2), but the product is split into two fluxes. In this way the derivation chain rule is:

$$k_j^* = k_h^* = \left(\frac{\partial E_0}{\partial (E_j + E_h)}\right) = \left(\frac{\partial E_0}{\partial E_i}\right) \cdot \left(\frac{\partial E_i}{\partial (E_j + E_h)}\right) = k_i^* \cdot \left(\frac{\partial E_i}{\partial (E_j + E_h)}\right). \tag{2.81}$$

If a linear characteristic equation is assumed, a variation of the fuel E_0 causes the same proportional variation of the two products, so the equation 2.81 can be written:

$$k_j^* = k_h^* = \frac{k_i^*}{(k_{ji} + k_{hi})}. \tag{2.82}$$

All the products of a component are so evaluated at the same unit cost. If a different evaluation is needed for the two products, the productive structure must be modified. A possible solution is to assume one of the products as a negative fuel. In this case it will appears as the product (negative) of another component, which will determine its cost.

Branching points represent a particular case of this kind of components: they are used to split an exergy flux into more fluxes, but this operation is realized without irreversibility, so that the entering exergy flow equals the sum of the exiting ones.

4) Component characterized by more than one fuel and one product

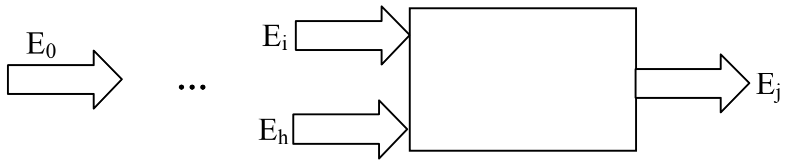

Figure 2.8 - Component characterized by more than one fuel and one product

The application of the hypothesis of linear characteristic equation to the system represented in figure 2.8 puts on evidence that a proportional variation of the product E_j causes the same proportional variation in the two fuels E_h and E_i, so that the derivation chain rule can be written as:

$$k_j^* = \left(\frac{\partial E_0}{\partial E_j}\right) = \left(\frac{\partial E_0}{\partial E_i}\right) \cdot \left(\frac{\partial E_i}{\partial E_j}\right) + \left(\frac{\partial E_0}{\partial E_h}\right) \cdot \left(\frac{\partial E_h}{\partial E_j}\right). \tag{2.83}$$

Using the introduced notation the equation 2.83 can be written:

$$k_j^* = k_i^* \cdot k_{ij} + k_h^* \cdot k_{hj}. \tag{2.84}$$

Junctions represents a particular case of this kind of components: they operate to combine different fluxes into one. This process is made ideally without exergy destruction.

The equations exposed above represent the possible relations between entering and exiting fluxes. In a matrix notation the all equations can be written:

$$\mathbf{k}_{out}^* = |\mathbf{EG}\rangle^t \cdot \mathbf{k}_{in}^* + \mathbf{k}_{ext}^* \tag{2.85}$$

where:

- $\mathbf{K}_{out}^*$ is the vector of the unit cost of the fluxes exiting from the components of the system;
- $|\mathbf{EG}>$ is the matrix containing the marginal exergy consumptions, i.e. the derivates of the fluxes exiting the components respect to the entering ones;
- $\mathbf{K}_{in}^*$ is the vector of the unit cost of the fluxes entering the components of the system;
- $\mathbf{K}_{ext}^*$ is the vector of the evaluation of the unit cost of the fluxes entering the system from the external environment.

As the fluxes exiting a component enters other components (or the environment) the two vectors $\mathbf{K}_{out}^*$ and $\mathbf{K}_{in}^*$ are equal, so they can be both indicated as $\mathbf{k}^*$. In this way the equation 2.85 becomes:

$$\mathbf{k}^* = |\mathbf{EG}\rangle^t \cdot \mathbf{k}^* + \mathbf{k}_{ext}^* \tag{2.86}$$

which can be resolved for the vector of the unit costs:

$$\mathbf{k}^* = (\mathbf{U}_D - |\mathbf{EG}\rangle^t)^{-1} \cdot \mathbf{k}_{ext}^* \tag{2.87}$$

2.9.6 Lagrange multipliers and marginal costs

In this part the equivalence between the Lagrange multipliers, used in some thermoeconomic optimization methods [El-Sayed, Evans 1970, Lazzaretto, Macor 1990], and the marginal costs is shown. The optimization problem of an energy system has the objective to find the values of the internal parameters minimizing the total cost of the necessary resources to obtained the required production:

$$\Pi_0(\chi, \mathbf{E}) = \sum_{i \in \mathbf{O}_0} c_i \cdot E_i + \sum_{u \in \mathbf{N}} Z_u(\chi, \mathbf{E}), \tag{2.88}$$

with the constraints represented by the characteristic equations and the required products:

$$E_i = g_i(\mathbf{E}, \chi_u) \qquad i \in \mathbf{I}_u \qquad u \in \mathbf{N} \tag{2.89}$$

$$E_i = \omega_i \qquad i \in \mathbf{I}_0 \tag{2.90}$$

The Lagrange multipliers theorem (see [Vanderplaats 1985]) affirms that the optimum constrained condition is also defined by the Lagrangian function:

$$L(\chi, \mathbf{E}, \Lambda) = \sum_{i \in \mathbf{O}_0} c_i \cdot E_i + \sum_{u \in \mathbf{N}} Z_u(\chi, \mathbf{E}) + \sum_{\substack{i \in \mathbf{O}_u \\ u \in \mathbf{N}}} \lambda_i \cdot (g_i(\mathbf{E}, \chi) - E_i) + \sum_{i \in \mathbf{O}_0} \lambda_i \cdot (\omega_i - E_i) \tag{2.91}$$

where Λ is the whole of the Lagrange multipliers λi. The equation 2.91 can be rewritten:

$$L(\chi, \mathbf{E}, \Lambda) = \sum_{i \in \mathbf{O}_0} (c_i - \lambda_i) \cdot E_i + \sum_{u \in \mathbf{N}} \left(\Gamma_u(\chi, \mathbf{E}, \Lambda) - \sum_{i \in \mathbf{O}_u} \lambda_i \cdot E_i \right) + \sum_{i \in \mathbf{O}_0} \lambda_i \cdot \omega_i \tag{2.92}$$

where:

$$\Gamma_u(\chi, \mathbf{E}, \Lambda) = Z_u(\chi, \mathbf{E}) + \sum_{i \in \mathbf{O}_u} \lambda_i \cdot g_i(\mathbf{E}, \chi) \tag{2.93}$$

which is the cost of the resources entering in the component u.

The values of the Lagrange multipliers satisfy the conditions:

$$\lambda_i = c_i \qquad i \in \mathbf{O}_0 \tag{2.94}$$

$$\lambda_i = \frac{\partial \Gamma_u}{\partial E_i} = \frac{\partial Z_u}{\partial E_i} + \sum_{i \in \mathbf{O}_u} \frac{\partial g_j}{\partial E_i} \qquad i \in \mathbf{O}_u \qquad u \in \mathbf{N} \tag{2.95}$$

in every point verifying the constraints 2.89 and 2.90. Equation 2.95 coincides with the definition of marginal cost 2.69.

2.9.7 Calculation of the cost in monetary units

A universally known scale of measurement of a product is its monetary cost, as the economic aspect always must be taken into account in a productive process. All the decisions in these kind of systems are taken according to their economic convenience, so that the knowledge of the monetary costs of the fluxes is the most useful information for the plant management given by the thermoeconomic analysis.

Money is a extensive quantity fulfilling the second premise of the structural analysis, in fact a monetary cost of a flow can be expressed as product of the unit cost and the flow itself; for example the cost of a exergy flow can be expressed as product of the monetary unit cost of the exergy and the exergy flow:

$$\Pi_i = c_i \cdot E_i \qquad (2.96)$$

where Π_i is the monetary cost associated to the flux E_i and c_i is its unit cost.

The characteristic equations described in paragraph 2.9.5 are general and do not depends on the scale of measurement of costs. In this way the calculation of the economic cost of the fluxes can be simply made by changing the exergetic unit cost of the overall plant fuels for their monetary unit cost and keeping the same characteristic equations of the components.

This procedure does not take into account the cost rate of the components, which is usually neglected in the exergetic cost analysis. If these costs are required in the calculation, the productive structure must be changed, in fact they represent additional resources of the components [Serra 1994]. Therefore in every component will enter a flux corresponding to its cost rate. The component cost rate is usually assumed as the price paid for it, split on its life time, as discussed in paragraph 2.3. Figure 2.9 shows how the productive structure, relative to the simple steam turbine cycle, represented if figure 2.4, changes when the cost of the component is considered. In the figure the cost rate of the component has been indicated as c_{SG}, c_T, c_A, c_C and c_P, respectively for the steam generator, the turbine, the alternator, the condenser and the pump. The fictitious component is clearly characterised by a null cost.

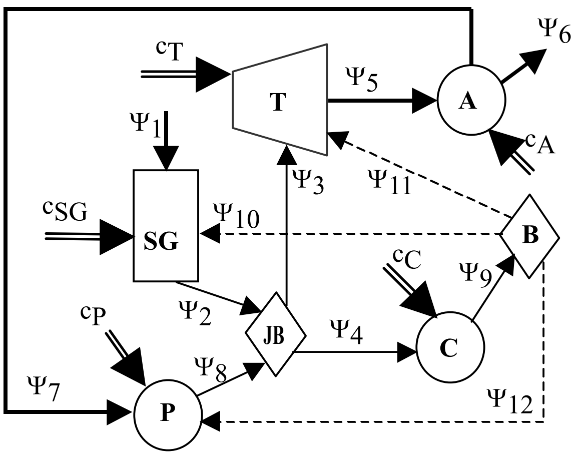

Figure 2.9 - Productive structure for the monetary cost calculation

Such a productive structure has four fluxes more than the structure without the component costs, therefore four characteristic equations are needed. These equations correspond to the evaluation of the cost rate of every component, according to what has been said at the point 1) of paragraph 2.9.5.

CHAPTER 3

Thermoeconomic analysis of the Moncalieri plants

In this chapter the structural theory of thermoeconomics is applied to the Moncalieri thermal systems in order to calculate the exergetic and thermoeconomic costs of all the fluxes. Some representative working conditions, corresponding to different electric and thermal loads, are considered. The application of the complete matrix approach is proposed for a productive structure relative to the gas turbine plant, while the results corresponding to other productive structures are shown, to highlight the effects of this choice on the calculated values of the thermoeconomic costs. The productive structures are then used for the thermoeconomic diagnosis in chapters 5 and 6.

Every working condition is calculated using the physical model of the plants described in chapter 1. The hypothesis of linear thermoeconomic model is not necessary, as no prediction of the costs is made. The relation between the input and the output of the components, i.e. the unit exergy consumptions, is determined separately for every working condition.

3.1 Productive structures for thermoeconomic analysis and diagnosis

The first step of the thermoeconomic analysis consists on the choice of the productive structure. Fuels and products of the system components are expressed in thermoeconomics as exergy flows or parts of them, depending on how detailed is the analysis. The detail must be sufficiently high to put on evidence the main energy transformations occurring in the plant, but a too high detail does not add any information and sometimes makes difficult the comprehension of the cost formation mechanism. The productive structure must be a good compromise between the two necessities.

The graphical representation of the productive structures has been made using the following notation:

━━━▶ (thick solid arrow)	Exergy flow	- - - - -▶ (dashed arrow)	Mechanical exergy flow
–·–·–▶ (dash-dot arrow)	Negentropy flow	───▶ (thin solid arrow)	Thermal exergy flow

3.1.1 Steam turbine case

A look on the overall system puts on evidence an entering flux, corresponding to the natural gas consumption, and three exiting fluxes: the electric and the thermal power provided by the plant and the thermal flux transferred to the condensing water. This last flux is a loss, as it is not useful in the overall process or outside it, while the two other fluxes are the plant products.

The productive structures analysed in this chapter are built for analysis and diagnosis purposes, which makes suitable a grade of detail sufficient not only to calculate the effect of every process on the costs, but also to locate the malfunctions in appropriate control volumes. These volumes are required to be as small as possible, in order to reduce the time necessary for the maintenance. The thermodynamic quantities at their boundaries must be known, so, the higher is the number of volumes characterizing the system and the higher is the number of required measures. Moreover the incidence of the errors associated to the measures generally depends on the dimensions of the control volumes. The productive structures, in fact, often involve differences between the exergy flows of the streams entering and exiting the control volumes in the physical structure. If the difference between the intensive quantities decreases, the difference between the exergy flows decreases too and the per cent errors associated to the productive fluxes increases.

In the first productive structure, indicated as TV1, the subsystems are identified with the components. The turbine is separated into high, middle and low-pressure sections, and the feed water heaters are separated into eight heat exchangers; the steam leakage condenser is considered together with the first heat exchanger.

Fuels and products are expressed as exergy fluxes. Their representation in the productive structure is made by fluxes respectively entering and exiting the components.

The role of the steam generator is to increase the exergy of the fluid, which involves the evaporation of the water and the successive superheating and the steam re-heating. The component product is defined as the difference between the exiting and the entering water fluxes. To achieve this objective it uses the exergy made disposal by the fossil fuel (Ψ_4 in figure 3.1). In figure 3.1 physical and productive exergy fluxes of the steam generator are shown.

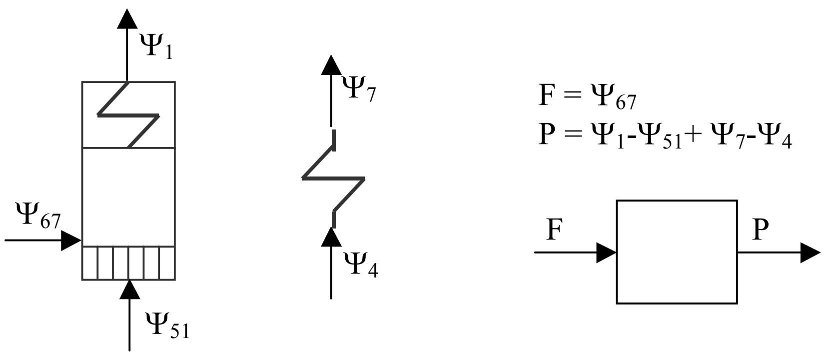

Figure 3.1 - Physical and productive exergy fluxes of the steam generator

The feed water heaters increase the exergy of the fluid too; in particular, the heat exchangers increase the exergy of the cold fluid, so their product is represented by the difference between exiting and entering exergy flows associated in the physical structure to the cold fluid (Ψ_{49}-Ψ_{48} in figure 3.2). In figure 3.2 physical and productive exergy fluxes of the heat exchanger HE5 (see figure 1.2) are shown.

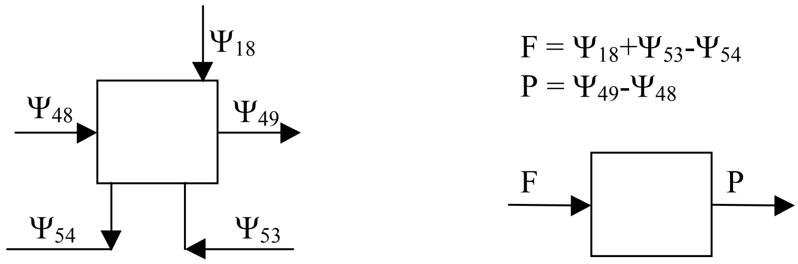

Figure 3.2 - Physical and productive exergy fluxes of the heat exchanger HE5

The product of each heat exchanger and of the steam generator is so constituted by the exergy flow provided to the fluid. Other components require this kind of exergy as resource to realize their productive processes. A fictitious element is used in the structure TV1 to mix these fluxes into one and split it among the components, according to their needs. The unit cost of the fluxes exiting the fictitious component is the same for all and is equal to the average cost of the fuels. Figure 3.3 shows in detail the fictitious component.

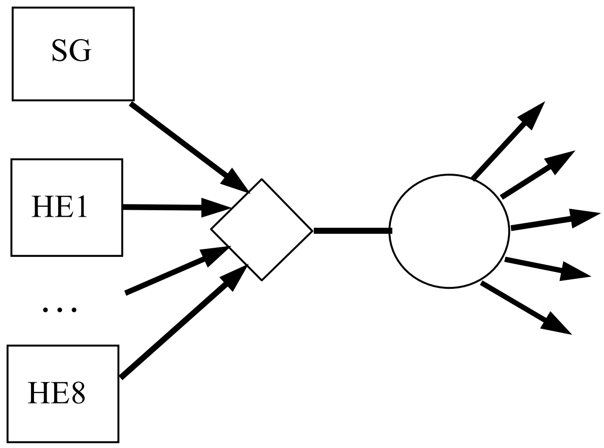

Figure 3.3 - Detail of the fictitious component

This fictitious component can be considered coinciding with the water flowing in the plant: some components increase its exergy containt, while other ones subtracts a part of it to make a thermodynamic process. The sum of the exergy flows provided to the water equals the amount subtracted as the thermodynamic cycle is closed.

The resource of the heat exchangers is constituted by the exergy drop of the hot fluid, so it is defined as difference between the entering and the exiting exergy flows of the hot fluid ($\Psi_{18}+\Psi_{53}-\Psi_{54}$ in figure 3.2).

The turbines uses the exergy of the fluid in order to produce mechanical power. Figure 3.4 shows the case of the high pressure turbine.

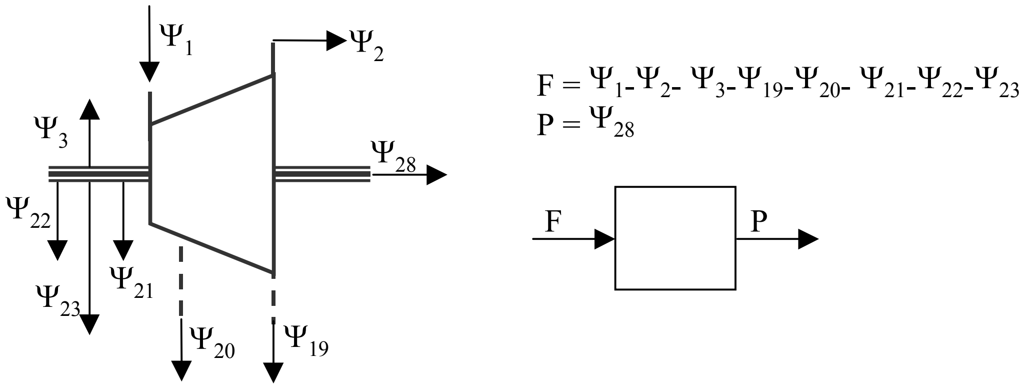

Figure 3.4 - Physical and productive exergy fluxes of the high pressure turbine

The mechanical power produced by the turbines is transformed into electric power by the alternator, so the first term represents its fuel while the second its product. The alternator also transfers heat to the fluid by mean of the cooling circuit. The difference between the exergy flows of the fluid exiting and entering the alternator is a by-product. The structural theory does not allow to indicate more than one product of a component, unless they are all characterised by the same nature. In alternative it is possible to accept the same unit cost for all, which corresponds to assume a single product of the component. The case of by-product is usually treated as a negative fuel of the component. In this way its unit cost is determined by another component. Assuming this option, the fuel of the alternator also include the difference between the exergy flows of the fluid entering and exiting it (this quantity is negative). The physical and productive fluxes of this component are shown in figure 3.5. The mechanical power, resource of the component, is equal to the sum of the mechanical powers produced by high, middle and low pressure turbines ($E_{m2}+E_{m3}+E_{m4}$).

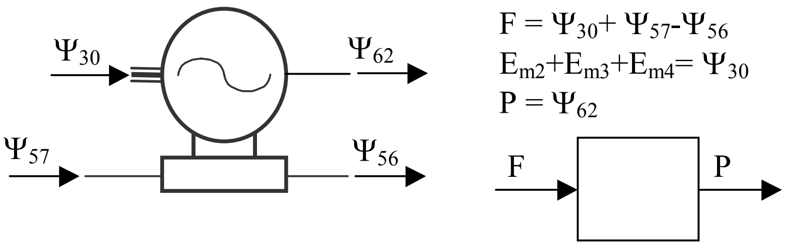

Figure 3.5 - Physical and productive exergy fluxes of the alternator

Not all the electric power produced by the alternator is let disposal for the users: a part of it is necessary for the internal needs of the plant. In particular the pumps need it to increase the fluid pressure and so their exergy. Physical and productive structure of the circulation pump are shown in figure 3.6. Its product is constituted by the difference between the exiting and entering exergy of the fluid, while its fuel is constituted by the required electric power. The electric power is distributed among the pumps and to the external users, by means of a fictitious splitter.

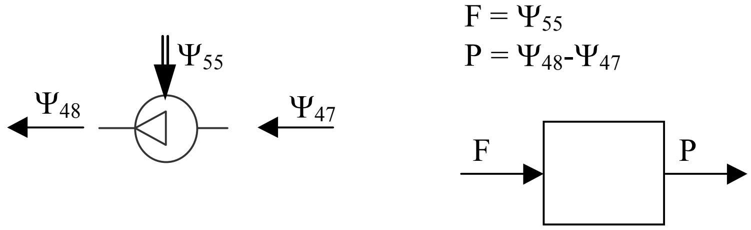

Figure 3.6 - Physical and productive exergy fluxes of the circulation pump

A problem of the thermoeconomic analysis of steam power plants is the identification of the condenser product. A first solution is to consider the condenser joined to the part of the low-pressure turbine working at sub-atmospheric pressure [Muñoz, Valero 1989]. This assumption is justified by the fact that the presence of the condenser makes the turbine able to last the expansion at a pressure lower than the atmospheric value. Therefore this assumption is not generally acceptable in the thermoeconomic diagnosis, as the control volume would be too large and, in case of malfunction, the inspection should be made on two components. For this reason the product of the condenser can be considered as the exergy transferred to the condensing water (productive structure TV1a). This flux is a loss and not a plant product, so it can not exit the overall system in the productive representation. It must be assigned as a fuel to other components. A criterion to make this operation is to split the condenser product among all the components, proportionally to the increase of the entropy flow Ψ_S occurring in everyone, being this quantity defined as:

$$G_{S_j} = \sum_{i=1}^{n_j} \pm G_i \cdot s_i \tag{3.1}$$

where n_j is the number of fluxes associated to the fluid entering (sign -) and exiting (sign +) the component j. This assumption is based on the consideration that the role of the condenser in a steam power plant is the closure of the thermodynamic cycle.

the productive structure of the condenser is represented in figure 3.7. The product of the condenser is fuel of a fictitious splitter which distributes this flux among the components according to their contribute to the increase of the fluid entropy.

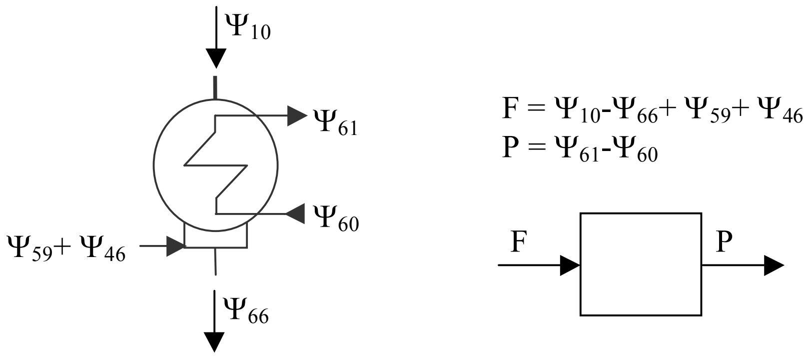

Figure 3.7 - Physical and productive fluxes of the condenser

An equivalent productive structure, here called TV1b, can be obtained considering negentropy as product of the condenser. The product is split among the components depending on their requirement, which is, for the jth component:

$$N_j = T_0 \cdot \sum_{i=1}^{n_j} \pm G_i \cdot s_i . \tag{3.2}$$

Another productive structure, indicated as TV1c, which use is possible only to locate the anomalies, can be built starting from the structure TV1a and considering the exergy flow transferred to the condensing water as a plant product. This structure can not be used for costing purposes, as specified above, because the thermal exergy exchanged with the condensing water does not have any utility, so that its cost must be charged on the other products. Nevertheless the diagnosis does not have this kind of exigences, on the contrary the factious fluxes sometimes represent an obstacle in the procedure. The quantities Ψ_S and N have the same meaning, but the first one is to be preferred as its value is lower than the corresponding negentropy flow. This means that the contribution to the cost accounting is the same, but the undesired effect on the thermoeconomic diagnosis is reduced, in fact in every component these fictitious fluxes are much lower than the exergy flows processed. On the contrary the negentropy flows and the exergy flows are comparable.

All the productive structures TV1a, TV1b and TV1c can be represented as shown in figure 3.10, where the indicated quantities are subscripts indicating the kind of fluxes. The following nomenclature has been used for all the productive structures used for the steam turbine plant:

- E exergy flow of the productive structure;
- Ψ exergy flow of the physical structure;
- b exergy associated to fluid;
- m exergy associated to mechanical power;
- p mechanical exergy of the liquid;
- pv mechanical exergy of the vapour;
- s appropriate function of entropy, calculated using the equation 3.1 in the case of the structure TV1a, the equation 3.2 in the case of the structure TV1b and assuming zero this quantity in the case of the structure TV1c;
- t thermal exergy.

The numbers refer to the component which uses or produces the flux. In particular if the number precedes the letter indicating the kind of flux, the flux is a component fuel. As an example the flux E_{1b} indicate an exergy flow fuel of the steam generator. If the number follows the letter, the flux is product of the component. In this way the flux E_{b1} is product of the steam generator.

In these structures the regulation valve located on the cross-over pipe and the pump necessary to join the fluid extracted for the cogeneration to the main fluid have been considered together with the recuperator. In this way the fuel of the recuperator also includes the exergy destructed in the valve and the electric power required by the pump. The product of the recuperator is constituted by the increased exergy of the district heating fluid. Moreover it contributes to decrease the entropy of the plant fluid (which causes the increase of the entropy of the district heating fluid, according to the second law), so a by-product is also produced. This last productive flux has been represented as a negative entering flux, in order to assign it an unit cost equal to the unit cost of the condenser product. Physical and productive structure of this element are shown in figure 3.8.

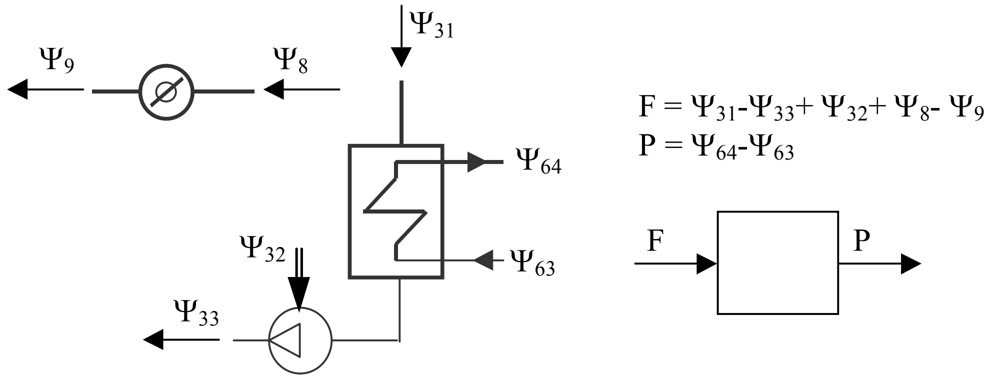

Figure 3.8 - Physical and productive fluxes of the recuperator (including the regulation valve and the pump)

The expression of the fluxes in the productive structures are shown in table 3.1, while in figure 3.14 the numeration of the physical fluxes is indicated.

For diagnosis purposes the subsystems of the productive structure can also cut across the physical covering of the components. In particular the turbines can be broken down upon groups of stages, so that the location of the malfunctions can be made in reduced control volumes. The structures TV2a, TV2b and TV2c have been obtained separating the turbines of the corresponding structures TV1. The figure 3.11 shows in detail how the productive fluxes characterizing the three section of the turbine have changed: every fuel and product of the high, middle and low pressure sections have been split into the contributes relative to each stage.

The successive step consists on splitting the exergy of the fluid into mechanical and thermal components. This can be made in different ways, depending on how the components of exergy are calculated, as an unambiguous calculation is possible only for ideal gases and incompressible liquids [Tsatsaronis et al 1990]. In a steam power plant the components responsible to increase the pressure, compensating all the pressure drops, are the pumps; in this way it is possible to think that all the mechanical exergy is provided by them. Such an assumption would not take into account the effect of the fluid change of phase on the exergy components, in fact the passage of the liquid to steam is a process involving a variation of both thermal and mechanical exergy. It is possible to consider an ideal steam generator, where no pressure drop occurs, so that the pressure of the entering fluid is equal to the pressure of the exiting one. Figure 3.9 shows the ideal process in a steam generator[1]

1. The calculation has been made considering as entering and exiting conditions respectively 150 bar, 170 °C and 150 bar, 450 °C. The mechanical exergy produced by the pump has been calculated by considering an isentropic compression. The point 1 is characterized by a pressure of 7 bar.

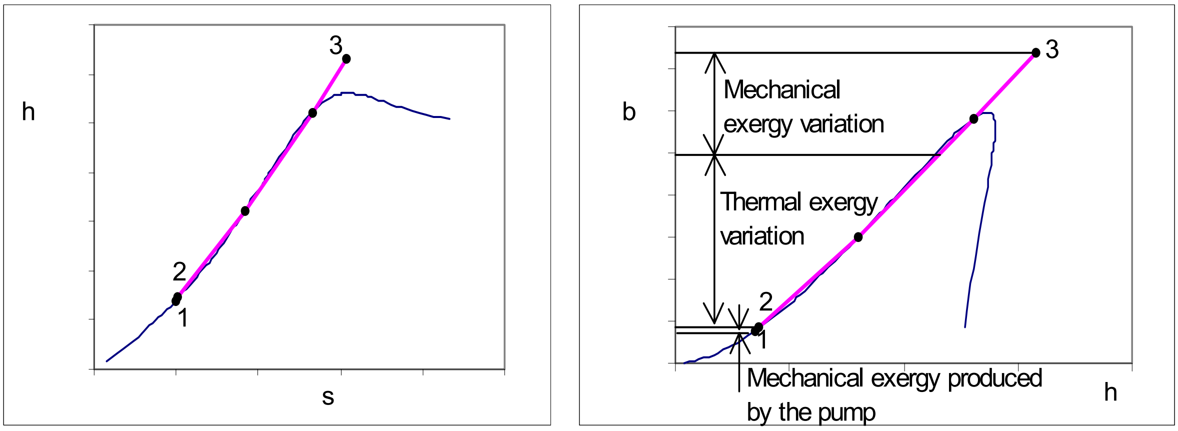

Figure 3.9 - Thermodynamic representations of the ideal process in a steam generator

The calculation of mechanical and thermal exergy in points 1 and 2, corresponding to the conditions of the fluid at the entrance and at the exit of the steam generator, can be made using some proposed expressions [Tsatsaronis et al 1990]:

$$b_{m_2} = h(T_0, p_2) - h(T_0, p_0) - T_0 \cdot [s(T_0, p_2) - s(T_0, p_0)] \tag{3.3}$$

$$b_{t_2} = h(T_2, p_2) - h(T_0, p_2) - T_0 \cdot [s(T_2, p_2) - s(T_0, p_2)] \tag{3.4}$$

$$b_{m_3} = h(T_3, p_3) - h(T_3, p_0) - T_0 \cdot [s(T_3, p_3) - s(T_3, p_0)] \tag{3.5}$$

$$b_{t_3} = h(T_3, p_0) - h(T_0, p_0) - T_0 \cdot [s(T_3, p_0) - s(T_0, p_0)] \tag{3.6}$$

The consequence of this assumption is that a variation of the mechanical exergy occurs in the steam generator, although no pressure drops take place in the component ($p_2 = p_3$):

$$\begin{aligned} b_{m_3} - b_{m_2} &= [h(T_3, p_3) - h(T_3, p_0) + h(T_0, p_2) - h(T_0, p_0)] \\ &\quad -T_0 \cdot [s(T_3, p_3) - s(T_3, p_0) + s(T_0, p_2) - s(T_0, p_0)] \end{aligned} \tag{3.7}$$

This quantity is represented in the thermodynamic diagram b-h in figure 3.9. This kind of diagram, particularly helpful in the cryogenic applications [Cavallini, Mattarolo 1988], allows to highlight that the specific mechanical exergy variation in the steam generator is comparable to the thermal one and it is much bigger than the specific exergy produced by the pumps. This means that the mechanical exergy variation must be considered as a product of the steam generator.

The productive structures TV3 have been built considering the mechanical and thermal components of exergy. In particular mechanical exergy has been considered as product of the pumps and by-product of the steam generator. The mechanical exergy of the fluid in a general condition can be considered as sum of two contribution: the first corresponding to the liquid at the same pressure and the second corresponding to the difference between the total mechanical exergy and the first term. The first contribution is provided by the pumps and corresponds to the mechanical exergy required to compensate for the pressure drops which would occur if liquid water flew in all the components. This quantity can be calculated as:

$$\Psi_{m_{liq}} = \sum_{i=1}^{n_j} \pm G_i \cdot v_{liq} \cdot (p_i - p_0) \tag{3.8}$$

where v_{liq} is the specific volume of the liquid water, assumed constant, and p_0 is the pressure of the reference environment. The mechanical exergy altogether required as fuel by the components is higher than the value calculated applying the equation 3.8 to all the components. The remaining part is so provided by the steam generator.

The mechanical exergy of the water is calculated using the equations 3.3 and 3.5 respectively for superheated steam and liquid water. Other cases have been considered, in particular:

saturated steam

$$b_m = x \cdot b_{m_{vapour}} + (1-x) \cdot b_{m_{liquid}} \tag{3.9}$$

$$b_t = x \cdot b_{t_{vapour}} + (1-x) \cdot b_{t_{liquid}} \quad ; \tag{3.10}$$

superheated steam at temperature lower than the saturation temperature corresponding to the reference environment pressure

$$b_t = h(T,p) - h(T_0,p) - T_0 \cdot [s(T,p) - s(T_0,p)] \tag{3.11}$$

$$b_m = h(T_0,p) - h(T_0,p_0) - T_0 \cdot [s(T_0,p) - s(T_0,p_0)]\,; \tag{3.12}$$

superheated steam at temperature lower than the reference environment temperature

$$b_m = h(T_{sat(p_0)},p) - h(T_{sat(p_0)},p_0) - T_0 \cdot [s(T_{sat(p_0)},p) - s(T_{sat(p_0)},p_0)] \tag{3.13}$$

$$b_t = b - b_m\,. \tag{3.14}$$

The mechanical exergy provided by the steam generator is calculated in every point of the plant using the formulae 3.3, 3.5, 3.9, 3.12 and 3.13 and subtracting the mechanical exergy corresponding to the liquid at the same pressure. In this way the mechanical exergy provided by the steam generator is different to zero only in the points where the fluid is at the vapour state.

The productive structures corresponding to these considerations, indicated as TV3 and TV4, corresponding to two different grades of details, are shown in figures 3.12 and 3.13. The particularity of this structure is constituted by the two products of the steam generator: mechanical and thermal exergy flows (E_{t1} and E_{1pv}), in particular the thermoeconomic model has been made considering the mechanical exergy as a negative fuel (by-product). This construction does not influence the thermoeconomic analysis, in fact the two product have the same cost, so the same result would by obtained considering them as a single flux.

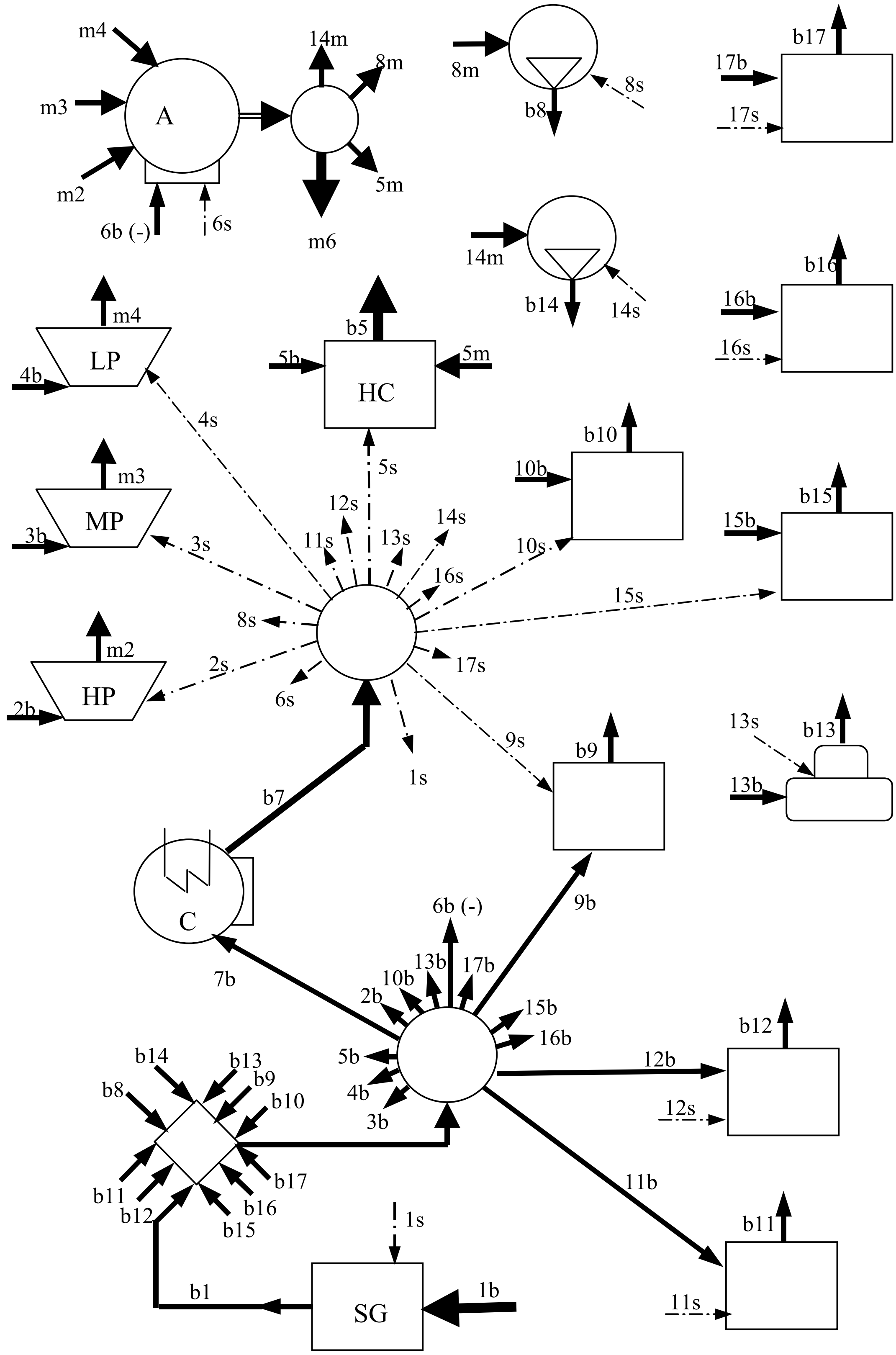

Figure 3.10 - Productive structures TV1a, TV1b and TV1c

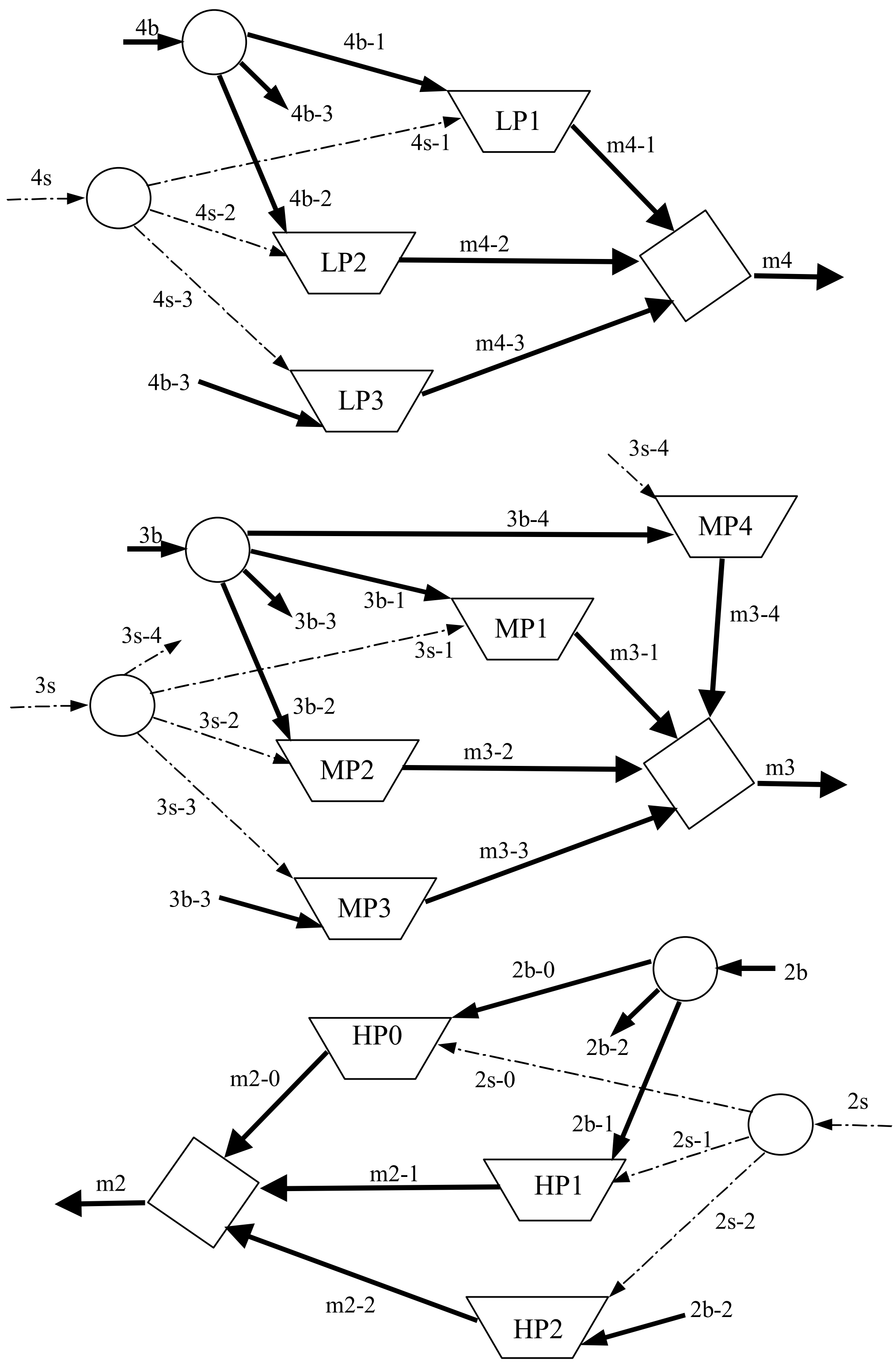

Figure 3.11 - Detail of the turbines in the productive structures TV2a, TV2b and TV2c

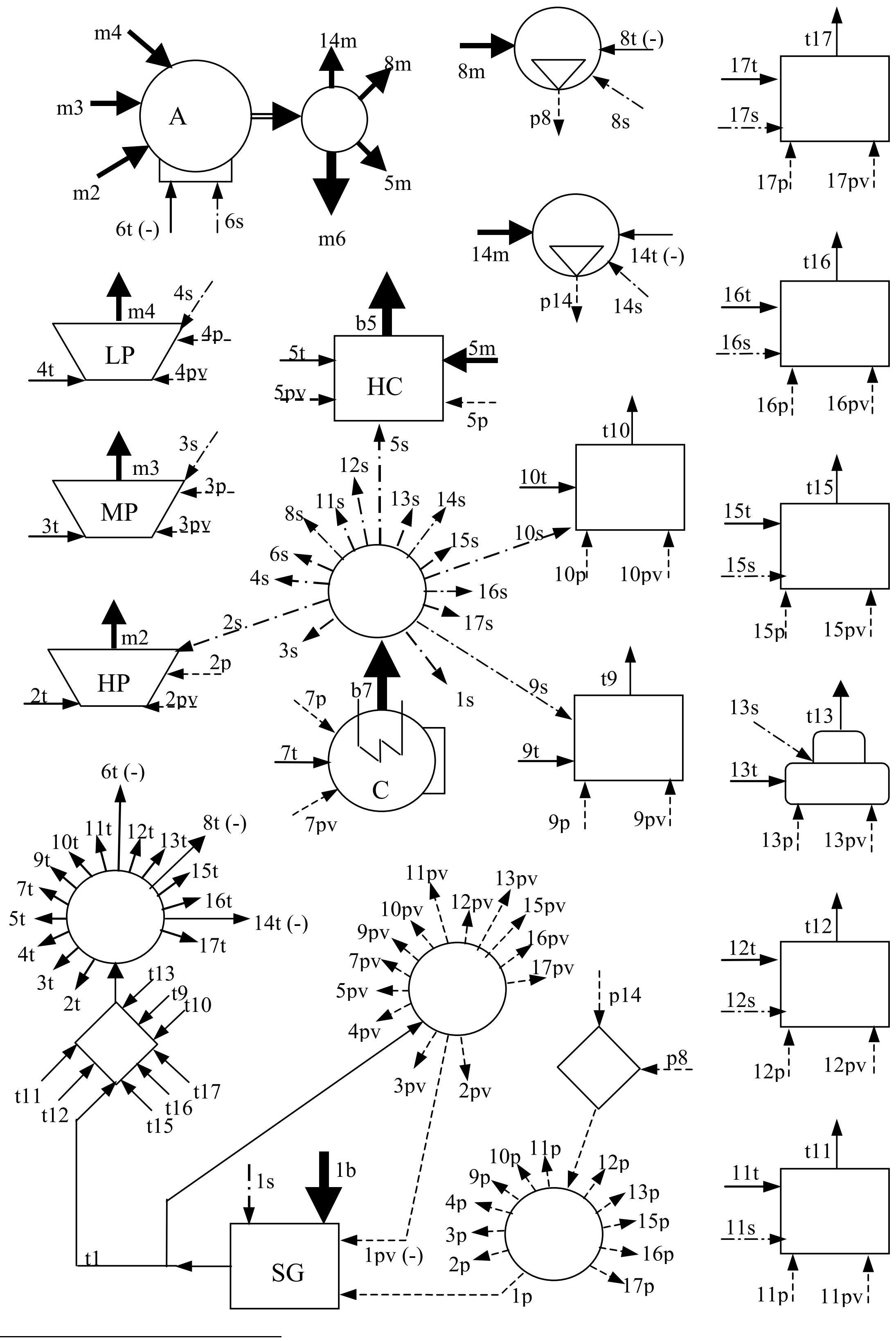

Figure 3.12 - Productive structures TV3a, TV3b and TV3c

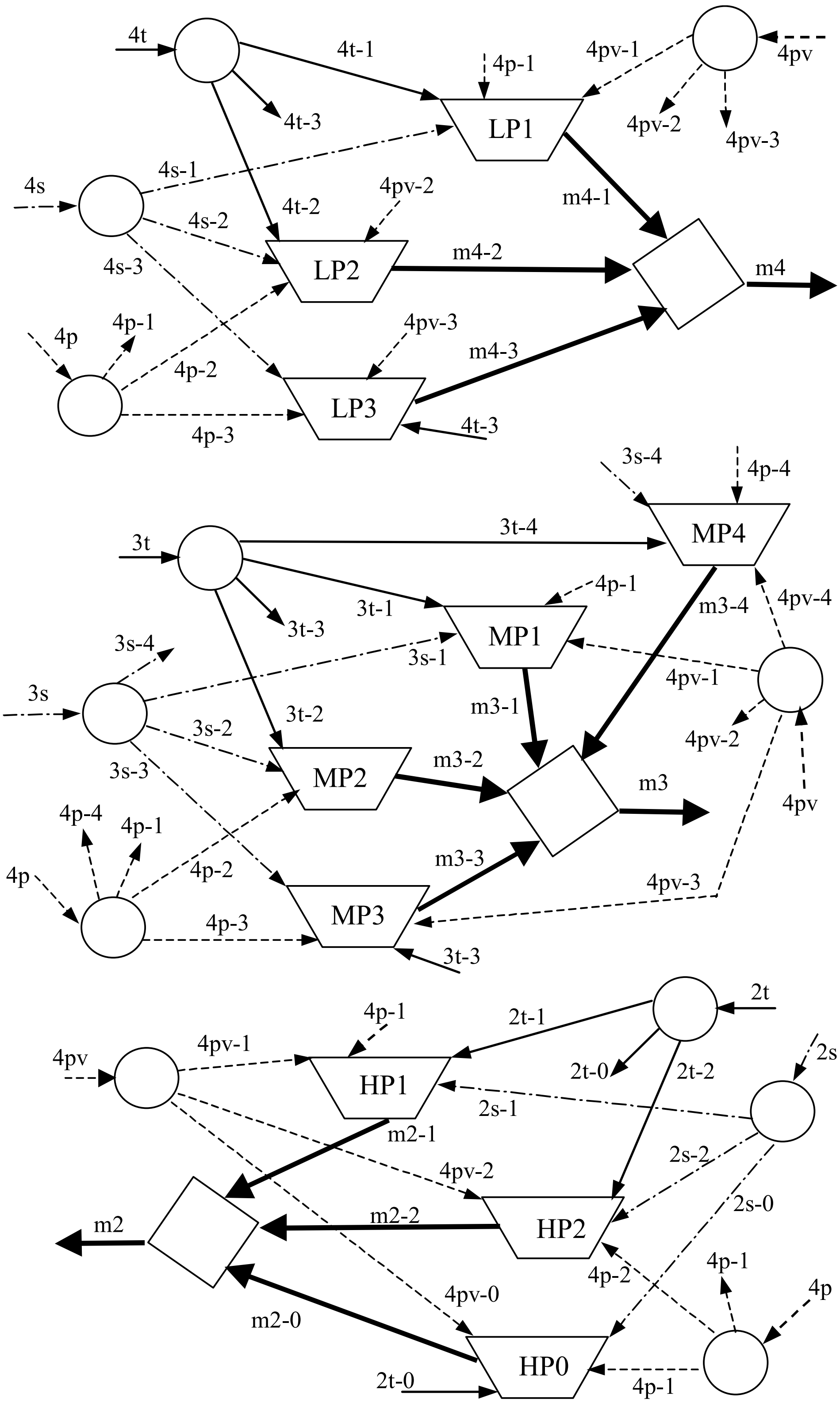

Figure 3.13 - Detail of the turbines in the productive structures TV4a, TV4b and TV4c

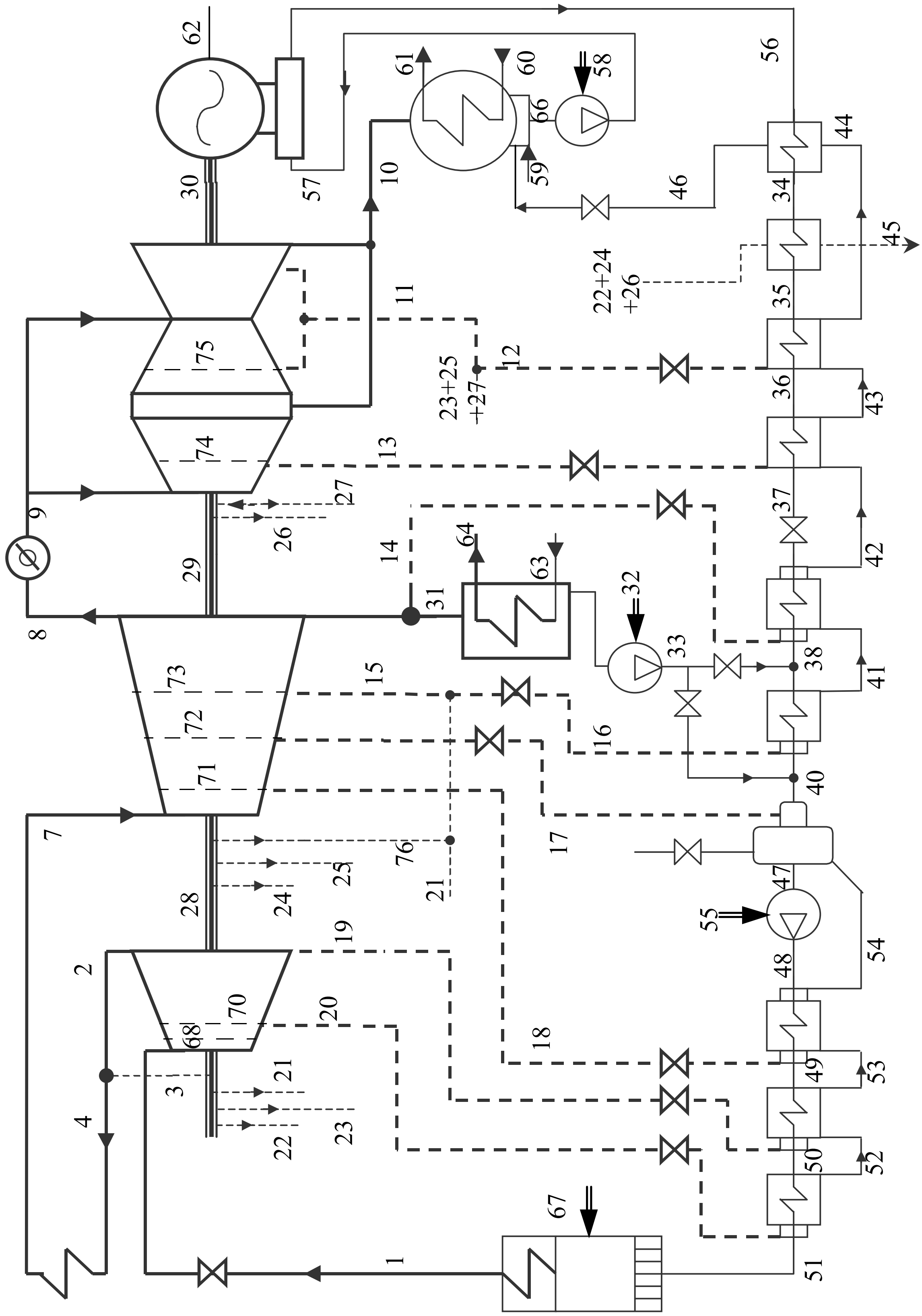

Figure 3.14 - Numeration of physical fluxes

Fluxes	Expression
E_{1b}	Ψ_{67}
E_{b1}	$\Psi_{51b}-\Psi_{1b}-\Psi_{7b}+\Psi_{3b}+\Psi_{2b}-\Psi_{5b}$
E_{1p}	$\Psi_{51p}-\Psi_{1p}-\Psi_{7p}+\Psi_{3p}+\Psi_{2p}-\Psi_{5p}$
E_{1pv}	$\Psi_{51pv}-\Psi_{1pv}-\Psi_{7pv}+\Psi_{3pv}+\Psi_{2pv}-\Psi_{5pv}$
E_{1s}	$\Psi_{1s}+\Psi_{7s}-\Psi_{3s}-\Psi_{2s}+\Psi_{5s}+\Psi_{51s}$
E_{t1}	$\Psi_{1t}-\Psi_{51t}+\Psi_{7t}-\Psi_{3t}-\Psi_{2t}+\Psi_{5t}$
E_{2b}	$\Psi_{1b}-\Psi_{2b}-\Psi_{3b}-\Psi_{19b}-\Psi_{20b}-\Psi_{21b}-\Psi_{22b}-\Psi_{23b}$
E_{2t}	$\Psi_{1t}-\Psi_{2t}-\Psi_{3t}-\Psi_{19t}-\Psi_{20t}-\Psi_{21t}-\Psi_{22t}-\Psi_{23t}$
E_{2p}	$\Psi_{1p}-\Psi_{2p}-\Psi_{3p}-\Psi_{19p}-\Psi_{20p}-\Psi_{21p}-\Psi_{22p}-\Psi_{23p}$
E_{2pv}	$\Psi_{1pv}-\Psi_{2pv}-\Psi_{3pv}-\Psi_{19pv}-\Psi_{20pv}-\Psi_{21pv}-\Psi_{22pv}-\Psi_{23pv}$
E_{2s}	$\Psi_{2s}+\Psi_{3s}+\Psi_{19s}+\Psi_{20s}+\Psi_{21s}+\Psi_{22s}+\Psi_{23s}-\Psi_{1s}$
E_{m2}	Ψ_{28}
E_{2b-0}	$\Psi_{1b}-\Psi_{68b}-\Psi_{3b}-\Psi_{21b}/2-\Psi_{22b}/2-\Psi_{23b}/1$
E_{2t-0}	$\Psi_{1t}-\Psi_{68t}-\Psi_{3t}-\Psi_{21t}/2-\Psi_{22t}/2-\Psi_{23t}/2$
E_{2p-0}	$\Psi_{1p}-\Psi_{68p}-\Psi_{3p}-\Psi_{21p}/2-\Psi_{22p}/2-\Psi_{23p}/2$
E_{2pv-0}	$\Psi_{1pv}-\Psi_{68pv}-\Psi_{3pv}-\Psi_{21pv}/2-\Psi_{22pv}/2-\Psi_{23pv}/2$
E_{2s-0}	$\Psi_{68s}-\Psi_{1s}+\Psi_{3s}+\Psi_{21s}/2+\Psi_{22s}/2+\Psi_{23s}/2$
E_{m2-0}	$Gh_{1}-Gh_{68}-Gh_{3}-Gh_{21}/2-Gh_{22}/2-Gh_{23}/2$
E_{2b-1}	$\Psi_{68b}-\Psi_{70b}-\Psi_{20b}$
E_{2t-1}	$\Psi_{68t}-\Psi_{70t}-\Psi_{20t}$
E_{2p-1}	$\Psi_{68p}-\Psi_{70p}-\Psi_{20p}$
E_{2pv-1}	$\Psi_{68pv}-\Psi_{70pv}-\Psi_{20pv}$
E_{2s-1}	$\Psi_{70s}+\Psi_{20s}-\Psi_{68s}$
E_{m2-1}	$Gh_{68}-Gh_{70}-Gh_{20}$
E_{2b-2}	$\Psi_{70b}-\Psi_{2b}-\Psi_{19b}-\Psi_{21b}/2-\Psi_{22b}/2-\Psi_{23b}/1$
E_{2t-2}	$\Psi_{70t}-\Psi_{2t}-\Psi_{19t}-\Psi_{21t}/2-\Psi_{22t}/2-\Psi_{23t}/2$
E_{2p-2}	$\Psi_{70p}-\Psi_{2p}-\Psi_{19p}-\Psi_{21p}/2-\Psi_{22p}/2-\Psi_{23p}/2$
E_{2pv-2}	$\Psi_{70pv}-\Psi_{2pv}-\Psi_{19pv}-\Psi_{21pv}/2-\Psi_{22pv}/2-\Psi_{23pv}/2$
E_{2s-2}	$\Psi_{2s}-\Psi_{70s}+\Psi_{19s}+\Psi_{21s}/2+\Psi_{22s}/2+\Psi_{23s}/2$
E_{m2-2}	$Gh_{70}-Gh_{2}-Gh_{19}-Gh_{21}/2-Gh_{22}/2-Gh_{23}/2$
E_{3b}	$\Psi_{7b}-\Psi_{8b}-\Psi_{14b}-\Psi_{31b}-\Psi_{15b}-\Psi_{17b}-\Psi_{18b}-\Psi_{24bb}-\Psi_{25b}-\Psi_{76b}$
E_{3t}	$\Psi_{7t}-\Psi_{8t}-\Psi_{14t}-\Psi_{31t}-\Psi_{15t}-\Psi_{17t}-\Psi_{18t}-\Psi_{24t}-\Psi_{25t}-\Psi_{76t}$
E_{3p}	$\Psi_{7p}-\Psi_{8p}-\Psi_{14p}-\Psi_{31p}-\Psi_{15p}-\Psi_{17p}-\Psi_{18p}-\Psi_{24p}-\Psi_{25p}-\Psi_{76p}$
E_{3pv}	$\Psi_{7pv}-\Psi_{8pv}-\Psi_{14pv}-\Psi_{31pv}-\Psi_{15pv}-\Psi_{17pv}-\Psi_{18pv}-\Psi_{24pv}-\Psi_{25pv}-\Psi_{76pv}$
E_{3s}	$\Psi_{8s}-\Psi_{7s}+\Psi_{14s}+\Psi_{31s}+\Psi_{15s}+\Psi_{17s}+\Psi_{18s}+\Psi_{24s}+\Psi_{25s}+\Psi_{76s}$
E_{m3}	$\Psi_{29}-\Psi_{28}$
E_{3b-1}	$\Psi_{7b}-\Psi_{71b}-\Psi_{18b}-\Psi_{24b}/2-\Psi_{25b}/2-\Psi_{76b}$
E_{3t-1}	$\Psi_{7t}-\Psi_{71t}-\Psi_{18t}-\Psi_{24t}/2-\Psi_{25t}/2-\Psi_{76t}$
E_{3p-1}	$\Psi_{7p}-\Psi_{71p}-\Psi_{18p}-\Psi_{24p}/2-\Psi_{25p}/2-\Psi_{76p}$

Fluxes	Expression
E_{3pv-1}	$\Psi_{7pv}-\Psi_{71pv}-\Psi_{18pv}-\Psi_{24pv}/2-\Psi_{25pv}/2-\Psi_{76pv}$
E_{3s-1}	$\Psi_{71s}-\Psi_{7s}+\Psi_{18s}+\Psi_{24s}/2+\Psi_{25s}/2+\Psi_{76s}$
E_{m3-1}	$Gh_{7}-Gh_{71}-Gh_{18}-Gh_{24}/2-Gh_{25}/2-Gh_{76}$
E_{3b-2}	$\Psi_{71b}-\Psi_{72b}-\Psi_{17b}$
E_{3t-2}	$\Psi_{71t}-\Psi_{72t}-\Psi_{17t}$
E_{3p-2}	$\Psi_{71p}-\Psi_{72p}-\Psi_{17p}$
E_{3pv-2}	$\Psi_{71pv}-\Psi_{72pv}-\Psi_{17pv}$
E_{3s-2}	$\Psi_{72s}+\Psi_{17s}-\Psi_{71s}$
E_{m3-2}	$Gh_{71}-Gh_{72}-Gh_{17}$
E_{3b-3}	$\Psi_{72b}-\Psi_{73b}-\Psi_{15b}$
E_{3t-3}	$\Psi_{72t}-\Psi_{73t}-\Psi_{15t}$
E_{3p-3}	$\Psi_{72p}-\Psi_{73p}-\Psi_{15p}$
E_{3pv-3}	$\Psi_{72pv}-\Psi_{73pv}-\Psi_{15pv}$
E_{3s-3}	$\Psi_{73s}-\Psi_{72s}+\Psi_{15s}$
E_{m3-3}	$Gh_{72}-Gh_{73}-Gh_{15}$
E_{3b-4}	$\Psi_{73b}-\Psi_{8b}-\Psi_{14b}-\Psi_{31b}$
E_{3t-4}	$\Psi_{73t}-\Psi_{8t}-\Psi_{14t}-\Psi_{31t}$
E_{3p-4}	$\Psi_{73p}-\Psi_{8p}-\Psi_{14p}-\Psi_{31p}$
E_{3pv-4}	$\Psi_{73pv}-\Psi_{8pv}-\Psi_{14pv}-\Psi_{31pv}$
E_{3s-4}	$\Psi_{8s}+\Psi_{31s}+\Psi_{14s}-\Psi_{73s}$
E_{m3-4}	$Gh_{73}-Gh_{8}-Gh_{14}-Gh_{31}$
E_{4b}	$\Psi_{9b}-\Psi_{10b}-\Psi_{11b}-\Psi_{13b}-\Psi_{26b}-\Psi_{27b}$
E_{4t}	$\Psi_{9t}-\Psi_{10t}-\Psi_{11t}-\Psi_{13t}-\Psi_{26t}-\Psi_{27t}$
E_{4p}	$\Psi_{9p}-\Psi_{10p}-\Psi_{11p}-\Psi_{13p}-\Psi_{26p}-\Psi_{27p}$
E_{4pv}	$\Psi_{9pv}-\Psi_{10pv}-\Psi_{11pv}-\Psi_{13pv}-\Psi_{26pv}-\Psi_{27pv}$
E_{4s}	$\Psi_{10s}-\Psi_{9s}+\Psi_{11s}+\Psi_{13s}+\Psi_{26s}+\Psi_{27s}$
E_{m4}	$\Psi_{30}-\Psi_{29}$
E_{4b-1}	$\Psi_{9b}-\Psi_{74b}-\Psi_{13b}-\Psi_{26b}/2-\Psi_{27b}/1$
E_{4t-1}	$\Psi_{9t}-\Psi_{74t}-\Psi_{13t}-\Psi_{26t}/2-\Psi_{27t}/2$
E_{4p-1}	$\Psi_{9p}-\Psi_{74p}-\Psi_{13p}-\Psi_{26p}/2-\Psi_{27p}/2$
E_{4pv-1}	$\Psi_{9pv}-\Psi_{74pv}-\Psi_{13pv}-\Psi_{26pv}/2-\Psi_{27pv}/2$
E_{4s-1}	$\Psi_{74s}-\Psi_{9s}+\Psi_{13s}+\Psi_{26s}/2+\Psi_{27s}/2$
E_{m4-1}	$Gh_{9}-Gh_{74}-Gh_{13}-Gh_{26}/2-Gh_{27}/2$
E_{4b-2}	$\Psi_{74b}-\Psi_{75b}-\Psi_{11b}$
E_{4t-2}	$\Psi_{74t}-\Psi_{75t}-\Psi_{11t}$
E_{4p-2}	$\Psi_{74p}-\Psi_{75p}-\Psi_{11p}$
E_{4pv-2}	$\Psi_{74pv}-\Psi_{75pv}-\Psi_{11pv}$
E_{4s-2}	$\Psi_{75s}+\Psi_{11s}-\Psi_{74s}$
E_{m4-2}	$Gh_{74}-Gh_{75}-Gh_{11}$
E_{4b-3}	$\Psi_{75b}-\Psi_{10b}-\Psi_{26b}/2-\Psi_{27b}/1$

Fluxes	Expression
E_{4t-3}	$\Psi_{75t}-\Psi_{10t}-\Psi_{26t}/2-\Psi_{27t}/2$
E_{4p-3}	$\Psi_{75p}-\Psi_{10p}-\Psi_{26p}/2-\Psi_{27p}/2$
E_{4pv-3}	$\Psi_{75pv}-\Psi_{10pv}-\Psi_{26pv}/2-\Psi_{27pv}/2$
E_{4s-3}	$\Psi_{10s}-\Psi_{75s}+\Psi_{26s}/2+\Psi_{27s}/2$
E_{m4-3}	$Gh_{75}-Gh_{10}-Gh_{26}/2-Gh_{27}/2$
E_{5b}	$\Psi_{31b}-\Psi_{33b}+\Psi_{8b}-\Psi_{9b}$
E_{5t}	$\Psi_{31t}-\Psi_{33t}+\Psi_{8t}-\Psi_{9t}$
E_{5p}	$\Psi_{31p}-\Psi_{33p}+\Psi_{8p}-\Psi_{9p}$
E_{5pv}	$\Psi_{31pv}-\Psi_{33pv}+\Psi_{8pv}-\Psi_{9pv}$
E_{5s}	$\Psi_{33s}-\Psi_{31s}+\Psi_{9s}-\Psi_{8s}$
E_{m5}	Ψ_{32}
E_{b5}	$\Psi_{64}-\Psi_{63}$
E_{6b}	$\Psi_{57}-\Psi_{56}$
E_{6t}	$\Psi_{57}-\Psi_{57}$
E_{6s}	$\Psi_{57s}-\Psi_{56s}$
E_{m6}	Ψ_{62}
E_{7b}	$\Psi_{10b}+\Psi_{45b}+\Psi_{46b}-\Psi_{66b}$
E_{7t}	$\Psi_{10t}+\Psi_{45t}+\Psi_{46t}-\Psi_{66t}$
E_{7p}	$\Psi_{10p}+\Psi_{45p}+\Psi_{46p}-\Psi_{66p}$
E_{7pv}	$\Psi_{10pv}+\Psi_{45pv}+\Psi_{46pv}-\Psi_{66pv}$
E_{b7}	$\Psi_{61}-\Psi_{60}$
E_{8t}	$\Psi_{66t}-\Psi_{57t}$
E_{8s}	$\Psi_{57s}-\Psi_{66s}$
E_{8m}	Ψ_{58}
E_{p8}	$\Psi_{57p}-\Psi_{66p}$
E_{b8}	$\Psi_{57b}-\Psi_{66b}$
E_{9b}	$\Psi_{43b}+\Psi_{11b}+\Psi_{23b}+\Psi_{25b}+\Psi_{27b}+\Psi_{22b}+\Psi_{24b}+\Psi_{26b}-\Psi_{45b}-\Psi_{46b}$
E_{9t}	$\Psi_{43t}+\Psi_{11t}+\Psi_{23t}+\Psi_{25t}+\Psi_{27t}+\Psi_{22t}+\Psi_{24t}+\Psi_{26t}-\Psi_{45t}-\Psi_{46t}$
E_{9p}	$\Psi_{43p}+\Psi_{11p}+\Psi_{23p}+\Psi_{25p}+\Psi_{27p}+\Psi_{22p}+\Psi_{24p}+\Psi_{26p}-\Psi_{45p}-\Psi_{46p}+\Psi_{56p}-\Psi_{36p}$
E_{9pv}	$\Psi_{43pv}+\Psi_{11pv}+\Psi_{23pv}+\Psi_{25pv}+\Psi_{27pv}+\Psi_{22pv}+\Psi_{24pv}+\Psi_{26pv}-\Psi_{45pv}-\Psi_{46pv}$
E_{9s}	$\Psi_{45s}-\Psi_{11s}-\Psi_{23s}-\Psi_{25s}-\Psi_{27s}-\Psi_{22s}-\Psi_{24s}-\Psi_{26s}-\Psi_{43s}+\Psi_{46s}-\Psi_{56s}+\Psi_{36s}$
E_{b9}	$\Psi_{36b}-\Psi_{56b}$
E_{t9}	$\Psi_{36t}-\Psi_{56t}$
E_{10b}	$\Psi_{42b}+\Psi_{13b}-\Psi_{43b}$
E_{10t}	$\Psi_{42t}+\Psi_{13t}-\Psi_{43t}$
E_{10p}	$\Psi_{42p}+\Psi_{13p}-\Psi_{43p}+\Psi_{36p}-\Psi_{37p}$
E_{10pv}	$\Psi_{42pv}+\Psi_{13pv}-\Psi_{43pv}$
E_{10s}	$\Psi_{43s}-\Psi_{13s}-\Psi_{42s}-\Psi_{36s}+\Psi_{37s}$

Fluxes	Expression
E_{b10}	$\Psi_{37b}-\Psi_{36b}$
E_{t10}	$\Psi_{37t}-\Psi_{36t}$
E_{11b}	$\Psi_{41b}+\Psi_{14b}-\Psi_{42b}$
E_{11t}	$\Psi_{41t}+\Psi_{14t}-\Psi_{42t}$
E_{11p}	$\Psi_{41p}+\Psi_{14p}-\Psi_{42p}+\Psi_{37p}-\Psi_{38p}$
E_{11pv}	$\Psi_{41pv}+\Psi_{14pv}-\Psi_{42pv}$
E_{11s}	$\Psi_{42s}-\Psi_{14s}-\Psi_{41s}-\Psi_{37s}+\Psi_{38s}$
E_{b11}	$\Psi_{38b}-\Psi_{37b}$
E_{t11}	$\Psi_{38t}-\Psi_{37t}$
E_{12b}	$\Psi_{16b}-\Psi_{41b}$
E_{12t}	$\Psi_{16t}-\Psi_{41t}$
E_{12p}	$\Psi_{16p}+\Psi_{33p}-\Psi_{41p}+\Psi_{38p}-\Psi_{40p}$
E_{12pv}	$\Psi_{16pv}-\Psi_{41pv}$
E_{12s}	$\Psi_{41s}-\Psi_{33s}-\Psi_{16s}-\Psi_{38s}+\Psi_{40s}$
E_{b12}	$\Psi_{40b}-\Psi_{38b}-\Psi_{33b}$
E_{t12}	$\Psi_{40t}-\Psi_{38t}-\Psi_{33t}$
E_{13b}	$\Psi_{54b}+\Psi_{17b}-\Psi_{47b}*(1-G_{40}/G_{47})$
E_{13t}	$\Psi_{54t}+\Psi_{17t}-\Psi_{47t}*(1-G_{40}/G_{47})$
E_{13p}	$\Psi_{54p}+\Psi_{17p}+\Psi_{40p}-\Psi_{47p}$
E_{13pv}	$\Psi_{54pv}+\Psi_{17pv}$
E_{13s}	$\Psi_{47s}-\Psi_{17s}-\Psi_{54s}-\Psi_{40s}$
E_{b13}	$\Psi_{47b}*(G_{40}/G_{47})-\Psi_{17b}$
E_{t13}	$\Psi_{47t}*(G_{40}/G_{47})-\Psi_{17t}$
E_{14t}	$\Psi_{47t}-\Psi_{48t}$
E_{14s}	$\Psi_{48s}-\Psi_{47s}$
E_{14m}	Ψ_{55}
E_{p14}	$\Psi_{48p}-\Psi_{47p}$
E_{b14}	$\Psi_{48b}-\Psi_{47b}$
E_{15b}	$\Psi_{53b}+\Psi_{18b}-\Psi_{54b}$
E_{15t}	$\Psi_{53t}+\Psi_{18t}-\Psi_{54t}$
E_{15p}	$\Psi_{53p}+\Psi_{18p}-\Psi_{54p}+\Psi_{48p}-\Psi_{49p}$
E_{15pv}	$\Psi_{53pv}+\Psi_{18pv}-\Psi_{54pv}$
E_{15s}	$\Psi_{54s}-\Psi_{18s}-\Psi_{53s}-\Psi_{48s}+\Psi_{49s}$
E_{b15}	$\Psi_{49b}-\Psi_{48b}$
E_{t15}	$\Psi_{49t}-\Psi_{48t}$
E_{16b}	$\Psi_{52b}+\Psi_{19b}-\Psi_{53b}$
E_{16t}	$\Psi_{52t}+\Psi_{19t}-\Psi_{53t}$
E_{16p}	$\Psi_{52p}+\Psi_{19p}-\Psi_{53p}+\Psi_{49p}-\Psi_{50p}$
E_{16pv}	$\Psi_{52pv}+\Psi_{19pv}-\Psi_{53pv}$

Fluxes	Expression
E_{16s}	$\Psi_{53s}-\Psi_{19s}-\Psi_{52s}-\Psi_{49s}+\Psi_{50s}$
E_{b16}	$\Psi_{50b}-\Psi_{49b}$
E_{t16}	$\Psi_{50t}-\Psi_{49t}$
E_{17b}	$\Psi_{20b}-\Psi_{52b}$
E_{17t}	$\Psi_{20t}-\Psi_{52t}$
E_{17p}	$\Psi_{20p}-\Psi_{52p}+\Psi_{50p}-\Psi_{51p}$
E_{17pv}	$\Psi_{20pv}-\Psi_{52pv}$
E_{17s}	$\Psi_{52s}-\Psi_{20s}-\Psi_{50s}+\Psi_{51s}$
E_{b17}	$\Psi_{51b}-\Psi_{50b}$
E_{t17}	$\Psi_{51t}-\Psi_{50t}$

Table. 3.1 - Fluxes in the productive structures of the Moncalieri steam turbine plant

3.1.2 Gas turbine case

The application of the thermoeconomic theories to the power plants based on the gas turbine technology must be made very carefully, taking into account that the thermodynamic cycle is open. The fluid exits the plant in conditions different from the entering ones, but the exiting flux does not have any utility. It represents a loss of the system and therefore the plant components must be charged for the cost associated to its production. The different criteria which can be utilized to make this charging determines as many possible productive structures.

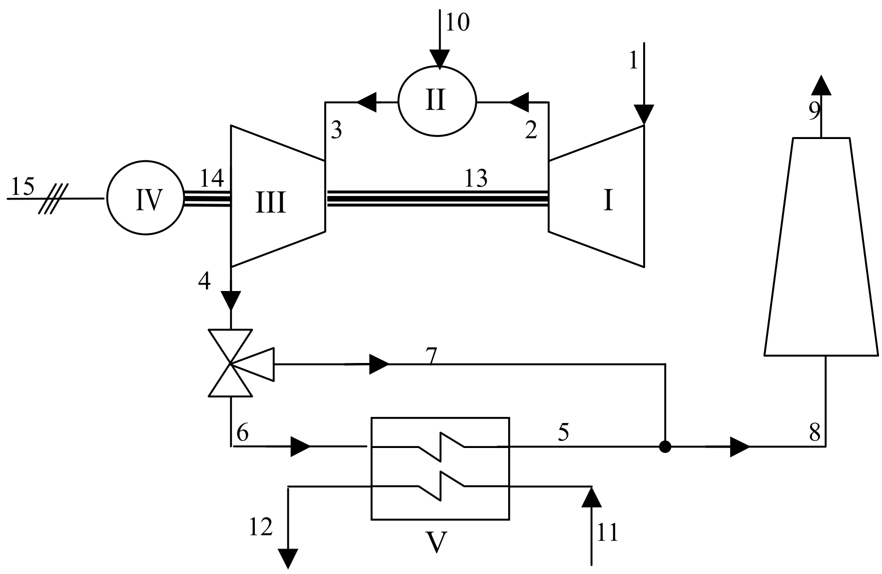

Figure 3.15 - Physical fluxes of the Moncalieri gas turbine plant

The first productive structure, indicated as TG1 and represented in figure 3.16 is close to the physical structure. It has been obtained considering the exergy fluxes associated to the mass and energy flows in the physical model as fuels and products of the components. The physical representation is shown in figure 3.15. The fluxes entering every component constitute its resources, while the fluxes exiting it are its products. The fuel of the plant Ψ_{10}, is used by the combustor, to increase the temperature of the gas, and then its exergy. The product is represented by the exergy flow associated to the combustion gas Ψ_3. The combustor also uses the exergy produced by the compressor Ψ_2, obtained transforming the part Ψ_{13} of the mechanical power, provided by the turbine, into mechanical and thermal exergy of the air flow. The fuel of the plant also includes the exergy flow of the air entering the compressor from the environment. This flux Ψ_1, has a value different to zero if the pressure or the temperature of the environment differ from the reference values. Here the exergy of this flux is considered zero. The product of the combustor is resource of the turbine and the heat exchanger. These components transform it respectively into mechanical power (Ψ_{13} + Ψ_{14}) and thermal exergy flow (Ψ_{12} - Ψ_{11}). This last flow is one of the products of the plant. Finally the alternator transform the mechanical power into electricity which constitutes the second product.

The particularity of this structure is that the loss associated to the exhausted gas has been considered as a product of the heat exchanger and fuel of the combustor. This component is so charged for it.

The structure TG2 is conceptually equivalent to the TG1, in fact exergy fluxes are used for the definition of fuels and products, moreover the combustor is totally charged for the losses. The philosophy is therefore different. The structure TG2 has been built considering the criteria of the functional analysis [Frangopoulos 1994]. This means that the fuel of every component is represented by the amount of exergy effectively consumed and its product is not simply provided to the components physically connected with it, but to all the components which makes use of that kind of flux. In the structure TG2 the exergy associated to the combustion gas required by turbine and recuperator is directly provided by the combustor. In the TG1 the fuel of the recuperator is instead produced by the turbine, what seams to be less correct as the turbine role of the turbine is the transformation of the exergy of the fluid into mechanical power. The exiting gases are effectively a waste and not a product.

The choice of the productive structure causes a different costs distribution, in fact in the structure TG1 the fuel of the recuperator has the cost of the turbine product, while in the TG2 it has the cost of the combustor product. The impact on the costs of the overall products is sensible, as shown in table 3.8.

The structure TG3 has the same graphical representation of the TG2, nevertheless the values assumed by the fluxes is different, as the losses are here totally charged on the recuperation heat exchanger, as reported in table 3.2. The heat exchanger is charged for all the losses when it design does not allow to recuperate all the thermal exergy of the gas; in this case the operation is thermodynamically impossible, as the water enters at about 70 °C, so the exhausted gas can not be cooled over this value. Nevertheless it is interesting to examine this case in order to verify the effect of the assumption on cost accounting and thermoeconomic diagnosis.

Another criterion to make the loss charging is based on the entropy increasing in every component. As said before, the thermodynamic cycle built representing the transformations of the gas turbine is open. It can be artificially closed by considering the environment as the component which ’transforms’ the exhausted gas exiting the chimney into the air entering the compressor. The cycle closure, from the thermodynamic point of view, requires an isobar process which brings the entropy to the value assumed by the entering air. The fuel of this process is the thermal exergy of the exhausted gas and its product is negentropy. All the components have negentropy as fuel, according to their contribution to the entropy flow increasing. The same operation can be made without using negentropy flows, but directly charging the components for the losses, proportionally to the entropy flow increasing in each one. The charge of the loss on the combustor is made considering the largest entropy increase takes place in this component.

The productive structure created by applying this concept, indicated as TG4, is shown in figure 3.16, while the corresponding fluxes are reported in table 3.2. In this table the total variation of entropy flows, indicated as Gs_{tot}, is calculated as:

$$Gs_{tot} = G_9 \cdot (s_9 - s_1) \tag{3.15}$$

so that the contribution of the recuperator to reduce the entropy of the gas has not be considered. In this way the recuperator is not charged for the loss. If its negative contribution to the entropy flow increasing were considered the recuperator would have two products: the thermal exergy provided to the district heating network and this negative loss. This last assumption contains a theoretical error: if the recuperator realised a reversible heat exchange the component would be characterised by a production larger than the fuel, in fact the main product (the thermal exergy) would be equal to the fuel and there would be also the additional negentropy production. The consequence in the cost distribution is that the product would cost less than the fuel. For this reason the losses have been charged only on the components presenting a positive contribution to the entropy flow increase.

Other productive structures can include the separation of exergy into mechanical and thermal components for the definition of the fluxes of the productive structure. In the case of the gas turbine analysis these two terms are defined:

$$b_m = T_0 \cdot R \cdot \ln\frac{p}{p_0} \tag{3.16}$$

$$b_t = \overline{c_p} \cdot \left(T - T_0 - T_0 \cdot \ln\frac{T}{T_0}\right) \tag{3.17}$$

where $\overline{c_p}$ is the average specific heat calculated between the temperatures T and T_0.

The compressor is the only component producing mechanical exergy, while the others use this resource to compensate the pressure drops or, in the case of the turbine, to expand the fluid. The compressor also produces thermal exergy, which must be evaluated using an additional equation. In the productive structures TG5 and TG6, shown in figure 3.17, the unit cost of the thermal exergy has been assumed equal to the unit cost of the mechanical exergy produced. This assumption has been obtained considering the total exergy flow (mechanical plus thermal) as product of the compressor.

A fictitious component is necessary to spit the thermal exergy produced by the combustor between all the components. This component allows to define, in the case of the structure TG5, a thermal fuel also for the combustor itself. This flux represents the charge for the losses. The charge would be also realised simply reducing the thermal exergy produced of a quantity corresponding to the losses. Such a structure would be equivalent to the TG2 from the cost calculation point of view, but in the application for the thermoeconomic diagnosis the behaviour of the two structures would be different. The use of the branching point allows to consider separately the effect of the variation of the losses on the variation of the unit exergy consumption, while without the branching point this effect would be hidden.

In the structure TG6 the fictitious component would not be necessary, as the combustor only produces thermal exergy for the other components and not for itself. The losses in the structure TG6 are totally charged on the recuperator.

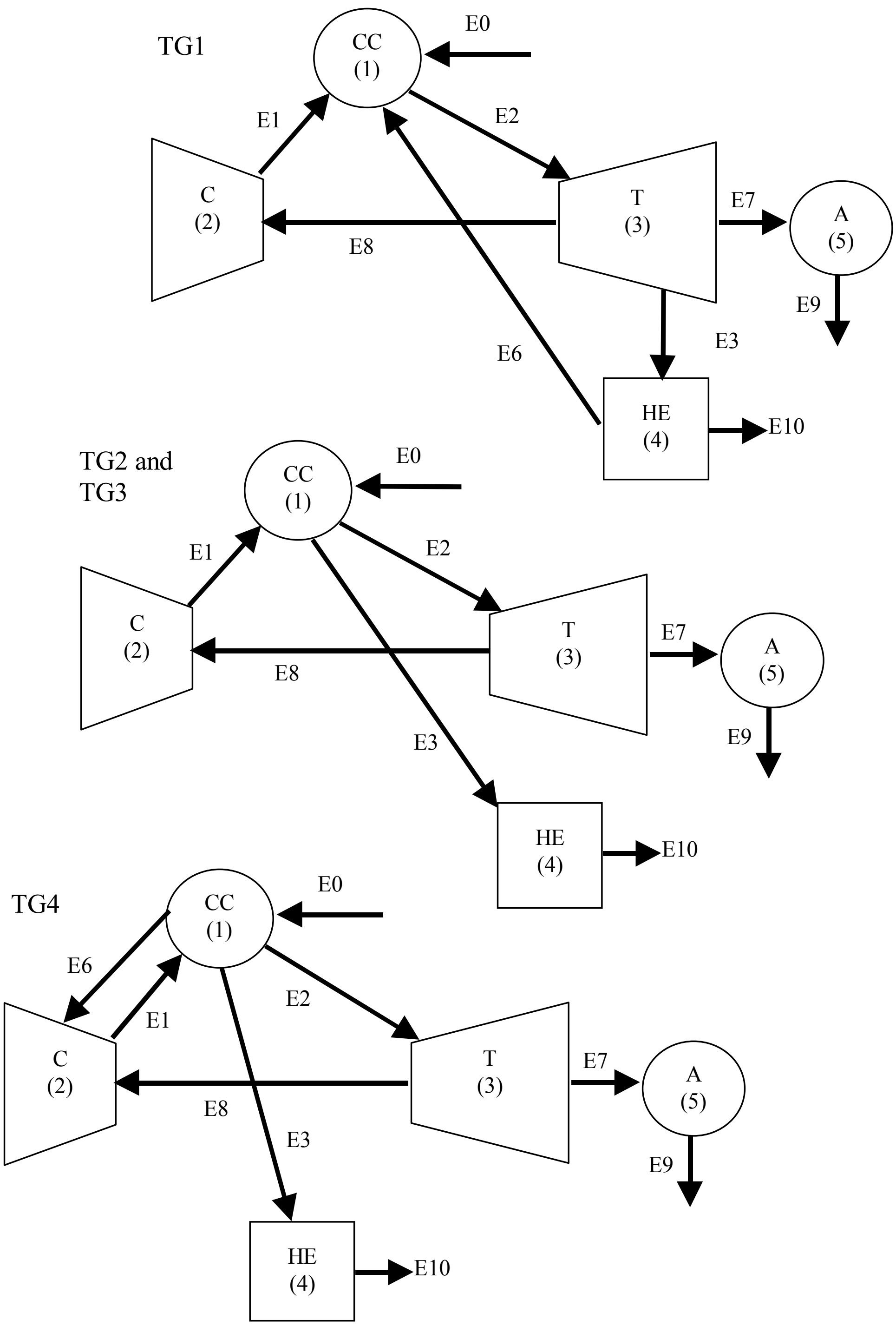

Figure 3.16 - Productive structures TG1-TG4

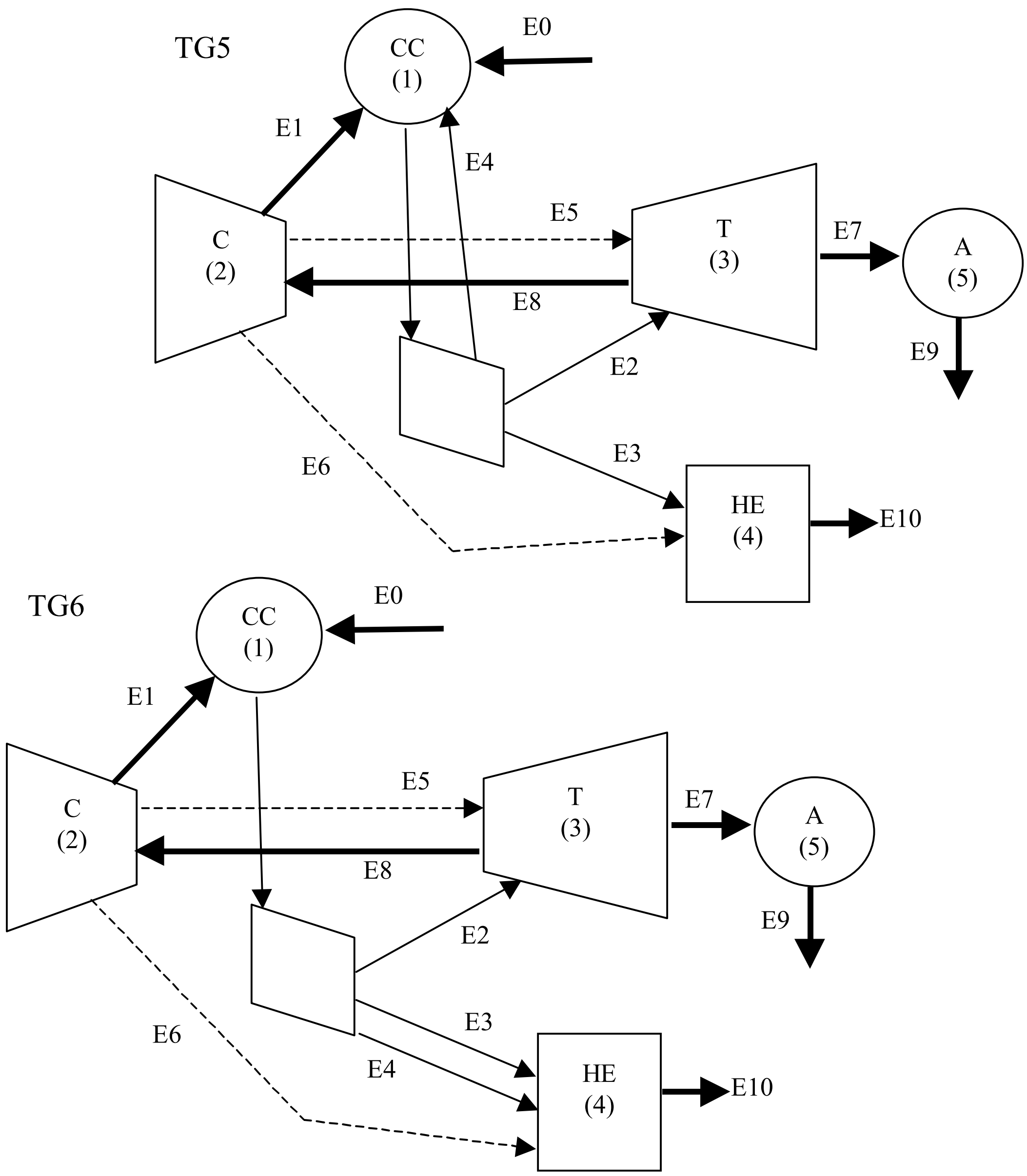

Figure 3.17 - Productive structures TG5 and TG6

Fluxes	TG1	TG2	TG3	TG4	TG5	TG6
E_0	Ψ_{10}	Ψ_{10}	Ψ_{10}	Ψ_{10}	Ψ_{10}	Ψ_{10}
E_1	Ψ_2	Ψ_2-Ψ_1	Ψ_2-Ψ_1	Ψ_2-Ψ_1	Ψ_2-Ψ_1	Ψ_2-Ψ_1
E_2	Ψ_3	Ψ_3-Ψ_4	Ψ_3-Ψ_4	Ψ_3-Ψ_4-Ψ_6*(Gs_4-Gs_3)/Gs_{tot}	Ψ_{3t}-Ψ_{4t}	Ψ_{3t}-Ψ_{4t}
E_3	Ψ_4	Ψ_6-Ψ_5	Ψ_4	Ψ_6-Ψ_5	Ψ_{6t}-Ψ_{5t}	Ψ_{6t}-Ψ_{5t}
E_4					Ψ_{7t}+Ψ_{5t}	Ψ_{7t}+Ψ_{5t}
E_5					Ψ_{3p}-Ψ_{4p}	Ψ_{3p}-Ψ_{4p}
E_6	Ψ_5+Ψ_7			Ψ_6*(Gs_2-Gs_1)/Gs_{tot}	Ψ_{6p}	Ψ_{6p}
E_7	Ψ_{14}	Ψ_{14}	Ψ_{14}	Ψ_{14}	Ψ_{14}	Ψ_{14}
E_8	Ψ_{13}	Ψ_{13}	Ψ_{13}	Ψ_{13}	Ψ_{13}	Ψ_{13}
E_9	Ψ_{15}	Ψ_{15}	Ψ_{15}	Ψ_{15}	Ψ_{15}	Ψ_{15}
E_{10}	Ψ_{12}-Ψ_{11}	Ψ_{12}-Ψ_{11}	Ψ_{12}-Ψ_{11}	Ψ_{12}-Ψ_{11}	Ψ_{12}-Ψ_{11}	Ψ_{12}-Ψ_{11}

Table. 3.2 - Fluxes in the productive structures of the Moncalieri gas turbine plant

3.2 Calculation of thermoeconomic costs

In this paragraph the complete matrix procedure for the thermoeconomic analysis is applied to the productive structure TG3. The costs of the internal fluxes are calculated.

The starting point of the procedure is represented by the knowledge of the thermodynamic quantities (mass flow, temperature, pressure and mechanical power) at the boundaries of the control volume delimitating every component. Table 3.3 shows the values of the thermodynamic quantities relative to the Moncalieri gas turbine (see figure 3.15) in maximum thermal load condition.

The difference between exergy and thermoeconomic analyses begins once the productive structure is defined. The exergy analysis considers every single process separately, so that its efficiency only depends on the thermodynamic conditions of the entering fluxes and on the process itself. On the contrary the productive structure builds a functional link among the processes, so that the thermoeconomic evaluation of a process also depends on the others.

Point	Fluid	G kg/s	p bar	T K	W kW
1	Air	154.85	1.013	278.15	
2	Air	154.85	11.080	598.81	
3	Combustion gas	157.22	10.747	1218.27	
4	Combustion gas	157.22	1.044	767.32	
5	Combustion gas	149.36	1.023	393.94	
6	Combustion gas	149.36	1.044	767.32	
7	Combustion gas	7.86	1.044	767.32	
8	Combustion gas	157.22	1.023	412.61	
9	Combustion gas	157.22	1.013	412.61	
10	Natural gas	2.37	15.000	278.15	
11	Water	288.35	5.000	343.15	
12	Water	288.35	3.000	393.15	
13					50889
14					33250
15					32585

Table. 3.3 - Thermodynamic quantities relative to the Moncalieri gas turbine plant

The definition of the productive structure can be made graphically, as shown in the previous paragraph, but it is also necessary to quantify every flux, because the same graphical representation can correspond to different productive structures. A table indicating the values of the exergy productive fluxes must be so added. Table 3.4 shows the values corresponding to the structure TG3.

Fluxes	E_0	E_1	E_2	E_3	E_7	E_8	E_9	E_{10}
Exergy flow (kW)	120251	48221	90580	33627	33245	52399	32580	16187

Table. 3.4 - Fluxes of the productive structure TG3 in maximum thermal load condition

Alternatively a matrix representation of the structure, called fuel/product diagram [Torres et al. 1999], is also possible. The fuel/product diagram is mainly constituted by a squared matrix characterised by a number of rows and columns equal to the number of components. The environment, usually indicated as component 0, must be included too. Every element E_{ij} of this matrix represents the fuel of the jth component, produced by the ith component. This term is zero if the assumed productive structure does not consider any direct productive relation between the two components *i* and *j*. The fuels of the plant are considered as products of the environment, so the flux E_{0i} corresponds to the external fuel of the ith component. Vice versa the products of the plant are fuels of the environment, so the flux E_{i0} corresponds to the product of the i^{th} component exiting the overall plant. The diagram is completed by a row and a column respectively containing the sum of the columns and the sum of the rows. The i^{th} term of the added row corresponds to the total fuel of the i^{th} component (F_i) and the i^{th} term of the added column corresponds to its total product (P_i).

The fuel/product diagram relative to the structure TG3 is shown in table 3.5. The numeration of the components has been assumed, from the number 0 to 5, respectively for environment, combustor, compressor, turbine, heat recuperator and alternator.

	F_0	F_1	F_2	F_3	F_4	F_5	Total product
P_0	0	120251	0	0	0	0	120251
P_1	0	0	0	90580	33627	0	124206
P_2	0	48221	0	0	0	0	48221
P_3	0	0	52399	0	0	33245	85644
P_4	16187	0	0	0	0	0	16187
P_5	32580	0	0	0	0	0	32580
Total fuel	48767	168472	52399	90580	33627	33245	

Table. 3.5 - Fuel/product diagram corresponding to the structure TG3

The unit exergy consumption of a flux E_{ij} can be obtained, using the fuel/product diagram, dividing it for the total product of the j^{th} component, which can be written:

$$k_{ij} = \frac{E_{ij}}{P_j}. \tag{3.18}$$

The matrix containing all the unit exergy consumption of the example is shown in table 3.6. In this matrix the first row corresponds to the unit consumption of the external fuels of the plant (**Kext**), while the other rows corresponds to the unit consumption of the internal products <**KP**>.

(**Kext**)^t	0.968156	0	0	0	0
	0	0	1.057631	2.077421	0
	0.388236	0	0	0	0
<**KP**>	0	1.08664	0	0	1.020408
	0	0	0	0	0
	0	0	0	0	0

Table. 3.6 - Unit exergy consumption matrix

The cost calculation is obtained using the equation 2.87. This equation can be rewritten, considering the information contained in the matrix of the unit exergy consumptions. A part of the total product of a component can fuel of the environment E_{i0} (i.e. a plant product) or fuel of other components; in this way it can be written:

$$P_i = E_{i0} + \sum_{j=1}^{n} E_{ij} \quad \text{i=0...n} \tag{3.19}$$

where n is the number of the plant components.

Equation 3.19 can be rewritten using the definition of the unit exergy consumption 3.18:

$$P_i = E_{i0} + \sum_{j=1}^{n} k_{ij} \cdot P_j \quad \text{i=0...n} \tag{3.20}$$

or, using a matrix notation

$$\mathbf{P} = \mathbf{P_{ext}} + \langle \mathbf{KP} \rangle \cdot \mathbf{P} \tag{3.21}$$

where **P** is the vector of the total products of the components and $\mathbf{P_{ext}}$ is the vector of the plant products. The vector of the products can be calculated as:

$$\mathbf{P} = |\mathbf{P}\rangle \cdot \mathbf{P_{ext}} \tag{3.22}$$

being

$$|\mathbf{P}\rangle = (\mathbf{U_D} - \mathbf{KP})^{-1} \tag{3.23}$$

and $\mathbf{U_D}$ the identity matrix.

The overall fuel is the sum of the resources entering the plant from the environment. It can be also expressed as the sum of the unit exergy consumption of external resources of each component, multiplied for its product:

$$F_T = \sum_{i=1}^{n} E_{0i} = \sum_{i=1}^{n} k_{0i} \cdot P_i \tag{3.24}$$

or, using matrix notation:

$$F_T = (\mathbf{k_{ext}})^t \cdot \mathbf{P} = (\mathbf{k_{ext}})^t \cdot |\mathbf{P}\rangle \cdot \mathbf{P_{ext}} \tag{3.25}$$

where the vector $\mathbf{k_{ext}}$ contains the unit exergy consumption of the external resources of the components.

Now the unit cost of the products, defined as:

$$k_{P_i}{}^* = \frac{P_i{}^*}{P_i} \tag{3.26}$$

can be expressed as function of the unit exergy consumptions. The exergetic cost of a component product is equal to the sum of the cost of its fuels. This term can be written as sum of every resource, multiplied for its unit cost. The unit cost of each resource is also equal to the unit cost of the product of the component which had provided it:

$$P_i{}^* = F_i{}^* = \sum_{j=0}^{n} k_{P_j}{}^* \cdot E_{ji} \quad \text{i=1...n} \tag{3.27}$$

so the expression 3.27 of the unit cost becomes:

$$k_{P_i}^* = \frac{\sum_{i=0}^{n} k_{P_j}^* \cdot E_{ji}}{P_i} = \sum_{i=0}^{n} k_{P_j}^* \cdot k_{ji} \qquad (3.28)$$

and, considering the unit cost of the external resources equal to 1:

$$k_{P_i}^* = k_{0i} + \sum_{i=1}^{n} k_{ji} \cdot k_{P_j}^* \quad \text{i=1...n.} \qquad (3.29)$$

The equation 3.29 in matrix notation is:

$$\mathbf{k_P}^* = \mathbf{k_{ext}} + (\mathbf{KP})^t \cdot \mathbf{k_P}^* \qquad (3.30)$$

so the vector of the unit costs can be calculated as:

$$\mathbf{k_P}^* = ((\mathbf{KP})^t - \mathbf{U_D})^{-1} \cdot \mathbf{k_{ext}} = ((\mathbf{KP} - \mathbf{U_D})^{-1})^t \cdot \mathbf{k_{ext}} = |\mathbf{P}\rangle \cdot \mathbf{k_{ext}} \qquad (3.31)$$

The matrix operator $|\mathbf{P}\rangle$ in the case of the productive structure TG3 is:

|P>

1.80566	2.07518	1.90972	3.75111	1.94869
0.70102	1.80566	0.74142	1.45631	0.75655
0.76176	1.9621	1.80566	1.58249	1.84251
0	0	0	1	0
0	0	0	0	1

so that the unit cost of the products are:

$\mathbf{k_p}^*$

1.748
2.009
1.849
3.632
1.887

where the last two terms respectively are the exergetic unit costs of thermal and electric productions of the plant.

3.3 Application of the structural analysis to the Moncalieri plants

The application of the equation 3.31 to the Moncalieri system is here made to describe the effect of the variation of thermal and electric loads on the cost of the products. The effect of the choice of the productive structure on the results of the cost accounting process is also analysed.

3.3.1 Exergetic costs of the steam turbine plant

In the case of the steam turbine plant, the choice of the productive structure does not sensibly affect the cost of the plant products. The cost of the resources of all components is mainly determined by the steam generator, which does not change a lot. In particular the table 3.7 shows the cost of the products of the components, corresponding to the condition of maximum thermal production, calculated using the structures TV1 and TV3. The main difference is located in the circulation pump: in the structure TV1 the pump product is the difference between the exergy flows of the exiting and entering fluxes associated to the feed water; on the contrary in the structure TV3 the product is the difference between the two corresponding mechanical exergy flows. The increase of the thermal exergy is considered as a by-product and evaluated at the unit cost of the thermal exergy, which is close to the unit cost of the steam generator product. For this reason the cost of the pump product is higher in the case of the accounting made using the structure TV3.

	SG	HPT	MPT	LPT	A	C	HE1	HE2
TV1	1.9895	2.3198	2.1911	2.5311	2.3228	2.5338	3.604	3.4676
TV3	1.9941	2.3553	2.178	2.5439	2.3289	2.5449	3.6529	3.4834

	HE3	HE4	HC	D	CP	HE6	HE7	HE8
TV1	2.7676	2.3505	2.474	2.2948	3.4709	2.3105	2.1738	2.128
TV3	2.7628	2.3653	2.4602	2.3034	3.823	2.3105	2.1636	2.1243

Table. 3.7 - Cost of the products of the components

The variation of the electric and thermal loads determines a variation of the costs. The effect of the thermal load, evaluated using the structure TV1 and fixing the regulation of the throttles, is shown in figure 3.18. The cost of the thermal exergy flow, indicated as k^*_{th}, varies sensibly only for very low thermal loads, as its value must be zero in non cogenerative conditions[2]. For higher loads the cost slightly decreases. On the contrary the cost of the electric power k^*_{el} linearly decreases as the thermal load increases.

2. This point is not represented in the figure. The first working condition represented corresponds to a thermal load of 0.5 MW.

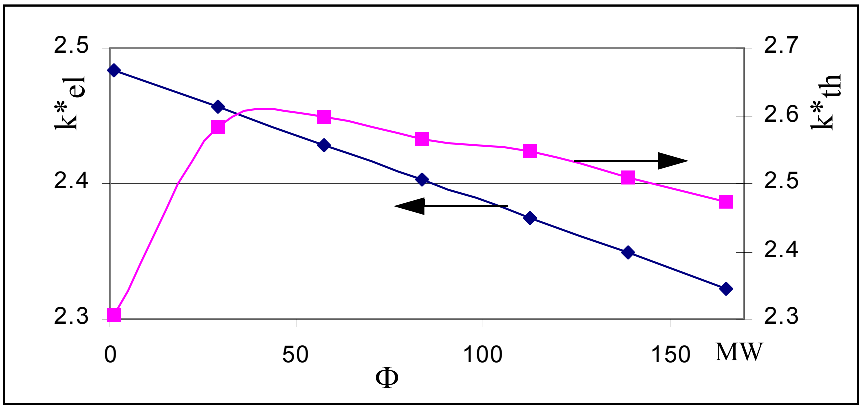

Figure 3.18 - Variation of the unit costs of the products depending on the thermal load

The effect of the electric load variation is shown, for the non cogenerative mode, in figure 3.19.

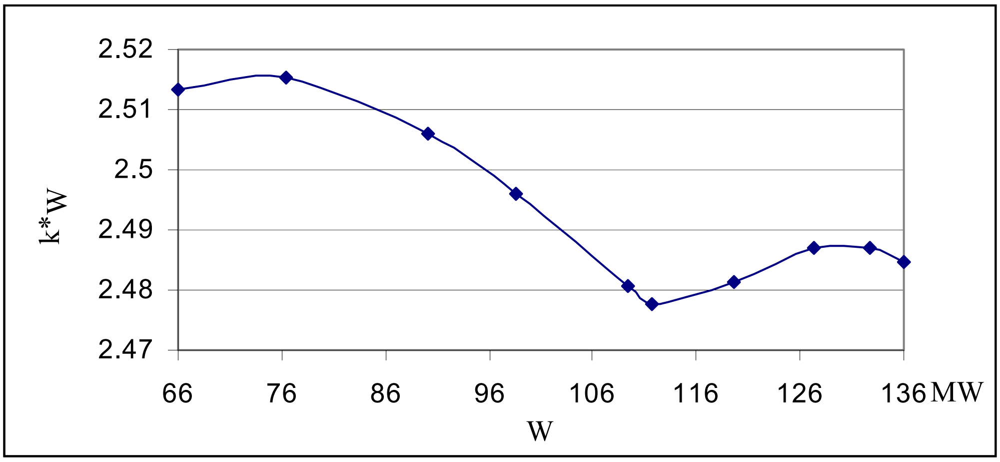

Figure 3.19 - Variation of the unit cost of the electric power depending on the load

The behaviour of the cost, to which corresponds an inverse behaviour of the plant efficiency, is determined by the regulation system. In particular the minimum corresponds to a condition where one of the valves is completely closed, so that the effect of the lamination is low.

3.3.2 Exergetic costs of the gas turbine plant

The unit costs of the gas turbine plant, working at maximum thermal load condition calculating using the productive structures TG1-TG6, are shown in table 3.8. As discussed in the paragraph 3.1 the use of a physical structure or a functional structure determines a sensible difference in the costs, although the losses are charged in the same way. In the structure TG1 the fuel of the recuperator is produced by the turbine, while in the structure TG2 is produced by the combustor, which is characterised by an average cost lower than the turbine product. Moreover the recuperator in the structure TG1 produces the exhausted gas, successively charged on the combustor. On the contrary in the structure TG2 the unit cost of the losses is determined by the combustor itself. As the unit cost of the combustor product is always lower than the recuperator one, the product of the recuperator is characterized by a lower cost, when the calculation is made using the structure TG2. The differences between the costs calculated using the productive structures TG2 and TG3 are caused by the loss charging: in the structure TG3 the recuperator is charged for the loss, so the cost of its product is higher than it happens in the case of structure TG2. On the contrary in the structure TG2 the cost of the combustor product is higher, as it pays for the loss. The structure TG5 and TG6 have the same behaviour. In this case it is possible to notice how the definition of resources and products using mechanical and thermal components of the exergy determines a higher cost of the electricity. The turbine, which is the main users of the mechanical exergy, in TG5 and TG6 pays it at the cost of the compressor product. In the structures TG2 and TG3 the mechanical exergy required by the turbine is hidden in the combustor product, which is characterized by a lower unit cost. This determines a lower cost of the turbine product and consequently an higher cost of the recuperator product, as the total costs must be balanced.

Structure	$K^*_{p\ combustor}$	$K^*_{p\ compressor}$	$K^*_{p\ turbine}$	$K^*_{p\ recuoerator}$	$K^*_{p\ alternator}$
TG1	1.785	2.020	1.859	3.612	1.897
TG2	1.777	2.042	1.879	3.569	1.918
TG3	1.748	2.009	1.849	3.632	1.887
TG4	1.741	2.001	1.843	3.644	1.880
TG5	1.702	2.117	1.948	3.428	1.988
TG6	1.675	2.084	1.918	3.490	1.957

Table. 3.8 - Exergetic unit costs of the products of the components

The choice of the productive structure also determines the behaviour of the costs as the thermal and electric loads vary. Figures 3.20, 3.21 and 3.22 show the dependence of the unit cost of the plant products on the loads, having calculated the costs using respectively the structures TG1, TG2 and TG3.

Every graph shows three curves, each one corresponding to a different electric load: 32.6 MW, 24.7 MW and 16.5 MW, obtained calculating the costs of the products by varying the thermal load provided. The unit costs of the electric and thermal exergy fluxes have been indicated respectively as k^*_{el} and k^*_{th}.

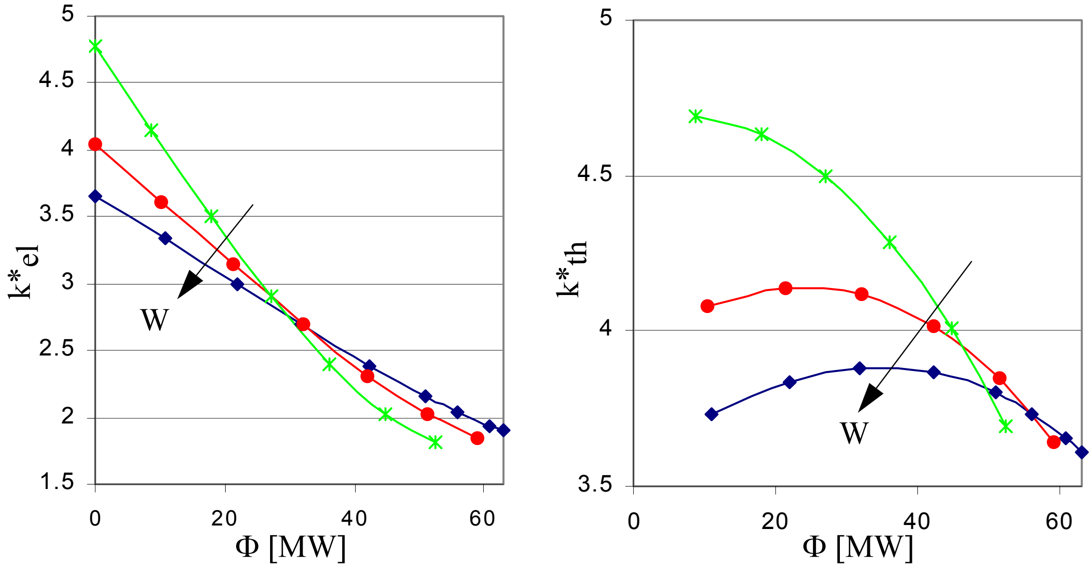

Figure 3.20 - Dependence of the unit costs on the electric and thermal load using TG1

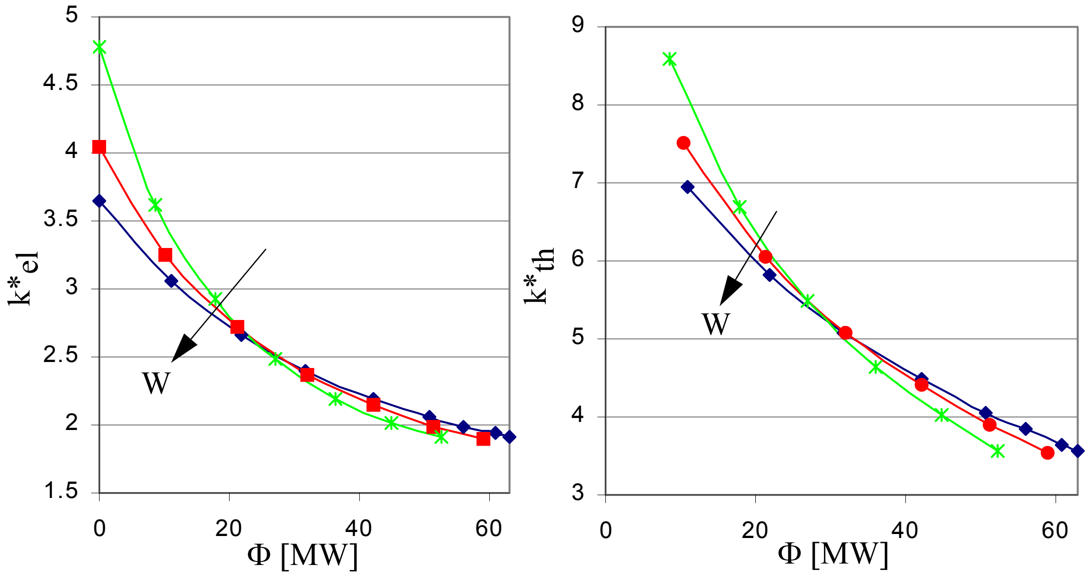

Figure 3.21 - Dependence of the unit costs on the electric and thermal load using TG2

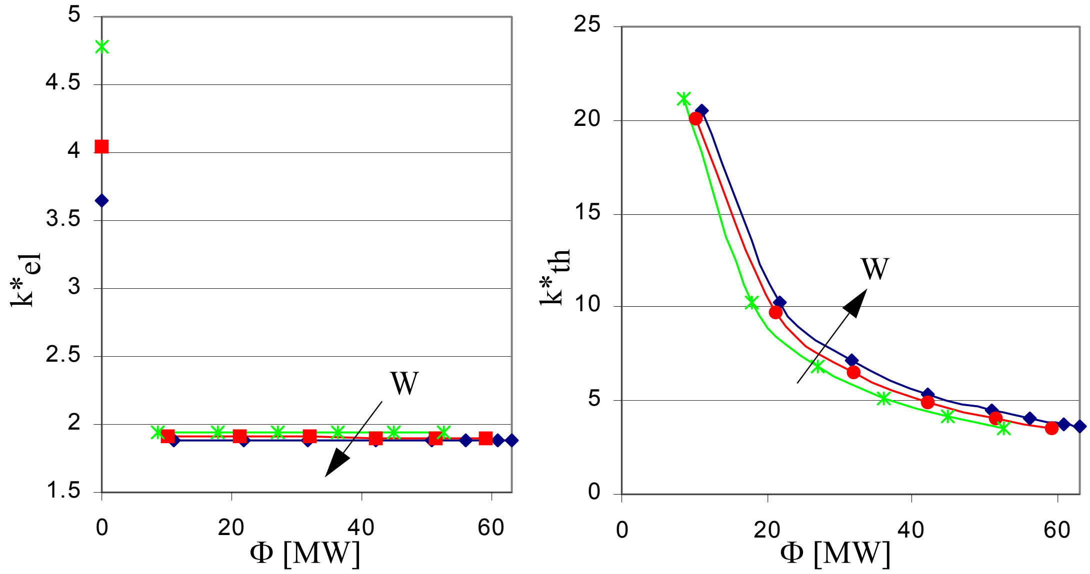

Figure 3.22 - Dependence of the unit costs on the electric and thermal load using TG3

The unit cost of the electric power, calculated using the structures TG1 and TG2 decreases as the thermal load increases, while the behaviour is completely different if the structure TG3 is used. In this case the cost slightly increases as the thermal load increases, which is due to the increasing pressure drop in the recuperator; if the regulation remained fix the electric production would decrease. If no thermal power is produced, the cost becomes much higher, due to the lower efficiency of the plant. The behaviour of this cost, about constant, is balanced by the unit cost of the thermal exergy flux, which is characterised by a variation larger than it happens for the other structures.

The behaviour of the costs calculated using the structures TG5 and TG6 is similar to the costs calculated using respectively TG3 and TG2.

The choice of the best productive structure for cost accounting purposes is a difficult operation, as it determines a strong impact on the results. It is possible notice as the cost at partial thermal loads are influenced by the choice of the productive structure and, in particular, by the charge of the losses.

On the contrary the results of the thermoeconomic diagnosis do not depend on the charge of the losses, but they depend on the grade of detail of the productive structure: if mechanical and thermal exergy are used to describe the thermoeconomic model the information is more accurate than it happens if simple exergy fluxes are used, but the malfunction location becomes more difficult. This is the object of the chapter 5.

3.3.3 Thermoeconomic costs in monetary units

An expression, similar to equation 3.29, expressing the monetary unit cost of a component product can be obtained starting from its cost balance. The general component *i* of a system is represented in figure 3.23. It is characterised by resources produced by the other component (and eventually by itself) and by the environment too.

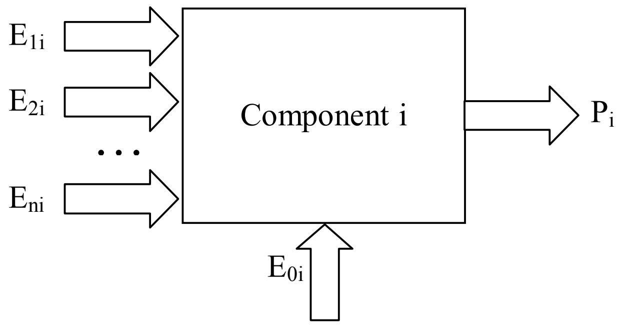

Figure 3.23 - Fluxes in a system component

All these fluxes are characterized by a cost, which can be expressed as the unit cost of the fuel multiplied for the exergy of the flux. The unit cost is determined by the component which has produced the flux:

$$\Pi_{E_{ji}} = c_{P_j} \cdot E_{ji} \tag{3.32}$$

The cost of the external resources $\Pi_{E_{0i}}$ includes the cost of fuels and the capital cost rate of the component, as in the structural theory this term is represented as an external flux.

The cost balance of the components is:

$$\Pi_{P_i} = \Pi_{E_{0i}} + \sum_{i=1}^{n} \Pi_{E_{ji}} \quad \text{i=1...n} \tag{3.33}$$

or, using the unit costs:

$$c_{P_i} \cdot P_i = c_{P_{0i}} \cdot E_{0i} + \sum_{i=1}^{n} c_{P_{ji}} \cdot E_{ji} \quad \text{i=1...n.} \tag{3.34}$$

where the unit cost associated to the capital cost rate of the component is:

$$c_{P_{0i}}(Z) = \frac{Z}{E_{0i}} \tag{3.35}$$

If all the term are divided for the component product and the definition of the unit exergy consumption is considered, the equation 3.34 becomes:

$$c_{P_i} = k_{0i} \cdot c_{P_{0i}} + \sum_{i=1}^{n} k_{ji} \cdot c_{P_j} \quad \text{i=1...n.} \tag{3.36}$$

If no external fuel is required by a component and the only contribution of the capital cost rate is present, the unit exergy consumption k_{0i} is assumed unitary, so that the term E_{0i} coincides with the component product.

The equation 3.36 can be expressed using matrix notation:

$$\mathbf{c_P} = |\mathbf{P}\rangle \cdot \mathbf{k_{ext}} \cdot (\mathbf{c_{P_{ext}}})_D \qquad (3.37)$$

where $(\mathbf{c_{P_{ext}}})_D$ is a diagonal matrix which not null terms contain the evaluation of the unit costs of the external resources of the plant.

The vector of unit exergy consumptions does not coincide with the same vector used for the exergy cost calculation, in fact they refer to two different productive structure. In particular as the productive structure for the monetary cost calculation is characterised by flows entering the components from the environment, the terms of the vector $\mathbf{K_{ext}}$, corresponding to components having a cost not null, are different to zero.

Table 3.9 shows the cost of the products of the components of the two thermal systems. In the table the cost of the components [Macor et al 1997] and the corresponding capital cost rates are also indicated. The capital cost rates have been calculated considering an useful life of 15 and 30 years respectively for the gas turbine and the steam turbine plant and a rate of return equal to 8%. Finally, in the fifth column, the unitary cost of the external flux is indicated.

Plant	Component	Cost $	Z $/s	c_{Ei0} $/GJ	c_p $/GJ
Steam turbine	SG	4.21E+07	0.2417	5.101	10.54
	HPT	3.46E+06	0.0198	0.542	13.18
	MPT	5.91E+06	0.0339	0.590	12.50
	LPT	3.88E+06	0.0223	2.642	16.47
	A	8.21E+06	0.0471	0.471	13.88
	C	3.36E+06	0.0193	9.487	23.23
	EP	8.47E+04	0.0005	28.171	51.09
	HE1	6.98E+05	0.0040	22.933	41.12
	HE2	6.64E+05	0.0038	16.925	36.03
	HE3	8.73E+05	0.0050	2.937	18.10
	HE4	6.52E+05	0.0037	1.847	14.66
	HC	3.36E+05	0.0019	0.045	12.30
	D	4.30E+05	0.0025	0.943	13.44
	CP	4.17E+05	0.0024	1.062	21.87
	HE6	1.02E+06	0.0058	0.769	13.35
	HE7	1.10E+06	0.0063	0.775	12.59
	HE8	6.70E+05	0.0038	0.982	12.54
Gas turbine	CC	3.90E+06	0.0317	4.456	8.85
	AC	5.11E+06	0.0415	0.861	11.68
	GT	6.32E+06	0.0514	0.600	9.96
	CR	1.24E+06	0.0101	0.622	19.01
	A	5.01E+06	0.0407	1.249	11.41

Table. 3.9 - Table of monetary costs

The costs of the gas turbine plant fluxes have been calculated using the productive structure TG3. The cost of the thermal exergy produced by the gas turbine is higher than the one produced by the steam turbine plant, while the opposite happens for the cost of the electric power. The higher unit cost of the electric power in the steam turbine plant is mainly due to the higher cost of the thermal exergy provided to the fluid in the plant: the cost rate of the steam generator is higher than the combustor, moreover the exergy efficiency of the process is lower. On the contrary the recuperator in the gas turbine is characterized by a lower efficiency than the hot condenser, as its resources has an higher unit exergy and the product is the same. The unit cost of the product of the recuperator is so higher, although the unit cost of its resource is lower.

The result does not change if another productive structure would have used, but different costs would have found.

CHAPTER 4

Thermoeconomic Diagnosis

The performances of an energy system vary with the time, above all because of the interactions between the fluid and the machine, which involve corrosion, erosion, substances sediment (fouling), thermal and mechanical stresses etc. All these phenomena make degrade the efficiency of the components, due to modifications in heat transfer and friction coefficients, in flowing areas, in fluid leakages.

The thermoeconomic diagnosis is a experimental technique applied to energy systems in order to evaluate their behaviour in working conditions, find possible sign of malfunctions, quantify their effects and understand their causes. The use of thermoeconomics allows to directly express the effects of the malfunctions in terms of exergy or monetary costs, which is an useful information for the maintenance programming.

The direct effect of an anomaly on the component where it has occurred, measured in terms of additional fuel consumption, is called intrinsic malfunction. As every flux of the system is the result of a productive process occurred in a component, their variation makes change the production of several components. This effect is called dysfunction. The efficiency of the components generally depends on the production and on the thermodynamic conditions (mass flows, temperatures and pressures) of the entering fluids. This means that the efficiency of a component can so vary, although no anomalies have taken place in it. A second malfunction, called induced malfunction, can occur in consequence of the intrinsic malfunction.

If an anomaly has happened and the fuel has been kept constant, the overall production has decreased, as the system efficiency has decreased. The plant production is a controlled variable. Its value is externally imposed. Moreover, some other controlled variables, like the internal set-points, can have changed too. Therefore, the system must be regulated in order to restore the previous production and to comply the internal constraints. This operation causes other induced malfunctions in the components.

A new diagnosis procedure, particularly suitable to locate the component where the anomaly has taken place, is proposed in this chapter. This procedure takes into account the effects of the regulation system, filtering the induced malfunctions which it causes. The procedure is based on the calculation of the artificial working condition in which the plant would work if no interventions of the control system happened. The condition is clearly artificial as the constraints represented by the set-points and the external loads are not respected.

This part constitues the main innovation made in this thesis. The application of this procedure is made in next chapters. The results show that it constitues an important improvement of the known thermoeconomic diagnosis procedures.

4.1 Fuel Impact

The study of the behaviour of a system in consequence of an anomaly, using the thermoeconomic tools, is made by comparing an actual working condition, called operation condition, with a reference condition. The thermodynamic variables relative to the reference condition are usually measured when the plant is new. Otherwise they can refer to the design condition, i.e the condition forecast during the project phase, or whatever working conditions obtained in the past. The only constraint is that the plant must be the same, so, if a component is replaced, a new reference condition is needed.

Some other constraints are usually imposed by the analyst, in order to make easier the analysis. In particular, operation and reference conditions are chosen characterised by the same environment temperature, pressure and humidity, in order to avoid their effects, usually sensible, on the plant performances. Moreover the external loads are usually the same. If a thermal flux is also produced, its temperature, pressure and eventually the thermodynamic quality are imposed the same in reference and operation conditions. So much constraints make useful a mathematical model of the plant, in order to determine the most appropriate reference corresponding to every operation condition.

If the total production is kept constant, the effect of an anomaly on the overall plant is pointed out by the variation of the overall fuel consumption. This quantity, also called fuel impact [Reini 1994].

A mathematical expression of the fuel impact can obtained directly from the equation 3.25:

$$\Delta F_T = \Delta \mathbf{K_{ext}}^t \cdot \mathbf{P} + (\mathbf{K_{ext}})^t \cdot \Delta \mathbf{P} \quad . \tag{4.1}$$

Matrix $\Delta \boldsymbol{K_{ext}}$ is the difference between the two vectors of the external unit exergy consumptions, calculated in operation and reference conditions, while $\Delta \boldsymbol{P}$ is the difference between the total production of the components. This expression means that the variation of the fuel consumption is determined by two factors: the variation of the unit exergy consumption of the components (which relate to their exergetic efficiency) and the variation of their production. This last term can be expressed using equation 3.21:

$$\Delta \mathbf{P} = \Delta \mathbf{P_{ext}} + \Delta \langle \mathbf{KP} \rangle \cdot \mathbf{P} + \langle \mathbf{KP} \rangle \cdot \Delta \mathbf{P} \tag{4.2}$$

which can also be written:

$$\mathbf{U_D} \cdot \Delta \mathbf{P} = \mathbf{U_D} \cdot \Delta \mathbf{P_{ext}} + \Delta \langle \mathbf{KP} \rangle \cdot \mathbf{P} + \langle \mathbf{KP} \rangle \cdot \Delta \mathbf{P} \tag{4.3}$$

and, using the operator product, defined in equation 3.23:

$$\Delta \mathbf{P} = |\mathbf{P}\rangle \cdot (\Delta \mathbf{P_{ext}} + \Delta \langle \mathbf{KP} \rangle \cdot \mathbf{P}) . \tag{4.4}$$

The variation of the fuel consumption is so:

$$\Delta F_T = \Delta (\mathbf{K_{ext}})^t \cdot \mathbf{P} + (\mathbf{K_{ext}})^t \cdot |\mathbf{P}\rangle \cdot (\Delta \mathbf{P_{ext}} + \Delta \langle \mathbf{KP} \rangle \cdot \mathbf{P}) . \tag{4.5}$$

which can be also written using the equation 3.31 and transposing the terms appearing in it:

$$(\mathbf{K_P}^*)^t = (\mathbf{K_{ext}})^t \cdot |\mathbf{P}\rangle ; \tag{4.6}$$

$$\Delta F_T = \Delta (\mathbf{K_{ext}})^t \cdot \mathbf{P} + (\mathbf{K_P}^*)^t \cdot \Delta \mathbf{P_{ext}} + (\mathbf{K_P}^*)^t \cdot \Delta \langle \mathbf{KP} \rangle \cdot \mathbf{P} ; \tag{4.7}$$

and finally

$$\Delta F_T = (\Delta(\mathbf{K_{ext}})^t + (\mathbf{K_P}^*)^t \cdot \Delta\langle\mathbf{KP}\rangle) \cdot \mathbf{P} + (\mathbf{K_P}^*)^t \cdot \Delta\mathbf{P_{ext}} \,. \tag{4.8}$$

It has been demonstrated [Torres, Valero 1999] that this formula allows to calculate the exact value of the total fuel impact, and not only an approximate value, if the product of every component is calculated in reference condition and the unit cost of the product in operation condition. A superscript *0* is used in the following to indicate the reference condition.

In scalar form equation 4.8 is:

$$\Delta F_T = \sum_{i=1}^{n} \left(\sum_{j=0}^{n} K_{P,j}^{\;*} \cdot \Delta k_{ji} \right) \cdot P_i^0 + \sum_{i=1}^{n} K_{P,i}^{\;*} \cdot \Delta P_{ext_i} \,. \tag{4.9}$$

If operation and reference conditions are characterized by the same production, as it usually happens in the diagnosis procedures, the last term of the equation 4.9 is zero:

$$\Delta F_T = \sum_{i=1}^{n} \left(\sum_{j=0}^{n} K_{P,j}^{\;*} \cdot \Delta k_{ji} \right) \cdot P_i^0 \,. \tag{4.10}$$

Every component contributes to the total fuel impact if its unit exergy consumptions vary, or if its product is a part of the overall plant production and it varies:

$$\Delta F_i = \left(\sum_{j=0}^{n} K_{P,j}^{\;*} \cdot \Delta k_{ji} \right) \cdot P_i^0 + K_{P,i}^{\;*} \cdot \Delta P_{ext_i} \,. \tag{4.11}$$

4.2 Intrinsic malfunction, induced malfunction and dysfunction

The efficiency variation in a component, caused by an anomaly, determines a corresponding variation of its resources in order to keep constant its production. The other components of the plant must vary their production, in order to provide the additional fuel required by the malfunctioning component. As the efficiency of the components generally depends on their production, this variation has a direct impact on it, which means that other malfunctions join the one directly caused by the anomaly.

If the total production of the plant is kept constant the additional fuel required by the plant is equal to the variation of the irreversibilities occurring in the components. The exergy balance of the plant, considered in the two conditions, allows to write:

$$\Delta F_T = \Delta I = \sum_{i=1}^{n} \Delta I_i \,. \tag{4.12}$$

If equations 4.1 and 4.12 are considered, two sources of irreversibility variation can be pointed out: the first one, called malfunction *MF*, is due to the variation of the exergy consumption of a component. A malfunction in a component is always associated to a variation of its efficiency. The expression of the malfunction in a component is:

$$MF_i = P_i^0 \cdot \Delta k_i = \sum_{j=0}^{n} P_i^0 \cdot \Delta k_{ji}. \tag{4.13}$$

The intrinsic malfunction occurs in the component which has originated the variation of the overall plant fuel consumption, i.e. in the component where the anomaly is located. On the contrary the induced malfunctions occur in the other components, caused by the variation of their working condition.

The second cause of irreversibility variation, called dysfunction *DF*, is the variation of the component production, induced by the intrinsic malfunction. Dysfunctions are not joined to a variation of the component efficiency, i.e. a dysfunction can also occur in a component which exergy efficiency has maintained constant. The dysfunction induced in a component can be expressed:

$$DF_i = (k_i - 1) \cdot \Delta P_i, \tag{4.14}$$

where the unit exergy consumption is calculated in reference condition.

The sum of malfunction and dysfunction in a component is equal to the variation in its irreversibilities. This can be demonstrated, starting from the exergy balance of a component:

$$\mathbf{I} = \mathbf{F} - \mathbf{P} \tag{4.15}$$

and using the concept of unit exergy consumption:

$$\mathbf{I} = \mathbf{K_D} \cdot \mathbf{P} - \mathbf{P} \tag{4.16}$$

The irreversibility variation between the operation and reference condition can be so expressed:

$$\Delta\mathbf{I} = (\Delta\mathbf{K_D} \cdot \mathbf{P}^0) - (\mathbf{K_D} - \mathbf{U_D}) \cdot \Delta\mathbf{P} \tag{4.17}$$

If the expression 4.4 is substituted in 4.17:

$$\Delta\mathbf{I} = (\Delta\mathbf{K_D} \cdot \mathbf{P}^0) - (\mathbf{K_D} - \mathbf{U_D}) \cdot (|\mathbf{P}\rangle \cdot (\Delta\mathbf{P_{ext}} + \Delta\langle\mathbf{KP}\rangle \cdot \mathbf{P}^0)) \tag{4.18}$$

If the production of the plant is constant, equation 4.18 can be written:

$$\Delta\mathbf{I} = (\Delta\mathbf{K_D} + |\mathbf{I}\rangle \cdot \Delta\langle\mathbf{KP}\rangle) \cdot \mathbf{P}^0 \tag{4.19}$$

In scalar format the irreversibility variation in the ith component is:

$$\Delta I_i = \sum_{j=0}^{n} P_i^0 \cdot \Delta k_{ji} + \sum_{j=1}^{n} \sum_{h=1}^{n} \phi_{ih} \cdot \Delta k_{hj} \cdot P_i^0 = MF_i + \sum_{j=1}^{n} DF_{ij}. \tag{4.20}$$

where the term ϕ_{ih} is the element of the irreversibility matrix operator $|\mathbf{I}\rangle$ and the term DF_{ij} is the dysfunction generated in the component *i* by the component *j*. [Torres et al. 1999]

4.3 Diagnosis problems

The application of the thermoeconomic diagnosis to an energy system can be made to achieve two different purposes: the first, indicated as direct problem, consists on the detection of a possible anomaly and its location in an appropriate control volume. It is the main objective of the diagnosis procedures. The second, indicated as inverse problem, consists on the quantification of the effects of the anomalies in term of thermoeconomic quantities, such fuel impact and malfunction. The inverse problem allows to classify all the anomalies, depending on their economic impact on the plant management.

The application of the inverse problem to an energy system can be made with two different objectives, depending on the source of the operation condition data. The first application is made once the direct diagnosis problem has been solved. Supposing that more than one intrinsic malfunction have taken place in the system, the direct problem is not able to furnish any information about the incidence of everyone on the total fuel impact. As demonstrated by the law of non equivalence of the irreversibilities, the same irreversibility variation causes a different fuel impact, depending on the position of the component where it has occurred. The results of the direct problem only tell us where the efficiency variations are located and quantify them in term of efficiency variation. The amount of resources technically saved by restoring the reference working condition also depends on the characteristics of the components where the anomalies have taken place and on the productive characteristics of the system. Equation 4.9 shows that the larger the production and the cost of the resources of the component are and the higher is the technical energy saving corresponding to the same efficiency improving. In this way a high efficiency variation can involve a low fuel impact and vice versa. The inverse problem directly provides some economic information about the malfunctions: the intrinsic malfunction associated to the maximum fuel impact is the first to eliminate, if it is economically convenient.

A second use of the inverse problem can be made together with a mathematical model of the system. The system behaviour in different operation conditions, corresponding to different malfunctions, can be simulated by varying the values of the characteristic parameters of the components. This approach allows to predict the quantitative effects of the possible anomalies on the overall system.

The total fuel impact can also be written by substituting the equation 4.20 in the 4.12, in this way the effect of an anomaly on every component is completely expressed in term of malfunctions and dysfunctions:

$$\Delta F_T = \sum_{i=1}^{n} \left(MF_i + \sum_{j=1}^{n} DF_{ij} \right) , \tag{4.21}$$

or, grouping this expression by the component production:

$$\Delta F_T = \sum_{i=1}^{n} \left(\Delta k_i + \sum_{j=1}^{n} \phi_{ih} \cdot \Delta k_{hj} \right) \cdot P_i^0 . \tag{4.22}$$

This information can be represented using a particular table, called malfunction and dysfunction table. All the dysfunctions are reported in a squared matrix, characterised by n rows and columns, which constitutes the main part of the table. Its general element DF_{ji} represents the dysfunction caused by the component *i* in the component *j*, so that the sum of the elements in the i^{th} row, DF_i is equal to the total dysfunction caused in the component *i*, while the sum of the elements in the j^{th} column DI_j is equal to the total dysfunction caused by the component *j*. Two more rows and columns complete the table, where the malfunctions in every component and the total sum of every column and every row are respectively reported. The total sum of the i^{th} row is equal to the variation of the irreversibility in the i^{th} component, according to equation 4.20. The total sum of the j^{th} column represents the malfunction cost of the j^{th} component. It includes the malfunction in the component plus all the dysfunctions caused by the components itself:

$$MF_i^* = MF_i + \sum_{h=1}^{n} DF_{hi} \quad i = 1...n. \tag{4.23}$$

If the behaviour of the components does not depend on the production, i.e. no induced malfunctions happen, equation 4.23 is equal to the total fuel impact, otherwise this term represents the fuel impact caused by the presence of a malfunction (intrinsic or induced) in the i^{th} component.

Not all the dysfunctions are caused by malfunctions: some of them can be associated to a variation the total request: if operation and reference conditions are characterised by a different plant production, some dysfunctions take place, also if the plant efficiency has not changed. Dysfunctions then do not necessarily have a negative meaning. Similarly, a positive fuel impact does not mean a malfunctioning plant, as it can be associated to a variation of the total production. Moreover a null fuel impact does not imply that the plant is working correctly, in fact the total production can have changed.

4.4 Direct diagnosis problem

The presence of a malfunction in a thermal system is usually easily detected. In fact, as it has been said in paragraph 4.1, if the production of a plant is constant, the variation of the irreversibility in one or more components has a direct impact on the fuel consumption. The fuel of a system is always measured because of its economic importance, so the comparison between the fuel consumption in two working conditions allows the manager to verify the correct behaviour of the plant. The successive step consists on locating where the malfunction has happened.

To achieve this goal some diagnosis techniques, based on the thermoeconomic concepts, have been developed [Stoppato, Lazzaretto 1996, Torres et al. 1999]. These techniques are based on the application of exergy and thermoeconomic analyses to the system, considered in the operation and reference conditions. The comparison between the two working conditions allows to calculate some performance indices of the components of the plant, which are shown below.

If a component is characterized by an anomaly its fuel impact, calculated using equation 4.11, is different to zero. This quantity is generally different to zero also in other components, due to the presence of dysfunctions and induced malfunctions. Therefore if the intrinsic malfunction constitutes the main effect, the relative fuel impact, defined as the ratio between the fuel impact in the component and the total fuel impact:

$$\frac{\Delta F_i}{\Delta F_T} \tag{4.24}$$

is the highest in the malfunctioning component. The numerator contains the variation of the unit exergy consumption multiplied for the component product and for the unit cost of the fuel, according to the equation 4.10. In some cases it becomes particularly sensitive to the induced malfunctions, in fact it tends to assume high values in the components characterised by a high product or/and a high unit cost of the resources. In this way the maximum value of the relative fuel impact can occur in the component where only induced effects have taken place.

Another effect of the malfunction is the variation of the irreversibility, which can be normalized, defining the parameter as:

$$\frac{\Delta I_i}{\sum_{i=1}^{n} \Delta I_j}. \tag{4.25}$$

The values of the ΔI_i produced in the plant components can not be directly compared, as this quantity depends on the amount of the exergy transformed in the components and on the efficiency of the transformations, according to the principle of non equivalence of the irreversibilities. If the same efficiency variation is considered in the components, the larger is the amount of the exergy flow transformed and the larger is the variation of irreversibility produced, moreover the lower is the efficiency of the process and the larger is the variation of irreversibility produced. These effects can be avoided simply by dividing the irreversibility variation for the irreversibility in design condition:

$$\frac{\Delta I_i}{I^0}. \tag{4.26}$$

The irreversibility variation in a component can be split into malfunction and dysfunctions, according to equation 4.20. The malfunction MF_i in a component represents the contribution of the component efficiency variation to the irreversibility variation, so it constitutes another parameter useful for the localization of the malfunctioning component, in particular it can be used dividing its value for the irreversibility in design condition:

$$\frac{MF_i}{I^0} \tag{4.27}$$

for the same reasons analysed in the case of the irreversibility variation.

Finally the terms of matrix Δ**KP** are also indices of the components behaviour, as they are directly related to the variation of the exergy efficiency of a component.

The application of these techniques to some energy systems has shown that the malfunction location is possible only in some cases, when all the parameters give the same answer to the diagnosis problem. This occurs when the induced malfunctions are negligible respect to the intrinsic malfunctions. In the next paragraph an important cause of induced malfunctions is analysed: the regulation system intervention. A technique to filter those contributions is then proposed.

4.5 A new procedure for malfunction detection and localization

The simply comparison between operation and reference conditions does not provide any information about the incidence of the control system on the plant behaviour in case of malfunctions. The effect of a malfunction in a component generally induces a variation in the thermodynamic properties of the downstream flows, but the control system imposes some barriers to the malfunction propagation. For example if the isentropic efficiency of a compressor, in a gas turbine cycle, decreases, the outlet temperature becomes higher and the temperature of the combustion gas increases too. In the gas turbine plant the temperature of the gas entering the turbine is usually kept constant, because an increase can determine a turbine failure while a decrease makes the plant efficiency lower. There is a cause-effect relation between the malfunctions and the regulation system intervention, in fact as the compressor changes its behaviour, the plant control system operates a variation in the regulation parameters in order to keep the gas temperature (and the plant production) constant.

The set points and the external loads all represent constraints that must be respected by the control system, whatever happens in the plant. These constraints change the natural propagation of the effects of the malfunctions, generating other induced malfunctions and dysfunctions, which make difficult or impossible the location some kind of anomalies. In the example of the isentropic efficiency variation, the natural effect of the anomaly consists on an higher inlet turbine temperature. Once the regulation system has intervened the previous value is restored.

The most important idea which constitutes this proposed procedure is that the detection of the malfunction causes is easier if the effects of external loads (thermal or electrical power) and set points are eliminated. This kind of diagnosis requires that the operation and reference conditions are characterised by the same regulation of the plant. In the classical diagnosis procedures the two conditions are characterised by the same external loads, the same environment conditions and the same set points. These ones are two real working conditions, corresponding to different regulations, if there are anomalies in the system. If the regulation of one of the conditions is modified, an artificial working condition takes place, in fact one or more system constraints are not respected. In particular, the artificial condition obtained by starting from the operation condition and restoring the same regulation as in the reference condition is here called *free condition*. The free condition contains the same anomalies of the operation condition, but the malfunction propagation is here natural, in fact there is no intervention of the regulation system. This means that the comparison between free and reference conditions does not include the malfunctions induced by the regulation system. On the contrary the direct comparison between operation and reference condition hides the effects of the regulation.

Figure 4.1 summarizes the characteristics of the three working conditions: reference and operation conditions are characterized by the same values assumed by the constrained quantities (loads and set points). Nevertheless the regulation system is set in different positions if the system presents malfunctions in the operation condition. Reference and free conditions have the same regulation but the values assumed by the constrained quantities are different, in particular the free condition is not externally constrained. The fact that the same regulation produces a different behaviour of these two system is due to the presence of malfunctions in the free condition.

The diagnosis methodologies are based on the direct comparison between the operation and reference conditions (OvR); the methodology here proposed is based on the comparison between free and reference conditions (FvR).

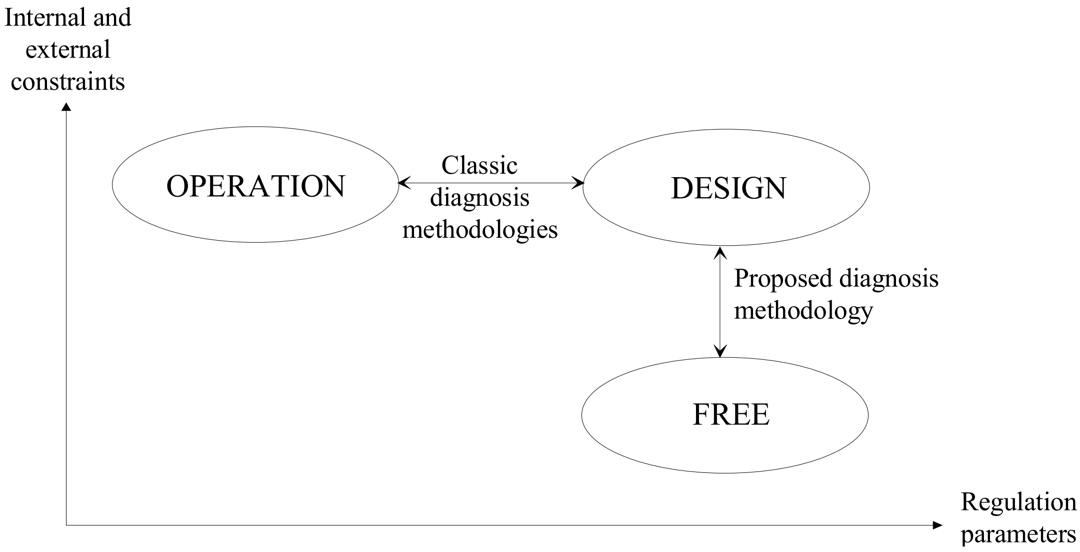

Figure 4.1 - The three working conditions for the thermoeconomic diagnosis

As indicated above, the free working condition is generally impossible to obtain in a real plant, because the internal set points can not be modified at will and the external loads are determined by the users. The necessary data must be so found using a theoretical procedure, in particular a Taylor development can be used to model the plant behaviour as each regulation parameter varies. The Taylor development can be applied to calculate all the thermodynamic quantities relative to the free condition or directly the values of the thermoeconomic quantities, in particular the unit exergy consumptions.

Assumed *r* the number of the regulation variables, the general variable in free condition is:

$$y_{free}(x_{1_{free}}\dots x_{r_{free}}) = y_{op} + \sum_{i=1}^{r}\left(\frac{dy}{dx_i}\right)_{op}\cdot(x_{i_{free}} - x_{i_{op}}) + \frac{1}{2}\cdot\sum_{i=1}^{r}\left(\frac{d^2y}{dx_i^2}\right)_{op}\cdot(x_{i_{free}} - x_{i_{op}})^2 + \dots \quad (4.28)$$

where

y_{free} is the general thermodynamic or thermoeconomic variable in free condition;

y_{op} is the general thermodynamic or thermoeconomic variable in operation condition;

x_{iop} is the a regulation variable in operation condition;

x_{ifree} is the a regulation variable in free condition. Its value is equal to the regulation variable in reference condition.

If the malfunctions in the system are sufficiently low, the behaviour of the system as the regulation variables are moved can be assumed linear. Moreover the derivate can be calculated in reference condition, so that the equation 4.28 can be written:

$$y_{free} = y_{op} - \sum_{i=1}^{r}\left(\frac{dy}{dx_i}\right)_{ref}\cdot(x_{i_{op}} - x_{i_{ref}}) \quad (4.29)$$

The derivates of the general variable respect to the regulation variables can be analytically calculated if a model of the plant is available, otherwise it must be numerically calculated by using operation data. In the following the two approaches are shown.

Assumed *n* the number of thermodynamic and technical quantities characterising a system, its mathematical model is composed by *m* equations, representing the characteristic behaviour of the components, *l* constraints, representing the boundary conditions (environment conditions, values assumed by the characteristic parameters of the components, etc.) and *n-m-l* values assumed by the independent variables. These last equations can be seen as constraints too, once the working condition is defined. The kind of the independent variables is chosen depending on the purposes of the model. If the plant analysis is required, the independent variables are generally the products of the plant and the values assumed by the set points, in order to immediately determine a particular working condition. On the contrary, in the model required for the application of the proposed diagnosis procedure, the independent variables are the regulation parameters. This kind of model is the closest to the real behaviour of the plant, where the products and the values assumed by the set points are maintained by the control system, which operates on the plant by means of the regulation system. The model necessary for the procedure must clearly include not only the characteristic equations of the components but also the variables characterising the regulation system and the equations linking them to the model of the thermal system.

The problem constituted by the *n* equations above described is a constrained problem. The analytical solution of the derivates can be directly obtained, building a single equation, function of the independent variables; otherwise the Lagrangian function can be built for all the *n* variables.

For a general variable y_i the Lagrangian function is:

$$L_i = y_i + \sum_{j=1}^{m} \lambda_j \cdot (f_j(\bar{y}) - y_j) + \sum_{j=m+1}^{m+l} \lambda_j \cdot (y_j^* - y_j) + \sum_{j=m+l}^{n} \lambda_j \cdot (x_j^* - x_j) \qquad (4.30)$$

where:

- y_j is the j^{th} variable of the model;
- λ_j is the Lagrange multiplier associated to the j^{th} variable;
- f_j is the j^{th} equation describing the behaviour of the components;
- $\bar{y}_j$ represents the variable set of the model;
- y_j^* is the value assumed by the j^{th} variable, representing one of the boundary conditions;
- x_j is the j^{th} independent variable;
- x_j^* is the value assumed by the j^{th} independent variable.

The expression of the general Lagrangian function derivate, made respect to the set of the model variables is:

$$\frac{\partial L_i}{\partial y_k} = \frac{\partial y_i}{\partial y_k} - \lambda_k + \left[\frac{\partial}{\partial y_k}\left(\sum_{j=1}^{m} \lambda_j \cdot f_j(\bar{y} - y_j) + \sum_{j=m+1}^{m+l} \lambda_j \cdot (y_j^* - y_j) + \sum_{j=m+l}^{n} \lambda_j \cdot (x_j^* - x_j)\right)\right]_{j \neq k} = 0 \qquad (4.31)$$

k = 1...n.

The set of *n* equations associated to the derivates of the function L_i respect to the variables of the model can be solved for the *n* Lagrange multipliers. In matrix notation the problem can be written as:

$$\mathbf{D} \cdot \Lambda + \mathbf{N} = \mathbf{0} \tag{4.32}$$

where:

- **D** is the $n \cdot n$ coefficient matrix, function only of the variables y;
- Λ is the $n \cdot 1$ vector containing the Lagrange multipliers;
- **N** is the $n \cdot 1$ vector of known terms. It is composed by all 0, excepted a 1 in the i^{th} row;
- **0** is a $n \cdot 1$ null vector.

The *n-m-l* Lagrangian multipliers associated to the variation of the variable y_i respect to the independent variables characterising the regulation system coincide with the derivates required in the equation 4.29, which also means that:

$$n - m - l = r\,. \tag{4.33}$$

This interpretation of the derivates is conceptually important, as the Lagrange multipliers have the meaning of marginal costs. If the fluxes of the productive structure are included in the whole of the variables y and the parameters associated to the regulation system are expressed in terms of exergy fluxes, the costs are comparable with the costs of the internal fluxes. In the next paragraph a different formulation of the cost associated to the regulation system is proposed, in order to make it independent on the expression of the regulation variables.

The Lagrangian associated to a variable $y_h \neq y_i$ differs from equation 4.30 only for the first term at the right hand side. The set of the *n* Lagrange multipliers associated to the variable y_h can be easily determined writing, in equation 4.32, a vector **N** containing only a 1 in the h^{th} row.

In this way the set of $r \cdot n$ Lagrange multipliers necessary for the diagnosis purposes can be obtained. They are used for the calculation of the *n* variables of the model, by means of the equation 4.29. The value assumed by a general variable of the model in the free working condition is so determined:

$$y_{j_{free}} = y_{j_{op}} - \sum_{i=1}^{r} \lambda_{ji} \cdot (x_{i_{op}} - x_{i_{ref}}) \tag{4.34}$$

where:

- $y_{j_{free}}$ is the value assumed by the variable y_j in free condition;
- $y_{j_{op}}$ is the value assumed by the variable y_j in operation condition;
- λ_{ji} is the Lagrangian multiplier associated to the variation of the variable y_j respect to the independent variable x_i;
- $x_{i_{ref}}$ is the value assumed by the variable x_i in reference condition, which is equal to the value assumed in free condition;
- $x_{i_{op}}$ is the value assumed by the variable x_i in operation condition.

The advantage of this method is the possibility of application in real plants, in fact the derivates respect to the regulation parameters can be also numerically calculated, directly using measured data and without make use of a mathematical model of the plant. Nevertheless it is necessary to determine what are the effect of the regulation variables on the plant behaviour, in fact the Lagrangian multipliers used in this procedure express the variation of thermodynamic or thermoeconomic quantities as the regulation parameters vary. In the case of a real plant this effect can be measured considering the plant at the reference time. At this time it is necessary to measure the thermodynamic quantities in as many conditions as the regulation parameters are. For everyone of the *r* working condition the value assumed by the regulation parameters must be measured too. These conditions must be characterized by not proportional variations of all the regulation parameters, i.e. if all the regulation parameters measured in these conditions are written in a matrix its determinant must be different to zero. Moreover these working conditions must be as close as possible to the reference condition, so that the hypothesis of linear behaviour is available. Nevertheless the closer are the operation conditions to the reference condition and the bigger is the effect of the measure errors. In this way a compromise between the two exigences must be found when the procedure is applied to a real system. The derivates are calculated as:

$$\frac{dy_j}{dx_i} = \frac{\Delta y_j}{\Delta x_i} = \lambda_{ji} \tag{4.35}$$

A larger number of working conditions is advised, so that in the choice of the *r* conditions the random effects (like errors in the measures) can be reduced.

All these information can be written in a matrix problem to find the values of the Lagrange multipliers:

$$\begin{bmatrix} x_{11}-x_{1_{ref}} & x_{12}-x_{2_{ref}} & \dots & x_{1h}-x_{h_{ref}} & \dots & x_{1r}-x_{r_{ref}} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ x_{j1}-x_{1_{ref}} & x_{j2}-x_{2_{ref}} & \dots & x_{jh}-x_{h_{ref}} & \dots & x_{jr}-x_{r_{ref}} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ x_{r1}-x_{1_{ref}} & x_{r2}-x_{2_{ref}} & \dots & x_{rh}-x_{h_{ref}} & \dots & x_{rr}-x_{r_{ref}} \end{bmatrix} \begin{bmatrix} \lambda_{i1} \\ \dots \\ \lambda_{ih} \\ \dots \\ \lambda_{ir} \end{bmatrix} = \begin{bmatrix} y_{i1}-y_{i_{ref}} \\ \dots \\ y_{ij}-y_{i_{ref}} \\ \dots \\ y_{ir}-y_{i_{ref}} \end{bmatrix} \tag{4.36}$$

where:

- x_{jh} is the value of the h^{th} regulation parameter in the j^{th} working condition;
- $x_{h_{ref}}$ is the value of the h^{th} regulation parameter in reference condition;
- λ_{ih} is the Lagrange multiplier associated to the variation of the i^{th} thermodynamic or thermoeconomic variable respect to the h^{th} regulation parameter;
- y_{ij} is the value assumed by the i^{th} thermodynamic or thermoeconomic quantity in the j^{th} working condition;
- $y_{i_{ref}}$ is the value assumed by the i^{th} thermodynamic or thermoeconomic quantity in the reference condition.

The problem of the Lagrange multipliers determination can be written in a more compact form:

$$\Delta\mathbf{X} \cdot \Lambda = \Delta\mathbf{Y} \tag{4.37}$$

the vector of the derivates can so be calculated as:

$$\Lambda = \Delta\mathbf{X}^{-1} \cdot \Delta\mathbf{Y} \tag{4.38}$$

The disadvantage of this method is that the hypothesis of the first order Taylor development falls in case of high malfunction. If the method is used for the on-line analysis of a system this does not represent a real problem as malfunctions do not appear suddenly, but their value increases time by time. However the progress of the malfunction can be maintained controlled by continuously replacing the reference condition with an actual operation condition, which so becomes the successive reference condition. If the reference condition are updated the derivates (or the Lagrange multipliers) must be updated too. The successive variations in malfunction are checked by the comparison between the successive free conditions and the new reference condition.

The use of a more accurate model of the regulation system is also possible, like a second order Taylor development, but it requires a large whole of known data.

Once the free condition has been determined, the fluxes of the productive structure and the corresponding unit exergy consumptions must be calculated. The matrix $\Delta\boldsymbol{K}$, obtained as difference between the matrices of unit exergy consumptions relative to free and reference conditions, is the main tool for this diagnosis procedure of the thermal systems. The maximum term ΔK_{ji} indicates a variation of the efficiency in the component i, which is symptom of an intrinsic malfunction, because it means that the production of the component j increases more than its i^{th} fuel. In a general diagnosis procedure also system improvement are taken into account, so that the variation to be examined are the ones having the same sign of the fuel impact. A negative variation of the fuel impact is associated to a system improvement. In this case the maximum negative term ΔK_{ji} must be found and analysed.

In the next paragraph a different expression is proposed, useful for the application to the free versus reference diagnosis approach.

4.6 A fuel impact expression for the free versus reference approach

The diagnosis methodology proposed in this chapter (free versus reference, FvR) is particular sensitive to this possible misunderstanding: if the fuel mass flow is one of the regulation variables, the free and reference conditions are characterised by the same fuel consumption and the fuel impact is so null. In this case the malfunction symptom is represented by the different production.

A different definition of the fuel impact can be introduced for the FvR diagnosis approach, where the quote of the fuel impact associated to the variation of the plant production is subtracted. This quantity represents the fuel impact caused by the presence of malfunctions, so it is equal to the sum of the malfunction costs, calculated using the equation 4.23. The fuel impact associated to the variation of the plant production is now calculated.

If the total production of the plant varies, the production of every component must vary too. This variation can be directly obtained from the equation 3.22, keeping the unit exergy consumption constant, equal to the values assumed in reference condition:

$$\Delta \mathbf{P} = |\mathbf{P}\rangle \cdot \Delta \mathbf{P_{ext}} \tag{4.39}$$

which implies a fuel impact in every component, determined by:

$$\Delta \mathbf{F_{\Delta P}} = (\mathbf{K_D} - \mathbf{U_D}) \cdot \Delta \mathbf{P} = (\mathbf{K_D} - \mathbf{U_D}) \cdot |\mathbf{P}\rangle \cdot \Delta \mathbf{P_{ext}} \tag{4.40}$$

where $\mathbf{K_D}$ is a diagonal matrix which elements are the total exergy unit costs of the components. In this way the fuel impact directly associated to the variation of the plant efficiency is:

$$\Delta \mathbf{F_{\Delta k}} = \Delta \mathbf{F_T} - \Delta \mathbf{F_{\Delta P}} = \Delta \mathbf{F_T} - ((\mathbf{K_D} - \mathbf{U_D}) \cdot |\mathbf{P}\rangle \cdot \Delta \mathbf{P_{ext}}). \tag{4.41}$$

The total fuel impact caused by the malfunction, coinciding with the sum of the elements of the vector $\Delta\mathbf{F_{\Delta k}}$, is also expressed by the equation 4.8, having eliminated the term associated to the variation of the external production:

$$\Delta F_{\Delta k} = (\Delta(\mathbf{K_{ext}})^t + (\mathbf{K_P}^*)^t \cdot \Delta\langle\mathbf{KP}\rangle) \cdot \mathbf{P} \tag{4.42}$$

or, in scalar form:

$$\Delta F_{\Delta k} = \sum_{i=1}^{n}\left(\sum_{j=0}^{n} K_{P,j}^{\;*} \cdot \Delta k_{ji}\right) \cdot P_i^0 \;. \tag{4.43}$$

The total fuel impact associated to the variation of the overall production $\Delta F_{\Delta P}$ is so:

$$\Delta F_{\Delta P} = (\mathbf{K_P}^*)^t \cdot \Delta\mathbf{P_{ext}}, \tag{4.44}$$

or

$$\Delta F_{\Delta P} = \sum_{i=1}^{n} K_{P,i}^{\;*} \cdot \Delta P_{ext_i}. \tag{4.45}$$

If the free and reference conditions are considered, the total fuel impact is zero, so:

$$\Delta F_{\Delta k} = -\Delta F_{\Delta P}. \tag{4.46}$$

4.7 A procedure for the multiple malfunction detection

In a general operation condition a plant can be characterized by more than one anomaly. The procedure shown in the previous paragraph allows to locate only the anomaly associated to the maximum element of the $\Delta\boldsymbol{K}$ matrix. In this way the location of all the anomalies passes through the location and the complete removal of every anomaly separately. This means that this procedure must be repeated as many times as the number of malfunctions.

Supposing that all the induced effects could be eliminated, the contemporary location of all the anomalies would be possible. In this paragraph a procedure to eliminate the induced effects is proposed.

The plant components are each characterized by its own behaviour, so they act differently when the working conditions vary. The effects must be analysed for each one separately. If the productive structure is considered, the characteristic behaviour of a component can be modeled by varying all its resources and determining the corresponding product.

The dependence of the product of every component from its fuels can be found if three hypotheses are complied:

1) the known working conditions are linearly independent;
2) the number of known conditions is higher than the fuels of every components;
3) the anomalies are sufficiently low.

The procedure for the location of the anomalies, proposed in the previous paragraphs, is based on the use of known working conditions corresponding to different regulations. The same knowledge can be used to eliminate the induced effects from the matrix $\Delta\boldsymbol{K}$. The values of the fuels of a component are assumed equal to the known values in free condition. If the third condition is complied, the product can assumed linearly dependent on its fuels:

$$P_i = P_{i_{ref}} + \sum_{j=1}^{n} \frac{dP_i}{dE_j} \cdot (E_{j_{free}} - E_{j_{ref}}). \tag{4.47}$$

If the known working conditions are sufficiently close to the reference condition, the derivates can be calculated as:

$$\frac{dP_i}{dE_j} = \frac{\Delta P_i}{\Delta E_j}. \tag{4.48}$$

Assuming *f* the number of maximum fuels for every component, at least *f* working conditions must be available. In these conditions the components do not present any anomalies, so the induced effects can be determined.

Figure 4.2 shows the productive structures of a system. The component 3 is characterized by two fuels, so two independent working conditions are required.

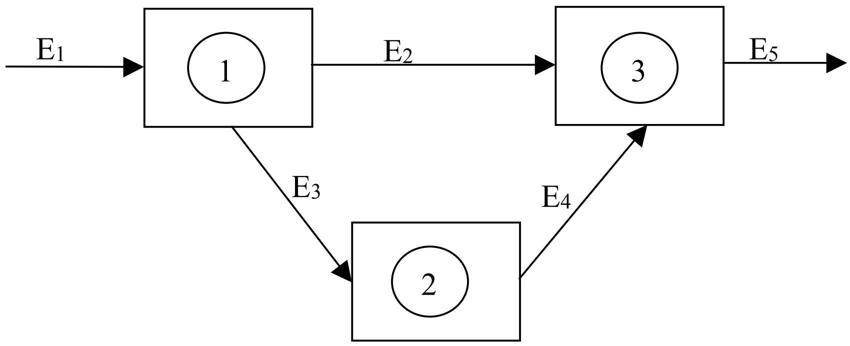

Figure 4.2 - Productive structure of a general system

The equation 4.47 can be applied to determine the behaviour of the components when the resources change. To achieve this goal each flow, except the overall products, is considered as resource. The product of each component, that would be obtained by varying its resources from the reference condition value to the free condition value, can be determined by means of the following equations:

$$E_2 + E_3 = (E_2 + E_3)_{ref} + \frac{\partial(E_2 + E_3)}{\partial E_1} \cdot (E_{1_{free}} - E_{1_{ref}}) \tag{4.49}$$

$$E_4 = (E_4)_{ref} + \frac{\partial(E_4)}{\partial E_3} \cdot (E_{3_{free}} - E_{3_{ref}}) \tag{4.50}$$

$$E_5 = (E_5)_{ref} + \frac{\partial(E_5)}{\partial E_2} \cdot (E_{2_{free}} - E_{2_{ref}}) + \frac{\partial(E_5)}{\partial E_4} \cdot (E_{4_{free}} - E_{4_{ref}}) \tag{4.51}$$

The products calculated in this form approximately take into account the effects induced by the behavior of the components. The procedure is not exact because: 1) A linear behavior is assumed and 2) the derivatives are calculated under specific conditions corresponding to the regulation system, and it is assumed that this induced behavior is similar to the induced effect of the malfunctioning components.

The unit exergy consumptions of every component, calculated as

$$k_{01} = \frac{E_{1_{free}}}{E_2 + E_3}; \tag{4.52}$$

$$k_{12} = \frac{E_{3_{free}}}{E_4}; \tag{4.53}$$

$$k_{13} = \frac{E_{2_{free}}}{E_5}; \tag{4.54}$$

$$k_{23} = \frac{E_{4_{free}}}{E_5} \tag{4.55}$$

do not include any intrinsic malfunctions, as they have been calculated in a state obtained by regulating the system, starting from the reference condition. These values differ from the ones calculated in reference condition only if the efficiency of the components depends on the working conditions, i.e. if some induced effects have taken place. In this way, the matrix $\Delta\boldsymbol{K}_{\mathbf{ind}}$, calculated as difference between the values 4.52-4.55 and the corresponding values in reference condition, only includes the induced effects occurred in the free condition.

If these values are subtracted to the elements of the matrix $\Delta\boldsymbol{K}$, calculated using the free versus reference approach, the intrinsic effects can be isolated. The resulting matrix is indicated as $\Delta\boldsymbol{K}_{\mathbf{int}}$.

The same variation of an exergy flow (resource) can be obtained with different movement of the thermodynamic variables which constitute it: pressure, temperature, mass flow, and the effect on its efficiency is different. The model is so as much correct as the flows are disaggregated. For this reason a productive structure based on mechanical and thermal components of exergy must be chosen to achieve this purpose.

When this approach is applied to a real case, the third hypothesis above formulated usually falls, so that the results do not allow the complete erasure of all the induced effects. In this way only the main anomalies can be found. Anyway the procedure represents an improvement of the previous one, as it allows the location of more than one anomaly at the same time. In the next chapter the procedure is applied to a case of multiple malfunction of the gas turbine plant.

4.8 Cost associated to the regulation system intervention

The intervention of the regulation system causes the movement of the working condition, so its effect must be evaluated using quantities relative to differences between two states, rather than quantities representative of a particular state. The thermoeconomic quantity which best plays this role is the fuel impact. The fuel impact associated to the regulation ΔF_{T_r} can be defined as the difference between the fuel consumptions in operation ($F_{T_{op}}$) and free ($F_{T_{free}}$) conditions, or, what is the same, the difference between the fuel impacts calculated in the same conditions:

$$\Delta F_{T_r} = \Delta F_{T_{op}} - \Delta F_{T_{free}} = F_{T_{op}} - F_{T_{free}}. \tag{4.56}$$

The last term is equal to the fuel consumption is reference condition if the plant regulation is made also operating on the fuel mass flow, in this way the fuel impact associated to the regulation is equal to the total fuel impact.

The fuel impact calculated using the equation 4.56 takes into account two effects of the system intervention: the variation of the overall production and the variation of the efficiency of the components. This means that the intervention involves global dysfunctions, as the reference production is restored, but also malfunctions, as the efficiency of the components depends on their production. Dysfunctions do not have a negative impact by themselves, as they are associated to a variation of the overall production. Their contribution is expressed by the second term at the right hand side of the equation 4.8. On the contrary, the global malfunction involved in the regulation is associated to the plant efficiency variation. Its calculation can be made using the equation 4.43, where the variation of the unit exergy consumptions is calculated between operation and free conditions.

$$MF_r = \sum_{i=1}^{n} \left(\sum_{j=0}^{n} K_{P,j}^{\ *} \cdot (k_{ji_{op}} - k_{ji_{free}}) \right) \cdot P_i \qquad (4.57)$$

where MF_r indicates the malfunctions associated to the regulation system. The cost of the products of every component must be calculated in operation condition, while the total product of the components must be calculated in free condition.

This malfunction is an induced malfunction, as it is caused by the regulation system. The proposed procedure does not eliminate all the induced malfunctions, but it erase the malfunctions caused by the regulation. The equation 4.21 shows that the fuel impact is equal to the sum of malfunctions and dysfunctions. In the case of the classical thermoeconomic diagnosis approach, the whole fuel impact is associated to the anomalies of the plant, in fact the anomalies have generated the intrinsic and induced malfunctions and the relative dysfunctions. On the contrary in the case of the proposed diagnosis procedure, the fuel impact is partially due to the anomalies, which have generated intrinsic and induced malfunctions and dysfunctions, and partially due to the different plant production between operation and free conditions, which has generated some dysfunctions (and the corresponding induced malfunctions as the behaviour of the components depend on their production). This last term does not represent a system inefficiency, in fact it is also present if the system changes its overall production and any anomalies have taken place. The application of the equations 4.21, 4.23 and 4.45 to the two procedure allows to write:

$$\Delta F_T = \sum_{i=1}^{n} MF_i^* \ , \qquad (4.58)$$

in the case of the classical methodology and

$$\Delta F_T = \Delta F_{T_r} = \sum_{i=1}^{n} \tilde{MF}_i^* + \Delta F_{\Delta P} \ , \qquad (4.59)$$

in the case of the proposed methodology, where $\tilde{MF}_i^*$ is the cost of the malfunction calculated comparing operation and free conditions and $\Delta F_{T_{\Delta P}}$ is the fuel impact associated to the variation of the plant production.

The comparison between the equations 4.58 and 4.59 allows to express the cost of the malfunctions associated to the natural effects of the anomalies:

$$\sum_{i=1}^{n} \tilde{MF}_i^* = \sum_{i=1}^{n} MF_i^* - \Delta F_{\Delta P} . \tag{4.60}$$

The fuel impact calculated using equation 4.56 also represents the average cost of the intervention. The average unit cost k_r* associated the regulation system intervention can be calculated as the ratio between the fuel impact and the corresponding production variation:

$$k_r^* = \frac{\Delta F_{T_r}}{P_{ext_{op}} - P_{ext_{free}}} = \frac{\Delta F_{T_r}}{\Delta P_{ext_r}} . \tag{4.61}$$

The marginal unit cost associated to the regulation system can also be calculated:

$$k_r^* = \lim_{\Delta P_{ext_r} \to 0} \frac{\Delta F_{T_r}}{\Delta P_{ext_r}} = \frac{dF_T}{dP_{ext}} . \tag{4.62}$$

The unit cost of the regulation can assume anomalous values in correspondence of some regulation sets. In particular when the system in free condition is characterized by the same production as in operation condition, but a different fuel consumption, the unitary cost tends to be infinite. In reality this conditions can only occur when some of the system malfunctions are characterized by opposite signs, so that the efficiency of the plant could be the same in reference and free conditions. In fact, the overall fuel is always equal in reference and in free conditions, as it is usually one of the regulation parameters; moreover, the production is also the same in the two conditions if the denominator of the equation 4.61 is zero (reference and operation conditions are always characterized by the same overall production). In this way, if only degradations of the plant efficiency are analysed, the unit cost assumes finite values, as the efficiency becomes lower than in reference condition.

High values of the unit cost of the regulation means that the efficiency of the system in free condition is higher than in operation condition. The regulation system intervention has so caused a reduction of the plant efficiency and consequently an increase of the costs. This also means that the regulation has induced other malfunctions in the system, so the use of the proposed diagnosis procedure is advised.

A low value of this parameter means that the internal set-points, but also the external requirements, make the plant work better than in free conditions. This also means that the induced malfunctions has been reduced, but it does not mean that the proposed procedure falls. The regulation system intervention in fact changes the natural propagation of the anomalies effects, so if it makes decrease some induced malfunctions it can as well makes increase some others. The application of the two procedure to the steam turbine plant (see chapter 6) shows how in some cases the regulation system globally reduces the induced effects, but some of the element of the $\Delta\boldsymbol{K}$ have increased, which does not allow the correct location of the anomaly.

Finally negative values of the unit costs are associated to regulations causing the reduction of the plant efficiency and the reduction of its total production too.

4.9 Practical use of the proposed diagnosis approach

If all the formulated hypothesis are verified, the proposed methodology allows to erase all the induced effects from the matrix $\Delta \boldsymbol{K}$. The residual matrix, $\Delta \boldsymbol{K}_{\mathbf{int}}$, only contains the intrinsic effects so the direct diagnosis problem is solved, as all the anomalies can be located. The inverse diagnosis problem is still to be solved. The quantification of the anomalies in terms of fuel impact is required. In fact, before to stop the plant and operate the maintenance, the manager wants to know how much energy could be technically saved, i.e. he wants to know if the intervention is economically convenient.

Two cases can happen: 1) a single element of the matrix $\Delta \boldsymbol{K}_{\mathbf{int}}$ is different from zero or much bigger than the others; 2) several elements of the matrix have a comparable magnitude.

In the first case the diagnosis problems are completely solved. A single (significant) anomaly is present in the plant, so all the fuel impact, calculated as difference between the fuel consumption in operation and reference condition, is due to this anomaly. Its complete removal allows a technical energy saving equal to the fuel impact.

In the second case the problem can not be solved a priori, without using a mathematical model of the plant. The fuel impact associated to every single intrinsic effect can be calculated, using the expression:

$$\Delta F_{i_{int}} = K_{P,j}^{*} \cdot \Delta k_{ji_{int}} \cdot P_{i_{ref}} \tag{4.63}$$

where:

$K_{P,j}^{*}$ is the unit cost of the jth fuel (produced by the component j) of the ith component, calculated in the free condition;

$\Delta k_{ji_{int}}$ is a non zero element of the matrix $\Delta \boldsymbol{K}_{\mathbf{int}}$;

$P_{i_{ref}}$ is the product of the ith component calculated in reference condition.

The induced effects make differ this value from the real fuel impact associated to the anomaly. In particular the effects caused by the regulation system can be higher than the intrinsic effects, so a correct value of the fuel impact can not be predicted.

The value calculated using the equation 4.63 generally represents the minimum expected energy saving. If the unit cost associated to the regulation system intervention is higher than the average cost of the plant production, the fuel impact associated to regulation is positive too. In this way the fuel impact associated to the operation versus reference comparison is higher than the total fuel impact calculated by comparing free and reference conditions. If the anomaly in the ith component is completely removed, a fuel impact higher than the value calculated using the equation 4.63 is expected. An application of these considerations is proposed in the next chapter.

CHAPTER 5

Thermoeconomic diagnosis of the gas turbine plant

In this chapter the *free vs. reference* (FvR) and the *operation vs. reference (OvR)* procedures, presented in chapter 4, are applied to the Moncalieri cogenerative gas turbine plant, in order to compare their performances in the solution of the direct problem of the thermoeconomic diagnosis. The gas turbine technology represents one of the most interesting tests for the thermoeconomic diagnosis methods, in fact the characteristics of the fluid, the functional dependence among the components and the internal set points make difficult the malfunction location.

The operation conditions are simulated by modifying the values of the characteristic parameters of the components, but keeping the same environment conditions and the same electric and thermal loads as in reference condition. The determination of the corresponding free conditions requires the use of a regulation system model, in order to calculate the Lagrange multipliers associated to the regulation variables. In particular the gas turbine is characterised by four regulation variables: the opening grade of the inlet guided valve (IGV), the fuel mass flow, the percentage of gas mass flow passing through the by pass pipe and the water mass flow. These are the independent variables of the model, indicated respectively as x_1, x_2, x_3 and x_4. In this way the equation 4.34 becomes:

$$y_{j_{free}} = y_{j_{op}} - \lambda_{j1} \cdot (x_{1_{op}} - x_{1_{ref}}) - \lambda_{j2} \cdot (x_{2_{op}} - x_{2_{ref}}) - \lambda_{j3} \cdot (x_{3_{op}} - x_{3_{ref}}) - \lambda_{j4} \cdot (x_{4_{op}} - x_{4_{ref}}) \quad (5.1)$$

Equation 5.1 allows to calculate the values of the thermodynamic quantities, mass flows, temperatures and pressures, in the free condition corresponding to every operation condition, once the values of the regulation parameters are known.

5.1 Analytical calculation of the gas turbine plant Lagrange multipliers

A simplified model of the gas turbine plant has been used for the analytical calculation of the Lagrange multipliers. In this model the properties of the gases in every component are considered as constants, calculated using the simulator described in chapter 1. In such hypothesis the refrigeration system of the turbine blade can be here neglected. The equation constituting the mathematical model of the system are shown below

$$\beta_c = \frac{p_2}{p_1 \cdot (1 - pp_f)} \quad (5.2)$$

$$T_2 = T_1 \cdot \left(1 + \frac{1}{\eta_c} \cdot \left(\left(\beta_c^{\frac{R_a}{c_{p_{1-2}}}}\right) - 1\right)\right) \quad (5.3)$$

$$W_c = (G_a)_d \cdot igv \cdot c_{p_{1-2}} \cdot (T_2 - T_1) \quad (5.4)$$

$$\eta_c = (\eta_c)_d \cdot \left[a_2 \cdot \left(\frac{(G_a)_d \cdot igv}{\rho_1}\right)^2 + a_1 \cdot \frac{(G_a)_d \cdot igv}{\rho_1} + a_0\right] \quad (5.5)$$

$$\rho_1 = \frac{p_1}{R_a \cdot T_1} \quad (5.6)$$

$$p_3 = p_2 \cdot (1 - pp_{cc}) \quad (5.7)$$

$$(G_a)_d \cdot igv \cdot c_{p_{0-2}} \cdot (T_2 - T_0) + G_c \cdot H_i \cdot \eta_{cc} = G_g \cdot c_{p_{0-3}} \cdot (T_3 - T_0) \quad (5.8)$$

$$(G_a)_d \cdot igv + G_c = G_g \quad (5.9)$$

$$\frac{G_g}{(G_g)_d} = \sqrt{\frac{p_3 \cdot \rho_3}{(p_3 \cdot \rho_3)_d}} \cdot \sqrt{\frac{1 - \frac{1}{(\beta_t)^2}}{1 - \frac{1}{((\beta_t)_d)^2}}} \quad (5.10)$$

$$\beta_t = \frac{p_3}{p_4} \quad (5.11)$$

$$\rho_3 = \frac{p_3}{R_g \cdot T_3} \quad (5.12)$$

$$T_4 = T_3 \cdot \left(1 - \eta_t \cdot \left(\left(\beta_t^{\frac{R_a}{c_{p_{1-2}}}}\right) - 1\right)\right) \quad (5.13)$$

$$\eta_t = (\eta_t)_d \cdot [b_2 \cdot (G_g)_d^{\;2} + b_1 \cdot (G_g)_d + b_0] \quad (5.14)$$

$$W_c + W_t = G_g \cdot c_{p_{3-4}} \cdot (T_3 - T_4) \quad (5.15)$$

$$W_{el} = \eta_{alt} \cdot W_t \quad (5.16)$$

$$p_1 = p_4 \cdot (1 - pp_{he}) \quad (5.17)$$

$$P \cdot G_g \cdot c_{p_{4-5}} \cdot (T_4 - T_5) = G_w \cdot c_{p_w} \cdot (T_{out} - T_{in}) \quad (5.18)$$

$$r = \frac{C_{min}}{C_{max}} = \frac{P \cdot G_g \cdot c_{p_{4-5}}}{G_w \cdot c_{p_w}} \quad (5.19)$$

$$NTU = \frac{K \cdot A}{P \cdot G_g \cdot c_{p_{4-5}}} \tag{5.20}$$

$$\varepsilon = \frac{1 - e^{-NTU \cdot (1-r)}}{1 - r \cdot e^{-NTU \cdot (1-r)}} \tag{5.21}$$

$$\varepsilon = \frac{T_4 - T_5}{T_4 - T_{in}} \tag{5.22}$$

$$\Phi = G_w \cdot c_{p_w} \cdot (T_{out} - T_{in}) \tag{5.23}$$

$y_1=p_1$	$y_2=p_2$	$y_3=p_3$	$y_4=p_4$		
$y_5=T_1$	$y_6=T_2$	$y_7=T_3$	$y_8=T_4$	$y_9=T_5$	
$y_{10}=Gc$	$y_{11}=Gg$	$y_{12}=igv$	$y_{13}=Wel$	$y_{14}=Wc$	$y_{15}=Wt$
$y_{16}=\Phi$	$y_{17}=Gw$	$y_{18}=Tin$	$y_{19}=Tout$		
$y_{20}=\beta_c$	$y_{21}=pp_f$	$y_{22}=\eta_c$	$y_{23}=(\eta_c)_d$	$y_{24}=\rho_1$	$y_{25}=pp_{cc}$
$y_{26}=\eta_{cc}$	$y_{27}=\rho_3$	$y_{28}=\eta_t$	$y_{29}=(\eta_t)_d$	$y_{30}=h_{alt}$	$y_{31}=pp_{he}$
$y_{32}=P$	$y_{33}=r$	$y_{34}=NTU$	$y_{35}=K$	$y_{36}=\varepsilon$	$y_{37}=\beta_t$

Table. 5.1 - Variables of the model

The complete model equations can be written using the variables shown in table 5.1.

$$y_1 = \alpha_1 \qquad y_2 = \frac{y_3}{1 - y_{25}} \qquad y_3 = y_{37} \cdot y_4$$

$$y_4 = \frac{y_1}{1 - y_{31}} \qquad y_5 = \alpha_5 \qquad y_6 = y_5 \cdot \left(1 + \frac{1}{y_{22}} \cdot \left(y_{20}^{\ c_1} - 1\right)\right)$$

$$y_7 = c_4 + \frac{y_{12} \cdot c_3}{y_{11}} \cdot (y_6 - c_4) + \frac{y_{10} \cdot y_{26} \cdot c_5}{y_{11}} \qquad y_8 = y_7 \cdot \left(1 - y_{28} \cdot \left(1 - y_{37}^{\ c_2}\right)\right)$$

$$y_9 = y_8 - y_{36} \cdot (y_8 - y_{18}) \qquad y_{10} = x_{10} \qquad y_{11} = y_{12} \cdot c_6 + y_{10}$$

$$y_{12} = x_{12} \qquad y_{13} = y_{15} \cdot y_{30} \qquad y_{14} = c_7 \cdot y_{12} \cdot (y_6 - y_5)$$

$$y_{15} = c_8 \cdot y_{11} \cdot (y_7 - y_8) - y_{14} \qquad y_{16} = c_9 \cdot y_{17} \cdot (y_{19} - y_{18})$$

$$y_{17} = x_{17} \qquad y_{18} = \alpha_{18} \qquad y_{19} = y_{18} + \frac{y_{32} \cdot c_{18} \cdot y_{11}}{y_{17} \cdot c_9} \cdot (y_8 - y_9)$$

$$y_{20} = \frac{y_2}{y_1 \cdot (1 - y_{21})} \qquad y_{21} = \eta_{21}$$

$$y_{22} = y_{23} \cdot \left(\frac{c_{10} \cdot y_{12}^2}{y_{24}^2} + \frac{c_{11} \cdot y_{12}}{y_{24}} + c_{12} \right) \qquad y_{23} = \eta_{23}$$

$$y_{24} = \frac{y_1}{y_2 \cdot c_{13}} \qquad y_{25} = \eta_{25} \qquad y_{26} = \eta_{26}$$

$$y_{27} = \frac{y_3}{y_7 \cdot c_{14}} \qquad y_{28} = y_{29} \cdot \left(c_{15} \cdot y_{11}^2 + c_{16} \cdot y_{11} + c_{17} \right)$$

$$y_{29} = \eta_{29} \qquad y_{30} = \eta_{30} \qquad y_{31} = \eta_{31}$$

$$y_{32} = x_{32} \qquad y_{33} = \frac{y_{11} \cdot c_{19} \cdot y_{32}}{y_{17}} \qquad y_{34} = \frac{y_{35} \cdot c_{20}}{y_{11} \cdot y_{32}}$$

$$y_{35} = \eta_{35} \qquad y_{36} = \frac{1 - e^{-y_{34} \cdot (1 - y_{33})}}{1 - y_{33} \cdot e^{-y_{34} \cdot (1 - y_{33})}} \qquad y_{37} = \frac{1}{\sqrt{1 - \frac{c_{21} \cdot y_{11}^2}{y_3 \cdot y_{27}}}}$$

where:

$$c_1 = \frac{R_a}{c_{p_{1-2}}} \qquad c_2 = \frac{-R_g}{c_{p_{3-4}}} \qquad c_3 = \frac{(G_a)_d \cdot c_{p_{1-2}}}{c_{p_{0-3}}}$$

$$c_4 = T_0 \qquad c_5 = \frac{H_i}{c_{p_{0-3}}} \qquad c_6 = (G_a)_d$$

$$c_7 = (G_a)_d \cdot c_{p_{1-2}} \qquad c_8 = c_{p_{3-4}} \qquad c_9 = c_{p_w}$$

$$c_{10} = (G_a)_d^2 \cdot a_2 \qquad c_{11} = (G_a)_d \cdot a_1 \qquad c_{12} = a_0$$

$$c_{13} = R_a \qquad c_{14} = R_g \qquad c_{15} = b_2$$

$$c_{16} = b_1 \qquad c_{17} = b_0 \qquad c_{18} = c_{p_{4-5}}$$

$$c_{19} = \frac{c_{p_{4-5}}}{c_{p_w}} \qquad c_{20} = \frac{A}{c_{p_{4-5}}} \qquad c_{21} = \left(\frac{p_3 \cdot \rho_3 \cdot \left(1 - \frac{1}{\beta_t^2} \right)}{G_g^2} \right)_d$$

The known values are indicated using symbols x, η and α respectively for the regulation variables, the characteristic parameters of the components and the environment conditions.

The expression of the i[th] Lagrangian, representing the constrained variation of the i[th] variable, is:

$$
\begin{aligned}
L_i &= y_i + \lambda_1 \cdot (\alpha_1 - y_1) + \lambda_2 \cdot \left(\frac{y_3}{1-y_{25}} - y_2 \right) + \lambda_3 \cdot (y_{37} \cdot y_4 - y_3) + \lambda_4 \cdot \left(\frac{y_1}{1-y_{31}} - y_4 \right) + \\
& \lambda_5 \cdot (\alpha_5 - y_5) + \lambda_6 \cdot \left(y_5 \cdot \left(1 + \frac{1}{y_{22}} \cdot \left(y_{20}^{c_1} - 1 \right) \right) - y_6 \right) + \\
& \lambda_7 \cdot \left(c_4 + \frac{y_{12} \cdot c_3}{y_{11}} \cdot (y_6 - c_4) + \frac{y_{10} \cdot y_{26} \cdot c_5}{y_{11}} - y_7 \right) + \lambda_8 \cdot \left(y_7 \cdot \left(1 - y_{28} \cdot \left(1 - y_{37}^{c_2} \right) \right) - y_8 \right) + \\
& \lambda_9 \cdot (y_8 - y_{36} \cdot (y_8 - y_{18}) - y_9) + \lambda_{10} \cdot (x_{10} - y_{10}) + \lambda_{11} \cdot (y_{12} \cdot c_6 + y_{10} - y_{11}) + \\
& \lambda_{12} \cdot (x_{12} - y_{12}) + \lambda_{13} \cdot (y_{15} \cdot y_{30} - y_{13}) + \lambda_{14} \cdot (c_7 \cdot y_{12} \cdot (y_6 - y_5) - y_{14}) + \\
& \lambda_{15} \cdot (c_8 \cdot y_{11} \cdot (y_7 - y_8) - y_{14} - y_{15}) + \lambda_{16} \cdot (c_9 \cdot y_{17} \cdot (y_{19} - y_{18}) - y_{16}) + \\
& \lambda_{17} \cdot (x_{17} - y_{17}) + \lambda_{18} \cdot (\alpha_{18} - y_{18}) + \lambda_{19} \cdot \left(y_{18} + \frac{y_{32} \cdot c_{18} \cdot y_{11}}{y_{17} \cdot c_9} \cdot (y_8 - y_9) - y_{19} \right) + \\
& \lambda_{20} \cdot \left(\frac{y_2}{y_1 \cdot (1-y_{21})} - y_{20} \right) + \lambda_{21} \cdot (\eta_{21} - y_{21}) + \lambda_{22} \cdot \left(y_{23} \cdot \left(\frac{c_{10} \cdot y_{12}^2}{y_{24}^2} + \frac{c_{11} \cdot y_{12}}{y_{24}} + c_{12} \right) - y_{22} \right) + \\
& \lambda_{23} \cdot (\eta_{23} - y_{23}) + \lambda_{24} \cdot \left(\frac{y_1}{y_2 \cdot c_{13}} - y_{24} \right) + \lambda_{25} \cdot (\eta_{25} - y_{25}) + \lambda_{26} \cdot (\eta_{26} - y_{26}) + \\
& \lambda_{27} \cdot \left(\frac{y_3}{y_7 \cdot c_{14}} - y_{27} \right) + \lambda_{28} \cdot \left(y_{29} \cdot \left(c_{15} \cdot y_{11}^2 + c_{16} \cdot y_{11} + c_{17} \right) - y_{28} \right) + \lambda_{29} \cdot (\eta_{29} - y_{29}) + \\
& \lambda_{30} \cdot (\eta_{30} - y_{30}) + \lambda_{31} \cdot (\eta_{31} - y_{31}) + \lambda_{32} \cdot (x_{32} - y_{32}) + \\
& \lambda_{33} \cdot \left(\frac{y_{11} \cdot c_{19} \cdot y_{32}}{y_{17}} - y_{33} \right) + \lambda_{34} \cdot \left(\frac{y_{35} \cdot c_{20}}{y_{11} \cdot y_{32}} - y_{34} \right) + \lambda_{35} \cdot (\eta_{35} - y_{35}) + \\
& \lambda_{36} \cdot \left(\frac{1 - e^{-y_{34} \cdot (1 - y_{33})}}{1 - y_{33} \cdot e^{-y_{34} \cdot (1-y_{33})}} - y_{36} \right) + \lambda_{37} \cdot \left(\frac{1}{\sqrt{1 - \frac{c_{21} \cdot y_{11}^2}{y_3 \cdot y_{27}}}} - y_{37} \right)
\end{aligned}
\tag{5.24}
$$

The Lagrange multipliers calculation requires the derivation of all the equations 5.24, obtained considering the term $y_i = y_1 ... y_{36}$. As the Lagrangians differ only for the term y_i, their derivates differ for the position of a unitary term, while the terms depending on the Lagrange multipliers λ are equal for every L_i. Here the terms depending on the Lagrange multipliers of the general Lagrangian derivates are shown:

$$
\frac{\partial L_i}{\partial y_1} = -\lambda_1 + \lambda_4 \cdot \frac{1}{1-y_{31}} - \lambda_{20} \cdot \frac{y_2}{(1-y_{21}) \cdot y_1^2} + \lambda_{24} \cdot \frac{1}{y_2 \cdot c_{13}} \tag{5.25}
$$

$$\frac{\partial L_i}{\partial y_2} = -\lambda_2 + \lambda_{20} \cdot \frac{1}{(1-y_{21}) \cdot y_1} - \lambda_{24} \cdot \frac{y_1}{c_{13} \cdot y_2^2} \tag{5.26}$$

$$\frac{\partial L_i}{\partial y_3} = -\lambda_3 + \lambda_2 \cdot \frac{1}{1-y_{25}} + \lambda_{27} \cdot \frac{1}{y_7 \cdot c_{14}} - \lambda_{37} \cdot \frac{1}{2} \cdot \left(1 - \frac{c_{21} \cdot y_{11}^2}{y_3 \cdot y_{27}}\right)^{-\frac{3}{2}} \cdot \frac{c_{21} \cdot y_{11}^2}{y_{27} \cdot y_3^2} \tag{5.27}$$

$$\frac{\partial L_i}{\partial y_4} = -\lambda_4 + \lambda_3 \cdot y_{37} \tag{5.28}$$

$$\frac{\partial L_i}{\partial y_5} = -\lambda_5 + \lambda_6 \cdot \left(1 + \frac{1}{y_{22}} \cdot \left(y_{20}^{c_1} - 1\right)\right) - \lambda_{14} \cdot y_{12} \cdot c_7 \tag{5.29}$$

$$\frac{\partial L_i}{\partial y_6} = -\lambda_6 + \lambda_7 \cdot \frac{c_3 \cdot y_{12}}{y_{11}} + \lambda_{14} \cdot y_{12} \cdot c_7 \tag{5.30}$$

$$\frac{\partial L_i}{\partial y_7} = -\lambda_7 + \lambda_8 \cdot \left(1 - y_{28} \cdot \left(1 - y_{37}^{c_2}\right)\right) + \lambda_{15} \cdot y_{11} \cdot c_8 - \lambda_{27} \cdot \frac{y_3}{c_{14} \cdot y_7^2} \tag{5.31}$$

$$\frac{\partial L_i}{\partial y_8} = -\lambda_8 + \lambda_9 \cdot (1 - y_{36}) - \lambda_{15} \cdot y_{11} \cdot c_8 + \lambda_{19} \cdot \frac{c_{18} \cdot y_{32} \cdot y_{11}}{y_{17} \cdot c_9} \tag{5.32}$$

$$\frac{\partial L_i}{\partial y_9} = -\lambda_9 - \lambda_{19} \cdot \frac{c_{18} \cdot y_{32} \cdot y_{11}}{y_{17} \cdot c_9} \tag{5.33}$$

$$\frac{\partial L_i}{\partial y_{10}} = -\lambda_{10} + \lambda_7 \cdot \frac{c_5 \cdot y_{26}}{y_{11}} + \lambda_{11} \tag{5.34}$$

$$\begin{aligned}\frac{\partial L_i}{\partial y_{11}} = {} & -\lambda_{11} - \lambda_7 \cdot \frac{c_3 \cdot y_{12} \cdot (y_6 - c_4) + c_5 \cdot y_{26} \cdot y_{10}}{y_{11}^2} + \lambda_{15} \cdot c_8 \cdot (y_7 - y_8) + \\ & \lambda_{19} \cdot \frac{c_{18} \cdot y_{32} \cdot (y_8 - y_9)}{c_9 \cdot y_{17}} + \lambda_{28} \cdot y_{29} \cdot (2 \cdot c_{15} \cdot y_{11} + c_{16}) + \\ & \lambda_{33} \cdot \frac{c_{19} \cdot y_{32}}{y_{17}} - \lambda_{34} \cdot \frac{c_{20} \cdot y_{35}}{y_{32} \cdot y_{11}^2} + \lambda_{37} \cdot \left(1 - \frac{c_{21} \cdot y_{11}^2}{y_3 \cdot y_{27}}\right)^{-\frac{3}{2}} \cdot \frac{c_{21} \cdot y_{11}}{y_{27} \cdot y_3}\end{aligned} \tag{5.35}$$

$$\frac{\partial L_i}{\partial y_{12}} = -\lambda_{12} + \lambda_7 \cdot \frac{c_3 \cdot (y_6 - c_4)}{y_{11}} + \lambda_{11} \cdot c_6 + \lambda_{14} \cdot c_7 \cdot (y_6 - y_5) + \lambda_{22} \cdot y_{23} \cdot \left(\frac{2 \cdot c_{10} \cdot y_{12}}{y_{24}^2} + \frac{c_{11}}{y_{24}}\right) \tag{5.36}$$

$$\frac{\partial L_i}{\partial y_{13}} = -\lambda_{13} \tag{5.37}$$

$$\frac{\partial L_i}{\partial y_{14}} = -\lambda_{14} - \lambda_{15} \tag{5.38}$$

$$\frac{\partial L_i}{\partial y_{15}} = -\lambda_{15} + \lambda_{13} \cdot y_{30} \tag{5.39}$$

$$\frac{\partial L_i}{\partial y_{16}} = -\lambda_{16} \tag{5.40}$$

$$\frac{\partial L_i}{\partial y_{17}} = -\lambda_{17} + \lambda_{16} \cdot c_9 \cdot (y_{19} - y_{18}) - \lambda_{19} \cdot \frac{y_{32} \cdot y_{11} \cdot c_{18} \cdot (y_8 - y_9)}{y_{17}^2 \cdot c_9} - \lambda_{33} \cdot \frac{y_{32} \cdot y_{11} \cdot c_{19}}{y_{17}^2} \tag{5.41}$$

$$\frac{\partial L_i}{\partial y_{18}} = -\lambda_{18} + \lambda_9 \cdot y_{36} - \lambda_{16} \cdot c_9 \cdot y_{17} + \lambda_{19} \tag{5.42}$$

$$\frac{\partial L_i}{\partial y_{19}} = -\lambda_{19} + \lambda_{16} \cdot c_9 \cdot y_{17} \tag{5.43}$$

$$\frac{\partial L_i}{\partial y_{20}} = -\lambda_{20} + \lambda_6 \cdot \frac{c_1 \cdot y_5 \cdot y_{20}^{c_1 - 1}}{y_{22}} \tag{5.44}$$

$$\frac{\partial L_i}{\partial y_{21}} = -\lambda_{21} + \lambda_{20} \cdot \frac{y_2}{y_1 \cdot (1 - y_{21})^2} \tag{5.45}$$

$$\frac{\partial L_i}{\partial y_{22}} = -\lambda_{22} - \lambda_6 \cdot \frac{y_5 \cdot \left(y_{20}^{c_1} - 1\right)}{y_{22}^2} \tag{5.46}$$

$$\frac{\partial L_i}{\partial y_{23}} = -\lambda_{23} + \lambda_{22} \cdot \left(\frac{c_{10} \cdot y_{12}^2}{y_{24}^2} + \frac{c_{11} \cdot y_{12}}{y_{24}} + c_{12}\right) \tag{5.47}$$

$$\frac{\partial L_i}{\partial y_{24}} = -\lambda_{24} - \lambda_{22} \cdot y_{23} \cdot \left(2 \cdot \frac{c_{10} \cdot y_{12}^2}{y_{24}^3} + \frac{c_{11} \cdot y_{12}}{y_{24}^2}\right) \tag{5.48}$$

$$\frac{\partial L_i}{\partial y_{25}} = -\lambda_{25} + \lambda_2 \cdot \frac{y_3}{(1 - y_{25})^2} \tag{5.49}$$

$$\frac{\partial L_i}{\partial y_{26}} = -\lambda_{26} + \lambda_7 \cdot \frac{c_5 \cdot y_{10}}{y_{11}} \tag{5.50}$$

$$\frac{\partial L_i}{\partial y_{27}} = -\lambda_{27} - \lambda_{37} \cdot \frac{1}{2} \cdot \left(1 - \frac{c_{21} \cdot y_{11}^2}{y_3 \cdot y_{27}}\right)^{-\frac{3}{2}} \cdot \frac{c_{21} \cdot y_{11}^2}{y_{27}^2 \cdot y_3} \tag{5.51}$$

$$\frac{\partial L_i}{\partial y_{28}} = -\lambda_{28} - \lambda_8 \cdot y_7 \cdot \left(1 - y_{37}^{c_2}\right) \tag{5.52}$$

$$\frac{\partial L_i}{\partial y_{29}} = -\lambda_{29} + \lambda_{28} \cdot \left(c_{15} \cdot y_{11}^2 + c_{16} \cdot y_{11} + c_{17}\right) \tag{5.53}$$

$$\frac{\partial L_i}{\partial y_{30}} = -\lambda_{30} + \lambda_{13} \cdot y_{15} \tag{5.54}$$

$$\frac{\partial L_i}{\partial y_{31}} = -\lambda_{31} + \lambda_4 \cdot \frac{y_1}{(1 - y_{31})^2} \tag{5.55}$$

$$\frac{\partial L_i}{\partial y_{32}} = -\lambda_{32} + \lambda_{19} \cdot \frac{c_{18} \cdot y_{11} \cdot (y_8 - y_9)}{c_9 \cdot y_{17}} + \lambda_{33} \cdot \frac{c_{19} \cdot y_{11}}{y_{17}} - \lambda_{34} \cdot \frac{c_{20} \cdot y_{35}}{y_{32}^2 \cdot y_{11}} \tag{5.56}$$

$$\frac{\partial L_i}{\partial y_{33}} = -\lambda_{33} + \lambda_{36} \cdot \frac{e^{-y_{34} \cdot (1 - y_{33})} \cdot (1 - y_{34} + y_{33} \cdot y_{34})}{\left(1 - y_{33} \cdot e^{-y_{34} \cdot (1 - y_{33})}\right)^2} \tag{5.57}$$

$$\frac{\partial L_i}{\partial y_{34}} = -\lambda_{34} + \lambda_{36} \cdot \frac{e^{-y_{34} \cdot (1 - y_{33})} \cdot (1 - y_{33})^2}{\left(1 - y_{33} \cdot e^{-y_{34} \cdot (1 - y_{33})}\right)^2} \tag{5.58}$$

$$\frac{\partial L_i}{\partial y_{35}} = -\lambda_{35} + \lambda_{34} \cdot \frac{c_{20}}{y_{11} \cdot y_{32}} \tag{5.59}$$

$$\frac{\partial L_i}{\partial y_{36}} = -\lambda_{36} - \lambda_9 \cdot (y_8 - y_{18}) \tag{5.60}$$

$$\frac{\partial L_i}{\partial y_{37}} = -\lambda_{37} + \lambda_3 \cdot y_4 + \lambda_8 \cdot c_2 \cdot y_7 \cdot y_{28} \cdot y_{37}^{c_2 - 1} \tag{5.61}$$

In these equation it is necessary to add a term 1 in the i^{th} derivate.

The equations 5.25-5.61 can be written in matrix notation, as specified in equation 4.32:

$$\mathbf{D} \cdot \Lambda + \mathbf{N} = \mathbf{0}$$

The matrix **D** is equal for all the Lagrangian L_i and contains coefficients of the Lagrange multipliers, the vector Λ contains the Lagrange multipliers and the vector **N** contains one term equal to 1 in the i^{th} row, while the other terms are zero.

Table 5.2 shows the values assumed by the constants c and the variables y in reference condition.

y1	101300	Pa	y16	60726	kW	y31	0.03		c8	1.1868	kJ/kgK
y2	1107960	Pa	y17	288.35	kg/s	y32	0.95		c9	4.212	kJ/kgK
y3	1074722	Pa	y18	343.15	K	y33	0.134		c10	-0.385	$(kg/m^3)^2$
y4	104411	Pa	y19	393.15	K	y34	2.306		c11	0.6843	kg/m^3
y5	278.15	K	y20	11.048		y35	0.12	kW/m^2K	c12	0.7	
y6	598.811	K	y21	0.01		y36	0.88		c13	287.4	J/kgK
y7	1218.27	K	y22	0.8339		y37	10.29		c14	291.07	J/kgK
y8	767.32	K	y23	0.835		c1	0.28		c15	-3E-06	$(s/kg)^2$
y9	393.943	K	y24	1.2672	kg/m^3	c2	-0.25		c16	0.0014	s/kg
y10	2.367	kg/s	y25	0.03		c3	143.4	Kg/s	c17	0.86	
y11	157.216	kg/s	y26	0.98		c4	278.2	K	c18	1.0889	kJ/kgK
y12	0.98006		y27	3.0308	kg/m^3	c5	44288	K	c19	0.2585	
y13	32585	kW	y28	0.85		c6	158	kg/s	c20	2869.8	m^2kgK/kJ
y14	50889.1	kW	y29	0.851		c7	161.9	kW	c21	130.54	$1/m^4$
y15	33250	kW	y30	0.98							

Table. 5.2 - Calculated variables and constancts of the gas turbine model

The Lagrange multipliers associated to a variation of the four regulation parameters (the fuel mass flow, the inlet guide vanes opening grade, the water mass flow and the by pass grade), respectively λ_{10}, λ_{12}, λ_{17} and λ_{32} are shown in table 5.3. These values are obtained considering all the 36 Lagrangians, corresponding to the constrained variation of all the model variables.

λ10	λ12	λ17	λ32
0	0	0	0
137828.3	857345.6	0	0
133693.4	831625.2	0	0
0	0	0	0
0	0	0	0
22.82076	119.6163	0	0
290.4915	-545.312	0	0
164.9526	-482.492	0	0
20.46747	55.15285	118.2844	0
1	0	0	0
1	158	0	0
0	1	0	0
19930.01	1891.129	0	0
3621.666	70907.58	0	0
20336.75	1929.723	0	0
23885.31	-26413.9	44684.32	0
0	0	0	0
0	0	0	0
19.66647	-21.7484	36.79177	0.173402
1.374338	8.54892	0	0
0	0	0	0
1.78E-06	0.058103	0	0
0	0	0	0
-4E-05	-0.00025	0	0
0	0	0	0
0	0	0	0
-0.34566	3.701884	0	0
0.000335	0.052958	0	0
1.82E-18	1.13E-17	0	0
0	0	0	0
0	0	0	0
0	0	1	0
0.000852	0.13458	0.140961	0
-0.01467	-2.3172	-2.42706	0
0	0	0	0
-0.00169	-0.26624	-0.27886	0
1.280448	7.964884	0	0

Table. 5.3 - Lagrange multipliers associated to the regulation parameters variation

These multipliers are used to calculate the free condition corresponding to every working condition, defined by the values assumed by the four regulation parameters. The equation 5.1 can be rewritten:

$$y_j = y_{j_{op}} - \lambda_{j10} \cdot (x_{10_{op}} - x_{10_{ref}}) - \lambda_{j12} \cdot (x_{12_{op}} - x_{12_{ref}}) - \lambda_{j17} \cdot (x_{17_{op}} - x_{17_{ref}}) - \lambda_{j32} \cdot (x_{32_{op}} - x_{32_{ref}}) \quad (5.62)$$

5.2 Costs and malfunctions of the regulation system intervention

The objective of this paragraph is the calculation of costs and malfunctions related to the regulation system intervention, when each of the regulation parameters varies. In particular a constant value of the water mass flow has been considered in order to make the analysis simpler without losing generality, while variations of the three other regulation variables are imposed. These conditions are obtained by varying the values of three independent malfunctions. Each combination of malfunctions causes a different reaction of the regulation system. It differently operates on the three regulation parameters in order to restore an acceptable working condition, where the internal and external constraints are respected. In particular, the considered malfunctions consist on the variation of the isentropic efficiency of the compressor, the variation of the combustion efficiency and the variation of the recuperator heat transfer coefficient.

The cost of the malfunctions caused by the regulation system is expressed by the fuel impact, calculated using the equation 4.60, necessary to compensate the variation of the plant efficiency. A graphical representation of this quantity is shown in figure 5.1 for a fixed value of the gas mass flow percentage passing through the by pass pipe (*p*). This value has been assumed the same as in reference condition, equal to 0.95. In the figure the point corresponding to the reference condition regulation set is also represented. The fuel impact calculated in this condition is null. A second graphical representation, shown in figure 5.2, has been made by fixing the value of the inlet guided vanes opening grade (*igv*), assumed equal to the reference condition value, which is 0.98.

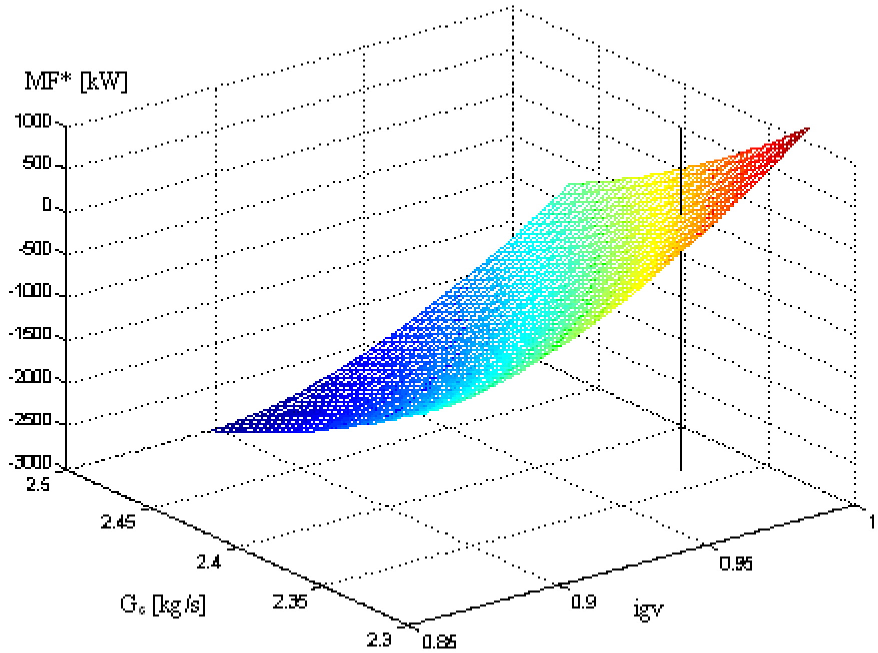

Figure 5.1 - Dependence of the cost of the malfunctions caused by the regulation system on the fuel mass flow and the igv opening grade

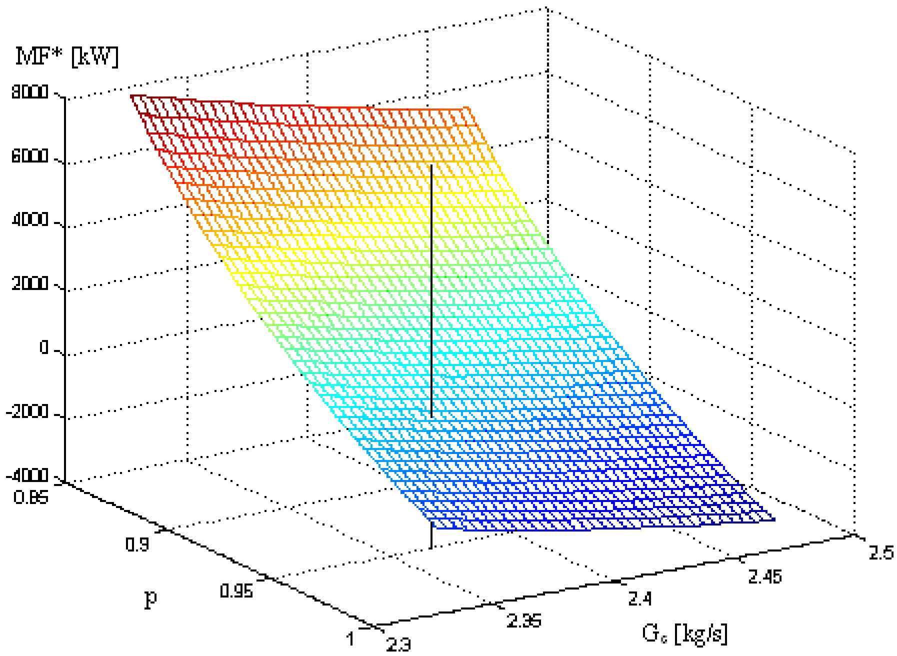

Figure 5.2 - Dependence of the cost of the malfunctions caused by the regulation system on the fuel mass flow and the by-pass percentage

The cost associated to the regulation represents an opportunity cost [de Neufville], as it is the additional cost to pay because the system is not able to work in the free condition. Due to the internal and external constraints the system must be controlled, so every time the set points are not complied the regulation system intervenes. Positive values of this cost mean that the regulation intervention has induced malfunctions on the system so that its efficiency has become lower.

Although this information is useful, it is not complete, in fact a relative value is required as evaluation parameter in order to compare between them different conditions. This parameter can be defined as the ratio between the cost of the malfunctions, calculated using the equation 4.60, and the total fuel impact, which corresponds to the cost of the malfunctions calculated using the classical thermoeconomic diagnosis procedure:

$$\frac{\tilde{MF}^*}{|\Delta F_T|}.$$

The absolute value at the denominator allows to associate a positive value to a malfunctioning behaviour and a negative value to an efficiency improving. The dependence of this parameter on fuel mass flow and inlet guided vanes opening grade is shown in figure 5.3, while the dependence on fuel mass flow and by-pass percentage is shown in figure 5.4. In correspondence of a fuel impact equal to zero, the value assumed by the evaluation parameter can be anomalous. This condition takes place when the malfunctions of the system assume such values that the plant efficiency in free and reference conditions is the same.

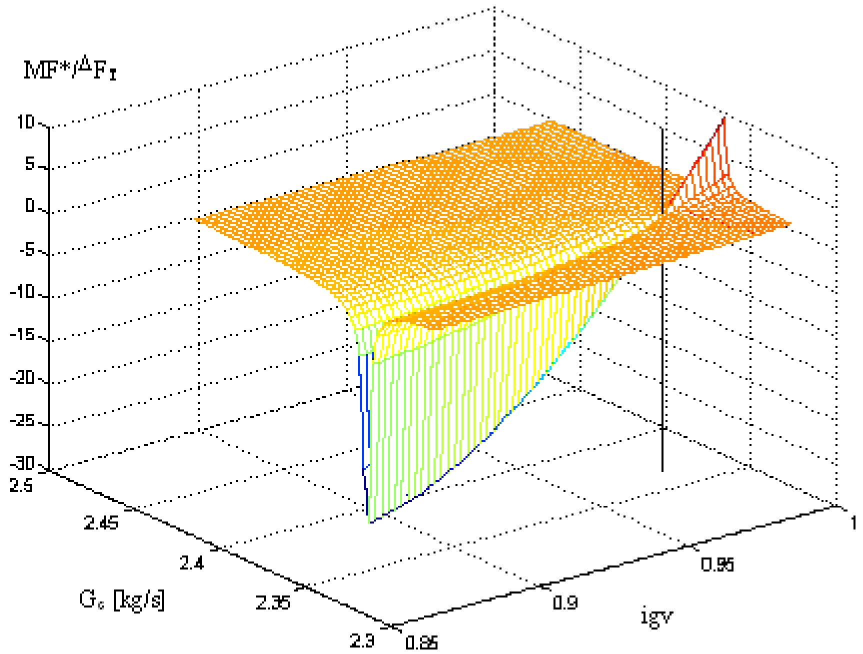

Figure 5.3 - Dependence of the evaluation parameter on fuel mass flow and igv opening grade

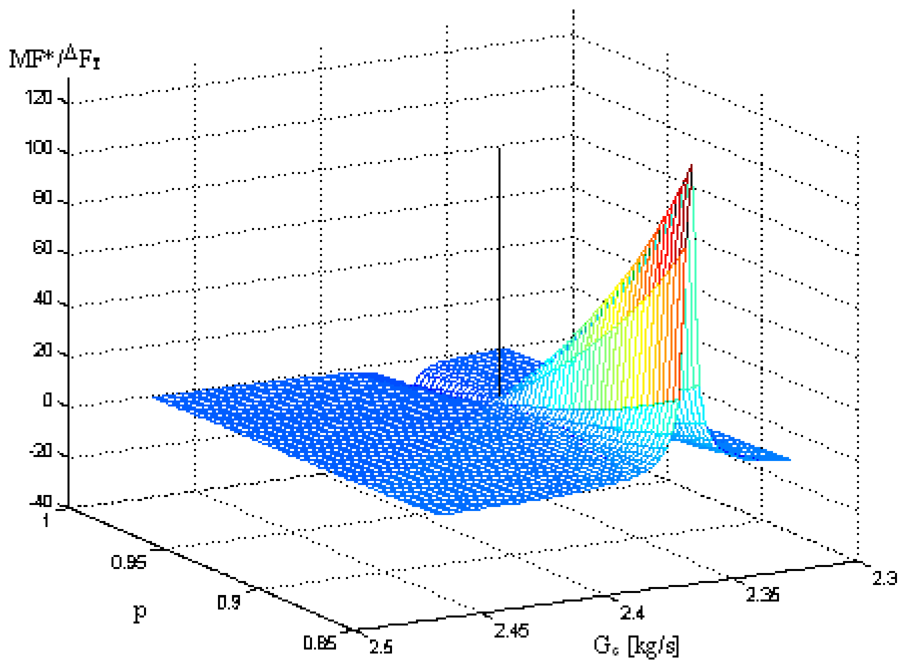

Figure 5.4 - Dependence of the evaluation parameter on fuel mass flow and by-pass percentage

The dependence of the unit cost of the regulation on the fuel mass flow, calculated using the equation 4.61, is reported in figure 5.5 for a particular value of the by-pass percentage and the inlet guided vanes opening grade. The cost tends to become infinite when the plant product in free and reference conditions is the same. For values of the fuel mass flow lower than the reference value, the unit cost of the regulation becomes lower than the unit cost of the products. The regulation system intervention so makes increase the plant efficiency. This part of the diagram corresponds to anomalies that altogether give a positive effect (improving), so that the efficiency in operation and free conditions is higher than in reference condition. On the contrary the right part of the diagram corresponds to a negative effect of the anomalies, which makes decrease the plant efficiency. In this case the regulation system intervention contributes to this decreasing. The regulation so induces malfunctions in the thermal system. The proposed procedure is here particularly helpful as it allows to eliminate these induced effects in the analysis.

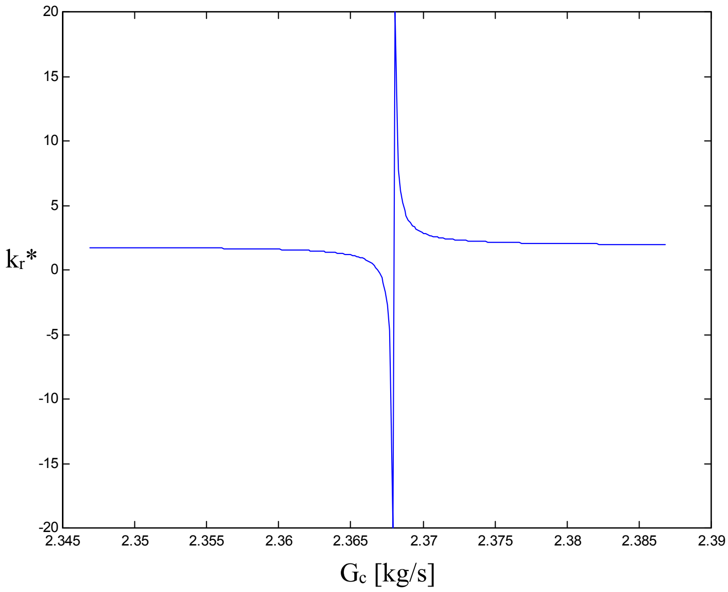

Figure 5.5 - Exergetic unit cost assigned to the system regulation

5.3 Diagnosis of single malfunctions of the gas turbine plant

The specific aim of this part is to verify if the thermoeconomic diagnosis procedures are able to localize the anomalies. Different productive structures are applied in order to analyse the influence of the choice on the results of the direct diagnosis problem and to compare the information furnished by each one.

This comparison also provides general criteria for a more rational choice of the productive structure to be used for the thermoeconomic analysis: the location of the anomalies depends on how intrinsic the malfunctions are. If no induced malfunctions take place the location does not depend on the productive structure nor on the diagnosis procedure. On the contrary if induced malfunctions take place, the correct diagnosis is only possible if the variation of the unit exergy consumption in the malfunctioning component is higher than the variations in the other components. Moreover, the higher is the difference between intrinsic and induced malfunctions, the easier is the location. In this way the best structure is the one which generates the lowest induced malfunctions. In the thermoeconomic analysis the productive structure charges the components for their unit exergy consumptions, so if the structure does not induce any malfunctions, the cost accounting is the most correct, as the effects of the irreversibilities are located in the components where they have taken place. Not all the induced malfunctions can be avoided in the reality as the efficiency of the components generally depends on the working condition; nevertheless the correct definition of fuels and products and the charge for the plant losses allow to reduce their contribution.

Eight cases of single malfunctions and a case triple malfunction are here simulated by modifying the values of the independent parameters of the model. The diagnosis is made considering some of the productive structures shown in chapter 3. The cost associated to the regulations, made to restore the reference production and the set-points constraints, is calculated in every conditions.

5.3.1 Application of the complete diagnosis procedure to a case of filter pressure drop variation

A typical malfunction occurring in the gas turbine plants is the increase of the pressure drop in the filter, caused by the entrapment of the dust carried by the air. The value of the pressure drop considered in reference (design) condition is 1% of the atmospheric pressure [A.E.M. 1989]. An operation condition characterized by a 2% pressure drop has been simulated. Figure 5.6 shows the thermodynamic data relative to reference (first column) and operation (second column) conditions. The two conditions are characterized by the same electric production; moreover the quality and the quantity of the thermal production is the same in the two cases, which means that the flux is characterised by the same exergy flow and the same specific exergy.

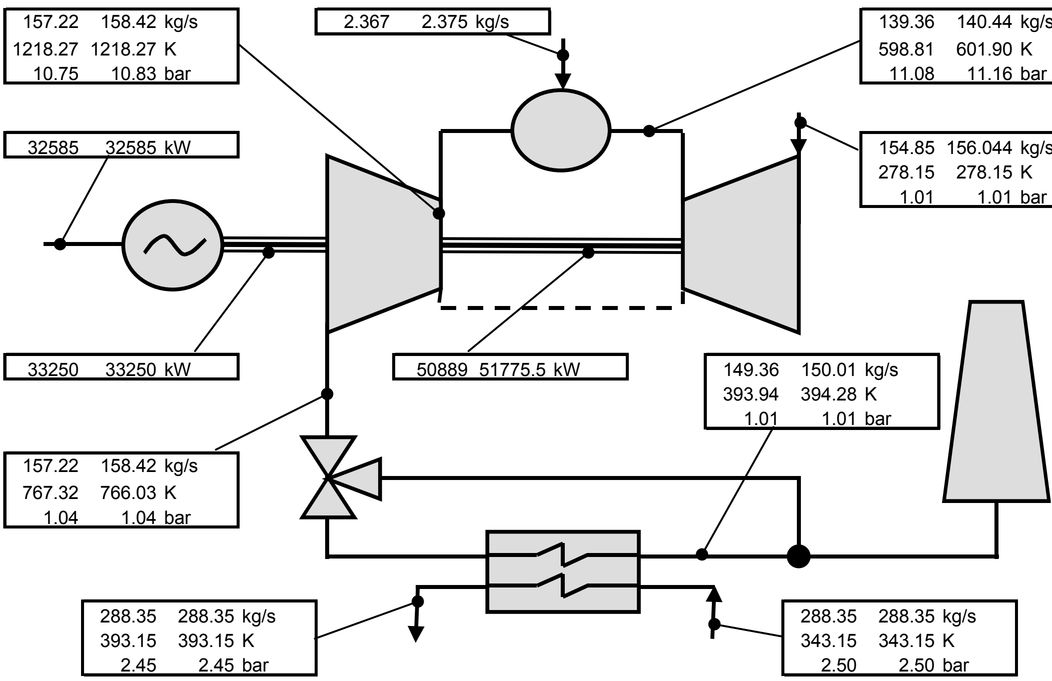

Figure 5.6 - Thermodynamic data relative to reference and operation conditions

The filter has been included in the same control volume of the compressor, so the expected result is a malfunction in the compressor. It is possible to notice that no measure of the pressure downstream the filter is necessary for the analysis.

The fuel/product diagrams relative to the productive structure TG2 in reference and operation conditions are shown respectively in table 5.4 and table 5.5. The numeration of the components is the same considered in chapter 3.

	F0	F1	F2	F3	F4	F5	Tot p
P0	0	118343	0	0	0	0	118343
P1	0	0	0	88620	30688	0	119307
P2	0	46653	0	0	0	0	46653
P3	0	0	50889	0	0	33250	84139
P4	14845	0	0	0	0	0	14845
P5	32585	0	0	0	0	0	32585
	47430	164996	50889	88620	30688	33250	

Table. 5.4 - Fuel/product diagram of TG2 in design condition

	F0	F1	F2	F3	F4	F5	Tot p
P0	0	118740	0	0	0	0	118740
P1	0	0	0	89534	30675	0	120210
P2	0	47372	0	0	0	0	47372
P3	0	0	51775	0	0	33250	85025
P4	14845	0	0	0	0	0	14845
P5	32585	0	0	0	0	0	32585
	47430	166112	51775	89534	30675	33250	

Table. 5.5 - Fuel/product diagram of TG2 in operation condition

As reference and operation conditions are characterized by the same production, the fuel impact in every component can be calculated, considering the equation 4.10 and separating the single contributions:

$$\Delta F_{T_i} = \left(\sum_{j=0}^{n} K_{P,j}^{*} \cdot \Delta k_{ji} \right) \cdot P_i^0 \quad (5.63)$$

The terms of equation 5.63 are:

$$\mathbf{K_P}^* = \begin{bmatrix} 1 \\ 1.808 \\ 2.080 \\ 1.903 \\ 3.735 \\ 1.942 \end{bmatrix} \qquad \mathbf{P} = \begin{bmatrix} 120210 \\ 47372 \\ 85025 \\ 14845 \\ 32585 \end{bmatrix} \qquad (\Delta\mathbf{K_{ext}})^t = \begin{bmatrix} -0.00414 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\Delta\mathbf{KP} = \begin{bmatrix} 0 & 0 & -0.00022 & -0.00085 & 0 \\ 0.00305 & 0 & 0 & 0 & 0 \\ 0 & 0.00216 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The complete $\Delta\mathbf{K}$ matrix, including the variation of the unit exergy consumptions of the internal and external resources, can be built as shown in table 5.6. Its general element Δk_{ij} represents the efficiency variation caused in a component i by the component j; in this way, if the induced malfunctions are negligible respect to the intrinsic malfunction, the biggest value of Δk_{ij} is symptom of an anomaly located in component j.

Combustor	Compressor	Turbine	Heat Exch.	Alternator
-0.004139	0	0	0	0
0	0	-0.000221	-0.000852	0
0.0030467	0	0	0	0
0	0.0021558	0	0	0
0	0	0	0	0
0	0	0	0	0

Table. 5.6 - Complete unit exergy consumption variation matrix

In this case the biggest value takes place in the combustor, not in the compressor, as expected; it means that the induced malfunctions have the same magnitude of the intrinsic malfunction.

The fuel impact in every component and its relative value, defined by the equation 4.41, are reported in table 5.7. It is possible to notice that also the biggest fuel impact takes place in the combustor. So in this case the value assumed by the fuel impact does not suggest the correct malfunction location.

COMPONENTS	Fuel Impact (kW)	Relative Fuel Impact
Combustor	262	0.661
Compressor	191	0.482
Turbine	-34	-0.085
Heat Exchanger	-23	-0.058
Alternator	0	0.000

Table. 5.7 - Fuel impact in the components

The parameters based on the irreversibility variation, shown in table 5.8, give contrasting results: the biggest value of the relative irreversibility variation takes place in the combustor, while the ratio between the irreversibility variation and the design irreversibility indicate the compressor as the malfunctioning component.

COMPONENTS	Irreversibility Variation (kW)	Relative Irreversibility Variation	$\Delta I/I$
Combustor	214	0.539	0.005
Compressor	167	0.421	0.040
Turbine	28	0.071	0.006
Heat Exchanger	-13	-0.032	-0.001
Alternator	0	0.000	0.000

Table. 5.8 - Design parameters based on irreversibility variation

The last group of parameters is derived from the malfunction and dysfunction analysis. The malfunction and dysfunction table is represented in table 5.9. It allows to better understand the results: the bigger malfunction happens in the compressor, while in the combustor there is a big dysfunction. This means that the high value of the irreversibility variation and the fuel impact in the combustor is due to the dysfunction, i.e. the combustor must increase its production in order to face the increased requirement.

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	292	62	39	0	0	393	-130	262
DI2	74	7	10	0	0	91	101	191
DI3	-13	-1	-1	0	0	-15	-19	-34
DI4	-9	-1	-1	0	0	-10	-13	-23
DI5	0	0	0	0	0	0	0	0
DI	344	67	47	0	0	458		
MF	-130	101	-19	-13	0		-61	
Total	214	167	28	-13	0			397

Table. 5.9 - Malfunction and dysfunction table

The information given by the diagnosis made comparing reference and operation conditions must be carefully analysed and it does not allow an automatic location of the anomaly.

The application of the *FvD* method requires the knowledge of the Lagrange multipliers and the values of the regulation variables in design and operation conditions. These data allow to calculate the free condition corresponding to the actual operation condition. Table 5.10 summarizes the values assumed by the regulation variables in the two working conditions.

Regulation variable	Design	Operation
x1	0.9801	0.9876
x2	2.3669	2.3748
x3	288.35	288.35
x4	0.9500	0.9469

Table. 5.10 - Regulation variables in design and operation conditions

The values assumed by the thermodynamic quantities characterizing the free condition are reported in annex 3, while the corresponding fuel product diagram is shown in table 5.11.

	F0	F1	F2	F3	F4	F5	Tot p
P0	0	118343	0	0	0	0	118343
P1	0	0	0	88765	30789	0	119554
P2	0	46833	0	0	0	0	46833
P3	0	0	51211	0	0	33074	84285
P4	14889	0	0	0	0	0	14889
P5	32412	0	0	0	0	0	32412
	47301	165176	51211	88765	30789	33074	

Table. 5.11 - Fuel product diagram in free condition

The main tool to determine the malfunction location is the Δ**KP** matrix, calculated as difference between the unit exergy consumptions in free and design conditions. This matrix must also include the variation of the exergy unit consumption of the external resources, i.e. the vector $(\Delta \mathbf{K_{ext}})^t$. The maximum variariation of Δk_{ij} is index of a malfunction located in the component *j*.

Combustor	Compressor	Turbine	Heat Exch.	Alternator
-0.002046	0	0	0	0
0	0	-9.53E-05	0.0007563	0
0.0006959	0	0	0	0
0	0.0026859	0	0	0
0	0	0	0	0
0	0	0	0	0

Table. 5.12 - Unit exergy consumption variation in the components

The variation in the compressor is about three times bigger than the variation in the combustor or in the heat exchanger, so it can be assumed as the component where the malfunction is located. If the values in table 5.12 are compared to the values in table 5.6, corresponding to the variation of the unit exergy consumption between operation and design conditions, it is possible to notice that the term relative to the compressor has maintained the same magnitude, while the term relative to the combustor is here lower. It means that the regulation system affects the system, causing induced malfunctions and dysfunctions which have magnitude comparable to the intrinsic malfunction. In order to quantify this consideration the malfunction and dysfunction table, relative to the *free versus reference* (FvR) comparison, is shown in table 5.13. The table evidences that the maximum malfunction takes place in the compressor, while the combustor is the main cause of dysfunctions.

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	66	14	9	0	0	89	-161	-72
DI2	92	9	12	0	0	113	125	238
DI3	-6	-1	0	0	0	-6	-8	-14
DI4	8	1	0	0	0	9	11	20
DI5	0	0	0	0	0	0	0	0
DI	160	23	21	0	0	205		
MF	-161	125	-8	11	0		-33	
Total	-1	148	13	11	0			172

Table. 5.13 - Malfunction and dysfunction table relative to the FvR comparison, using TG2

The difference between the total malfunction and the total dysfunction in tables 5.9 and 5.13 is a measure of the effect of the regulation system on the induced malfunctions and dysfunctions. Graph in figure 5.7 summarizes the effect of the malfunctions and dysfunctions caused by the augmented filter pressure drop, respectively MF_i and DI_i, and the ones caused by the regulation system intervention, respectively MF_r and DI_r.

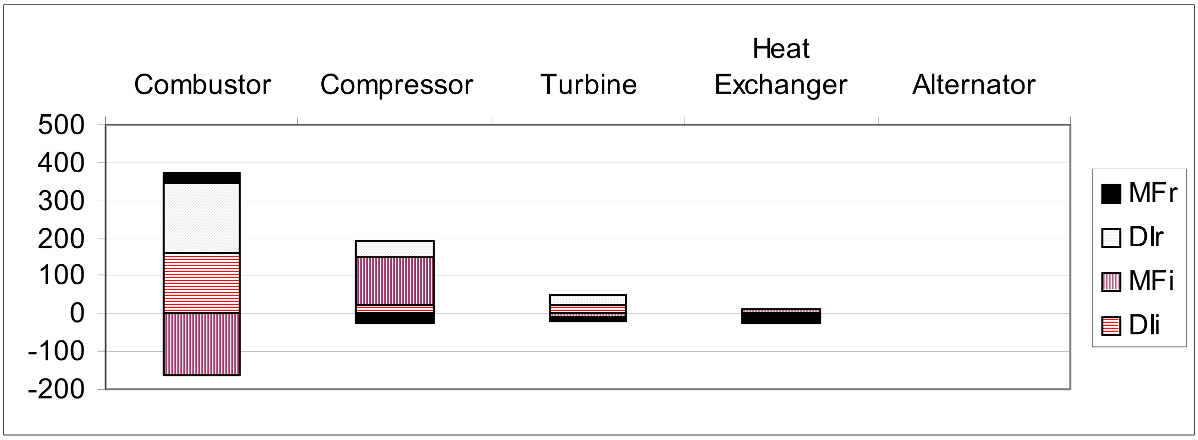

Figure 5.7 - Malfunctions and Dysfunctions caused by the filter malfunction and by the regulation system.

The effects (malfunctions and dysfunctions) induced by the regulation in the combustor are bigger than in the other components and comparable with the intrinsic effects of the anomaly, which makes difficult the correct location using the operation vs. reference approach. On the contrary the diagnosis made avoiding the contribution of the regulation system allows a clearer result.

The cost, calculated using equation 4.61, associated to the regulation set necessary to obtain acceptable operation conditions has been calculated as the pressure drops vary. The results are shown in figure 5.8.

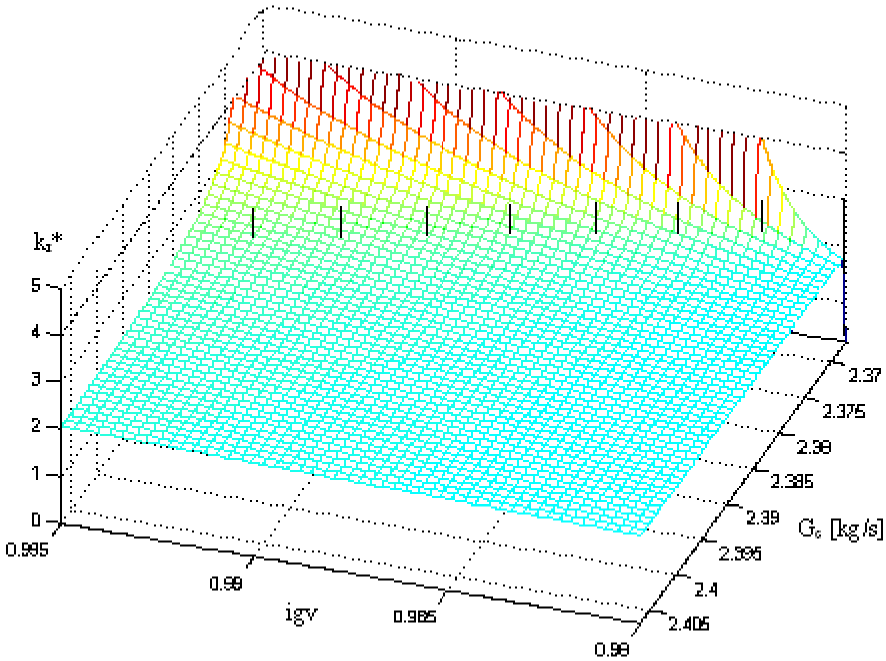

Figure 5.8 - Unit cost associated to the regulation

The figure shows as the relation between the malfunction and the corresponding regulation is linear in the examined range, which corresponds to a variation of the pressure drop in reference condition from 0% to 300% The calculated unit cost of the intervention is about constant in a large part of this range, being obviously zero in correspondence of the reference condition, as no intervention takes place.

5.3.2 Malfunction location

In this paragraph the results obtained by applying the productive structure TG5 to the cases of single malfunctions are shown. In table 5.14 the characteristics of the simulated malfunctions are shown.

Name	Component	Characteristic parameter	Values	
			reference	operation
MF1	Compressor	pp_f	0.01	0.02
MF2	Compressor	η_{cd}	0.835	0.82
MF3	Combustor	pp_{cc}	0.03	0.04
MF4	Combustor	η_{cc}	0.98	0.97
MF5	Turbine	η_{td}	0.851	0.847
MF6	Recuperator	pp_{he}	0.0298	0.049
MF7	Recuperator	K [kW/m^{2}K]	0.12	0.108
MF8	Alternator	η_{alt}	0.98	0.97

Table. 5.14 - Characteristics of the simulated single malfunctions

In figure 5.9 the corresponding normalized values assumed by the maximum Δk_{ij} in every component, using the productive structure TG5, have been depicted. The dashed areas represent, for every malfunction, the induced effects. Only in the case of malfunction MF5 the induced effects are higher than the intrinsic one. This result does not mean that the proposed diagnosis method is not able to correctly locate this anomaly, as explained below.

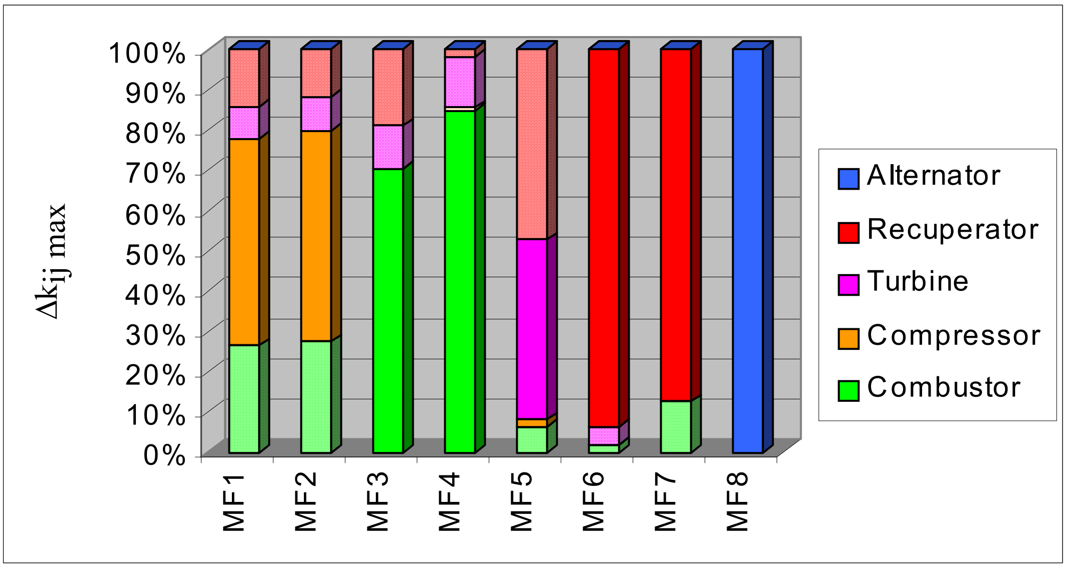

Figure 5.9 - Normalized values of the maximum Δk_{ij} in every component, corresponding to the cases of single malfunctions, analysed using TG5

The $\Delta\mathbf{k}$ matrix relative to the malfunction MF5 is shown in table 5.15.

Combustor	Compressor	Turbine	Heat Exch.	Alternator
-3.39E-05	0	0	0	0
0.000256	0	0.0006313	0.0018935	0
-3.44E-06	0	0.0017887	-0.000165	0
0	6.424E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

Table. 5.15 - $\Delta\mathbf{k}$ matrix relative to the malfunction MF5 using the structure TG5

It is possible to notice that two effects occur both in the turbine and in the heat exchanger. This is due to the separation of the exergy into mechanical and thermal components made to define fuels and products. In this way two unit exergy consumptions are defined for turbine and heat exchanger. The variation of the isentropic efficiency of the turbine involves the variation of both the contributions in the turbine itself, while in the diagnosis procedure only the maximum contribution has been considered. Therefore a look on the complete matrix shows that the intrinsic effect is, in reality, bigger than it has been reported in the graph of figure 5.9. If a different productive structure, built using total exergy fluxes, is considered, the contribution of the two Δk_{ij} relative to the turbine are joined into one single value. In this way the parameter used for the malfunction location gives a better quantitative result, while the qualitative result is the same, i.e. a malfunction is located in the turbine. The $\Delta\mathbf{k}$ matrix obtained using the productive structure TG3 is shown in table 5.16

Combustor	Compressor	Turbine	Heat Exch.	Alternator
-2.03E-05	0	0	0	0
0	0	0.0024201	0.0013283	0
-6.16E-06	0	0	0	0
0	6.424E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

Table. 5.16 - $\Delta\mathbf{k}$ matrix relative to the malfunction MF5 using the structure TG3

Moreover the proposed methodology is based on a linear model of the regulation system effects on the system. The error made by considering this evaluation increases as the malfunction increases, as the physical model of the system is not linear. The graph in figure 5.10 allows the evaluation of the error committed by considering the equation 5.62 in spite of the values determined by modelling the free condition as the malfunction varies. The two lines corresponds to the linear evaluation and the simulated value of the ratio between the maximum Δk_{ij} in the turbine and in the heat exchanger, both corresponding to the structure TG5. This parameter is so the ratio between the main intrinsic effect and the main induced effect.

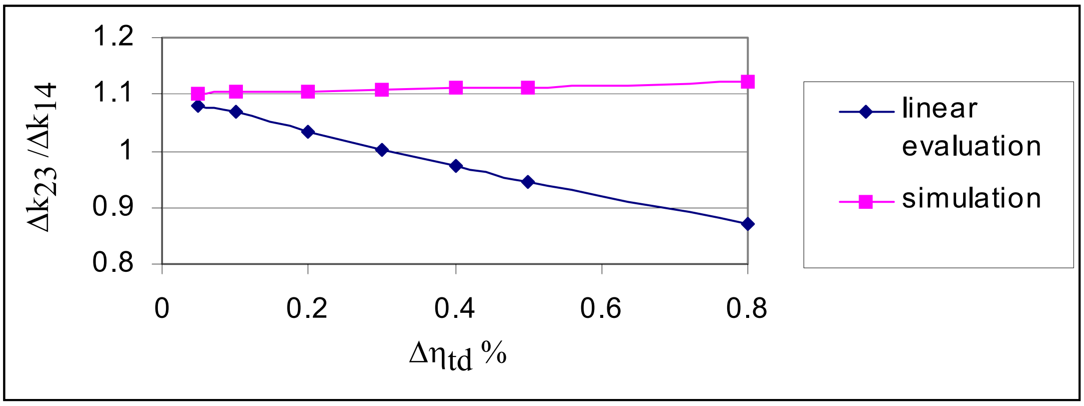

Figure 5.10 - Δk_{ij} ratios calculated and simulated

The graph shows that the intrinsic effect is always bigger than the induced one, as the ratio obtained by simulating the free condition is higher than 1. Moreover the intrinsic effect tends to increase as the malfunction increases. The values of the ratio obtained by using the linear evaluation are close to the simulated ones only for low values of the malfunction. When the percent variation of the isentropic efficiency assumes values upper to 0.3%, the error is so high that the main induced effect becomes higher than the main intrinsic effect.

Also in case of high malfunction the results obtained using the productive structure TG3 allow a correct anomaly location, as shown for example in table 5.16. This could suggest the use of this kind of structure for the diagnosis. The results of this structure are very good for all the cases of single malfunction, as shown in figure 5.11

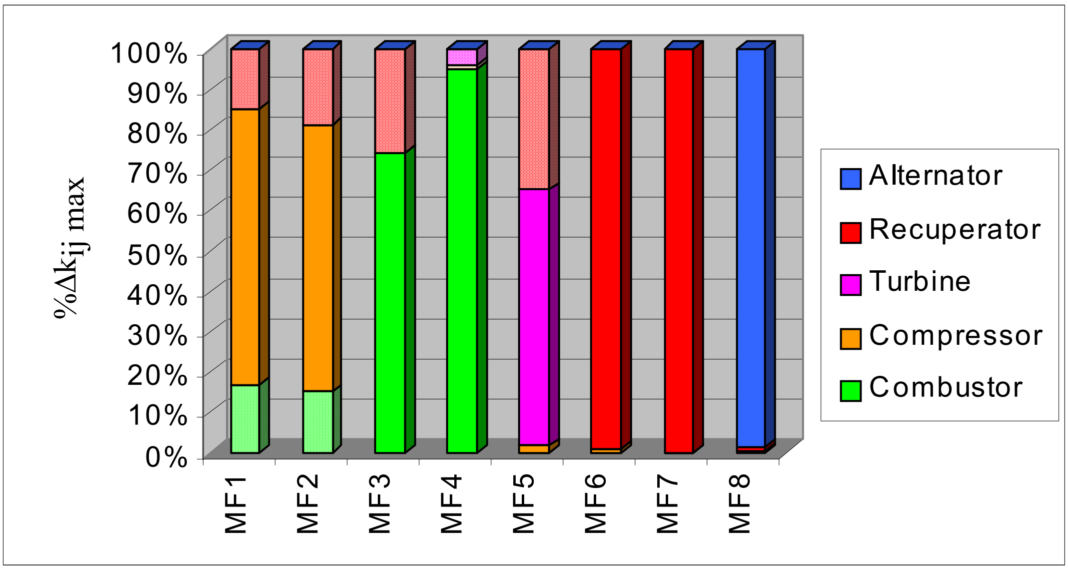

Figure 5.11 - Normalized values of the maximum Δk_{ij} in every component, corresponding to the cases of single malfunctions, analysed using TG3

In spite of the quantitative results obtained using the structure TG3 seams to be much better than the ones obtained using the structure TG5, the contemporary use of the two structure is suggest. The structure TG5 (or the TG6), being based on the use of the exergy components, provides more detailed information. Moreover the indication given by this kind of structure about the malfunction location does not differ from the indication given by the other structures, although the results must be examined first.

The information provided by the structure TG5 is examined in the next paragraph.

5.3.3 Information provided by the productive structures

In this part the results obtained applying the productive structures TG3 and TG5 to the operation conditions indicated as MF7 and MF6 are analysed in deep. The first malfunction corresponds to a reduction of the heat transfer coefficient in the recuperator. Both the structures allow the malfunction location, as shown in table 5.17. The maximum value of the Δk_{ij} in the case of the structure TG5 is the Δk_{14}, which means that a larger flow of thermal exergy is required by the component, so that the cause of malfunction is thermal. On the contrary the structure TG3 does not provide such an information, as the fuel is an exergy flow.

CC	AC	GT	CR	A
0	0	0	0	0
0.0061	0	0	0.0486	0
0	0	0	0.0011	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
0	0	0	0	0
0	0	0	0.1035	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

Table. 5.17 - Variation of the unit exergy consumption relative to the MF7 case

The second malfunction corresponds to an increase of the pressure drop in the recuperator. The $\Delta \mathbf{k}$ matrices, shown in table 5.18, allow once more the malfunction location whatever is the chosen productive structure.

CC	AC	GT	CR	A
-1E-04	0	0	0	0
0.0003	0	0.0008	0.0025	0
2E-05	0	-8E-04	0.017	0
0	0.0002	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-6E-05	0	0	0	0
0	0	-1E-05	0.019	0
-4E-06	0	0	0	0
0	0.0002	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

Table. 5.18 - Variation of the unit exergy consumption relative to the MF6 case

In this case the maximum value of the Δk_{ij} relative to the structure TG5 is the Δk_{24}, so a larger flow of mechanical exergy is required by the recuperator. Also for this kind of malfunction the more detailed productive structure provides information about cause.

This analysis puts on evidence that the contemporary use of two different productive structures allows a more complete diagnosis. In particular, a structure defined using exergy flows is more suitable for the malfunction location, while a structure defined by using mechanical and thermal exergy flows allows to understand the cause of pure mechanical or thermal malfunctions.

The charge for the loss does not influence the diagnosis result. In table 5.19 the $\Delta \mathbf{k}$ matrices obtained using the structures TG2 and TG6 are shown.

	TG2					TG6				
	CC	AC	GT	CR	A	CC	AC	GT	CR	A
MF7	0.0048	0	0	0	0	0	0	0	0	0
	0	0	0	0.0497	0	0	0	0	0.1023	0
	0.0019	0	0	0	0	0	0	0	0.0011	0
	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0

	TG2					TG6				
	CC	AC	GT	CR	A	CC	AC	GT	CR	A
MF6	0.0002	0	0	0	0	-1E-04	0	0	0	0
	0	0	-1E-05	0.0195	0	0	0	0.0008	0.002	0
	1E-04	0	0	0	0	2E-05	0	-8E-04	0.017	0
	0	0.0002	0	0	0	0	0.0002	0	0	0
	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0

Table. 5.19 - Variation of the unit exergy consumption relative to the MF7 and MF6 cases

5.3.4 Intrinsic and induced malfunctions

In this paragraph the calculated results of the malfunctions associated to the anomalies is proposed. The malfunctions have been calculated using both the diagnosis procedures in order to also determine the terms related to the regulation system intervention. Table 5.20 shows the results obtained using the structure TG3. In particular the columns titled *Free vs. reference* shows the malfunctions calculated using the proposed approach. These malfunctions would take place without the regulation system intervention, so they are the natural malfunctions. In particular for every case the intrinsic malfunctions have been highlighted. It is possible to notice that in most cases the intrinsic malfunction is the biggest. The only case where it does not happen is the one corresponding to a pressure drop variation in the combustor (MF3). This means that this component works better in free condition than in reference condition.

In the right part of the table the malfunctions induced on the components by the regulation system are shown. The recuperator is the component which much suffers this intervention, due to the charge of the losses on it. In most cases this effects do not allow the operation vs. reference approach to correctly locate the anomalies.

	Free vs. reference: CC	AC	GT	CR	A	Regulation effects: CC	AC	GT	CR	A
MF1	-159	121	-7	7	0	-113	-21	-12	123	0
MF2	-544	420	-36	38	0	-323	-109	-23	383	0
MF3	-37	-12	-8	9	0	-112	-24	-11	124	0
MF4	1292	4	27	-29	0	-68	-3	-26	26	0
MF5	-3	3	204	20	0	-179	-33	-29	412	0
MF6	-8	9	-1	282	0	-230	-47	-33	530	0
MF7	0	0	0	1536	0	0	0	0	-1536	0
MF8	-2	2	-2	2	346	-144	-26	-19	146	-4

Malfunctions [kW]

Table. 5.20 - Intrinsic and induced malfunctions calculated using TG3

5.3.5 Cost associated to the regulation system intervention

In this part the calculation of the cost associated to the regulation system intervention is proposed. The graph in figure 5.12 shows the variation of the unit cost assigned to the regulation system as the malfunction grade varies. The malfunction grade is a parameter here introduced to indicate the variation of different malfunctions; in particular it can be defined, for the efficiencies, as per cent variation:

$$g = \frac{\Delta\eta}{\eta_{ref}} \tag{5.64}$$

and as per cent variation of the pressure ratio for the pressure drops:

$$g = \frac{\Delta pp}{pp_{ref}}. \tag{5.65}$$

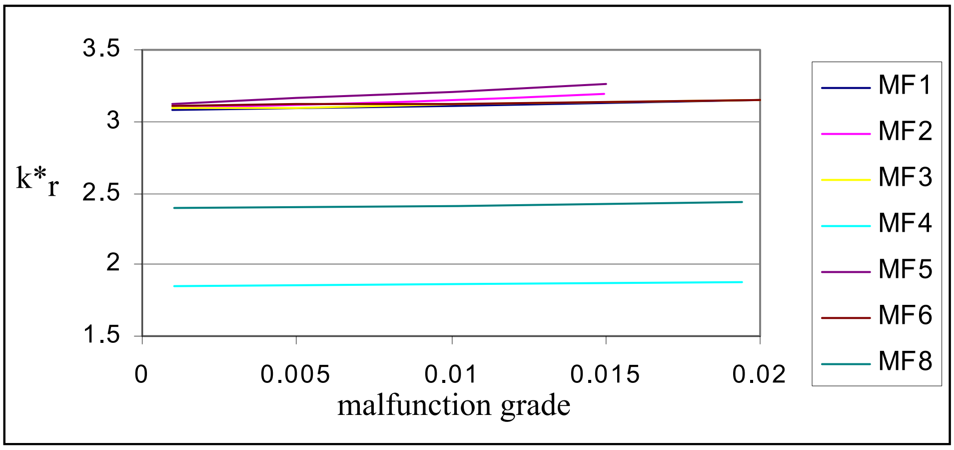

Figure 5.12 - Dependence of the unit cost of the regulation system on the malfunction grade

The cost associated to the regulation made for the malfunction MF7 is zero, as it does not involve any additional fuel consumption, in fact the regulation is made only by mean of the by-pass valve. The cost associate to the malfunction MF4 is lower than the average cost of the products. This means that, if the efficiency of the combustor decreases the plant works better in the operation condition than in the corresponding free condition. In the case of the regulation necessary for the malfunction MF8 the unit cost associated to the regulation is close to the average unit cost of the plant products, which means that the efficiency of the plant in free and operation conditions is very close. In all the other cases of single malfunction the plant has an higher efficiency in free condition than in operation, so the use of the proposed diagnosis technique is particularly helpful.

5.4 Diagnosis of combined malfunctions of the gas turbine plant

When the diagnosis procedure is applied to an energy system, the number of anomalies is generally unknown. If several anomalies have taken place, the total induced effects can be higher than some of the intrinsic effects. This fact makes impossible to detect all of them at the same time by using the comparison between free and reference conditions, as the intrinsic and induced effects can not be distinguished. The only way to find all the sources of malfunction consists on discovering and then eliminating the main one and repeating the process as many times as the anomalies are. The alternative is the application of the methodology to erase the induced effects, proposed in paragraph 4.7. When this methodology is applied to a real case it generally does not allow to find all the possible source of malfunctions at the same time, but only some of them. Nevertheless it generally constitutes an improvement of the previous procedure. Here both procedures are shown.

5.4.1 Application of the procedure for single anomaly location

In this paragraph a significant example of triple malfunction is developed, in order to show the location procedure. The simulation corresponds to a reduction of the isentropic efficiencies of compressor (-1.8%) and turbine (-0.5%) and an increase of the pressure drop in the heat exchanger (+1%). The values assumed in reference, operation and free conditions are shown in table 5.21.

	ref	op	free		ref	op	free
y1	101300	101300	101300	y21	11.0479	11.523	11.07731
y2	1107960	1155607	1110910	y22	0.01	0.01	0.01
y3	1074722	1120939	1077583	y23	0.833922	0.821019	0.818536
y4	104411.5	105467	105467	y24	0.835	0.82	0.82
y5	278.15	278.15	278.15	y25	1.267206	1.267206	1.267219
y6	598.811	611.7424	605.2963	y26	0.03	0.03	0.03
y7	1218.271	1218.271	1224.574	y27	0.98	0.98	0.98
y8	767.3203	763.642	774.606	y28	3.030811	3.161148	3.023201
y9	393.9435	394.9065	394.6617	y29	0.84996	0.848284	0.846002
y11	2.366859	2.42537	2.366859	y30	0.851	0.84717	0.84717
y12	157.2164	164.0258	157.2164	y31	0.98	0.98	0.98
y13	0.98006	1.022787	0.98006	y32	0.0298	0.03951	0.03951
y14	32585	32585	31338.07	y33	0.95	0.922023	0.95
y15	50889.06	55249.34	52007.75	y34	0.133913	0.135599	0.133742
y16	33250	33250	31977.62	y35	2.305707	2.277046	2.309009
y17	60725.97	60725.97	61707.15	y36	0.12	0.12	0.12
y18	288.3474	288.3474	288.3474	y37	0.880252	0.876914	0.880587
y19	343.15	343.15	343.15	y38	10.29314	10.62834	10.2131
y20	393.15	393.15	393.9579				

Table. 5.21 - Values of the model variables in reference, operation and free conditions

These values allow to calculate the fluxes of the productive structures. The total fuel impact, calculated as difference between the fuel consumption in operation and reference conditions is:

$$\Delta F_T = E_{0_{op}} - E_{0_{ref}} = 121268 - 118343 = 2925 kW \quad (5.66)$$

which quantifies the anomalies in the system. The fuel impact caused by the malfunction associated to the comparison between free and reference conditions can be calculated using the equations 4.45 and 4.46:

$$\Delta F_{\Delta k} = -\sum_{i=1}^{n} K_{P,i}^{*} \cdot \Delta P_{ext_i} = -(2.66 \cdot 284 + 2.05 \cdot (-1174)) = 1369 kW \quad (5.67)$$

where the costs of the external products have been calculated in free condition.

The difference between the two values represents the fuel impact associated to the regulation system intervention.

The location of the anomalies is made by considering the variation of the unit exergy consumptions in every component. In table 5.22 the matrices corresponding to the structures TG2 and TG5 are shown.

CC	AC	GT	CR	A
-0.007	0	0	0	0
0	0	0.0017	0.016	0
0.0022	0	0	0	0
0	0.0103	0	0	0
0	0	0	0	0
0	0	0	0	0

TG2

CC	AC	GT	CR	A
-0.011	0	0	0	0
0.0003	0	0.0022	0.008	0
0.0042	0	-5E-04	0.008	0
0	0.0103	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

Table. 5.22 - Matrices Δ**k** using the structures TG2 and TG5

Both the structures indicate the recuperator (CR) as the main malfunctioning component, although in the structure TG5 the effect is split on two elements of the matrix. This structure does not provide any information about the cause, in fact thermal and mechanical components of the fuel consumption are equally affected. This behaviour is due to the effects induced on the recuperator by the anomalies in the compressor and in the turbine.

If a maintenance operation is made on the recuperator and the anomaly is completely removed, the plant works in a new condition, defined in table 5.23 (Maintenance 1).

	Maintenance 1		Maintenance 2			Maintenance 1		Maintenance 2	
	op	free	op	free		op	free	op	free
y1	101300	101300	101300	101300	y21	11.5229	11.0773	11.1548	11.048
y2	1155600	1110910	1118681	1107967	y22	0.01	0.01	0.01	0.01
y3	1120932	1077583	1085120	1074728	y23	0.82102	0.81854	0.83446	0.8339
y4	105466	105466	104411	104411	y24	0.82	0.82	0.835	0.835
y5	278.15	278.15	278.15	278.15	y25	1.26721	1.26722	1.26721	1.26721
y6	611.741	605.296	600.371	598.812	y26	0.03	0.03	0.03	0.03
y7	1218.27	1224.57	1218.27	1218.29	y27	0.98	0.98	0.98	0.98
y8	763.642	774.605	767.708	769.376	y28	3.16113	3.0232	3.06014	3.03079
y9	394.907	394.662	393.843	394.178	y29	0.84828	0.846	0.84664	0.84613
y11	2.42536	2.36686	2.38484	2.36686	y30	0.84717	0.84717	0.84717	0.84717
y12	164.025	157.216	158.752	157.216	y31	0.98	0.98	0.98	0.98
y13	1.02278	0.98006	0.98967	0.98006	y32	0.0395	0.0395	0.0298	0.0298
y14	32585	31338.3	32585	32208.5	y33	0.92203	0.95	0.93958	0.95
y15	55248.8	52007.7	51637.9	50891.7	y34	0.1356	0.13374	0.13374	0.1339
y16	33250	31977.8	33250	32865.8	y35	2.27704	2.30901	2.30872	2.30596
y17	60726	61707	60726	61015.7	y36	0.12	0.12	0.12	0.12
y18	288.347	288.347	288.347	288.347	y37	0.87691	0.88059	0.8806	0.88028
y19	343.15	343.15	343.15	343.15	y38	10.6284	10.2132	10.3927	10.2932
y20	393.15	393.958	393.15	393.389					

Table. 5.23 - Values of the model variables in reference, operation and free conditions once the maintenance have been made

The residual fuel impact corresponding to the two approaches is:

$$\Delta F_T = E_{0_{op}} - E_{0_{ref}} = 120590 - 118343 = 2247kW \tag{5.68}$$

$$\Delta F_{\Delta k} = -\sum_{i=1}^{n} K_{P,i}^{*} \cdot \Delta P_{ext_i} = -(3.6 \cdot 229 + 2.03 \cdot (-962)) = 1124kW \quad . \tag{5.69}$$

This calculation put on evidence a limit of the proposed methodology, as the main fuel impact is not caused by the removed anomaly.

Table 5.24 shows the matrices of the unit exergy consumptions variation obtained by simulating the complete removal of the anomaly in the recuperator.

TG2

CC	AC	GT	CR	A
-0.007	0	0	0	0
0	0	0.0017	0.0056	0
0.0022	0	0	0	0
0	0.0096	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-0.011	0	0	0	0
0.0002	0	0.0018	0.0059	0
0.0042	0	-6E-05	-4E-04	0
0	0.0096	0	0	0
0	0	0	0	0
0	0	0	0	0

Table. 5.24 - Matrices **Δk** referring to the complete removal of the recuperator anomaly

The matrices show that the variation of the unit exergy consumption in the recuperator is not zero. The residual term is an induced effect.

Both the structures indicate the compressor as the most probable malfunctioning component. The maintenance operation will confirm it. Supposing that the anomaly could be completely removed, the corresponding operation and free condition are shown in table 5.23 (Maintenance 2). The fuel impact, calculated as difference between the fuel consumptions in operation and reference conditions, is still positive:

$$\Delta F_T = E_{0_{op}} - E_{0_{ref}} = 119242 - 118343 = 899kW \tag{5.70}$$

so an anomaly is still present. The terms of the **Δk** matrices can be calculated in order to locate it. The results are shown in table 5.25.

TG2

CC	AC	GT	CR	A
0.0002	0	0	0	0
0	0	0.0022	0.0015	0
7E-05	0	0	0	0
0	5E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-3E-05	0	0	0	0
0.0002	0	0.0006	0.0017	0
-3E-06	0	0.0016	-1E-04	0
0	5E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

Table. 5.25 - Matrices **Δk** referring to the complete removal of the compressor anomaly

The turbine is individuated as the most probable malfunctioning component. If the maintenance allows to completely remove the anomaly, the fuel impact becomes zero, so all the anomalies have been correctly detected and located.

5.4.2 Procedure for the filtration of the induced effects

In this part the application of the procedure described in paragraph 4.7 is proposed.

A detailed productive structure allows a better simulation of the induced effects, as mechanical and thermal effects are kept separated. The same variation of the fuel of a component can involve different combinations of mass flow, temperature and pressure. Their effects on the products are different, so the use of a structure like the TG5 is particularly suitable, respect to a simpler structure.

The values of the fuels calculated in free condition are assumed for all the components. If any anomalies took place, the corresponding products would include only induced effects, caused by the variation of the working conditions. Those products are here calculated by considering a linear dependence on every fuel:

$$P_1 = (P_1)_{ref} + \frac{\partial P_1}{\partial E_0} \cdot (E_{0_{free}} - E_{0_{ref}}) + \frac{\partial P_1}{\partial E_1} \cdot (E_{1_{free}} - E_{1_{ref}}) + \frac{\partial P_1}{\partial E_4} \cdot (E_{4_{free}} - E_{4_{ref}}) \tag{5.71}$$

where:

$$P_1 = E_2 + E_3 + E_4 \tag{5.72}$$

The fuel mass flow is the same in free and reference conditions; moreover the variation of the losses (E_4) does not influence the combustor product. In this way the equation 5.71 can be simplified:

$$P_1 = (P_1)_{ref} + \frac{\partial P_1}{\partial E_1} \cdot (E_{1_{free}} - E_{1_{ref}}) \tag{5.73}$$

The products of the other component can be expressed:

$$P_2 = (P_2)_{ref} + \frac{\partial P_2}{\partial E_8} \cdot (E_{8_{free}} - E_{8_{ref}}) \tag{5.74}$$

$$P_3 = (P_3)_{ref} + \frac{\partial P_3}{\partial E_2} \cdot (E_{2_{free}} - E_{2_{ref}}) + \frac{\partial P_3}{\partial E_5} \cdot (E_{5_{free}} - E_{5_{ref}}) \tag{5.75}$$

$$P_4 = (P_4)_{ref} + \frac{\partial P_4}{\partial E_3} \cdot (E_{3_{free}} - E_{3_{ref}}) + \frac{\partial P_4}{\partial E_6} \cdot (E_{6_{free}} - E_{6_{ref}}) \tag{5.76}$$

$$P_5 = (P_5)_{ref} + \frac{\partial P_5}{\partial E_7} \cdot (E_{7_{free}} - E_{7_{ref}}) \tag{5.77}$$

where:

$$P_2 = E_1 + E_5 + E_6 \tag{5.78}$$

$$P_3 = E_7 + E_8 \tag{5.79}$$

$$P_4 = E_{10} \tag{5.80}$$

$$P_5 = E_9 . \tag{5.81}$$

The derivates in the equations 5.73-5.77 can be calculated by means of two working conditions, corresponding to linearly independent regulations. The derivates can be evaluated as:

$$\frac{\partial P_i}{\partial E_j} = \frac{\Delta P_i}{\Delta E_j} . \tag{5.82}$$

In the case of the gas turbine plant the two conditions (*working1* and *working2*) can be determined by varying the fuel mass flow and opening grade of the inlet guided vanes. The two working conditions and the calculated values of the derivates are shown in table 5.26.

	reference	working 1	working 2	working 3	
igv	0.9801	0.9801	0.981	0.9801	
bpg	0.95	0.95	0.95	0.951	
Gc	2.3669	2.368	2.3669	2.3669	kg/s
E_0	118343	118400	118343	118343	kW
E_1	16592	16594	16618	16592	kW
E_2	58944	58969	58978	58944	kW
E_3	30303	30321	30283	30329	kW
E_4	4698	4700	4702	4671	kW
E_5	29676	29678	29713	29676	kW
E_6	385	385	385	385	kW
E_7	33250	33273	33252	33250	kW
E_8	50889	50893	50956	50889	kW
E_9	32585	32608	32587	32585	kW
E_{10}	14845	14853	14838	14859	kW

Derivates	
dP_2/dE_8	0.961
dP_1/dE_0	0.807
dP_1/dE_{1t}	0.713
dP_1/dE_{1m}	12.158
dP_1/dE_4	0
dP_3/dE_2	0.998
dP_3/dE_5	0.916
dP_4/dE_3	0.437
dP_4/dE_6	4.054
dP_5/dE_7	0.980

Table. 5.26 - Calculation of the derivates for the prediction of the induced effects

The productive structure TG5 does not allow the isolation of all the induced effects. The flux E_1 includes both thermal and mechanical components of exergy, but the effects of their variation on the component production are different. In particular, a variation of the mechanical exergy requirement does not affect the combustor product. In this way, if a variation of the pressure drop takes place in the combustor, the induced effects can not be noticed, unless the derivate $\partial P_1 / \partial E_1$ is split on the two exergy components. For this reason in table 5.26 the two terms of the derivate are indicated. The calculation of this second term requires the knowledge of a third working condition. This condition (*working3*) can be obtained by varying the opening grade of the by-pass valve (*bpg*). The equation 5.73 becomes:

$$P_1(E_1) = (P_1)_{ref} + \frac{\partial P_1}{\partial E_{1t}} \cdot (E_{1t_{free}} - E_{1t_{ref}}) + \frac{\partial P_1}{\partial E_{1m}} \cdot (E_{1m_{free}} - E_{1m_{ref}}) . \quad (5.83)$$

The calculation of the induced effects and the isolation of the intrinsic ones is now proposed for the malfunction cases TG1-TG8. Table 5.27 shows the values assumed by the fluxes of the productive structure in the eight free conditions. The system components are separately considered (see figure 5.13). The fluxes in free conditions are assumed as the fuels of the components. The products are calculated using the equations above indicated. These products corresponds to correctly working components, as if no anomalies have taken place. In the table the calculated values of the products are shown too.

	MF1	MF2	MF3	MF4	MF5	MF6	MF7	MF8
E_{1t}	16385.6	16759.4	16390	16170.7	16215.5	16218.7	16215.4	16215.4
E_{1m}	377.043	377.043	505.32	377.043	377.043	377.043	377.043	377.043
E_2	59079.8	59383.2	59082.6	58400.5	58699.6	58636.6	58943.9	58943.9
E_3	30404.1	30640.5	30406.2	29903.4	30525.5	30588.1	29733.4	30304.5
E_4	4709.12	4733.6	4709.35	4653.27	4722.16	4728.68	5267.36	4697.9
E_5	29685.1	29706.4	29685.3	29638.3	29675.8	29417.8	29675.7	29675.8
E_6	385.069	385.069	385.069	385.069	385.069	642.215	385.069	385.069
E_7	33073.8	32677.9	33070.1	32758.5	32822.5	32703	33250	33249.6
E_8	51210.8	51941.4	51217.6	50803.6	50892.3	50900.4	50889.1	50891.1
P_1	94066	94332.4	95608.5	93912.8	93944.8	93947	93944.7	93944.7
P_2	46962.3	47664.2	46968.8	46571.1	46656.3	46664.1	46653.2	46655.2
P_3	84283.3	84605.6	84286.2	83562.3	83895.2	83596.1	84139.1	84139
P_4	14889.7	14992.9	14890.6	14671	14942.7	16012.4	14596.8	14846.1
P_5	32412.3	32024.4	32408.7	32103.4	32166	32048.9	32585	32584.6

Table. 5.27 - Fuels of the components in free condition and calculated products

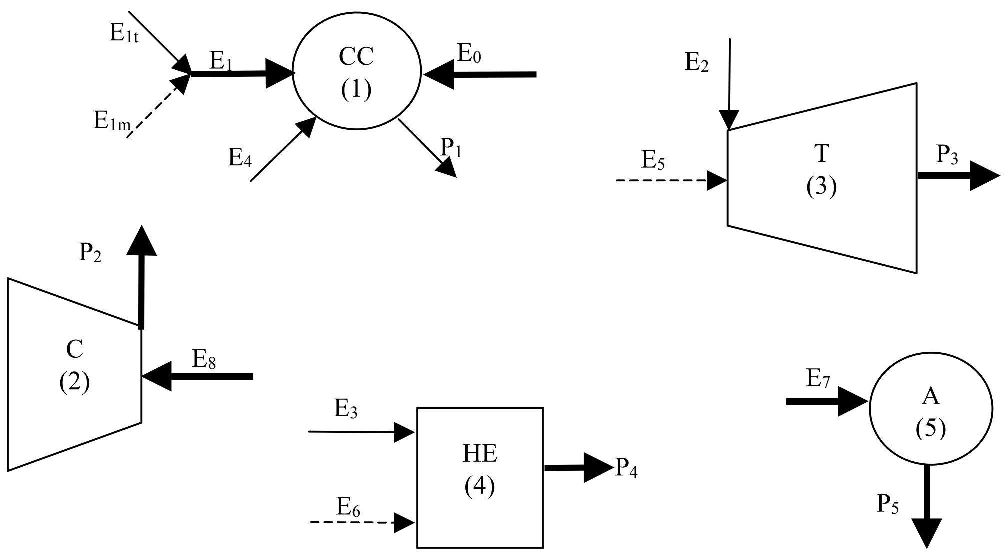

Figure 5.13 - Separated components of the structure TG5

The difference between the unit exergy consumptions of the separated components, calculated using the values shown in table 5.27 and the corresponding reference values, takes into accounts the induced effects. The matrix containing these values has been indicated as $\Delta\mathbf{k_{ind}}$. The difference between the elements of the matrices $\Delta\mathbf{k}$ and $\Delta\mathbf{k_{ind}}$ defines the matrix $\Delta\mathbf{k_{int}}$, representing the intrinsic effects of the anomalies. Table 5.28 shows the non zero elements of the two matrices in the eight cases of single malfunction.

	Δk_{ind} (induced effects)					Δk_{int} (intrinsic effects)				
MF1	-0.002	0	0	0	0	-0.002	0	0	0	0
	5E-05	0	4E-04	7E-04	0	-7E-05	0	-1E-05	9E-05	0
	0.002	0	-5E-04	-8E-05	0	-2E-04	0	-5E-06	1E-06	0
	0	-3E-04	0	0	0	0	0.003	0	0	0
MF2	-0.005	0	0	0	0	-0.006	0	0	0	0
	2E-04	0	0.001	0.002	0	-2E-04	0	-1E-04	1E-03	0
	0.005	0	-0.002	-3E-04	0	-8E-04	0	-6E-05	1E-05	0
	0	-0.001	0	0	0	0	0.01	0	0	0
MF3	-0.022	0	0	0	0	0.019	0	0	0	0
	-8E-04	0	4E-04	8E-04	0	7E-04	0	-1E-05	1E-04	0
	1E-04	0	-5E-04	-8E-05	0	0.003	0	-6E-06	1E-06	0
	0	-3E-04	0	0	0	0	7E-05	0	0	0
MF4	4E-04	0	0	0	0	0.013	0	0	0	0
	-5E-04	0	-0.002	-0.003	0	5E-04	0	1E-06	-9E-07	0
	-4E-04	0	0.002	3E-04	0	0.002	0	6E-07	-1E-08	0
	0	9E-05	0	0	0	0	9E-07	0	0	0
MF5	-1E-06	0	0	0	0	-3E-05	0	0	0	0
	3E-04	0	-9E-04	0.002	0	-1E-06	0	0.002	3E-04	0
	1E-06	0	0.001	-2E-04	0	-5E-06	0	8E-04	3E-06	0
	0	-3E-06	0	0	0	0	7E-05	0	0	0
MF6	-3E-05	0	0	0	0	-0.011	0	0	0	0
	3E-04	0	9E-04	-0.131	0	-4E-04	0	3E-04	0.134	0
	3E-05	0	-8E-04	0.014	0	0.004	0	-8E-04	-0.014	0
	0	-1E-05	0	0	0	0	0.009	0	0	0
MF7	0	0	0	0	0	0	0	0	0	0
	0.006	0	0	-0.004	0	0	0	0	0.053	0
	0	0	0	4E-04	0	0	0	0	7E-04	0
	0	0	0	0	0	0	0	0	0	0
MF8	-7E-07	0	0	0	0	-2E-05	0	0	0	0
	-9E-07	0	-8E-07	1E-05	0	-8E-07	0	-1E-05	1E-04	0
	7E-07	0	8E-07	-1E-06	0	-3E-06	0	-7E-06	2E-06	0
	0	-2E-06	0	0	0	0	4E-05	0	0	0.011

Table. 5.28 - Intrinsic and induced effects relative to the eight cases of single malfunction.

In all cases the procedure allows to better locate the anomalies respect to the simpler procedure applied in paragraph 5.3.2. The induced effects have been reduced, as it can be noticed by comparing figures 5.14 and 5.9. The procedure shows the significant contribution of a single malfunction in every case, as the intrinsic effect is much higher than the others.

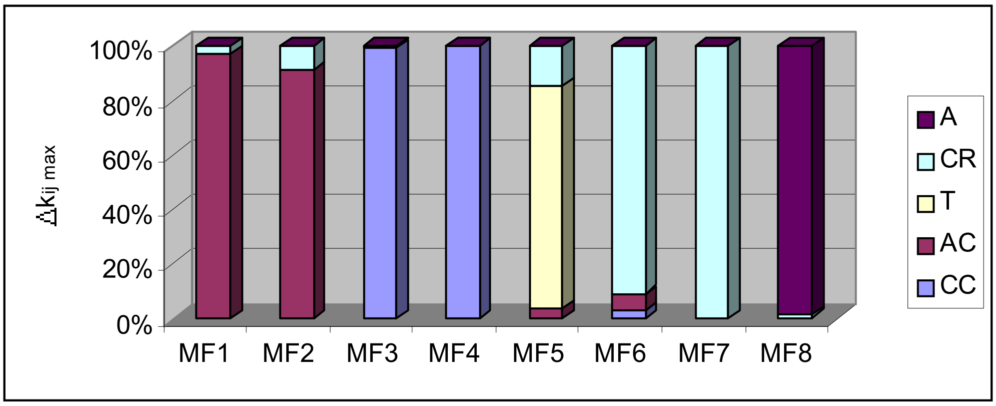

Figure 5.14 - Intrinsic effects in the cases of single malfunctions

5.4.3 Application of the procedure to a case of triple malfunction

In this paragraph the procedure for the erasure of the induced effects is applied to the case of triple malfunction described in paragraph 5.4.1. Table 5.29 shows the values assumed by the fluxes of the productive structure in free condition. The product obtained by every single component if any anomalies had taken place can be calculated by using the equations 5.74-5.77 and 5.83.

E_{1t}	E_{1m}	E_2	E_3	E_4	E_5	E_6	E_7	E_8	P_1	P_2	P_3	P_4	P_5	
16768	377	59020	31018	4770	29576	513	31978	52008	47728	94339	84124	15158	31338	kW

Table. 5.29 - Fuel and products of the separated components

The corresponding matrices $\Delta \mathbf{k}_{ind}$ and $\Delta \mathbf{k}_{int}$ are shown in table 5.30.

Δk_{ind} (induced effects)

CC	AC	T	CR	A
-0.005	0	0	0	0
6E-04	0	0.001	0.005	0
0.005	0	-0.001	0.008	0
0	-0.001	0	0	0
0	0	0	0	0
0	0	0	0	0

Δk_{int} (intrinsic effects)

CC	AC	T	CR	A
-0.006	0	0	0	0
-3E-04	0	0.001	0.003	0
-9E-04	0	6E-04	5E-05	0
0	0.011	0	0	0
0	0	0	0	0
0	0	0	0	0

Table. 5.30 - Intrinsic and induced effects

The matrices put on evidence that important induced effects have taken place in the recuperator and in the combustor. In the combustor not all the induced effects have been erased, due to the hypothesis of linear behaviour. Nevertheless all the anomalies can be located at the same time as the residual induced effect is negative. Moreover the quantification of every single anomaly is now more correct: the anomaly in the compressor is indicated as the highest, while the simpler procedure had indicated the recuperator as the most malfunctioning component.

A third information would be useful for the plant management: the quantification of the contribution of every single anomaly, expressed in terms of malfunctions or fuel impact. It would allow to understand the economic convenience of the maintenance operation, as the technical energy saving obtained by completely removing an anomaly could be calculated. The proposed procedure does not provide such an information, as it erases all the induced effects at the same time, without separating the contribution of every single anomaly. To obtain this information the mathematical model of the plant is necessary.

Here the contribution of every single effect can be calculated. It can only suggest the magnitude of the possible energy saving. In fact, the contribution of the effects induced by the component behaviour and the regulation system intervention can not be evaluated, unless only a single anomaly is detected. The fuel impact related to every single intrinsic effect and to the induced effects are shown in table 5.31. The intrinsic contributions have been calculated using the expression 4.63:

$$\Delta F_{i_{int}} = K_{P,j}{}^{*} \cdot \Delta k_{ji_{int}} \cdot P_{i_{ref}} \tag{5.84}$$

where the elements of the matrix $\Delta \mathbf{k_{int}}$ have been considered. The contribution of the effects induced by the behaviour of the components have been calculated as difference between the total fuel impact expressed by the equation 5.67 and the total fuel impact associated to the intrinsic effects. Finally the fuel impact associated to the regulation system can be calculated as difference between the values obtained using the equations 5.66 and 5.67.

Calculated contributions	Fuel impact [kW]
Intrinsic effect in the compressor	1055
Intrinsic effect in the recuperator	75
Intrinsic effect in the turbine	169
Total intrinsic effects	1298
Induced effects I (behaviour of the components)	71
Induced effects II (regulation system)	1556
Real contributions	
Intrinsic and induced effects in the compressor	1348
Intrinsic and induced effects in the heat exchanger	678
Intrinsic and induced effects in the turbine	899

Table. 5.31 - Intrinsic and induced effects associated to the case of triple malfunction

In the table the real contributions of every single anomaly are also indicated. These contributions have been calculated a posteriori, once every anomaly has removed (see equations 5.66, 5.68 and 5.70).

CHAPTER 6

Thermoeconomic diagnosis of the Moncalieri steam turbine plant

The application of the thermoeconomic diagnosis methodologies to the steam turbine plants is usually successful [Lerch 1999, Reini et al. 1999], as the malfunctions are mainly intrinsic. In this way the application of the operation versus reference (OvR) approach is usually sufficient for the diagnosis purposes. In some cases the effect of the induced malfunctions are not negligible so that the diagnosis made using the classical approach does not allow to correctly locate the anomalies. An improvement of the results can be so obtained by eliminating the contribution of the regulation system intervention.

In this chapter the application of the diagnosis methodology is proposed to some simulated cases of simple malfunctions of the Moncalieri steam turbine plant. Moreover the diagnosis is applied to the available measured data, relative to a particular working condition. The expected fuel impact associated to the main (intrinsic) malfunctions has been calculated and compared to the effective value, obtained by simulating the complete removal of the corresponding anomalies. It allows to check the contribution of the induced malfunctions.

6.1 Numerical calculation of the Lagrange multipliers associated to the steam turbine plant

The model of the steam turbine plant is too complicated for an analytical calculation of the derivates necessary for the determination of the free working condition; their numerical calculation is so proposed.

The regulation variables of the steam power plant are the opening grade of the throttles (x_1), the fuel mass flow (x_2) and the mass flow of the steam extracted for the hot condenser feeding (x_3). Another independent variable of the model is the mass flow of the water entering the hot condenser, but its value is determined once the temperature of the water in the outgoing network is fixed. Three working conditions are so required to calculate the Lagrange multipliers necessary for the determination of the free conditions.

As commented before, the procedure is based on the hypothesis of linear dependence of the thermodynamic or thermoeconomic quantities on the regulation variables. The hypothesis has been verified by simulating some operation conditions, everyone corresponding to a different regulation set. In particular three independent groups of real conditions have been simulated, respectively characterized by:

1) fixed values of the inlet turbine temperature and thermal load, but different electric loads;
2) fixed values of the inlet turbine temperature and electric load, but different thermal loads;
3) fixed values of the electric and thermal loads, but different inlet turbine temperatures.

In this last case little variations have been imposed, as the temperature is a plant set point.

The values of the productive structure fluxes have been calculated in every condition. In this case the hypothesis of linearity is a good approximation.

The Lagrange multipliers relative to the fluxes of the productive structure TV4, associated to the variation of the three independent variables, are shown in table 6.1

flux	λ_{x1}	λ_{x2}	λ_{x3}	flux	λ_{x1}	λ_{x2}	λ_{x3}	flux	λ_{x1}	λ_{x2}	λ_{x3}
1b	4066.9	50383.6	-0.088	m3-4	14352	6209	4.758	10p	-9.02	-1.736	-0.016
1p	-1727	-333.96	-3E-05	4t-1	10699	3567	-61.21	10s	-26.07	-4.26	-0.125
1s	-12069	-1688	-22.868	4p-1	-21.76	-3.629	-0.165	10pv	0.569	0.108	0.004
1pv	98409.8	14994.7	-4E-05	4s-1	-226.3	-43.2	-1.169	t10	-3530	-636.4	-20.19
t1	249529	80456.5	-0.037	4pv-1	-14534	-2002	-145.3	11t	-7671	-1314	-23.55
2t-0	19672.9	1743.93	-4E-06	m4-1	-44.42	2303	-187.8	11p	-5.916	-1.069	-0.015
2p-0	-517.19	-259.07	4E-07	4t-2	-2393	1064	-118.4	11s	5.252	7.824	-0.115
2s-0	-183.34	-49.709	-0.3177	4p-2	-6.502	-1.039	-0.044	11pv	-2163	-410.3	-3.436
2pv-0	13964.2	2412.43	0.0003	4s-2	-19.37	1.084	-0.469	t11	-10296	-1933	-26.86
m2-0	35561.4	4668.51	-2E-05	4pv-2	-192.2	-23.09	-0.306	12t	-2018	71.8	-5.885
2t-1	32144.8	12880.7	-2E-06	m4-2	269.4	1344	-108	12p	-3.598	-0.673	0.441
2p-1	-2219.2	-335.52	0	4t-3	-36628	-5089	-314.4	12s	98.81	30.71	-0.09
2s-1	-346.34	-52.297	-0.4692	4p-3	-4.269	-0.717	-0.032	12pv	-2334	-418.1	-1.386
2pv-1	6679.07	2995.91	2E-06	4s-3	-588.1	-86.8	-4.632	t12	-6407	-959	-6.129
m2-1	41633.1	16279	4E-12	4pv-3	60.51	2.41	0.235	13t	-14237	-3014	0.007
2t-2	15635.7	5174.45	-0.0033	m4-3	-27225	-3738	-238.9	13p	42.05	9.481	2E-05
2p-2	-296.94	-41.324	-6E-05	5t	71922	18067	675.6	13s	-26.54	-2.371	-0.051
2s-2	-38	0.88443	-0.1255	5p	-15.89	-2.204	-0.847	13pv	-4398	-1008	0.004
2pv-2	-2869	-215.7	-0.0022	5s	-3169	-908.1	-76.06	t13	-18257	-3995	0.011
m2-2	12773.9	4831.58	-0.0054	5m	3.964	-0.059	1.276	14t	1670	326.3	-0.003
3t-1	28644.1	9494.37	-0.016	5pv	-4556	-586.7	147.3	14s	-80.06	-15.4	-0.068
3p-1	-383.35	-60.923	3E-05	t5	41581	10386	621.4	14m	-11032	-2169	0.004
3s-1	-282.62	-58.202	-0.1985	6t	0.031	-0.031	0.002	p14	-5859	-1153	-3E-05
3pv-1	-10712	-1717.9	0.0018	6s	0.069	0.04	-8E-04	15t	1455	1677	0.002
m3-1	22268.3	8714.52	0.0037	m6	1E+05	52958	-516.4	15p	-229.9	-44.97	-5E-07
3t-2	31081.7	10148.7	0.019	7t	-28618	-4851	-173.2	15s	301.9	89.05	-0.151
3p-2	-242.94	-38.965	0.0001	7p	-1.105	-0.192	-0.006	15pv	-5897	-954.3	2E-04
3s-2	-190.18	-35.651	-0.1801	7pv	0.56	0.103	0.003	t15	-10910	-1097	0.004
3pv-2	-17722	-3139.9	0.0162	s7	-16842	-2769	-108.2	16t	-7796	-789.4	3E-04
m3-2	16133.7	7548.92	0.0332	8t	4.027	1.021	0.022	16p	-139.6	-27.07	-5E-06
3t-3	20645.9	6415.73	-0.0065	8s	-2.209	-0.398	-0.01	16s	121.2	39.15	-0.074
3p-3	-69.268	-9.9993	2E-05	8m	-268	-50.7	-1.171	16pv	-15398	-3117	4E-04
3s-3	-118.33	-20.887	-0.119	p8	-159.6	-30.2	-0.697	t16	-25882	-4717	0.004
3pv-3	-9699.3	-1468.2	0.0314	9t	-6502	-983.6	-45.15	17t	-1911	138.9	-0.002
m3-3	12731.4	5269.43	0.023	9p	-4.297	-0.805	-0.019	17p	-119.1	-23.42	-5E-07
3t-4	36620.6	10563.3	2.2977	9s	-80.32	-7.959	-0.753	17s	84.65	24.78	-0.023
3p-4	-44.124	-5.6466	0.0056	9pv	1.168	0.219	0.007	17pv	-6830	-1289	-0.001
3s-4	-3.9602	11.1038	-0.1281	t9	-5219	-872.3	-32.59	t17	-10544	-1657	-0.002
3pv-4	-21810	-4057	2.8485	10t	-3920	-699.9	-21.94				

Table. 6.1 - Lagrange multipliers associated to the productive structure TV4

6.2 Diagnosis of single malfunctions of the steam turbine plant

In this paragraph the complete analysis of a simulated case of a single malfunction is proposed step by step, while the results relative to other single malfunctions are shown. The two diagnosis approaches examined in this thesis are applied and the results are compared, in order to determine the effect of the regulation system intervention on the system diagnosis. Moreover the use of two productive structures is proposed for the malfunction location.

6.2.1 Application of the diagnosis procedures to a case of single malfunction

The complete diagnosis procedure is here applied to a particular case of single malfunction. A 2% reduction of the isentropic efficiency has been imposed in the second stage of the middle pressure turbine (MP2). The thermodynamic data relative to the reference condition and the simulated operation condition are shown in table 6.3.

The overall production in operation condition is the same as in reference condition, while the fuel impact is positive:

$$\Delta F_T = E_{1b_{op}} - E_{1b_{ref}} = 290367 - 289797 = 570 kW. \tag{6.1}$$

This means that the same production requires a larger fuel consumption than in reference condition, so a malfunction has taken place in the plant. Once the anomaly has been detected it is necessary its location.

The values assumed by mass flows, pressures and temperatures allow to determine the fluxes of the productive structure TV4 in reference, operation and then free conditions. This last calculation requires the use the equation 4.34, which can be rewritten considering the three regulation parameters of the plant:

$$E_{j_{free}} = E_{j_{op}} - \lambda_{j1} \cdot (x_{1_{op}} - x_{1_{ref}}) - \lambda_{j2} \cdot (x_{2_{op}} - x_{2_{ref}}) - \lambda_{j3} \cdot (x_{3_{op}} - x_{3_{ref}}) \tag{6.2}$$

where E_j is the j^{th} flux of the productive structure, x_i is the i^{th} regulation variable and λ_{ji} is the Lagrange multiplier representing the variation of the j^{th} flux caused by the unit variation of the i^{th} regulation variable (see table 6.1). The subscripts *free*, *op* and *ref* respectively indicate free, operation and reference conditions.

The values of the regulation parameters are shown in table 6.2 and the resulting productive fluxes are shown in table 6.4.

Variable	Reference	Operation
x_1	0.974	0.9715
x_2	5.795	5.807
x_3	35	34.96

Table. 6.2 - Values of the regulation variables

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.5	3450	98.09	124.5	3450	35	45.74	7	117	45.98	7	117
2	86.54	27.15	3104	86.74	27.21	3104	36	45.74	6.86	230	45.98	6.86	231
3	0.375	27.15	3381	0.376	27.21	3382	37	45.74	6.723	299	45.98	6.723	300
4	86.91	27.15	3105	87.12	27.21	3105	38	45.74	6.588	497	45.98	6.588	498
5	0	27.15	3105	0	27.21	3105	39	80.74	6.588	507	80.94	6.588	508
6	86.91	27.15	3105	87.12	27.21	3105	40	80.74	6.457	580	80.94	6.457	581
7	86.91	24.43	3552	87.12	24.49	3552	41	2.28	3.594	588	2.271	3.609	589
8	39.44	2.232	2938	39.64	2.25	2942	42	5.92	2.009	505	5.933	2.025	506
9	39.44	1.186	2938	39.64	1.193	2942	43	6.738	0.361	307	6.756	0.364	308
10	37.01	0.022	2417	37.21	0.022	2419	44	8.647	0.172	238	8.678	0.174	239
11	1.645	0.191	2630	1.64	0.193	2633	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.191	2711	1.923	0.193	2720	46	8.647	0.172	81.6	8.678	0.174	81.7
13	0.818	0.401	2744	0.823	0.404	2748	47	97.85	5.555	658	98.09	5.568	658
14	3.641	2.232	2938	3.661	2.25	2942	48	97.85	162.1	681	98.09	162.1	681
15	1.37	3.993	3062	1.374	4.01	3066	49	97.85	158.8	842	98.09	158.9	842
16	2.28	3.993	3170	2.271	4.01	3172	50	97.85	155.6	995	98.09	155.7	995
17	1.443	6.419	3174	1.435	6.439	3179	51	97.85	152.5	1063	98.09	152.6	1063
18	5.545	13.72	3380	5.563	13.76	3380	52	3.151	35.33	1052	3.162	35.41	1053
19	6.97	27.15	3104	6.99	27.21	3104	53	10.12	27.15	983	10.15	27.21	983
20	3.151	35.33	3162	3.162	35.41	3163	54	15.67	13.72	826	15.72	13.76	827
21	0.628	3.993	3235	0.619	4.01	3236	56	45.74	7	82	45.98	7	82.1
22	0.029	0.95	3235	0.029	0.95	3236	57	45.74	7	81.9	45.98	7	82.1
23	0.161	1.2	3235	0.172	1.2	3236	59	0.086	0.022	81.1	0.086	0.022	81.2
24	0.029	0.95	3209	0.029	0.95	3212	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.174	1.2	3213	61	4900	1	68.1	4900	1	68.2
26	0.029	0.95	3217	0.029	0.95	3224	63	401.9	4	293	402	4	293
27	-0.06	1.2	3217	-0.06	1.2	3224	64	401.9	3.98	504	402	3.98	504
31	35	2.232	2938	34.96	2.25	2942	66	45.74	0.022	81.1	45.98	0.022	81.2
33	35	11	520	34.96	11	521	68	97.09	89.58	3381	97.32	89.81	3382
34	45.74	7	112	45.98	7	112	69	80.74	6.457	580	80.94	6.457	581

point	W kW (Reference)	W kW (Operation)	point	W kW (Reference)	W kW (Operation)
28	33472	33502	55	2801	2809
29	83684	83466	58	53	54
30	103627	103595	62	101049	101018
32	45	44	67	289797	290367

Table. 6.3 - Thermodynamic data relative to reference and operation conditions

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	290367	289735	m3-4	9670	9680	9637	10p	1.606	1.62	1.619
1p	297.562	298.793	298.73	4t-1	7623	7656	7635	10s	7.993	8.059	8.043
1s	6297.69	6317.06	6307.5	4p-1	3.097	3.13	3.116	10pv	-0.082	-0.082	-0.082
1pv	-49761	-49882	-49827	4s-1	40.5	40.71	40.65	t10	594	598.9	597.4
t1	103245	103438	103036	4pv-1	769.8	804.5	787.9	11t	2535	2555	2552
2t-0	5900.07	5861.1	5888.1	m4-1	7626	7691	7654	11p	1.058	1.06	1.059
2p-0	347.838	346.388	348.4	4t-2	4865	4915	4891	11s	29.67	30.01	29.92
2s-0	87.4946	87.554	87.717	4p-2	0.837	0.849	0.844	11pv	352.5	358.3	358
2pv-0	2148.51	2135.3	2139.5	4s-2	18.36	18.55	18.47	t11	2325	2345	2343
m2-0	6733.25	6680.31	6709.7	4pv-2	5.608	5.986	5.788	12t	1763	1758	1752
2t-1	15293.1	15348.1	15264	m4-2	4434	4475	4455	12p	16.6	16.58	16.6
2p-1	526.7	529.431	528.16	4t-3	10762	10869	10829	12s	14.33	14.3	14.15
2s-1	129.216	129.694	129.48	4p-3	0.627	0.636	0.633	12pv	385	384.8	384.2
2pv-1	7850.41	7863.71	7842.2	4s-3	151.6	153.1	152.5	t12	1892	1888	1884
m2-1	21214	21278.6	21175	4pv-3	-2.941	-2.974	-2.844	13t	2114	2115	2118
2t-2	3567.58	3579.47	3552.6	m4-3	7878	7960	7930	13p	20.2	20.19	20.17
2p-2	77.8271	78.2356	78.02	5t	23703	23736	23713	13s	13.99	14.04	14
2s-2	34.5519	34.73	34.619	5p	-26.56	-26.4	-26.45	13pv	325	323.7	325.6
2pv-2	2536.38	2544.39	2540	5s	-2866	-2866	-2865	t13	2193	2192	2197
m2-2	5525	5542.64	5513	5m	44.59	44.46	44.52	14t	-353.9	-355.1	-355.1
3t-1	9921.7	9944.23	9894.8	5pv	6443	6500	6502	14s	18.71	18.78	18.77
3p-1	93.4906	93.9193	93.737	t5	21751	21756	21753	14m	2801	2809	2809
3s-1	54.3999	54.5582	54.586	6t	-0.124	-0.124	-0.124	p14	1532	1536	1536
3pv-1	5926.57	5937.14	5932.3	6s	0.092	0.092	0.091	15t	5205	5221	5203
m3-1	14907.7	14939.3	14884	m6	1E+05	1E+05	1E+05	15p	45.31	45.47	45.46
3t-2	10188.9	10017.8	9966.1	7t	5717	5763	5747	15s	41.54	41.7	41.31
3p-2	59.1595	59.4089	59.298	7p	0.13	0.131	0.131	15pv	1751	1758	1755
3s-2	49.6442	57.3993	57.371	7pv	-0.083	-0.084	-0.084	t15	6211	6232	6219
3pv-2	7361.13	7369.14	7364.9	s7	4245	4276	4265	16t	4332	4345	4336
m3-2	16665.6	16356.4	16301	8t	-0.929	-0.935	-0.937	16p	33.66	33.76	33.76
3t-3	4914.95	4944.29	4914.1	8s	0.381	0.383	0.382	16s	20.34	20.43	20.23
3p-3	19.2965	19.3697	19.324	8m	53.45	53.73	53.66	16pv	2608	2618	2619
3s-3	32.8064	32.8464	32.812	p8	31.92	32.08	32.04	t16	6587	6609	6604
3pv-3	4647.22	4650.4	4644.9	9t	1180	1195	1189	17t	1930	1938	1931
m3-3	8957.86	8990.37	8955	9p	0.771	0.776	0.775	17p	30.46	30.55	30.55
3t-4	5047.31	5073.02	5030	9s	19.73	20.06	19.93	17s	6.237	6.274	6.169
3p-4	13.7769	13.8039	13.766	9pv	-0.191	-0.193	-0.192	17pv	1262	1268	1267
3s-4	41.1731	40.6497	40.493	t9	805.3	814.4	811.2	t17	3105	3117	3111
3pv-4	5391.64	5364.89	5362.2	10t	744.4	750.4	748.6				

Table. 6.4 - Fluxes of the productive structures TV4a relative to the MP2 malfunction

The application of the operation versus reference approach in this case allows to correctly locate the malfunctioning component, in fact the maximum value of the unit exergy consumption variation takes place in the second stage of the middle pressure turbine (element $\Delta\mathbf{k}_{2\text{-}6}$). Some induced effects take place in the downstream components, in particular in the last stages of the middle pressure turbine, in the first stage of the low pressure turbine and in the cogenerative recuperator (hot condenser).

3E-04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-3E-04	6E-04	-5E-04	-2E-05	-1E-04	0.009	-0.002	-0.003	0.004	7E-05	-3E-07	0.003	0	-8E-09	0	1E-06	3E-07	0.001	4E-04	-5E-04	0	2E-04	1E-04	1E-04	0	-2E-04
0	0	0	0	0	0	0	0	0	0	0	0	-5E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	7E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	2E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	4E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	-0.003	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	3E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	7E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	4E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	8E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	-6E-06	0	0	2E-05	0	0	0	0	0	2E-04	0	0	0	0	0
7E-05	1E-04	4E-06	1E-05	3E-06	5E-04	-9E-06	-6E-05	-2E-05	4E-06	-1E-05	6E-05	9E-10	0	1E-05	1E-04	8E-07	4E-05	-4E-07	2E-05	1E-05	3E-06	4E-06	4E-06	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5E-05	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-7E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-5E-05	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4E-05
7E-06	2E-04	5E-05	3E-05	2E-05	8E-05	4E-07	1E-06	9E-07	9E-07	3E-07	8E-06	0	1E-07	0	-5E-06	2E-07	-3E-06	1E-05	-5E-06	0	1E-06	-1E-06	-1E-05	0	0
0	0.001	4E-04	9E-05	1E-04	0.001	0.001	0.002	-0.004	9E-04	-6E-04	0.001	-2E-09	0.001	-6E-05	0.002	-3E-04	-7E-04	-5E-04	9E-04	-2E-04	-3E-04	-1E-04	-1E-04	0	0

Table. 6.5 - Matrix Δ**k** relative to the comparison between operation and reference conditions

The corresponding malfunctions in every component are shown in table 6.6. The intrinsic malfunction is bigger than the induced ones, nevertheless an important induced malfunction takes place in the hot condenser, due to the high production of this component.

Component	Mfi [kW]	Component	Mfi [kW]	Component	Mfi [kW]
SG	8.8	LP1	-3.5	HE4	-0.3
HP0	13.2	LP2	4.4	HC	84.6
HP1	-1.0	LP3	-5.0	D	0.8
HP2	0.6	A	14.0	CP	0.0
MP1	-0.3	EP	0.0	HE6	-0.5
MP2	175.7	HE1	1.7	HE7	0.1
MP3	-2.3	HE2	-0.2	HE8	0.1
MP4	-12.1	HE3	1.2	C	4.6

Table. 6.6 - Malfunctions of the system

The malfunction location using the free vs. reference comparison needs the calculation of the fuel impact. As the overall fuel consumption in free and reference conditions is the same, this quantity is zero. Nevertheless the overall plant production has varied, so the fuel impact can be expressed as the amount of fuel necessary to restore the reference production. This quantity is equal to the sum of every external product variation, each multiplied for the exergy unit cost. This is the fuel impact associated to the variation of the efficiency of the components:

$$\Delta F_{\Delta P} = \sum_{i=1}^{n} K_{P,i}^{*} \cdot (P_{i_{ref}} - P_{i_{free}})_{ext} \tag{6.3}$$

For diagnosis purposes the unit exergy consumptions to be considered are the ones having the same sign of this fuel impact. A negative variation of the fuel impact associated to the variation of the production means that the plant in free condition works better than in reference condition. In that case the negative elements of the matrix $\Delta\mathbf{k}$ must be considered.

The calculated matrix $\Delta\mathbf{k}$ is shown in table 6.7. The application of the free vs. reference approach provides the same result to the direct diagnosis problem as the operation vs. reference approach.

The term Δk_{11} has varied a lot respect to the value assumed in the operation vs. reference approach. This term represents the variation of the unit consumption of the exergy flow associated to the fossil fuel. As the overall fuel consumption is the same in reference and free conditions, this variation is caused by a decreased production of the steam generator. In particular the temperature of the outlet steam has decreased, so that its specific exergy has decreased too. The regulation system intervention restores the value of the outlet temperature imposed by the set-point. This intervention requires an additional fuel consumption, which corresponds to the total fuel impact calculated in the equation 6.1.

The values of the malfunctions in the components, corresponding to the comparison between free and reference conditions, are shown in table 6.8.

0.005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.002	-2E-04	3E-04	0.002	0.001	0.01	-1E-04	-0.001	0.002	3E-05	1E-05	0.003	0	-1E-08	0	6E-07	3E-07	0.001	5E-04	-5E-05	0	4E-04	6E-04	6E-04	0	-7E-04
0	0	0	0	0	0	0	0	0	0	0	0	3E-05	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	5E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	4E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	-0.003	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	3E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	5E-05	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	6E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	4E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	8E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	-3E-06	0	0	2E-05	0	0	0	0	0	2E-04	0	0	0	0	0
2E-04	8E-05	2E-05	3E-05	2E-05	5E-04	2E-06	-6E-05	2E-07	5E-06	-8E-06	6E-05	5E-10	0	7E-08	7E-05	8E-06	1E-05	-6E-05	-8E-06	7E-06	-5E-05	-2E-05	-3E-05	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-05	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-5E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2E-05	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8E-05
2E-05	3E-04	1E-04	7E-05	3E-05	9E-05	4E-06	4E-06	9E-07	7E-07	2E-07	5E-06	0	9E-08	0	-3E-06	5E-06	-3E-06	4E-05	-3E-05	0	2E-05	2E-06	6E-06	0	0
0	0.001	-4E-05	-0.001	-7E-04	2E-05	8E-05	1E-05	-0.002	6E-04	-4E-04	4E-04	-1E-09	7E-04	-2E-04	1E-03	-2E-05	-0.001	-0.002	-2E-04	-2E-04	-0.001	-0.001	-0.001	0	0

Table. 6.7 - Matrix Δ**k** relative to the comparison between free and reference conditions

Component	Mfi [kW]	Component	Mfi [kW]	Component	Mfi [kW]
SG	382.2	LP1	-0.5	HE4	-2.6
HP0	9.4	LP2	2.7	HC	68.3
HP1	8.2	LP3	-3.2	D	-0.5
HP2	2.4	A	15.8	CP	0.0
MP1	4.7	EP	0.0	HE6	-6.1
MP2	179.5	HE1	0.9	HE7	-3.4
MP3	-0.1	HE2	0.0	HE8	-1.7
MP4	-11.3	HE3	0.2	C	3.0

Table. 6.8 - Malfunctions caused by the anomaly

The decreased value of the outlet steam generator temperature causes a sensible malfunction in this component, which represents an induced effect. This value is associated to a low value of the unit exergy consumption variation (i.e. a low efficiency decreasing) and is caused by the high product in reference condition. It confirms that the impact of an anomaly does not depend only on the efficiency variation.

Finally the average unit cost associated to the regulation can be calculated, using the equation 6.4:

$$k_r{}^* = \frac{\Delta F_{T_r}}{\Delta P_{ext_r}} = \frac{\Delta F_{T_r}}{(E_{t5_{op}} - E_{t5_{free}}) + (E_{m6_{op}} - E_{m6_{free}})} = \frac{570}{4 + 373} = 1.51 \,. \quad (6.4)$$

This cost is lower than the unit cost of the plant products. This means that the system intervention causes an improvement of the working condition of the overall plant.

6.2.2 Effect of the productive structures on the system diagnosis results

One of the main characteristics of the steam power plants is that the fluid change phase in the thermodynamic cycle. The same pressure variation involves different energy (and exergy) amounts, depending on the fluid state: if the fluid is liquid the corresponding mechanical exergy variation is much lower than it happens if the fluid is vapor. This allows to obtain high mechanical power from the steam expansion and to increase the pressure of the liquid water by using a much lower power.

The thermoeconomic model of the plant groups together a series of thermodynamic quantities. The behavior of the components is described by means of their unit exergy consumptions. Some information are so lost, hidden in these quantities.

It is important to know if all the productive structures are sensible to particular malfunctions such the pressure drop variations, being able to locate them. For this reason the proposed procedure is here applied to a case of 5% increase of the pressure drop at the steam side of the heat exchanger HE3 and to a 2% increase of the pressure drop at the liquid side of the heat exchanger HE7. The simple productive structure TV2, defined only by using exergy flows, and the more detailed structure TV4, where exergy is split into mechanical and thermal components, are both applied in order to examine the different results provided.

In the first case the thermodynamic data relative to reference and operation conditions are shown in table 6.9. The fuel impact is zero, but the total production of the plant has reduced, so a malfunction is detected:

$$\Delta P_T = E_{m6_{op}} - E_{m6_{ref}} + E_{b5_{op}} - E_{b5_{ref}} = 101007 - 101049 + 21756 - 21751 = -30 kW. \quad (6.5)$$

The plant simulator finds the solution of an operation condition by changing the regulation parameters. A low difference between the calculated product and the setting value is accepted. In this case the same regulation as in reference condition determines a solution in the allowed range. For this reason the malfunctioning behaviour is expressed by the product reduction. Therefore the corresponding fuel impact can be evaluated using the equation:

$$\Delta F_{\Delta P} = \sum_{i=1}^{n} K_{P,i}^{*} \cdot \Delta P_{ext_i} . \quad (6.6)$$

An approximate value can be obtained by using the values of the unit costs calculated in reference conditions (see chapter 3):

$$\Delta F_{\Delta P} = 2.4 \cdot (101049 - 101007) + 2.55 \cdot (21751 - 21756) = 97 kW . \quad (6.7)$$

The fluxes of the productive structure TV4 and TV2 relative to reference, operation and free conditions are shown in tables 6.9 and 6.10. The free condition have been determined using the equation 4.34 and considering the values assumed by the regulation parameters shown in table 6.12 and the Lagrange multipliers reported in tables 6.1 and 6.13.

	Reference			Operation				Reference			Operation		
point	G	p	h	G	p	h	point	G	p	h	G	p	h
	kg/s	bar	kJ/kg	kg/s	bar	kJ/kg		kg/s	bar	kJ/kg	kg/s	bar	kJ/kg
1	97.85	124.5	3450	97.85	124.5	3450	35	45.74	7	117	45.74	7	117
2	86.54	27.15	3104	86.54	27.15	3104	36	45.74	6.86	230	45.74	6.86	230
3	0.375	27.15	3381	0.375	27.15	3381	37	45.74	6.723	299	45.74	6.723	300
4	86.91	27.15	3105	86.91	27.15	3105	38	45.74	6.588	497	45.74	6.588	491
5	0	27.15	3105	0	27.15	3105	39	80.74	6.588	507	80.74	6.588	504
6	86.91	27.15	3105	86.91	27.15	3105	40	80.74	6.457	580	80.74	6.457	580
7	86.91	24.43	3552	86.91	24.43	3552	41	2.28	3.594	588	2.392	3.594	588
8	39.44	2.232	2938	39.47	2.239	2938	42	5.92	2.009	505	5.891	1.914	499
9	39.44	1.186	2938	39.47	1.188	2938	43	6.738	0.361	307	6.727	0.361	307
10	37.01	0.022	2417	37.02	0.022	2417	44	8.647	0.172	238	8.638	0.172	238
11	1.645	0.191	2630	1.649	0.191	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.191	2711	1.911	0.191	2711	46	8.647	0.172	81.6	8.638	0.172	81.6
13	0.818	0.401	2744	0.836	0.401	2745	47	97.85	5.555	658	97.85	5.555	658
14	3.641	2.232	2938	3.498	2.239	2938	48	97.85	162.1	681	97.85	162.1	681
15	1.37	3.993	3062	1.482	3.993	3062	49	97.85	158.8	842	97.85	158.8	842
16	2.28	3.993	3170	2.392	3.993	3165	50	97.85	155.6	995	97.85	155.6	995
17	1.443	6.419	3174	1.443	6.419	3174	51	97.85	152.5	1063	97.85	152.5	1063
18	5.545	13.72	3380	5.545	13.72	3380	52	3.151	35.33	1052	3.151	35.33	1052
19	6.97	27.15	3104	6.97	27.15	3104	53	10.12	27.15	983	10.12	27.15	983
20	3.151	35.33	3162	3.151	35.33	3162	54	15.67	13.72	826	15.67	13.72	826
21	0.628	3.993	3235	0.628	3.993	3235	56	45.74	7	82	45.74	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.74	7	82
23	0.161	1.2	3235	0.161	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.169	1.2	3201	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3218	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3218	64	401.9	3.98	504	401.9	3.98	504
31	35	2.232	2938	35	2.239	2938	66	45.74	0.022	81.1	45.74	0.022	81.1
33	35	11	520	35	11	521	68	97.09	89.58	3381	97.09	89.58	3381
34	45.74	7	112	45.74	7	112	69	80.74	6.457	580	80.74	6.457	580

point	W	W	point	W	W
	kW	kW		kW	kW
28	33472	33472	55	2801	2801
29	83684	83620	58	53	53
30	103627	103583	62	101049	101007
32	45	45	67	289797	289797

Table. 6.9 - Thermodynamic data relative to reference and operation conditions

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	290367	289729	m3-4	9670.1	9679.9	9597.4	10p	1.606	1.62	1.548
1p	297.562	298.793	298.01	4t-1	7623	7656.5	7627.9	10s	7.993	8.059	7.817
1s	6297.69	6317.06	6300.3	4p-1	3.0972	3.1304	3.11	10pv	-0.082	-0.082	-0.084
1pv	-49761	-49882	-49781	4s-1	40.501	40.714	40.637	t10	594	598.9	595.1
t1	103245	103438	103136	4pv-1	769.81	804.53	779.9	11t	2535	2555	2456
2t-0	5900.07	5861.1	5897.7	m4-1	7626.1	7691	7638.6	11p	1.058	1.06	1.132
2p-0	347.838	346.388	348.19	4t-2	4865.4	4915	4867.3	11s	29.67	30.01	29.42
2s-0	87.4946	87.554	87.566	4p-2	0.8367	0.8487	0.8386	11pv	352.5	358.3	340.7
2pv-0	2148.51	2135.3	2145.2	4s-2	18.364	18.552	18.378	t11	2325	2345	2239
m2-0	6733.25	6680.31	6726.9	4pv-2	5.6083	5.986	5.585	12t	1763	1758	1843
2t-1	15293.1	15348.1	15276	m4-2	4433.9	4475.3	4435.9	12p	16.6	16.58	16.6
2p-1	526.7	529.431	527.15	4t-3	10762	10869	10777	12s	14.33	14.3	15.12
2s-1	129.216	129.694	129.29	4p-3	0.6274	0.6363	0.6291	12pv	385	384.8	404.5
2pv-1	7850.41	7863.71	7846.4	4s-3	151.59	153.06	151.79	t12	1892	1888	1977
m2-1	21214	21278.6	21192	4pv-3	-2.941	-2.974	-2.918	13t	2114	2115	2118
2t-2	3567.58	3579.47	3560.6	m4-3	7878.4	7959.9	7889.8	13p	20.2	20.19	20.19
2p-2	77.8271	78.2356	77.884	5t	23703	23736	23685	13s	13.99	14.04	13.99
2s-2	34.5519	34.73	34.552	5p	-26.56	-26.4	-26.51	13pv	325	323.7	326.3
2pv-2	2536.38	2544.39	2536.7	5s	-2866	-2866	-2864	t13	2193	2192	2198
m2-2	5525	5542.64	5518.5	5m	44.592	44.462	44.561	14t	-353.9	-355.1	-354.4
3t-1	9921.7	9944.23	9909.1	5pv	6442.9	6500.3	6468.8	14s	18.71	18.78	18.73
3p-1	93.4906	93.9193	93.573	t5	21751	21756	21739	14m	2801	2809	2804
3s-1	54.3999	54.5582	54.494	6t	-0.124	-0.124	-0.124	p14	1532	1536	1533
3pv-1	5926.57	5937.14	5928.9	6s	0.0916	0.0917	0.0915	15t	5205	5221	5202
m3-1	14907.7	14939.3	14896	m6	101049	101018	100935	15p	45.31	45.47	45.37
3t-2	10188.9	10017.8	10175	7t	5716.7	5763.3	5725.7	15s	41.54	41.7	41.42
3p-2	59.1595	59.4089	59.211	7p	0.1295	0.1312	0.1297	15pv	1751	1758	1752
3s-2	49.6442	57.3993	49.694	7pv	-0.083	-0.084	-0.083	t15	6211	6232	6212
3pv-2	7361.13	7369.14	7365.2	s7	4245.4	4276.5	4250.9	16t	4332	4345	4333
m3-2	16665.6	16356.4	16655	8t	-0.929	-0.935	-0.868	16p	33.66	33.76	33.7
3t-3	4914.95	4944.29	4906.4	8s	0.381	0.3833	0.3848	16s	20.34	20.43	20.29
3p-3	19.2965	19.3697	19.31	8m	53.453	53.726	53.522	16pv	2608	2618	2613
3s-3	32.8064	32.8464	32.835	p8	31.918	32.081	31.959	t16	6587	6609	6594
3pv-3	4647.22	4650.4	4648.9	9t	1179.7	1194.6	1181.5	17t	1930	1938	1930
m3-3	8957.86	8990.37	8950.5	9p	0.7712	0.7758	0.7722	17p	30.46	30.55	30.49
3t-4	5047.31	5073.02	5001.9	9s	19.728	20.055	19.746	17s	6.237	6.274	6.204
3p-4	13.7769	13.8039	13.709	9pv	-0.191	-0.193	-0.192	17pv	1262	1268	1264
3s-4	41.1731	40.6497	40.88	t9	805.32	814.41	806.82	t17	3105	3117	3107
3pv-4	5391.64	5364.89	5358.7	10t	744.38	750.37	742.17				

Table. 6.10 - Fluxes of the productive structure TV4a

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	290367	289729	4b-1	8396	8464	8411	10s	7.993	8.059	7.817
1s	6297.69	6317.06	6300.3	4s-1	40.5	40.71	40.64	b10	594	598.9	595.1
b1	152708	153021	152619	m4-1	7626	7691	7639	11b	2889	2915	2798
2b-1	8396.42	8342.79	8391.1	4b-2	4872	4922	4874	11s	29.67	30.01	29.42
2s-1	87.4946	87.554	87.566	4s-2	18.36	18.55	18.38	b11	2325	2345	2239
m2-1	6733.25	6680.31	6726.9	m4-2	4434	4475	4436	12b	2165	2159	2264
2b-2	23670.2	23741.3	23649	4b-3	10760	10866	10775	12s	14.33	14.3	15.12
2s-2	129.216	129.694	129.29	4s-3	151.6	153.1	151.8	b12	1892	1888	1977
m2-2	21214	21278.6	21192	m4-3	7878	7960	7890	13b	2459	2459	2464
2b-3	6181.79	6202.09	6175.2	5b	30173	30263	30180	13s	13.99	14.04	13.99
2s-3	34.5519	34.73	34.552	5m	44.59	44.46	44.56	b13	2193	2192	2198
m2-3	5525	5542.64	5518.5	5s	-2866	-2866	-2864	14m	2801	2809	2804
3b-1	15941.8	15975.3	15932	b5	21751	21756	21739	14s	18.71	18.78	18.73
3s-1	54.3999	54.5582	54.494	6b	-0.124	-0.124	-0.124	b14	1885	1891	1887
m3-1	14907.7	14939.3	14896	6s	0.092	0.092	0.092	15b	7001	7024	7000
3b-2	17609.2	17446.3	17600	m6	1E+05	1E+05	1E+05	15s	41.54	41.7	41.42
3s-2	49.6442	57.3993	49.694	7b	5717	5763	5726	b15	6211	6232	6212
m3-2	16665.6	16356.4	16655	8s	0.381	0.383	0.385	16b	6974	6997	6979
3b-3	9581.47	9614.06	9574.6	8m	53.45	53.73	53.52	16s	20.34	20.43	20.29
3s-3	32.8064	32.8464	32.835	b8	32.85	33.02	32.83	b16	6587	6609	6594
m3-3	8957.86	8990.37	8950.5	9b	6625	3391	164.7	17b	3223	3236	3225
3b-4	10452.7	10451.7	10374	9s	15.61	9.374	3.137	17s	6.237	6.274	6.204
3s-4	41.1731	40.6497	40.88	b9	6328	3213	105.1	b17	3105	3117	3107
m3-4	9670.07	9679.86	9597.4	10b	745.9	751.9	743.6				

Table. 6.11 - Fluxes of the productive structure TV2a

Variable	Reference	Operation
x_1	0.974	0.974
x_2	5.795	5.796
x_3	35	35

Table. 6.12 - Values assumed by the regulation variables

flux	λ_{x1}	λ_{x2}	λ_{x3}	flux	λ_{x1}	λ_{x2}	λ_{x3}	flux	λ_{x1}	λ_{x2}	λ_{x3}
1b	4066.9	50383.6	-0.088	4b-1	-3857	1562	-206.7	10s	-26.07	-4.26	-0.125
1s	-12069	-1688	-22.868	4s-1	-226.3	-43.2	-1.169	b10	-3530	-636.4	-20.19
b1	152847	65795.7	-0.037	m4-1	-44.42	2303	-187.8	11b	-9841	-1726	-27
2b-1	33119.9	3897.29	0.0003	4b-2	-2592	1040	-118.8	11s	5.252	7.824	-0.115
2s-1	-183.34	-49.709	-0.3177	4s-2	-19.37	1.084	-0.469	b11	-10296	-1933	-26.86
m2-1	35561.4	4668.51	-2E-05	m4-2	269.4	1344	-108	12b	-4356	-347	-6.83
2b-2	36604.8	15541.1	6E-12	4b-3	-36572	-5088	-314.2	12s	98.81	30.71	-0.09
2s-2	-346.34	-52.297	-0.4692	4s-3	-588.1	-86.8	-4.632	b12	-6407	-959	-6.129
m2-2	41633.1	16279	4E-12	m4-3	-27225	-3738	-238.9	13b	-18593	-4013	0.011
2b-3	12469.7	4917.43	-0.0055	5b	67382	17482	823.7	13s	-26.54	-2.371	-0.051
2s-3	-38	0.88443	-0.1255	5m	3.964	-0.059	1.276	b13	-18257	-3995	0.011
m2-3	12773.9	4831.58	-0.0054	5s	-3169	-908.1	-76.06	14m	-11032	-2169	0.004
3b-1	17548.7	7715.59	-0.0141	b5	41581	10386	621.4	14s	-80.06	-15.4	-0.068
3s-1	-282.62	-58.202	-0.1985	6b	0.031	-0.031	0.002	b14	-7529	-1480	0.003
m3-1	22268.3	8714.52	0.0037	6s	0.069	0.04	-8E-04	15b	-4672	677.7	0.002
3b-2	13116.2	6969.8	0.0353	m6	1E+05	52958	-516.4	15s	301.9	89.05	-0.151
3s-2	-190.18	-35.651	-0.1801	7b	-28618	-4851	-173.2	b15	-10910	-1097	0.004
m3-2	16133.7	7548.92	0.0332	8s	-2.209	-0.398	-0.01	16b	-23334	-3933	7E-04
3b-3	10877.4	4937.55	0.0249	8m	-268	-50.7	-1.171	16s	121.2	39.15	-0.074
3s-3	-118.33	-20.887	-0.119	b8	-163.6	-31.22	-0.719	b16	-25882	-4717	0.004
m3-3	12731.4	5269.43	0.023	9b	-1469	-228.2	-5.704	17b	-8860	-1173	-0.003
3b-4	14767	6500.62	5.1517	9s	-26.71	-3.973	-0.125	17s	84.65	24.78	-0.023
3s-4	-3.9602	11.1038	-0.1281	b9	-1007	-159.1	-3.602	b17	-10544	-1657	-0.002
m3-4	14352.2	6209.4	4.7575	10b	-3929	-701.6	-21.95				

Table. 6.13 - Lagrange multipliers associated to the productive structure TV2

In table 6.14 and 6.15 the matrices $\Delta\mathbf{K}$ relative to the two productive structure are shown, while the normalized maximum values in every component are shown in table 6.16.

In both cases the higher value of the unit exergy consumption difference takes place in the heat exchanger, moreover the variations of the unit exergy consumptions induced in the other components are lower than the intrinsic value. The location of the anomaly can be obtained whatever productive structure is chosen.

In the case of the steam turbine the productive structure does not allow to obtain information about the malfunction cause. This is due to the different relation between the thermodynamic variables as the fluid is superheated steam, saturated steam or liquid. In particular, when the fluid is in condition of saturated steam, pressure and temperature are dependent the one from the other, so a pressure variation also involves a temperature variation. In this way a mechanical malfunction also involves a thermal malfunction. If the productive structure TV4 is used, the effects of the malfunction are split on three terms of the unit exergy consumption matrix: the consumptions of thermal exergy, mechanical exergy of the liquid water and mechanical exergy of the steam. It make more difficult the correct location of the anomalies. So the use of the simplest productive structure is suggested.

0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-7E-04	-2E-04	2E-04	6E-04	5E-04	5E-04	6E-04	8E-04	0.001	-6E-06	3E-06	0.001	0	-1E-08	0	-2E-07	-3E-06	6E-04	0.001	3E-04	0	1E-04	3E-04	3E-04	0	-3E-04
0	0	0	0	0	0	0	0	0	0	0	0	1E-05	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	2E-05	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	-3E-06	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	5E-05	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	8E-05	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	3E-05	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	-6E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	2E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	7E-05	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	2E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	-3E-07	0	0	6E-06	0	0	0	0	0	5E-05	0	0	0	0	0
9E-05	2E-05	1E-05	7E-06	9E-06	5E-06	6E-06	2E-06	9E-06	1E-06	-2E-06	4E-05	1E-10	0	1E-04	-2E-05	-3E-04	4E-04	7E-05	-1E-05	2E-06	-2E-05	-1E-05	-1E-05	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-7E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-5E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4E-05
7E-06	1E-04	5E-05	3E-05	1E-05	5E-06	3E-06	4E-06	1E-06	3E-07	1E-07	2E-06	0	7E-09	0	-6E-07	-1E-04	5E-05	-4E-04	-3E-05	0	8E-06	6E-07	3E-06	0	0
0	5E-04	-7E-05	-5E-04	-3E-04	-4E-04	-5E-04	-8E-04	-0.001	-8E-05	-1E-04	-2E-04	-5E-10	4E-04	0.002	-5E-04	-0.006	0.007	6E-04	-5E-04	-5E-05	-6E-04	-5E-04	-5E-04	0	0

Table. 6.14 - Matrix ΔK relative to the FvR approach using the structure TV4a

7E-04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1E-05	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-05	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3E-06	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	5E-05	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	8E-05	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	3E-05	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6E-04	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-04	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	7E-05	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-04	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-5E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4E-05	2E-05	1E-05	7E-06	9E-06	5E-06	6E-06	2E-06	9E-06	1E-06	-2E-06	4E-04	4E-05	-1E-05	1E-10	0	1E-04	-2E-05	-3E-04	7E-05	-1E-05	1E-06	-2E-05	-1E-05	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4E-08
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8E-06
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5E-04
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-05
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5E-05
0	4E-04	2E-04	1E-04	2E-04	8E-05	1E-04	2E-05	2E-04	-8E-05	-1E-04	0.007	0.001	-2E-04	-5E-10	4E-04	0	-5E-04	-0.006	0.001	-3E-04	0	-4E-04	-2E-04	0
0	5E-04	-7E-05	-5E-04	-3E-04	-4E-04	-5E-04	-8E-04	-0.001	-8E-05	-1E-04	-2E-04	-5E-10	4E-04	0.002	-5E-04	-0.006	0.007	6E-04	-5E-04	-5E-05	-6E-04	-5E-04	-5E-04	0

Table. 6.15 - Matrix ΔK relative to the FvR approach using the structure TV2a

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
TV2	9	5	2	2	2	1	1	0	2	0	0	16
TV4	35	7	3	9	7	8	9	12	17	0	0	20
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
TV2	3	5	2	0	0	100	18	0	0	0	0	0
TV4	3	6	29	0	0	100	17	4	1	2	4	4

Table. 6.16 - Normalized maximum values of the of Δk_{ij} calculated using the structures TV2 and TV4

The average unit cost associated to the regulation can be calculated, using the equation 6.4:

$$k_r{}^* = \frac{\Delta F_{T_r}}{\Delta P_{ext_r}} = \frac{\Delta F_{T_r}}{(E_{t5_{op}} - E_{t5_{free}}) + (E_{m6_{op}} - E_{m6_{free}})} = \frac{97}{17+83} = 1.13\,. \qquad (6.8)$$

This cost is lower than the unit cost of the plant products, so the intervention of the regulation system causes an increase of the plant efficiency.

The same procedure is now applied to the second case of mechanical malfunction. The thermodynamic data relative to the operation condition are shown in table 6.17.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.86	124.5	3450	35	45.74	7	117	45.75	7	117
2	86.54	27.15	3104	86.55	27.15	3104	36	45.74	6.86	230	45.75	6.86	230
3	0.375	27.15	3381	0.375	27.15	3381	37	45.74	6.723	299	45.75	6.723	299
4	86.91	27.15	3105	86.92	27.15	3105	38	45.74	6.588	497	45.75	6.588	497
5	0	27.15	3105	0	27.15	3105	39	80.74	6.588	507	80.75	6.588	507
6	86.91	27.15	3105	86.92	27.15	3105	40	80.74	6.457	580	80.75	6.457	580
7	86.91	24.435	3552	86.92	24.44	3552	41	2.28	3.594	588	2.28	3.594	588
8	39.44	2.2317	2938	39.42	2.233	2938	42	5.92	2.009	505	5.922	2.01	505
9	39.44	1.1859	2938	39.42	1.184	2938	43	6.738	0.361	307	6.739	0.361	307
10	37.01	0.0224	2417	37.02	0.022	2417	44	8.647	0.172	238	8.645	0.172	238
11	1.645	0.1914	2630	1.627	0.191	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.906	0.191	2717	46	8.647	0.172	81.6	8.645	0.172	81.6
13	0.818	0.401	2744	0.817	0.401	2745	47	97.85	5.555	658	97.86	5.555	658
14	3.641	2.2317	2938	3.642	2.233	2938	48	97.85	162.1	681	97.86	162.1	681
15	1.37	3.9928	3062	1.386	3.993	3062	49	97.85	158.8	842	97.86	158.8	842
16	2.28	3.9928	3170	2.28	3.993	3168	50	97.85	155.6	995	97.86	154.1	995
17	1.443	6.4188	3174	1.443	6.42	3174	51	97.85	152.5	1063	97.86	151	1063
18	5.545	13.724	3380	5.546	13.73	3380	52	3.151	35.33	1052	3.152	35.33	1052
19	6.97	27.15	3104	6.968	27.15	3104	53	10.12	27.15	983	10.12	27.15	983
20	3.151	35.325	3162	3.152	35.33	3162	54	15.67	13.72	826	15.67	13.73	826
21	0.628	3.9928	3235	0.617	3.993	3235	56	45.74	7	82	45.75	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.75	7	82
23	0.161	1.2	3235	0.172	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.174	1.2	3211	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3223	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3223	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35	2.233	2938	66	45.74	0.022	81.1	45.75	0.022	81.1
33	35	11	520	35	11	520	68	97.09	89.58	3381	97.1	89.58	3381
34	45.74	7	112	45.75	7	112	69	80.74	6.457	580	80.75	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33473	55	2801	2802
29	83684	83681	58	53	53
30	103627	103612	62	101049	101035
32	45	45	67	289797	289812

Table. 6.17 - Thermodynamic data relative to reference and operation conditions

These values allow to calculate the fluxes of the productive structures TV2 and TV4, shown in tables 6.18 and 6.19.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289797	289812	m3-4	9670.1	9670.1	9674	10p	1.606	1.606	1.607
1p	297.562	297.562	282.61	4t-1	7623	7623	7618.6	10s	7.993	7.993	7.994
1s	6297.69	6297.69	6298.6	4p-1	3.0972	3.0972	3.0905	10pv	-0.082	-0.082	-0.082
1pv	-49761	-49761	-49766	4s-1	40.501	40.501	40.458	t10	594	594	593.8
t1	103245	103245	103251	4pv-1	769.81	769.81	763.75	11t	2535	2535	2537
2t-0	5900.07	5900.07	5898.5	m4-1	7626.1	7626.1	7616.4	11p	1.058	1.058	1.058
2p-0	347.838	347.838	347.78	4t-2	4865.4	4865.4	4867.5	11s	29.67	29.67	29.69
2s-0	87.4946	87.4946	87.548	4p-2	0.8367	0.8367	0.8376	11pv	352.5	352.5	353
2pv-0	2148.51	2148.51	2148.8	4s-2	18.364	18.364	18.357	t11	2325	2325	2326
m2-0	6733.25	6733.25	6731.1	4pv-2	5.6083	5.6083	5.9054	12t	1763	1763	1760
2t-1	15293.1	15293.1	15295	m4-2	4433.9	4433.9	4431.7	12p	16.6	16.6	16.6
2p-1	526.7	526.7	526.81	4t-3	10762	10762	10769	12s	14.33	14.33	14.28
2s-1	129.216	129.216	129.24	4p-3	0.6274	0.6274	0.628	12pv	385	385	385
2pv-1	7850.41	7850.41	7850.9	4s-3	151.59	151.59	151.66	t12	1892	1892	1891
m2-1	21214	21214	21217	4pv-3	-2.941	-2.941	-2.913	13t	2114	2114	2114
2t-2	3567.58	3567.58	3568	m4-3	7878.4	7878.4	7883.8	13p	20.2	20.2	20.2
2p-2	77.8271	77.8271	77.844	5t	23703	23703	23704	13s	13.99	13.99	13.99
2s-2	34.5519	34.5519	34.61	5p	-26.56	-26.56	-26.55	13pv	325	325	325
2pv-2	2536.38	2536.38	2537.5	5s	-2866	-2866	-2866	t13	2193	2193	2193
m2-2	5525	5525	5525.5	5m	44.592	44.592	44.586	14t	-353.9	-353.9	-353.9
3t-1	9921.7	9921.7	9923.1	5pv	6442.9	6442.9	6453.3	14s	18.71	18.71	18.71
3p-1	93.4906	93.4906	93.509	t5	21751	21751	21751	14m	2801	2801	2802
3s-1	54.3999	54.3999	54.403	6t	-0.124	-0.124	-0.124	p14	1532	1532	1532
3pv-1	5926.57	5926.57	5927.2	6s	0.0916	0.0916	0.0916	15t	5205	5205	5205
m3-1	14907.7	14907.7	14910	m6	101049	101049	101035	15p	45.31	45.31	45.31
3t-2	10188.9	10188.9	10190	7t	5716.7	5716.7	5719	15s	41.54	41.54	41.55
3p-2	59.1595	59.1595	59.173	7p	0.1295	0.1295	0.1296	15pv	1751	1751	1751
3s-2	49.6442	49.6442	49.656	7pv	-0.083	-0.083	-0.083	t15	6211	6211	6212
3pv-2	7361.13	7361.13	7362	s7	4245.4	4245.4	4246.9	16t	4332	4332	4331
m3-2	16665.6	16665.6	16668	8t	-0.929	-0.929	-0.867	16p	33.66	33.66	48.89
3t-3	4914.95	4914.95	4915.7	8s	0.381	0.381	0.3844	16s	20.34	20.34	20.88
3p-3	19.2965	19.2965	19.301	8m	53.453	53.453	53.459	16pv	2608	2608	2608
3s-3	32.8064	32.8064	32.814	p8	31.918	31.918	31.922	t16	6587	6587	6591
3pv-3	4647.22	4647.22	4647.8	9t	1179.7	1179.7	1181.5	17t	1930	1930	1931
m3-3	8957.86	8957.86	8959	9p	0.7712	0.7712	0.7712	17p	30.46	30.46	30.16
3t-4	5047.31	5047.31	5046.1	9s	19.728	19.728	19.807	17s	6.237	6.237	6.229
3p-4	13.7769	13.7769	13.771	9pv	-0.191	-0.191	-0.191	17pv	1262	1262	1263
3s-4	41.1731	41.1731	40.68	t9	805.32	805.32	805.67	t17	3105	3105	3106
3pv-4	5391.64	5391.64	5387.3	10t	744.38	744.38	744.22				

Table. 6.18 - Fluxes of the productive structure TV4a

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289797	289812	4b-1	8395.9	8395.9	8385.4	10s	7.993	7.993	7.994
1s	6297.69	6297.69	6298.6	4s-1	40.501	40.501	40.458	b10	594	594	593.8
b1	152708	152708	152734	m4-1	7626.1	7626.1	7616.4	11b	2889	2889	2891
2b-1	8396.42	8396.42	8395.1	4b-2	4871.8	4871.8	4874.2	11s	29.67	29.67	29.69
2s-1	87.4946	87.4946	87.548	4s-2	18.364	18.364	18.357	b11	2325	2325	2326
m2-1	6733.25	6733.25	6731.1	m4-2	4433.9	4433.9	4431.7	12b	2165	2165	2162
2b-2	23670.2	23670.2	23673	4b-3	10760	10760	10766	12s	14.33	14.33	14.28
2s-2	129.216	129.216	129.24	4s-3	151.59	151.59	151.66	b12	1892	1892	1891
m2-2	21214	21214	21217	m4-3	7878.4	7878.4	7883.8	13b	2459	2459	2459
2b-3	6181.79	6181.79	6183.3	5b	30173	30173	30184	13s	13.99	13.99	13.99
2s-3	34.5519	34.5519	34.61	5m	44.592	44.592	44.586	b13	2193	2193	2193
m2-3	5525	5525	5525.5	5s	-2866	-2866	-2866	14m	2801	2801	2802
3b-1	15941.8	15941.8	15944	b5	21751	21751	21751	14s	18.71	18.71	18.71
3s-1	54.3999	54.3999	54.403	6b	-0.124	-0.124	-0.124	b14	1885	1885	1886
m3-1	14907.7	14907.7	14910	6s	0.0916	0.0916	0.0916	15b	7001	7001	7002
3b-2	17609.2	17609.2	17611	m6	101049	101049	101035	15s	41.54	41.54	41.55
3s-2	49.6442	49.6442	49.656	7b	5716.8	5716.8	5719.1	b15	6211	6211	6212
m3-2	16665.6	16665.6	16668	8s	0.381	0.381	0.3844	16b	6974	6974	6988
3b-3	9581.47	9581.47	9582.7	8m	53.453	53.453	53.459	16s	20.34	20.34	20.88
3s-3	32.8064	32.8064	32.814	b8	32.847	32.847	32.788	b16	6587	6587	6591
m3-3	8957.86	8957.86	8959	9b	6611.6	3388.6	164.51	17b	3223	3223	3224
3b-4	10452.7	10452.7	10447	9s	15.6	9.3624	3.1337	17s	6.237	6.237	6.229
3s-4	41.1731	41.1731	40.68	b9	6315.1	3210.6	104.95	b17	3105	3105	3106
m3-4	9670.07	9670.07	9674	10b	745.9	745.9	745.75				

Table. 6.19 - Fluxes of the productive structure TV2a

The normalized maximum values in every component are shown in table 6.20.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
TV2	31	39	12	22	9	6	8	0	13	90	0	25
TV4	92	20	8	32	19	21	25	13	24	47	0	29
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
TV2	12	28	10	88	0	0	0	0	0	0	100	0
TV4	7	16	84	50	0	7	12	10	2	6	100	11

Table. 6.20 - Normalized maximum values of the of Δk_{ij} calculated using the structures TV2 and TV4

Although the induced effects are particularly high, both the productive structures allow the correct location of the anomaly. In this case the use of the operation versus reference approach does not allow to correctly find where the anomaly has taken place (see annex 4).

6.2.3 Results of other cases of single malfunctions

In this paragraph the diagnosis results of some malfunctions are analyzed. Table 6.21 shows the characteristics of every single malfunction considered.

Name	Component	Characteristic parameter	Values		ΔF kW
			reference	operation	
MF9	SG	pp_{rh}	0.1	0.12	484
MF10	SG	η_g	0.953	0.943	2940
MF11	HP1	η_{td}	0.789	0.773	737
MF12	MP2	η_{td}	0.886	0.868	631
MF13	LP3	η_{td}	0.730	0.715	504
MF14	C	KA [kW/K]	17985	17086	0
MF15	HC	KA [kW/K]	2554	2475	264
MF16	HE2	TTD [°C]	2	3	63
MF17	HE3	TTD [°C]	2	3	86
MF18	HE3	pp_s	0	0.02	97
MF19	HE4	pp_s	0	0.02	-72
MF20	HE7	pp_s	0	0.02	188
MF21	HE7	pp_w	0.02	0.03	48
MF22	HE7	TTD [°C]	4	6	24

Table. 6.21 - Characteristics of the simulated single malfunctions

In the table the fuel impact associated to every operation condition has been indicated.

The graph in figure 6.1 shows the results of the diagnosis. In particular the normalized values assumed by the Δk_{ij} in every component, calculated using the structure TV2, are represented. The spotted areas refer to the intrinsic effects of the malfunctions. In all the cases the intrinsic effect is the largest. Nevertheless in some cases the malfunctioning component is not so clear, as important induced effects takes place in other component. This fact mainly happens when pressure drop variations are considered, due to the relation between pressures and mass flows. When the value of a pressure moves, it causes a different distribution of the mass flows in the plant. It involves a variation of the exergy flows and so a different distribution of fuels and products.

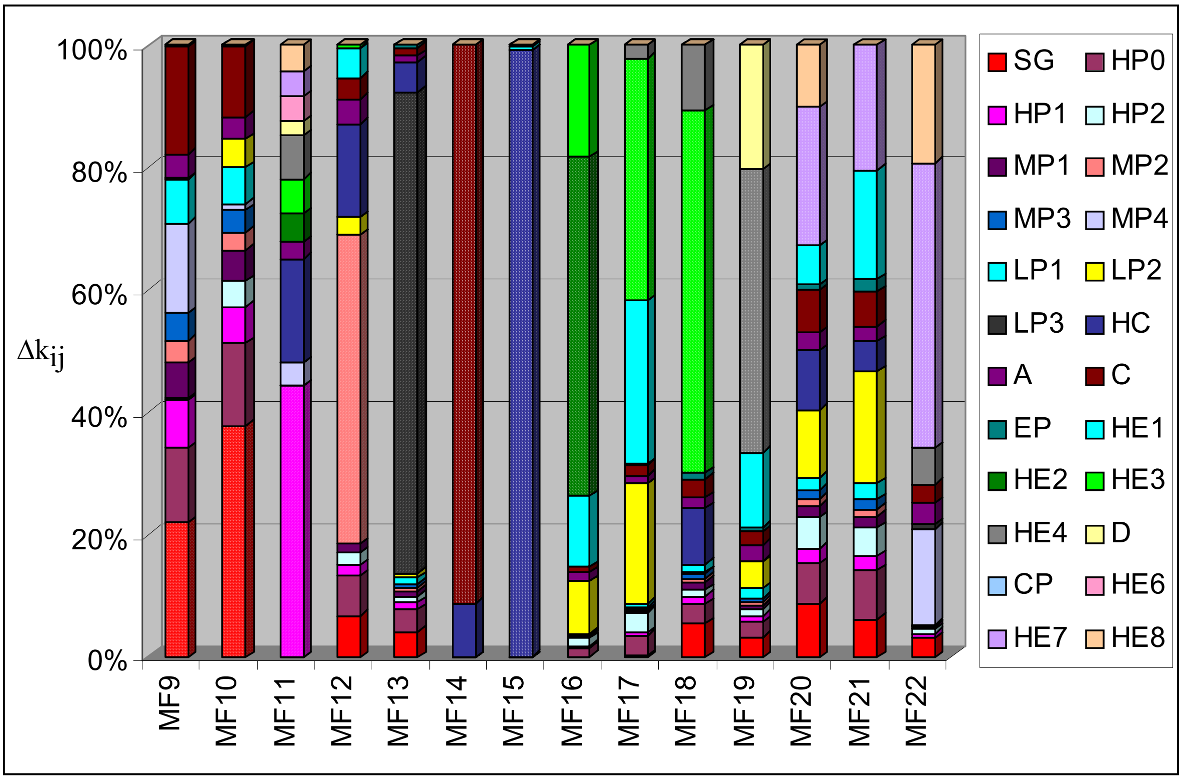

Figure 6.1 - Maximum per cent values of the Δk_{ij} in every components.

The variation of the pressure drop in the re-heater (MF9) affects a large number of components, in particular the condenser, where the induced effects are eighty percent of the intrinsic effect in the steam generator, and some turbine stages. The corresponding cost of the regulation is negative, as shown in figure 6.2.

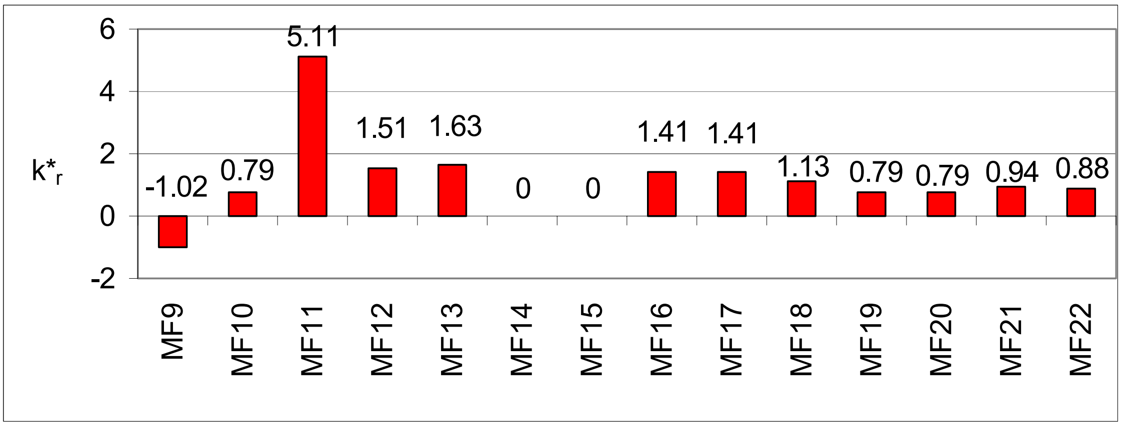

Figure 6.2 - Values of the unit cost associated to the regulation

The negative value means that the regulation intervention makes decrease both the plant efficiency and total production. Such an event can only happens when the plant in free condition is characterized by an efficiency higher than in reference condition, as in the simulation indicated as *MF9*. The increase of the pressure drop in the re-heater makes decrease the mass flow of the steam passing through the steam generator and the turbine. As the regulation is the same as in reference condition, the fuel mass flow has not varied, so the outlet steam generator temperature is higher than in reference condition. The overall efficiency of the plant is higher too. This condition is not real as the set-point constraints are not complied; the control system so commands the regulation. Once the regulation system has intervened the efficiency of the plant decreases. The regulation so induces malfunctions in the system. Table 6.22 shows the malfunctions and their corresponding costs evaluated before the regulation system intervention and the variation caused by its intervention.

	SG	HP0	HP1	A	C	MP1	MP2	LP1	LP2	MP3	HP2	MP4
MF	-1021	-25	-52	40	-22	-27	-18	-17	5	-12	0	-43
MF*	-1118	-52	-107	7	-44	-55	-37	-35	10	-25	-1	-89
MF_r	1304	63	44	17	30	29	18	18	16	13	8	3
MF^*_r	1447	131	91	80	61	59	37	36	32	26	17	7
	CP	EP	HE2	LP3	HE1	D	HE8	HE4	HE3	HE7	HE6	HC
MF	0	0	2	1	10	9	9	12	13	29	36	21
MF*	0	0	4	2	21	18	19	25	26	59	73	47
MF_r	0	0	-3	-4	-5	-9	-10	-14	-14	-18	-35	-47
MF^*_r	0	0	-5	-7	-11	-18	-20	-28	-30	-37	-73	-103

Table. 6.22 - Malfunctions caused by the anomaly and by the regulation system and corresponding costs (in kW)

The components main affected by the regulation are the steam generator and the two first stages of the high pressure turbine, due to the decrease of the outlet steam generator temperature. The impact on the unit exergy consumptions does not allow the correct location of the anomaly using the operation versus reference approach. Table 6.23 shows the normalized maximum values of the Δk_{ij} in every component calculated using the two diagnosis approaches (FvR and OvR). In particular negative values have been considered when the proposed procedure is applied, as the efficiency of the plant is higher than in reference condition, while the contrary happens when the operation versus condition is applied. The highest values have been highlighted.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	100	56	36	1	27	16	20	67	33	0	1	0
OvR	30	97	0	24	2	0	0	0	1	85	0	0
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	18	80	1	0	0	0	0	0	0	0	0	0
OvR	20	37	0	100	0	0	0	0	0	1	28	0

Table. 6.23 - Normalized maximum values of Δk_{ij} in the simulation MF9

Other simulations where high induced malfunctions have occurred are MF20 and MF21. The maximum normalized values of the Δk_{ij} in every component, calculated using the two diagnosis approaches, are shown in tables 6.24 and 6.25. In both cases the unit cost associated to the regulation is lower than the cost of the products. It means that the operation conditions are characterized by an higher efficiency than the corresponding free conditions. So the regulation system intervention has globally reduced the malfunctions taking place in the free conditions. The two tables confirms it. Nevertheless not all the malfunctions have decreased: some of them have increased. In particular, the case of simulation MF21 shows that the increase of the unit exergy consumption in the heat exchanger HE1 makes the operation versus reference approach unable to correctly locate where the anomaly has occurred.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	39	29	11	22	9	5	6	0	9	49	0	43
OvR	0	4	1	13	0	0	0	0	0	35	0	48
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	12	31	4	29	0	0	0	0	0	0	100	45
OvR	10	8	3	52	8	6	0	0	0	0	100	50

Table. 6.24 - Normalized maximum values of Δk_{ij} in the simulation MF20

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	31	39	12	22	9	6	8	0	13	90	0	25
OvR	0	13	0	11	0	0	0	0	0	66	0	32
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	12	28	10	88	0	0	0	0	0	0	100	0
OvR	4	4	8	100	5	3	0	0	0	0	94	0

Table. 6.25 - Normalized maximum values of Δk_{ij} in the simulation MF21

In all the other simulated cases the two approaches allows the correct location of the anomaly, as shown in annex 4.

6.3 Diagnosis of the plant using measured data

In this paragraph a diagnosis of the steam power plant using measured data is proposed. The data refers to the 26/5/1997. The working condition corresponds to the maximum electric load.

The purpose of this part is to verify if a reasonable thermoeconomic diagnosis is possible using the available instruments.

6.3.1 Data analysis

The values of the characteristic parameters of the model, considered in reference condition have been modified in order to simulate the real operation condition of the plant. Some of the available data have been modified too, because the measured values did not allow a reasonable solution, as discussed below. Table 6.26 shows the measured and the assumed data characterizing the operation condition.

First of all the measured values of the inlet and outlet reheater pressures have been modified as any pressure drop was detected. In particular the same pressure drop as in design condition have been assumed. The temperature of the extractions in high and middle pressure turbine have been considered correct. Only the first extraction temperature have been modified as the assumption of the measured value would have imply the improvement of the isentropic efficiency of the fist group of stages. For the same reason the outlet middle pressure turbine temperature has been considered higher than the measured value. On the contrary the temperature of the first extraction has been increased as it would have mean a too low efficiency of the first stages.

The mass flows extracted downstream every group of stages have been calculated by assuming correct the temperatures of the feed water exiting every heat exchanger and applying the energy balance. The pressure in the deareator have been assumed as the value corresponding to the saturated fluid at the calculated outlet temperature. Finally the temperature of the feed water exiting the two first heat exchanger as been assumed the same as in design condition, as the available data would not be in accord to the second law, if this plant configuration is considered.

POINT	MEASURED DATA G kg/s	MEASURED DATA p bar	MEASURED DATA T ºC	ASSUMED DATA G kg/s	ASSUMED DATA p bar	ASSUMED DATA T ºC
Steam inlet HP turbine	116.4	123.6	535.0	116.4	126.4	535.0
First extraction HP turbine			392.0			390.9
Steam outlet HP turbine		30.0	357.0		32.3	357.0
Steam inlet MP turbine	104.2	30.0	536.0	102.4	29.6	536.0
First extraction MP turbine			460.0			460.2
Second extraction MP turbine			348.0			347.9
Thirth extraction MP turbine			294.0			294.0
Steam outlet MP turbine		2.5	219.0		2.5	229.9
First extraction LP turbine			156.0			131.4
Second extraction MP turbine			101.0			104.1
Steam outlet LP turbine		0.032			0.032	
Water outlet extraction pump	95.9		31.0	95.9		28.5
Water outlet HE1a			44.0			33.0
Water outlet HE1			31.0			61.6
Water outlet HE2			56.0			89.5
Water outlet HE3			121.0			120.6
Water outlet HE4			144.0			143.7
Water outlet deareator		6.0	164.0		6.8	163.7
Water outlet circulation pump	115.3	142.0	166.0	116.4	142.0	166.0
Water outlet HE6			201.0			201.0
Water outlet HE7			231.5			231.4
Water outlet HE8			250.0			250.0
Condensing water in	5200.0	1.0	18.0	5200.0	1.0	18.0
Condensing water out	5200.0	1.0	26.5	5200.0	1.0	26.6
Condensate outlet condenser			32.0			24.9
Steam outlet first stage HP turbine		105.0			104.3	

POINT	W MW	Φ MW		W MW	Φ MW	
Electric power	136.6			137.2		
Fuel		329.2			329.2	

Table. 6.26 - Measured and assumed data

6.3.2 Thermoeconomic diagnosis

The assumptions described in the previous part have introduced important variations in the low pressure section of the plant. The results of the diagnosis are so not particularly significant for this part of the plant. Moreover the available data about the fuel consumption does not allow the diagnosis of the steam generator efficiency.

The reference condition differs from the one considered in the previous paragraphs, as the total plant production has changed. It has been simulated by using the same values of the characteristic parameters as in design condition and imposing the same load as in operation condition.

The productive fluxes corresponding to reference, operation and free conditions, calculated using the structure TV4, are shown in table 6.27.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	331109	329224	331028	m3-4	73.472	73.983	74.036	10p	1599	1662	1662
1p	127.696	119.832	127.87	4t-1	6578.8	6594.3	6579.8	10s	2993	2902	2918
1s	9020.58	8994.5	9020.2	4p-1	11200	11246	11382	10pv	1.375	1.382	1.382
1pv	-59037	-58997	-59057	4s-1	8476.1	8422.6	8581.8	t10	30.42	31.91	32.29
t1	771.44	770.153	771.47	4pv-1	14.455	14.388	14.484	11t	0	0	0
2t-0	119191	118109	119395	m4-1	118.22	122.03	122.31	11p	2532	2420	2430
2p-0	0	0	0	4t-2	9610.1	9579.9	9650.1	11s	3413	3570	3588
2s-0	4624.92	4604.99	4656.9	4p-2	16304	16167	16392	11pv	3.422	3.652	3.656
2pv-0	266.137	265.554	267.21	4s-2	10728	10769	10932	t11	38.68	42.73	43.39
m2-0	64.0506	64.3547	64.41	4pv-2	3.8387	3.8514	3.8795	12t	552.7	575	577.7
2t-1	1529.9	1526.66	1541.5	m4-2	75.946	79.686	80.893	12p	3381	3501	3511
2p-1	5447.69	5421.43	5489	4t-3	9.9643	9.9637	9.9675	12s	2444	2793	2810
2s-1	18342.3	17583.8	17759	4p-3	9467.6	9455.4	9598.7	12pv	1.321	1.328	1.327
2pv-1	713.824	714.701	717.11	4s-3	26263	26267	26275	t12	25.13	27.58	28.33
m2-1	178.314	222.568	220.87	4pv-3	2.719	2.7169	2.7089	13t	3269	2984	2951
2t-2	8331.22	8286.89	8235.4	m4-3	439.21	446.21	446.37	13p	-283.4	-282	-284.4
2p-2	24677.8	23210.7	23362	5t	611.54	705.03	704.7	13s	12.82	12.81	12.89
2s-2	4371.41	4441.22	4426.7	5p	2675.3	3080.7	3086.8	13pv	2738	2723	2748
2pv-2	113.016	112.965	112.84	5s	2754.4	2510.3	2494.2	t13	1575	1566	1581
m2-2	55.973	57.4518	56.693	5m	19.181	18.991	19.113	14t	6522	6102	6135
3t-1	2931.5	3004.37	2965.4	5pv	23.512	20.523	20.855	14s	28.78	28.62	28.88
3p-1	6565.4	6687.45	6645.2	t5	852.79	765.5	754	14m	55.26	52.93	53.6
3s-1	10877.5	10677.1	10898	6t	-0.709	-0.709	-0.71	p14	1974	1824	1794
3pv-1	125.63	124.263	125.22	6s	19591	19503	19509	15t	7684	7152	7146
m3-1	74.4288	75.0605	75.5	m6	-121.8	-121.5	-121.5	15p	4955	4697	4952
3t-2	6215.92	6153.69	6200.4	7t	10619	10721	10721	15s	50.72	50.83	52.27
3p-2	16088.1	15817	16079	7p	0.1295	0.1312	0.1297	15pv	38.02	38.55	42.3
3s-2	13711.4	13408.3	13530	7pv	-0.083	-0.084	-0.083	t15	3084	2873	3022
3pv-2	95.6118	95.5168	94.986	s7	4245.4	4276.5	4250.9	16t	7513	7037	7385
m3-2	65.9418	75.7631	75.159	8t	82.34	82.344	82.341	16p	2462	2941	2921
3t-3	9446.8	9410.44	9353.9	8s	139729	137180	138299	16s	27.79	27.63	27.88
3p-3	22251.8	21765.5	21839	8m	-5.678	-5.516	-5.706	16pv	13.17	16.64	16.95
3s-3	5557.4	5419.08	5523	p8	3.135	3.0205	3.1573	t16	1699	2017	1989
3pv-3	27.7116	28.0862	28.225	9t	164.23	162.06	165.03	17t	3988	4733	4681
m3-3	70.7767	83.4287	83.383	9p	393.2	278.65	278.13	17p	0	0	0
3t-4	5610.13	5672.24	5679.8	9s	2820.4	2729.4	2854.4	17s	0	0	0
3p-4	10119.8	9854.44	9966.7	9pv	1.9956	2.0203	2.0314	17pv	0	0	0
3s-4	5718.77	5754.2	5905.9	t9	59.232	96.992	65.085	t17	0	0	0
3pv-4	19.1467	19.1932	19.303	10t	0	0	0				

Table. 6.27 - Fluxes of the productive structure calculated using the structure TV4.

The maximum elements of the matrix $\Delta\mathbf{k}$ are shown in table 6.28. The contribution of the fictitious flows (negentropy) has been neglected.

The operation versus reference approach indicates the third stage of the middle pressure turbine and the first feed water heater as the most possible responsibles for the malfunctioning behaviour. On the contrary the free versus reference approach indicates the third stage of the middle pressure turbine and the first stage of the high pressure turbine. The working conditions corresponding to the complete removing of these two anomalies have been simulated (see table 6.30). The corresponding maximum elements of the matrix $\Delta\mathbf{k}$ are shown in the two last rows of the table.

	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	A
OvR	8E-04	0.019	0.003	0.003	0.008	0.021	2E-05	0.003	4E-04	5E-04	0.002
FvR	0	0.015	6E-06	7E-05	0.004	0.016	0	2E-04	4E-04	5E-04	0.002
Maintainance 1	9E-06	0.015	5E-06	7E-05	0.004	0	0	2E-04	4E-04	5E-04	0.002
Maintainance 2	7E-05	1E-04	0.002	7E-04	0.005	0	0	6E-04	4E-04	4E-04	0.002
	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8	C
OvR	0	0.021	0.001	8E-04	3E-04	5E-04	6E-04	3E-04	5E-04	2E-04	2E-06
FvR	1E-04	0.004	0.001	0.001	0	6E-04	1E-05	3E-04	7E-04	3E-04	2E-06
Maintainance 1	9E-05	0.004	0.001	9E-04	0	6E-04	1E-05	3E-04	7E-04	3E-04	2E-06
Maintainance 2	6E-05	0.004	0.001	8E-04	0	6E-04	1E-05	3E-04	8E-04	9E-04	2E-06

Table. 6.28 - Normalized maximum values of Δk_{ij} calculated using the structure TV4.

The first maintenance operation consists on the complete removal of the anomaly in the middle pressure turbine stage. The values of the corresponding Δk_{ij} becomes zero, which means that the effect indicated by the comparison between free and reference conditions is completely intrinsic. The same thing happens when the second anomaly is removed by means of a subsequent maintenance operation. The predict fuel impacts associated to the complete removal of the two anomalies can be calculated using the equation:

$$\Delta F_{i_{int}} = K_{P,j}^{*} \cdot \Delta k_{ji_{int}} \cdot P_{i_{ref}} \tag{6.9}$$

and compared with the obtained energy saving. These values are shown in table 6.29. The error, due to the induced effects, is about 11% in both cases. The contribution of the induced effects associated to the most important anomalies of the steam power plant are so negligible.

Energy saving [kW]	Maintainance 1	Maintainance 2
Predict	466	1949
Obtained	523	1750
error %	10.9	11.4

Table. 6.29 - Effect of the two maintenance operations

	Maintainance 1			Maintainance 2				Maintainance 1			Maintainance 2		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	116.4	127.55	3458	116.4	127.2	3449	35	45.74	7	117	95.72	7.358	141
2	101.7	33.107	3149	101.7	33.02	3129	36	45.74	6.86	230	95.72	7.211	259
3	0.444	33.107	3411	0.444	33.02	3403	37	45.74	6.723	299	95.72	7.067	375
4	102.2	33.107	3150	102.1	33.02	3130	38	45.74	6.588	497	95.72	6.926	507
5	0	33.107	3150	0	33.02	3130	39	80.74	6.588	507	95.72	6.926	507
6	102.2	33.107	3150	102.1	33.02	3130	40	80.74	6.457	580	95.72	6.787	606
7	102.2	29.737	3557	102.1	29.65	3549	41	2.28	3.594	588	3.765	4.65	629
8	85.45	2.5446	2936	85.37	2.536	2931	42	5.92	2.009	505	8.888	0.851	537
9	85.45	2.5446	2936	85.37	2.536	2931	43	6.738	0.361	307	13.12	0.851	399
10	77.34	0.0316	2376	77.26	0.032	2373	44	8.647	0.172	238	17.36	0.382	313
11	3.767	0.3825	2629	3.772	0.382	2626	45	0.086	0.95	411	0.088	0.95	412
12	4.241	0.3825	2695	4.245	0.382	2691	46	8.647	0.172	81.6	17.36	0.382	210
13	4.245	0.854	2747	4.231	0.851	2743	47	97.85	5.555	658	116.4	6.787	692
14	5.122	2.5446	2936	5.123	2.536	2931	48	97.85	162.1	681	116.4	142.2	710
15	2.732	4.666	3062	2.738	4.65	3056	49	97.85	158.8	842	116.4	139.7	862
16	3.759	4.666	3145	3.765	4.65	3138	50	97.85	155.6	995	116.4	137.3	1005
17	3.075	7.6892	3173	3.1	7.664	3167	51	97.85	152.5	1063	116.4	134.9	1089
18	5.228	17.54	3399	5.241	17.54	3393	52	3.151	35.33	1052	4.741	42.96	1108
19	8.551	33.107	3149	8.59	33.02	3129	53	10.12	27.15	983	12.33	17.54	1034
20	4.736	43.173	3209	4.741	42.96	3188	54	15.67	13.72	826	17.57	17.54	726
21	0.707	4.666	3280	0.707	4.65	3266	56	45.74	7	82	95.72	7.358	120
22	0.028	0.95	3280	0.028	0.95	3266	57	45.74	7	81.9	95.72	7.358	106
23	0.2	1.2	3280	0.2	1.2	3266	59	0.086	0.022	81.1	0.088	0.95	412
24	0.029	0.95	3247	0.029	0.95	3240	60	4900	1	50.5	4900	1	50.5
25	0.205	1.2	3247	0.205	1.2	3240	61	4900	1	68.1	4900	1	88.6
26	0.031	0.95	2936	0.031	0.95	2931	63	401.9	4	293	0	4	293
27	0.068	1.2	2936	0.068	1.2	2931	64	401.9	3.98	504	0	3.98	293
31	0	2.5065	2930	0	2.506	2930	66	45.74	0.022	81.1	95.72	0.032	105
33	0	11	536	0	11	536	68	97.09	89.58	3381	115.5	104.9	3403
34	95.8	7.3582	139	95.72	7.358	139	69	80.74	6.457	580	95.72	6.787	606

point	W kW	W kW	point	W kW	W kW
28	35496	36755	55	2748	2739
29	95132	96082	58	165	165
30	140478	141194	62	138511	139217
32	0	0	67	331028	331372

Table. 6.30 - Thermodynamic variables relative to the two maintenance operations

CHAPTER 7

Synthesis, contributions and perspectives

7.1 Synthesis

The thermoeconomic diagnosis is a exergy based technique for the detection, location and quantification of the anomalies in energy systems. In particular it is suitable for the analysis of those malfunctions causing the reduction of the plant efficiency, while the techniques usually applied allows to check the critical points, where an anomaly could cause failures.

In this Ph.D. Thesis a thermoeconomic diagnosis procedure which takes into account the contribution of the regulation system intervention on the propagation of the effects of the anomalies has been proposed. The procedure is applied to two energy systems, a steam power plant and a gas turbine plant, both producing electric and thermal power.

In chapter 1 the mathematical model of the energy systems is proposed. The plants have been divided into subsystems, each one is described by means of characteristic equations.

The thermoeconomic diagnosis of a steam power plant has been analysed in deep in literature [Lerch 1999, Uche 2000]. The corresponding direct diagnosis problem (consisting on the location of the anomalies in the control volumes where they have taken place) can be correctly solved in most cases, as the effects induced by the anomalies in the other components are generally lower than the intrinsic effects. On the contrary the gas turbine plant represents an interesting case study, as the induced effects are sometimes higher than the intrinsic one. Its thermoeconomic diagnosis must be so conducted very carefully [Stoppato, Lazzaretto 1996].

In chapter 2 the tools for the thermoeconomic diagnosis are summarized: the exergy and the thermoeconomic analyses. In particular a general thermoeconomic theory, the Structural Theory [Valero et Al. 1993], is here described. The application to the thermal systems is proposed in chapter 3, in order to introduce the productive structures and calculate the exergy costs of the corresponding fluxes, which are required in the following chapters.

The chapter 4 is the thesis core. The complete thermoeconomic diagnosis procedure is here presented. It is constituted by four topics:

1) Calculation of the fuel impact and the malfunction and dysfunction analysis. These quantities are determined by comparing the operation condition with an appropriate reference condition. They include the contribution of the intrinsic effects and all the induced ones.
2) Procedure for the erasure of the effects induced by the regulation system. This procedure is based on the determination of an artificial working condition, called free condition, characterized by the same regulation as the reference condition. This state is characterized by the same anomalies as the operation condition, in fact it is mathematically obtained, starting from this one, by restoring the reference regulation set.

The working condition is fictitious as the set values of the constrained variables are not complied. The comparison between free and reference conditions allows to avoid the effects induced on the thermal system by its control.

3) Calculation of the unit cost of the regulation. It constitutes an evaluation parameter of the usefulness of the free versus reference approach application. In fact this cost takes into account the efficiency variation caused by the regulation system intervention. A value higher than the average cost of the plant products means that the regulation has induced malfunctions on the system. In this case the thermoeconomic diagnosis made by comparing free and reference conditions is particularly suitable, as it allows to erase these induced malfunctions.
4) Erasure of the effects induced by the behaviour of the components. This procedure is particularly helpful in real applications, where the number of the anomalies is generally unknown. In this case it is difficult to understand if the main effects are all intrinsic or some of them are induced, so the erasure of the induced ones represent an important improving, as the location of the more sensible anomalies can be made at the same time. Moreover a better quantification of the anomalies is possible.

In chapters 5 and 6 the application of the diagnosis procedure to the considered energy systems is proposed.

Some cases of single malfunctions in the gas turbine plant have been analysed. The corresponding operation conditions have been simulated by means of the mathematical model. Different productive structures have been applied in order to study the dependence of their choice on the results of the diagnosis problem. The structures mainly differ for the charging of the losses on the components and for the grade of detail, as some of them are characterized by a definition of fuels and products based on total exergy, while the mechanical and thermal components are used in other ones. In particular all the considered structures have allowed the correct location of the anomalies.

The calculation of the unit cost of the regulation has provided a measure of the malfunctions induced by the regulation system, highlighting the improving obtained by applying the proposed procedure.

A particular case of triple malfunction has been considered in order to verify the possibly of the contemporary location of the most important anomalies.

The application of the procedure to the steam power plant has been particularly focused on the analysis of mechanical malfunctions (variation of the pressure drop) in some components. In these cases some important induced effects are generated, so the use of the proposed procedure is particularly suitable. A case of multiple malfunction, obtained using measured data, has been also analysed.

7.2 Main contributions

7.2.1 Effects of the regulation system

The main contribution of this Ph.D. Thesis is methodological: the correct solution of the thermoeconomic diagnosis problem of an energy system is generally impossible without considering the contribution of the regulation system on the propagation of the effects of the anomalies. A possible procedure to takes into account this contribution has been presented.

The procedure is based on the determination of the free working condition, which is characterized by the same regulation as the reference state and the same anomalies as the operation condition. The way here proposed to calculate this condition consists on the assumption of the linear dependence between the quantities describing the thermoeconomic model and the regulation parameters. The whole of these quantities can include the thermodynamic variables at the boundaries of every subsystem or the fluxes of the productive structure, etc. The assumption is acceptable when the anomalies are sufficiently low.

The angular coefficients of the regulation system linear model can be analytically calculated if a model of the plant is available, otherwise it can be numerically calculated, by using as many working conditions as the regulation parameters are.

The application of the diagnosis procedure to the gas turbine plant has pointed out that significant malfunctions are caused by the regulation system, so that the comparison between operation and reference conditions often do not allow to correctly locate where the anomalies have taken place. On the contrary, the comparison between free and reference conditions always allows to determine the main intrinsic contribution.

7.2.2 Effects induced by the dysfunctions

The second induced effects are caused by the dependence of the efficiency of the components on their resources. Therefore the dysfunctions (variation of the production of some components) generally cause induced effects.

To take into account this contribution a linear thermoeconomic model of each component can be built by means of the available working conditions, corresponding to different regulations. In these working conditions any anomaly is present in the system, so the pure induced effects can be calculated. These ones can so be erased.

The procedure has been applied to some gas turbine operation conditions, where single malfunctions and a triple malfunction have been simulated. A productive structure characterized by fluxes split into mechanical and thermal components have been used. The advantage of such a structure is that the effects of the two exergy components on the productive processes are different. In all the analysed simulations it has allowed to find, at the same time, the number of the anomalies and where they had occurred.

The alternative consists on the location and removal of the anomaly corresponding to the main effect. If some anomalies have occurred these two steps must be repeated as many times, until the total fuel impact is zero (supposing that the anomalies could be completely removed). Such a procedure presents two disadvantages: the plant would be stopped many times; the correct quantification of every single effect is not possible as intrinsic and induced effects are joined together.

7.2.3 Cost associated to the regulation system intervention

A definition of the unit cost associated to the regulation system has been proposed in this thesis. This cost is particularly useful because it provides information about the effects of the regulation on the system: an high cost means that the regulation system induces high malfunctions on the system. In this case the thermoeconomic analysis made using the proposed methodology is particularly suitable, as it allows to erase these contributions and make easier the solution of the diagnosis problem.

The cost to be assigned to the regulation system represents an opportunity cost [de Neufville], as it is the additional cost to be paid because the system is not able to work in the free condition. In chapter 5 the variation of this cost has been examined for every regulation parameter of the gas turbine plant.

7.2.4 Considerations about the productive structures

Among the initial objective of this thesis there was the application of the thermoeconomic diagnosis as a tool for the univocal definition of the productive structure to be used for costing and optimization purposes. Although many applications of the thermoeconomic theories have been proposed, an universally accepted definition of fuels and products has not been obtained. The only constraint in thermoeconomics is represented by the cost balance.

Some helps can become from outside. In particular some information were expected from the thermoeconomic diagnosis. If the efficiency of a process decreases (or a component characterized by a lower efficiency is chosen) it affects the other components of the system. The ideal productive structure would assign the cost related to the corresponding efficiency variation only to the responsible component. So it would make intrinsic all the induced effects. Such a structure would be useful also for costing purposes.

The results are disappointing, as any structure is better than the others. Nevertheless some useful advice can be provided.

In the gas turbine plant, if the productive structure is defined by using the exergy components and a pure mechanical or thermal inefficiency occurs the corresponding unit exergy consumption is the most affected. Such a structure is so recommended, as it allows a more correct inefficiencies accounting. The same information can not be obtained in the diagnosis of steam power plants, mainly due to the fluid changing phase. In this case the use of a more detailed structure does not add information and it makes more complex the analysis.

7.3 Perspectives

In last years some advances have been obtained in thermoeconomic diagnosis, from the formulation of the principle of non equivalence of the irreversibilities to the malfunction and dysfunction analysis. This thesis makes this discipline advance a step, but not all the initial questions have been solved and other questions have risen.

In particular, the proposed methodology allows to takes into account the contribution of the induced malfunctions. If several anomalies occur in the system, all their induced effects can be erased at the same time, without be able to assign to every intrinsic malfunction the corresponding induced ones. So the procedure does not allow to quantify every anomaly in terms of fuel impact. This last consideration has an important consequence, in fact the maintenance operation must be economically convenient. Before to stop the plant in order to restore the correct working condition of the component, an expected value of the energy saving must be calculated.

If a malfunction is only partially intrinsic the obtained energy saving could be lower than expected and the intervention could be not convenient. The proposed procedure only allows to calculate the minimum value expected. Sometimes it is close to the real value, in particular if the regulation system does not sensibly affect the working condition, like in the steam power plant. In other cases the real and the expected values differ a lot.

The actual knowledge does not allow to calculate a correct value of the expected energy saving without using a mathematical model of the plant. The research is so open in this direction.

Other applications of the proposed methodology are also necessary. In particular the field of the gas turbines and combined cycles technologies must be accurately explored. It furnishes the most interesting case-studies, where the effects of the regulation system on the malfunctions propagation are sensible.

Moreover the thermoeconomic diagnosis of real plants can involve problems related to the errors in the measured data. This aspect has been not examined in this thesis, but it represents an important step toward the application of thermoeconomic theories to the power plants.

ANNEX 1

Simulation results and model validation

In this part other results obtained by using the plant simulator are proposed. Tables A1.1-A1.5 show the values assumed by the thermodynamic variables characterising the steam power plant in some non cogenerative operation conditions. All the tables refer to the scheme in figure 3.14.

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	113.9	124.5	3450	35	92.99	7	148	1	110.9	124.5	3450	35	90.71	7	146
2	100	31.3	3124	36	92.99	6.86	298	2	97.51	30.53	3123	36	90.71	6.86	296
3	0.444	31.3	3410	37	92.99	6.723	377	3	0.432	30.53	3408	37	90.71	6.723	375
4	100.4	31.3	3125	38	92.99	6.588	513	4	97.94	30.53	3124	38	90.71	6.588	510
5	0	31.3	3125	39	92.99	6.588	513	5	0	30.53	3124	39	90.71	6.588	510
6	100.4	31.3	3125	40	92.99	6.457	600	6	97.94	30.53	3124	40	90.71	6.457	596
7	100.4	28.17	3548	41	3.169	4.082	608	7	97.94	27.48	3549	41	3.07	3.984	604
8	84.1	2.506	2930	42	8.296	2.256	521	8	82.11	2.445	2931	42	8.038	2.201	518
9	84.23	2.506	2930	43	10.95	0.755	385	9	82.24	2.445	2931	43	10.62	0.737	382
10	76.41	0.034	2373	44	16.49	0.355	306	10	74.63	0.034	2374	44	15.99	0.347	303
11	5.067	0.395	2621	45	0.088	0.95	411	11	4.934	0.385	2621	45	0.089	0.95	411
12	5.54	0.395	2667	46	16.49	0.355	116	12	5.377	0.385	2665	46	15.99	0.347	114
13	2.652	0.838	2736	47	113.9	6.393	682	13	2.578	0.819	2737	47	110.9	6.238	677
14	5.127	2.506	2930	48	113.9	165.8	705	14	4.968	2.445	2931	48	110.9	165.1	701
15	2.142	4.535	3056	49	113.9	162.5	871	15	2.059	4.426	3056	49	110.9	161.8	865
16	3.169	4.535	3151	50	113.9	159.2	1031	16	3.07	4.426	3153	50	110.9	158.6	1025
17	1.722	7.345	3170	51	113.9	156	1104	17	1.681	7.167	3170	51	110.9	155.4	1097
18	6.674	15.77	3376	52	3.973	40.98	1094	18	6.46	15.39	3377	52	3.816	39.95	1087
19	8.533	31.3	3124	53	12.51	31.3	1019	19	8.225	30.53	3123	53	12.04	30.53	1013
20	3.973	40.98	3185	54	19.18	15.77	856	20	3.816	39.95	3184	54	18.5	15.39	850
21	0.707	4.535	3259	56	92.99	7	112	21	0.696	4.426	3258	56	90.71	7	110
22	0.028	0.95	3259	57	92.99	7	112	22	0.028	0.95	3258	57	90.71	7	110
23	0.2	1.2	3259	59	0.088	0.034	111	23	0.188	1.2	3258	59	0.089	0.034	109
24	0.029	0.95	3207	60	4900	1	50.5	24	0.029	0.95	3197	60	4900	1	50.5
25	0.205	1.2	3207	61	4900	1	85.7	25	0.194	1.2	3197	61	4900	1	85
26	0.031	0.95	3046	63	0	4	293	26	0.031	0.95	3033	63	0	4	293
27	0.068	1.2	2778	64	0	3.98	504	27	0.062	1.2	2739	64	0	3.98	504
31	0	2.506	2930	66	92.99	0.034	111	31	0	2.445	2931	66	90.71	0.034	109
33	0	11	536	68	113	105	3410	33	0	11	533	68	110	102.2	3408
34	92.99	7	145	69	92.99	6.457	600	34	90.71	7	144	69	90.71	6.457	596

point	W kW	point	W kW	point	W kW	point	W kW
28	36650	55	3340	28	35775	55	3238
29	94824	58	109	29	92548	58	106
30	139519	62	136048	30	136146	62	132760
32	0	67	329454	32	0	67	321850

Table. A1.1 - Thermodynamic variables corresponding to 136 MWe and 133 MWe production

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	105.6	124.5	3450	35	86.66	7	143	1	97.85	124.5	3450	35	80.71	7	139
2	93.08	29.16	3117	36	86.66	6.86	291	2	86.53	27.14	3104	36	80.71	6.86	285
3	0.409	29.16	3401	37	86.66	6.723	370	3	0.375	27.14	3381	37	80.71	6.723	362
4	93.48	29.16	3119	38	86.66	6.588	503	4	86.91	27.14	3105	38	80.71	6.588	496
5	0	29.16	3119	39	86.66	6.588	503	5	0	27.14	3105	39	80.71	6.588	496
6	93.48	29.16	3119	40	86.66	6.457	589	6	86.91	27.14	3105	40	80.71	6.457	579
7	93.48	26.24	3550	41	2.904	3.805	597	7	86.91	24.43	3552	41	2.62	3.567	587
8	78.5	2.334	2931	42	7.587	2.1	511	8	73.24	2.207	2935	42	6.963	1.986	504
9	78.63	2.334	2931	43	10.03	0.705	378	9	73.35	2.207	2935	43	9.211	0.659	370
10	71.47	0.033	2376	44	15.1	0.332	299	10	66.77	0.031	2379	44	13.85	0.31	292
11	4.615	0.369	2622	45	0.088	0.95	411	11	4.258	0.344	2623	45	0.089	0.95	411
12	5.069	0.369	2671	46	15.1	0.332	110	12	4.64	0.344	2667	46	13.85	0.31	106
13	2.445	0.783	2738	47	105.6	5.96	670	13	2.249	0.732	2739	47	97.85	5.55	658
14	4.683	2.334	2931	48	105.6	163.9	693	14	4.343	2.207	2935	48	97.85	162	680
15	1.958	4.228	3057	49	105.6	160.6	856	15	1.717	3.963	3060	49	97.85	158.8	841
16	2.904	4.228	3151	50	105.6	157.4	1013	16	2.62	3.963	3154	50	97.85	155.6	995
17	1.613	6.848	3171	51	105.6	154.2	1083	17	1.473	6.398	3174	51	97.85	152.5	1063
18	6.083	14.71	3378	52	3.542	38.09	1073	18	5.544	13.71	3380	52	3.152	35.32	1052
19	7.704	29.16	3117	53	11.25	29.16	1001	19	6.974	27.14	3104	53	10.13	27.14	983
20	3.542	38.09	3178	54	17.33	14.71	841	20	3.152	35.32	3162	54	15.67	13.71	826
21	0.651	4.228	3252	56	86.66	7	108	21	0.623	3.963	3235	56	80.71	7	104
22	0.028	0.95	3252	57	86.66	7	108	22	0.029	0.95	3235	57	80.71	7	104
23	0.194	1.2	3252	59	0.088	0.033	107	23	0.166	1.2	3235	59	0.089	0.031	103
24	0.029	0.95	3222	60	4900	1	50.5	24	0.029	0.95	3203	60	4900	1	50.5
25	0.197	1.2	3222	61	4900	1	83.6	25	0.169	1.2	3203	61	4900	1	81.5
26	0.031	0.95	3063	63	0	4	293	26	0.031	0.95	3036	63	0	4	293
27	0.063	1.2	2800	64	0	3.98	504	27	0.048	1.2	2706	64	0	3.98	504
31	0	2.334	2931	66	86.66	0.033	107	31	0	2.207	2935	66	80.71	0.031	103
33	0	11	526	68	104.8	97.18	3401	33	0	11	519	68	97.09	89.57	3381
34	86.66	7	141	69	86.66	6.457	589	34	80.71	7	136	69	80.71	6.457	579

point	W kW	point	W kW	point	W kW	point	W kW
28	34657	55	3059	28	33478	55	2800
29	88959	58	101	29	83815	58	94
30	130562	62	127315	30	122737	62	119684
32	0	67	308754	32	0	67	289800

Table A1.2 - Thermodynamic variables corresponding to 127 MWe and 120 MWe production

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	90.06	124.5	3450	35	74.63	7	135	1	88.14	124.5	3450	35	73.16	7	134
2	79.92	25.09	3090	36	74.63	6.86	277	2	78.29	24.59	3090	36	73.16	6.86	275
3	0.341	25.09	3362	37	74.63	6.723	354	3	0.333	24.59	3362	37	73.16	6.723	352
4	80.26	25.09	3091	38	74.63	6.588	483	4	78.63	24.59	3091	38	73.16	6.588	482
5	0	25.09	3091	39	74.63	6.588	483	5	0	24.59	3091	39	73.16	6.588	482
6	80.26	25.09	3091	40	74.63	6.457	567	6	78.63	24.59	3091	40	73.16	6.457	564
7	80.26	22.58	3554	41	2.411	3.287	575	7	78.63	22.13	3554	41	2.323	3.235	573
8	67.88	2.015	2934	42	6.285	1.813	492	8	66.57	1.996	2936	42	6.149	1.797	491
9	67.98	2.015	2934	43	8.348	0.611	362	9	66.66	1.996	2936	43	8.16	0.599	360
10	62	0.029	2383	44	12.55	0.287	285	10	60.81	0.029	2384	44	12.26	0.282	283
11	3.85	0.319	2624	45	0.089	0.95	411	11	3.775	0.313	2624	45	0.089	0.95	411
12	4.2	0.319	2668	46	12.55	0.287	101	12	4.096	0.313	2665	46	12.26	0.282	100
13	2.062	0.679	2741	47	90.06	5.136	645	13	2.011	0.666	2741	47	88.14	5.035	642
14	3.874	2.015	2934	48	90.06	160.2	667	14	3.826	1.996	2936	48	88.14	159.8	664
15	1.576	3.652	3061	49	90.06	157	826	15	1.493	3.595	3062	49	88.14	156.6	822
16	2.411	3.652	3151	50	90.06	153.9	976	16	2.323	3.595	3155	50	88.14	153.5	971
17	1.388	5.91	3175	51	90.06	150.8	1041	17	1.342	5.804	3176	51	88.14	150.4	1035
18	5.001	12.69	3382	52	2.78	32.53	1030	18	4.872	12.44	3382	52	2.693	31.87	1024
19	6.262	25.09	3090	53	9.042	25.09	963	19	6.077	24.59	3090	53	8.769	24.59	958
20	2.78	32.53	3147	54	14.04	12.69	810	20	2.693	31.87	3147	54	13.64	12.44	806
21	0.578	3.652	3219	56	74.63	7	100	21	0.574	3.595	3219	56	73.16	7	99.5
22	0.029	0.95	3219	57	74.63	7	100	22	0.029	0.95	3219	57	73.16	7	99.5
23	0.154	1.2	3219	59	0.089	0.029	99.5	23	0.143	1.2	3219	59	0.089	0.029	98.6
24	0.029	0.95	3211	60	4900	1	50.5	24	0.029	0.95	3196	60	4900	1	50.5
25	0.156	1.2	3211	61	4900	1	79.4	25	0.145	1.2	3196	61	4900	1	78.8
26	0.031	0.95	3042	63	0	4	293	26	0.031	0.95	3024	63	0	4	293
27	0.04	1.2	2687	64	0	3.98	504	27	0.034	1.2	2605	64	0	3.98	504
31	0	2.015	2934	66	74.63	0.029	99.5	31	0	1.996	2936	66	73.16	0.029	98.6
33	0	11	506	68	89.36	82.03	3362	33	0	11	505	68	87.46	80.29	3362
34	74.63	7	131	69	74.63	6.457	567	34	73.16	7	130	69	73.16	6.457	564

point	W kW	point	W kW	point	W kW	point	W kW
28	32048	55	2548	28	31368	55	2485
29	78810	58	87	29	77058	58	86
30	114570	62	111720	30	112229	62	109437
32	0	67	270274	32	0	67	265091

Table A1.3 - Thermodynamic variables corresponding to 112 MWe and 109 MWe production

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	79.02	124.5	3450	35	66.04	7	128	1	71.74	124.5	3450	35	60.25	7	124
2	70.53	22.18	3089	36	66.04	6.86	266	2	64.27	20.23	3085	36	60.25	6.86	258
3	0.297	22.18	3359	37	66.04	6.723	341	3	0.268	20.23	3353	37	60.25	6.723	332
4	70.83	22.18	3090	38	66.04	6.588	471	4	64.53	20.23	3086	38	60.25	6.588	457
5	0	22.18	3090	39	66.04	6.588	471	5	0	20.23	3086	39	60.25	6.588	457
6	70.83	22.18	3090	40	66.04	6.457	550	6	64.53	20.23	3086	40	60.25	6.457	536
7	70.83	19.97	3556	41	2.018	2.937	559	7	64.53	18.21	3558	41	1.833	2.665	545
8	60.22	1.826	2940	42	5.423	1.643	479	8	55.08	1.636	2938	42	4.809	1.473	465
9	60.3	1.826	2940	43	7.203	0.543	349	9	55.16	1.636	2938	43	6.412	0.498	340
10	55.16	0.027	2390	44	10.79	0.256	274	10	50.57	0.026	2395	44	9.594	0.235	266
11	3.307	0.284	2626	45	0.089	0.95	411	11	2.933	0.261	2628	45	0.089	0.95	411
12	3.587	0.284	2667	46	10.79	0.256	95.2	12	3.182	0.261	2669	46	9.594	0.235	91.4
13	1.78	0.604	2743	47	79.02	4.548	625	13	1.603	0.553	2744	47	71.74	4.151	611
14	3.405	1.826	2940	48	79.02	157.7	647	14	2.976	1.636	2938	48	71.74	156	633
15	1.271	3.264	3065	49	79.02	154.5	802	15	1.154	2.962	3065	49	71.74	152.8	784
16	2.018	3.264	3160	50	79.02	151.4	946	16	1.833	2.962	3159	50	71.74	149.8	925
17	1.195	5.254	3178	51	79.02	148.4	1009	17	1.111	4.784	3179	51	71.74	146.8	985
18	4.263	11.24	3385	52	2.293	28.7	997	18	3.782	10.26	3386	52	1.992	26.12	973
19	5.232	22.18	3089	53	7.525	22.18	933	19	4.596	20.23	3085	53	6.588	20.23	911
20	2.293	28.7	3146	54	11.79	11.24	786	20	1.992	26.12	3141	54	10.37	10.26	768
21	0.517	3.264	3217	56	66.04	7	95.2	21	0.47	2.962	3212	56	60.25	7	91.7
22	0.029	0.95	3217	57	66.04	7	95.1	22	0.029	0.95	3212	57	60.25	7	91.6
23	0.127	1.2	3217	59	0.089	0.027	94.3	23	0.115	1.2	3212	59	0.089	0.026	90.8
24	0.029	0.95	3204	60	4900	1	50.5	24	0.029	0.95	3215	60	4900	1	50.5
25	0.128	1.2	3204	61	4900	1	76.3	25	0.116	1.2	3215	61	4900	1	74.2
26	0.031	0.95	3033	63	0	4	293	26	0.031	0.95	3044	63	0	4	293
27	0.025	1.2	2509	64	0	3.98	504	27	0.018	1.2	2387	64	0	3.98	504
31	0	1.826	2940	66	66.04	0.027	94.3	31	0	1.636	2938	66	60.25	0.026	90.8
33	0	11	493	68	78.41	72.01	3359	33	0	11	479	68	71.18	65.29	3353
34	66.04	7	124	69	66.04	6.457	550	34	60.25	7	119	69	60.25	6.457	536

point	W kW	point	W kW	point	W kW	point	W kW
28	28211	55	2196	28	25916	55	1970
29	69317	58	77	29	63659	58	70
30	101080	62	98565	30	92315	62	90019
32	0	67	240332	32	0	67	220478

Table A1.4 - Thermodynamic variables corresponding to 99 MWe and 90 MWe production

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	59.8	124.5	3450	35	50.71	7	116	1	50.35	124.5	3450	35	43.01	7	110
2	53.92	17.01	3068	36	50.71	6.86	243	2	45.62	14.41	3038	36	43.01	6.86	230
3	0.219	17.01	3329	37	50.71	6.723	316	3	0.18	14.41	3288	37	43.01	6.723	300
4	54.14	17.01	3069	38	50.71	6.588	437	4	45.8	14.41	3039	38	43.01	6.588	413
5	0	17.01	3069	39	50.71	6.588	437	5	7E-04	14.41	3039	39	43.01	6.588	413
6	54.14	17.01	3069	40	50.71	6.457	513	6	45.8	14.41	3039	40	43.01	6.457	489
7	54.14	15.31	3561	41	1.465	2.257	521	7	45.8	12.97	3563	41	1.241	1.894	498
8	46.69	1.393	2942	42	3.881	1.254	445	8	39.76	1.142	2937	42	3.134	1.028	421
9	46.68	1.393	2942	43	5.194	0.423	323	9	39.75	1.142	2937	43	4.221	0.362	308
10	42.89	0.024	2407	44	7.746	0.2	251	10	36.67	0.022	2420	44	6.253	0.171	238
11	2.52	0.222	2631	45	0.084	0.95	411	11	2.032	0.19	2634	45	0.084	0.95	411
12	2.552	0.222	2639	46	7.746	0.2	85.3	12	2.032	0.19	2634	46	6.253	0.171	80.7
13	1.313	0.47	2748	47	59.8	3.498	584	13	1.087	0.402	2751	47	50.35	2.97	560
14	2.415	1.393	2942	48	59.8	153.2	606	14	1.893	1.142	2937	48	50.35	150.9	581
15	0.874	2.508	3068	49	59.8	150.1	752	15	0.733	2.105	3068	49	50.35	147.9	722
16	1.465	2.508	3164	50	59.8	147.1	886	16	1.241	2.105	3155	50	50.35	144.9	851
17	0.918	4.039	3182	51	59.8	144.1	942	17	0.797	3.413	3183	51	50.35	142	903
18	3.024	8.647	3389	52	1.528	21.84	929	18	2.442	7.334	3392	52	1.19	18.37	889
19	3.619	17.01	3068	53	5.147	17.01	872	19	2.914	14.41	3038	53	4.104	14.41	836
20	1.528	21.84	3122	54	8.171	8.647	735	20	1.19	18.37	3090	54	6.547	7.334	706
21	0.411	2.508	3192	56	50.71	7	85.8	21	0.354	2.105	3157	56	43.01	7	81.3
22	0.029	0.95	3192	57	50.71	7	85.8	22	0.029	0.95	3157	57	43.01	7	81.2
23	0.08	1.2	3192	59	0.084	0.024	84.9	23	0.063	1.2	3157	59	0.084	0.022	80.4
24	0.027	0.95	3427	60	4900	1	50.5	24	0.027	0.95	3414	60	4900	1	50.5
25	0.016	1.2	3883	61	4900	1	70.8	25	0.004	1.2	3157	61	4900	1	68
26	0.028	0.95	3305	63	0	4	293	26	0.028	0.95	3278	63	0	4	293
27	-0.06	1.2	3305	64	0	3.98	504	27	-0.07	1.2	3278	64	0	3.98	504
31	0	1.393	2942	66	50.71	0.024	84.9	31	0	1.142	2937	66	43.01	0.022	80.4
33	0	11	458	68	59.34	54.1	3329	33	0	11	434	68	49.96	45.02	3288
34	50.71	7	111	69	50.71	6.457	513	34	43.01	7	104	69	43.01	6.457	489

point	W kW	point	W kW	point	W kW	point	W kW
28	22630	55	1609	28	20562	55	1332
29	54295	58	59	29	47705	58	50
30	78287	62	76340	30	67492	62	65814
32	0	67	187832	32	0	67	161930

Table A1.5 - Thermodynamic variables corresponding to 76 MWe and 66 MWe production

Tables A1.6-A1.8 show the thermodynamic variables corresponding to some cogenerative working conditions. The simulations have been made by keeping maximum the live steam produced and by varying the extraction downstream the middle pressure turbine.

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	113.9	124.5	3450	35	24.12	7	106	1	113.9	124.5	3450	35	58.03	7	126
2	100	31.33	3124	36	24.12	6.86	173	2	100	31.31	3124	36	58.03	6.86	251
3	0.444	31.33	3410	37	24.12	6.723	235	3	0.444	31.31	3410	37	58.03	6.723	323
4	100.5	31.33	3125	38	24.12	6.588	522	4	100.5	31.31	3125	38	58.03	6.588	515
5	0	31.33	3125	39	93.12	6.588	538	5	0	31.31	3125	39	93.03	6.588	524
6	100.5	31.33	3125	40	93.12	6.457	604	6	100.5	31.31	3125	40	93.03	6.457	601
7	100.5	28.19	3548	41	2.398	4.178	612	7	100.5	28.18	3548	41	2.811	4.113	609
8	18.49	2.627	2939	42	5.188	2.365	528	8	50.25	2.539	2933	42	7.328	2.286	523
9	18.49	0.559	2939	43	5.188	0.176	240	9	50.25	1.503	2933	43	8.481	0.456	331
10	18.38	0.019	2484	44	5.652	0.087	181	10	46.77	0.025	2398	44	11.18	0.217	259
11	0.169	0.097	2641	45	0.086	0.95	411	11	2.233	0.241	2625	45	0.088	0.95	411
12	0.464	0.097	3012	46	5.652	0.087	69.1	12	2.697	0.241	2718	46	11.18	0.217	89.5
13	0	0.195	2751	47	113.9	6.402	682	13	1.153	0.506	2740	47	113.9	6.396	682
14	2.79	2.627	2939	48	113.9	165.8	706	14	4.517	2.539	2933	48	113.9	165.8	705
15	1.347	4.642	3061	49	113.9	162.5	872	15	1.775	4.57	3058	49	113.9	162.5	871
16	2.398	4.642	3187	50	113.9	159.2	1032	16	2.811	4.57	3165	50	113.9	159.2	1031
17	1.596	7.422	3172	51	113.9	156.1	1105	17	1.68	7.37	3171	51	113.9	156.1	1104
18	6.689	15.81	3376	52	3.969	41	1094	18	6.679	15.79	3376	52	3.972	40.99	1094
19	8.518	31.33	3124	53	12.49	31.33	1020	19	8.528	31.31	3124	53	12.5	31.31	1020
20	3.969	41	3185	54	19.18	15.81	856	20	3.972	40.99	3185	54	19.18	15.79	856
21	0.723	4.642	3259	56	24.12	7	69.7	21	0.712	4.57	3259	56	58.03	7	89.3
22	0.028	0.95	3259	57	24.12	7	69.6	22	0.028	0.95	3259	57	58.03	7	89.2
23	0.183	1.2	3259	59	0.086	0.019	68.7	23	0.194	1.2	3259	59	0.088	0.025	88.4
24	0.029	0.95	3209	60	4900	1	50.5	24	0.029	0.95	3205	60	4900	1	50.5
25	0.199	1.2	3193	61	4900	1	59.5	25	0.203	1.2	3200	61	4900	1	72.5
26	0.029	0.95	3225	63	785.4	4	293	26	0.031	0.95	3042	63	398.1	4	293
27	-0.09	1.2	3225	64	785.4	3.98	504	27	0.068	1.2	2774	64	398.1	3.98	504
31	69	2.627	2939	66	24.12	0.019	68.7	31	35	2.539	2933	66	58.03	0.025	88.4
33	69	11	543	68	113	105	3410	33	35	11	538	68	113	105	3410
34	24.12	7	95.9	69	93.12	6.457	604	34	58.03	7	122	69	93.03	6.457	601

point	W kW	point	W kW	point	W kW	point	W kW
28	36629	55	3341	28	36643	55	3340
29	94083	58	28	29	94639	58	68
30	102517	62	99967	30	120557	62	117558
32	85	67	329352	32	43	67	329442

Table A1.6 - Thermodynamic variables corresponding to 165 MW_{th} and 84 MW_{th} production

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	113.9	124.5	3450	35	35.07	7	112	1	113.9	124.5	3450	35	46.07	7	119
2	100	31.32	3124	36	35.07	6.86	205	2	100	31.32	3124	36	46.07	6.86	230
3	0.444	31.32	3410	37	35.07	6.723	270	3	0.444	31.32	3410	37	46.07	6.723	298
4	100.5	31.32	3125	38	35.07	6.588	517	4	100.5	31.32	3125	38	46.07	6.588	517
5	0	31.32	3125	39	93.07	6.588	532	5	0	31.32	3125	39	93.07	6.588	529
6	100.5	31.32	3125	40	93.07	6.457	602	6	100.5	31.32	3125	40	93.07	6.457	602
7	100.5	28.19	3548	41	2.551	4.145	610	7	100.5	28.19	3548	41	2.645	4.145	610
8	28.55	2.581	2936	42	6.059	2.323	525	8	38.88	2.587	2936	42	6.736	2.328	526
9	28.55	0.86	2936	43	6.371	0.266	278	9	38.88	1.17	2936	43	7.431	0.357	306
10	27.52	0.02	2443	44	7.472	0.129	213	10	36.72	0.022	2418	44	9.272	0.171	237
11	0.779	0.143	2633	45	0.086	0.95	411	11	1.504	0.19	2630	45	0.086	0.95	411
12	1.101	0.143	2808	46	7.473	0.129	75	12	1.841	0.19	2740	46	9.272	0.171	81.6
13	0.312	0.295	2745	47	113.9	6.399	682	13	0.695	0.397	2744	47	113.9	6.399	682
14	3.507	2.581	2936	48	113.9	165.8	705	14	4.091	2.587	2936	48	113.9	165.8	705
15	1.522	4.606	3059	49	113.9	162.5	871	15	1.616	4.606	3059	49	113.9	162.5	871
16	2.551	4.606	3176	50	113.9	159.2	1031	16	2.645	4.606	3172	50	113.9	159.2	1031
17	1.636	7.396	3171	51	113.9	156.1	1104	17	1.636	7.396	3171	51	113.9	156.1	1104
18	6.684	15.8	3376	52	3.971	41	1094	18	6.684	15.8	3376	52	3.971	41	1094
19	8.523	31.32	3124	53	12.49	31.32	1020	19	8.523	31.32	3124	53	12.49	31.32	1020
20	3.971	41	3185	54	19.18	15.8	856	20	3.971	41	3185	54	19.18	15.8	856
21	0.708	4.606	3259	56	35.07	7	75.6	21	0.708	4.606	3259	56	46.07	7	81.9
22	0.028	0.95	3259	57	35.07	7	75.5	22	0.028	0.95	3259	57	46.07	7	81.9
23	0.199	1.2	3259	59	0.086	0.02	74.6	23	0.199	1.2	3259	59	0.086	0.022	81
24	0.029	0.95	3207	60	4900	1	50.5	24	0.029	0.95	3207	60	4900	1	50.5
25	0.206	1.2	3205	61	4900	1	63.8	25	0.206	1.2	3205	61	4900	1	68
26	0.029	0.95	3231	63	659.9	4	293	26	0.029	0.95	3232	63	534.8	4	293
27	-0.08	1.2	3231	64	659.9	3.98	504	27	-0.07	1.2	3232	64	534.8	3.98	504
31	58	2.581	2936	66	35.07	0.02	74.6	31	47	2.587	2936	66	46.07	0.022	81
33	58	11	540	68	113	105	3410	33	47	11	541	68	113	105	3410
34	35.07	7	105	69	93.07	6.457	602	34	46.07	7	113	69	93.07	6.457	602

point	W kW	point	W kW	point	W kW	point	W kW
28	36636	55	3340	28	36636	55	3340
29	94383	58	41	29	94331	58	54
30	108266	62	105573	30	113974	62	111139
32	71	67	329429	32	58	67	329428

Table A1.7 - Thermodynamic variables corresponding to 139 MW_{th} and 113 MW_{th} production

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	113.9	124.5	3450	35	69.03	7	133
2	100	31.31	3124	36	69.03	6.86	268
3	0.444	31.31	3410	37	69.03	6.723	342
4	100.5	31.31	3125	38	69.03	6.588	515
5	0	31.31	3125	39	93.03	6.588	521
6	100.5	31.31	3125	40	93.03	6.457	601
7	100.5	28.18	3548	41	2.904	4.113	609
8	60.83	2.545	2933	42	7.745	2.291	523
9	60.83	1.818	2933	43	9.349	0.549	350
10	56.04	0.028	2388	44	12.9	0.259	275
11	3.086	0.288	2624	45	0.088	0.95	411
12	3.55	0.288	2694	46	12.9	0.259	97.2
13	1.604	0.61	2739	47	113.9	6.396	682
14	4.841	2.545	2933	48	113.9	165.8	705
15	1.868	4.57	3058	49	113.9	162.5	871
16	2.904	4.57	3162	50	113.9	159.2	1031
17	1.68	7.37	3171	51	113.9	156.1	1104
18	6.679	15.79	3376	52	3.972	40.99	1094
19	8.528	31.31	3124	53	12.5	31.31	1020
20	3.972	40.99	3185	54	19.18	15.79	856
21	0.712	4.57	3259	56	69.03	7	96.2
22	0.028	0.95	3259	57	69.03	7	96.1
23	0.194	1.2	3259	59	0.088	0.028	95.3
24	0.029	0.95	3205	60	4900	1	50.5
25	0.203	1.2	3201	61	4900	1	76.7
26	0.031	0.95	3042	63	273	4	293
27	0.068	1.2	2775	64	273	3.98	504
31	24	2.545	2933	66	69.03	0.028	95.3
33	24	11	539	68	113	105	3410
34	69.03	7	129	69	93.03	6.457	601

point	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg
1	113.9	124.5	3450	35	80.99	7	140
2	100	31.3	3124	36	80.99	6.86	284
3	0.444	31.3	3410	37	80.99	6.723	361
4	100.4	31.3	3125	38	80.99	6.588	513
5	0	31.3	3125	39	92.99	6.588	516
6	100.4	31.3	3125	40	92.99	6.457	600
7	100.4	28.17	3548	41	3.069	4.082	608
8	72.46	2.5	2930	42	8.061	2.25	521
9	72.46	2.163	2930	43	10.18	0.65	369
10	66.19	0.031	2377	44	14.71	0.307	291
11	4.058	0.341	2620	45	0.088	0.95	411
12	4.529	0.341	2677	46	14.71	0.307	106
13	2.12	0.723	2736	47	113.9	6.393	682
14	4.992	2.5	2930	48	113.9	165.8	705
15	2.042	4.535	3056	49	113.9	162.5	871
16	3.069	4.535	3154	50	113.9	159.2	1031
17	1.722	7.345	3170	51	113.9	156	1104
18	6.674	15.77	3376	52	3.973	40.98	1094
19	8.533	31.3	3124	53	12.51	31.3	1019
20	3.973	40.98	3185	54	19.18	15.77	856
21	0.706	4.535	3259	56	80.99	7	104
22	0.028	0.95	3259	57	80.99	7	104
23	0.2	1.2	3259	59	0.088	0.031	103
24	0.029	0.95	3203	60	4900	1	50.5
25	0.204	1.2	3205	61	4900	1	81.2
26	0.031	0.95	3041	63	136.4	4	293
27	0.067	1.2	2765	64	136.4	3.98	504
31	12	2.5	2930	66	80.99	0.031	103
33	12	11	536	68	113	105	3410
34	80.99	7	137	69	92.99	6.457	600

point	W kW	point	W kW	point	W kW	point	W kW
28	36643	55	3340	28	36650	55	3340
29	94586	58	81	29	94882	58	95
30	126440	62	123295	30	133112	62	129801
32	30	67	329443	32	15	67	329449

Table A1.8 - Thermodynamic variables corresponding to 57.5 MW_{th} and 29 MW_{th} production

These data can be useful for the model validation. The validation has been made by comparing the values of the simulation with the design values, both corresponding to some cogenerative and non-cogenerative working modes. The design values refers to two different sources: [AEM, 1966] and [AEM, 1983], respectively corresponding to the first design and the cogenerative mode design. The values of the thermodynamic variables corresponding to maximum electric production are available in both documents. The model has been built by using [AEM, 1966], so the errors have been calculated by comparing the simulated condition and [AEM, 1983]. The design values are shown in tables A1.9-A1.10, while the results of the validation, expressed as per cent difference between simulated and design values of mass flows, pressures and enthalpies are shown in tables A1.11-A1.12.

	136 Mwe			118 Mwe - 83 MW_{th}			101 Mwe - 166 MW_{th}		
	G [kg/s]	p [bar]	h [kJ/kg]	G [kg/s]	p [bar]	h [kJ/kg]	G [kg/s]	p [bar]	h [kJ/kg]
1	113.8	124.5	3449	113.8	124.5	3449	113.8	124.5	3449
4	101.1	31.54	3117	101.1	31.54	3117	101.1	31.55	3117
7	101.1	28.69	3547	101.1	28.69	3547	101.1	28.7	3547
10	76.1	0.031	2395	46.7	0.025	2424	17.6	0.031	2538
11	4.5	0.394	2629	1.9	0.241	2633	0.0	0.097	2836
12	4.8	0.352	2641	2.2	0.216	2656	0.0	0.086	2836
13	3.7	0.824	2736	2.1	0.5	2739	0.7	0.184	2744
14	5.1	2.486	2927	4.3	2.486	2927	2.2	2.486	2930
15	2.8	4.531	3056	2.6	4.531	3056	2.5	4.56	3057
16	3.8	4.168	3127	3.6	4.197	3133	3.5	4.197	3134
17	2.5	7.375	3170	2.5	7.394	3171	2.5	7.394	3171
18	5.9	16.13	3379	5.9	16.13	3379	5.9	16.14	3379
19	6.9	31.54	3115	6.9	31.54	3115	6.9	31.54	3116
20	4.9	43.02	3189	4.9	43.02	3189	4.9	43.03	3189
31	0.0	2.486	2927	34.7	2.486	2927	69.4	2.486	2930
35	93.6		111	58.9		97	24.2		121
36	93.6		273	58.9		227	24.2		149
37	93.6		366	58.9		313	24.2		219
38	93.6		512	58.9		519	24.2		521
40	93.6		615	93.6		615	93.6		615
41	3.8		611	3.6		612	3.5		612
42	8.9		377	8.9		324	5.8		230
43	12.6		383	12.6		330	6.4		235
47	113.8		686	113.8		687	113.8		687
48	113.8		710	113.8		711	113.8		711
49	113.8		877	113.8		878	113.8		878
50	113.8		1009	113.8		1009	113.8		1009
51	113.8		1097	113.8		1097	113.8		1097
52	4.9		1092	4.9		1092	4.9		1092
53	11.8		1005	11.8		1006	11.8		1006
54	17.7		715	17.7		715	17.6		715
	W [kW]			W [kW]			W [kW]		
55	2760			2760			2760		
62	136268			118389			100983		

Table A1.9 - Design values assumed by the thermodynamic variables [AEM 1983]

	120 Mwe			95 Mwe		
	G [kg/s]	p [bar]	h [kJ/kg]	G [kg/s]	p [bar]	h [kJ/kg]
1	96.7	124.5	3453	75.5	124.5	3453
4	86.1	27.46	3108	67.8	21.57	3098
7	86.1	24.71	3550	67.8	19.42	3555
10	66.4	0.029	2370	53.3	0.025	2384
11	3.6	0.343	2618	2.8	0.275	2623
12						
13	3.2	0.716	2732	2.2	0.559	2738
14	4.2	2.138	2928	3.2	1.667	2930
15	2.7	3.923	3053	2.1	3.089	3056
16						
17	2.6	6.374	3169	1.7	4.511	3172
18	4.3	13.93	3381	3.3	10.89	3384
19	6.5	27.46	3113	4.6	21.57	3098
20	3.3	35.6	3182	2.4	28.24	3158
31						
35	80.1		155	63.5	0.0	139
36	80.1		265	63.5	0.0	256
37	80.1		359	63.5	0.0	338
38	80.1		498	63.5	0.0	472
40	80.1		580	63.5	0.0	553
41	2.7		585	2.1	0.0	551
42	6.9		500	5.3	0.0	466
43	10.1		364	7.4	0.0	337
47						
48	96.7		685	75.5	0.0	644
49	96.7		831	75.5	0.0	786
50	96.7		975	75.5	0.0	921
51	96.7		1061	75.5	0.0	999
52	3.3		1037	2.4	0.0	976
53	9.8		969	7.0	0.0	909
54	14.1		689	10.3	0.0	642
	W [kW]			W [kW]		
55						
62	120000			95000		

Table A1.10 - Design values assumed by the thermodynamic variables [AEM 1966]

	136 Mwe			118 Mwe - 83 MW_{th}			101 Mwe - 166 MW_{th}		
	ΔG/G	Δp/p	Δh/h	ΔG/G	Δp/p	Δh/h	ΔG/G	Δp/p	Δh/h
1	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0
4	-0.6	-0.8	0.3	-0.6	-0.7	0.3	-0.6	-0.7	0.2
7	-0.6	-1.9	0.0	-0.6	-1.8	0.0	-0.6	-1.8	0.0
10	0.4	9.0	-1.0	0.2	-2.0	-1.1	4.1	-68.3	-2.2
11	11.3	0.2	-0.3	14.2	-0.2	-0.3	100.0	-0.1	-7.4
12	13.7	10.8	1.0	19.9	10.4	2.3	98.5	11.0	5.9
13	-40.6	1.7	0.0	-84.3	1.2	0.0		5.7	0.3
14	1.4	0.8	0.1	5.7	2.1	0.2	20.3	5.4	0.3
15	-32.3	0.1	0.0	-46.6	0.9	0.0	-87.4	1.8	0.1
16	-21.0	8.1	0.8	-28.2	8.2	1.0	-47.1	9.6	1.7
17	-46.5	-0.4	0.0	-50.3	-0.3	0.0	-58.8	0.4	0.0
18	11.8	-2.3	-0.1	12.2	-2.2	-0.1	12.2	-2.1	-0.1
19	18.9	-0.8	0.3	18.9	-0.7	0.3	18.8	-0.7	0.3
20	-22.3	-5.0	-0.1	-22.4	-5.0	-0.1	-22.5	-4.9	-0.1
31		0.8	0.1	0.8	2.1	0.2	-0.6	5.4	0.3
35	-0.7		25.3	-1.5		23.0	-0.2		-14.2
36	-0.7		8.2	-1.5		9.4	-0.2		13.9
37	-0.7		3.0	-1.5		3.0	-0.2		6.6
38	-0.7		0.1	-1.5		-0.9	-0.2		0.3
40	-0.7		-2.6	-0.6		-2.4	-0.5		-1.9
41	-21.0		-0.5	-28.2		-0.5	-47.1		-0.1
42	-7.1		27.7	-21.3		38.1	-10.8		56.4
43	-15.2		0.5	-48.7		0.4	-24.1		2.1
47	0.1		-0.7	0.1		-0.7	0.1		-0.7
48	0.1		-0.8	0.1		-0.8	0.1		-0.7
49	0.1		-0.7	0.1		-0.8	0.1		-0.7
50	0.1		2.2	0.1		2.2	0.1		2.2
51	0.1		0.6	0.1		0.6	0.1		0.7
52	-22.3		0.2	-22.4		0.2	-22.5		0.2
53	5.8		1.4	5.8		1.4	5.7		1.4
54	7.9		16.5	7.9		16.4	8.0		16.5
	ΔW/W			ΔW/W			ΔW/W		
55	17.4			17.4			17.4		
62	-0.2			-0.7			-1.0		

Table A1.11 - Per cent difference between design [AEM 1983] and simulated values.

	120 Mwe			95 Mwe		
	ΔG/G	Δp/p	Δh/h	ΔG/G	Δp/p	Δh/h
1	1.2	0.0	-0.1	1.0	0.0	-0.1
4	1.0	-1.2	-0.1	1.0	-0.6	-0.3
7	1.0	-1.2	0.0	1.0	-0.6	0.0
10	0.5	5.1	0.4	0.3	4.6	0.3
11	16.3	0.3	0.2	12.3	0.2	0.1
12						
13	-40.5	2.2	0.3	-27.2	4.4	0.2
14	3.1	3.1	0.3	2.7	5.0	0.3
15	-56.5	1.0	0.2	-72.0	1.9	0.3
16						
17	-73.8	0.4	0.1	-43.3	11.2	0.2
18	22.3	-1.5	0.0	19.7	-0.1	0.0
19	6.7	-1.2	-0.3	7.1	-0.6	-0.3
20	-4.6	-0.8	-0.6	-9.6	-1.9	-0.4
31						
35	0.8		-11.6	0.5		-10.3
36	0.8		6.8	0.5		2.6
37	0.8		1.0	0.5		0.0
38	0.8		-0.5	0.5		-1.3
40	0.8		-0.2	0.5		-1.5
41	-2.5		0.4	-8.3		0.5
42	1.0		0.9	-1.4		1.7
43	-9.1		1.5	-7.8		2.6
47						
48	1.2		-0.6	1.0		-0.4
49	1.2		1.2	1.0		1.1
50	1.2		2.0	1.0		1.9
51	1.2		0.1	1.0		0.1
52	-4.6		1.4	-9.6		1.2
53	3.2		1.4	2.0		1.7
54	9.9		16.6	8.4		17.6
	ΔW/W			ΔW/W		
55						
62	-0.3			0.4		

Table A1.12 - Per cent difference between design [AEM 1966] and simulated values.

The most important differences are in the calculation of the extractions mass flow. In the model the extractions exiting the heat exchangers have been assumed in condition of saturated liquid as it happens in the reality, while in the design calculation this hypotesis is not verified.

In table A1.13 the results obtained by using the gas turbine model. The points refers to scheme in figure 3.15.

In this case the model validation is not possible as the thermodynamic data in design conditions are not available. The design data in condition of maximum electric load have been used to built the model, so the results in this case coincide.

p_1	[bar]	1.01	1.01	1.01	1.01	1.01	1.01
p_2	[bar]	11.11	10.36	9.03	7.72	6.75	5.69
p_3	[bar]	10.78	10.05	8.76	7.49	6.55	5.51
p_4	[bar]	1.04	1.04	1.04	1.04	1.04	1.04
T_1	[K]	278.15	278.15	278.15	278.15	278.15	278.15
T_2	[K]	599.29	588.33	568.43	547.35	529.95	507.48
T_3	[K]	1218.27	1218.27	1218.27	1218.27	1218.27	1192.00
T_4	[K]	766.81	778.94	803.38	831.83	856.51	868.96
T_1	[K]	399.76	393.27	381.28	368.63	359.37	351.56
G_{10}	[kg/s]	2.37	2.24	2.01	1.76	1.57	1.31
G_3	[kg/s]	157.68	146.93	127.84	109.03	95.05	80.46
igv		0.983	0.916	0.796	0.679	0.592	0.501
W_{15}	[kW]	32700	30000	25000	20000	16350	12000
W_{13}	[kW]	51117	45995	37434	29597	24124	18602
W_{14}	[kW]	33367	30612	25510	20408	16684	12245
Φ	[kW]	63000	61678	58735	54446	50016	43430
G_{11}	[kg/s]	299.15	292.87	278.89	258.53	237.49	206.22
T_{11}	[K]	343.15	343.15	343.15	343.15	343.15	343.15
T_{12}	[K]	393.15	393.15	393.15	393.15	393.15	393.15
βc		11.080	10.332	9.005	7.701	6.734	5.669
ηc		0.834	0.829	0.816	0.798	0.781	0.760
ηt		0.850	0.846	0.838	0.828	0.819	0.809
bpv		1.000	1.000	1.000	0.990	0.972	0.958
βt		10.32	9.63	8.39	7.17	6.27	5.28

Table A1.13 - Thermodynamic and characteristic variables corresponding to different simulations of the gas turbine plant

ANNEX 2

Evaluation indices

The results of the exergy and thermoeconomic analysis are here represented and evaluated using the indices shown in chapter 2. These parameters are particularly useful in the plant design, in order to improve its cost effectiveness.

The exergetic efficiency of a component is obviously the first index to consider. Its value gives information particularly interesting for the system diagnosis as a variation of the efficiency of a component is related to a variation of its behaviour. This can be determined by the variation of the working condition of the overall system or by an anomaly in the system. On the contrary the comparison between the values of the efficiency of the component in the plant design must be made very carefully, in fact different thermodynamic transformations, having different characteristics the ones from the others, take place in the components. In this way a low value of this parameter can be caused by the not avoidable irreversibilities of a transformation rather than the not correct design of the component. This is the case of the components where a combustion reaction is produced. The graph in figure A2.1 shows the exergetic efficiency of the steam turbine plant components. The lowest efficiency happens in the gland leakage steam condenser, which means a thermodynamically bad use of the resource. The gland leakage steam is in fact characterised by an high value of the specific exergy and a better use could be made, from the thermodynamic point of view, for example to heat the feed water in the high pressure part.

The steam generator is characterised by a low efficiency too, but its value is due to the combustion process and can not be sensibly modified, unless the plant technology is changed.

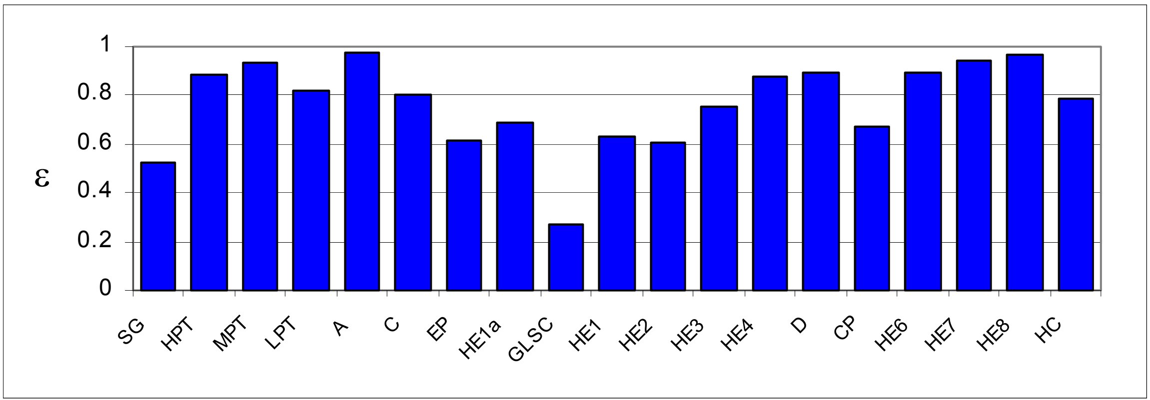

Figure A2.1 - Efficiency of the steam turbine plant components

The graph in figure A2.2 shows the exergetic efficiency of the gas turbine components. In this case the efficiency of the recuperator is the lowest, which is due to the use of the hot gas exiting the turbine to heat water from 70°C to 120°C. The design could be thermodynamically improved for example using the gas for the heating of the air entering the combustor first and then for the water heating.

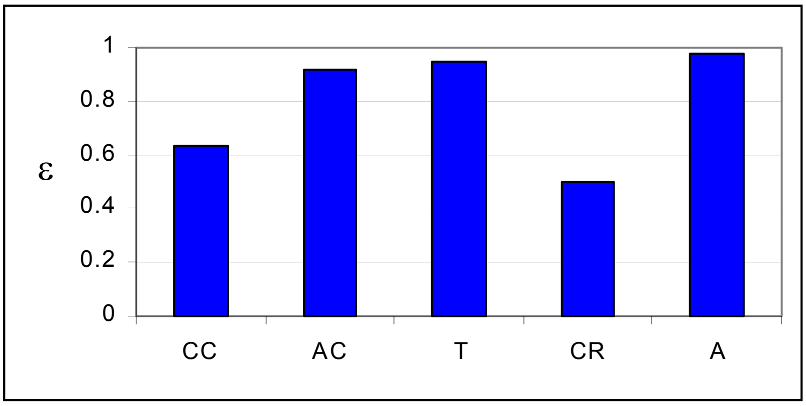

Figure A2.2 - Efficiency of the gas turbine plant components

Another possibility is the realization of a combined cycle plant, which would sensibly reduce the irreversibilities in the steam cycle, as the generator would be substituted by a heat recovery steam generator. In this case the only combustion would happen in the gas turbine plant, which is more efficient, as the fluid can last higher temperatures. Nevertheless technical and economic points of views must been also taken into account for every plant design variation, for this reason the exergy efficiency of the component does not give a complete information.

As discussed in chapter 2, thermoeconomics adds economic information to the exergy analysis, and consequently the thermoeconomic evaluation indices contain these consideration. Table A2.1 shows the thermoeconomic indices relative to the Moncalieri energy system. The order of the components in the table is the one recommended by the improvement procedure suggested by Bejan et al. [Bejan et al. 1996]. The components are ranked in decreasing order of a parameter, defined as the sum of the capital cost rate of the component and the cost rate of the exergy destruction. This last quantity is defined as the exergy flow destroyed in the component multiplied for the unit cost of the component fuel:

$$\Pi_{D_j} = \Psi_{i_i} \cdot c_{F_j} \tag{A2.1}$$

Plant	Component	k^*_P-k^*_F	c_P-c_F $/GJ	$\Delta c/c_F$	f_P	Π_I $/s	Z $/s
Steam turbine	SG	0.959	5.801	1.225	0.247	0.16010	0.24175
	A	0.271	0.805	0.072	0.586	0.00522	0.04711
	MPT	0.144	1.372	0.123	0.442	0.00788	0.03392
	HPT	0.481	2.019	0.180	0.278	0.00948	0.01985
	HE8	0.058	1.424	0.109	0.029	0.02664	0.00385
	LPT	0.488	5.269	0.475	0.513	0.00386	0.02228
	C	1.497	12.132	0.871	0.782	0.00113	0.01926
	D	0.992	2.285	0.203	0.038	0.01148	0.00246
	HE6	5.927	2.196	0.191	0.522	0.00099	0.00582
	HE7	1.250	1.463	0.129	0.792	0.00030	0.00629
	HE3	1.412	6.858	0.606	0.440	0.00117	0.00501
	CP	0.716	7.935	0.706	0.157	0.00190	0.00239
	HE4	0.302	3.491	0.313	0.541	0.00058	0.00374
	HE2	0.476	24.705	2.497	0.695	0.00029	0.00381
	HE1	0.247	27.501	2.466	0.759	0.00021	0.00360
	HC	1.147	2.405	0.173	0.393	0.00070	0.00193
	EP	0.262	37.148	3.330	0.761	0.00002	0.00049
	GLSC	0.127	33.070	2.973	0.300	0.00011	0.00026
	HE1a	0.081	5.446	0.490	0.388	0.00004	0.00014
Gas turbine	CC	0.459	1.572	0.238	0.098	0.29279	0.03172
	CR	0.160	8.986	1.098	0.478	0.04534	0.04154
	GT	0.101	2.667	0.326	0.560	0.04041	0.05136
	AC	1.884	1.802	0.166	0.066	0.14277	0.01007
	A	0.038	1.471	0.136	0.849	0.00722	0.04070

Table. A2.1 - Thermoeconomic evaluation indices for the Moncalieri energy system

The calculation of the unit cost of the fuel of every component can be made as following. the total cost of the product of a component is equal to the total cost of the fuel. This statement is true for the exergetic costs and, in the structural theory representation, for the monetary costs, in fact the cost of the component is treated as an external flux. The unit costs are then obtained as:

$$k_{F_i}^* = \frac{P_i^*}{F_i} \tag{A2.2}$$

or

$$c_{F_i} = \frac{\Pi_{P_i}}{F_i} \tag{A2.3}$$

where the fuel of the component F_i obviously contains only the exergy, and eventually negentropy, fluxes.

The improving procedure consists on analyse the components following the suggested order, but a particular attention must be paid to the ones presenting low efficiency and high relative cost difference. The exergoeconomic factor is used to determine the cause of the cost difference: the capital cost of the component or its efficiency, in this way it is possible to decide if accept the component as it is or to chose a different design, characterised by a lower cost or an higher efficiency.

In the case of the gas turbine for example the procedure starts from the analysis of the combustor: the value assumed by the exergoeconomic factor is low, so that a component with a higher efficiency is recommended. This suggestion does not consider any technical consideration, in fact the most important reason of the low efficiency of the component is the constraint represented by the inlet turbine temperature. Neither for the recuperator the information differs from the one given by the exergy analysis. On the contrary the thermoeconomic analysis advises to improve the efficiency of the compressor too. In this case the exergoeconomic factor is particularly low, so that a higher investment is suggested in order to improve its efficiency. Nevertheless the information must be considered with careful, in fact the cost of the equipment has been here only evaluated, as the true cost was not known and the error committed can have sensibly affect the result. This heuristic approach allows to determine the optimum design of a plant. Other optimization procedures and techniques can be found in literature (see for example [El-Sayed, Evans 1970, Evans 1980, von Spakovsky, Evans 1990, Frangopoulos 1987, Santarelli 1998, Uche 2000]).

ANNEX 3

Diagnosis of the Moncalieri gas turbine plant

In this part the results of the application of the thermoeconomic diagnosis procedures to the Moncalieri gas turbine plant, using the proposed productive structures are shown in detail.

First of all the thermodynamic parameters relative to the eight operation conditions, corresponding to as many simple malfunctions are shown in table A3.1. The reference condition is also shown in table. The values of the parameters calculated in the free conditions using the Lagrange multipliers are shown in table A3.2.

Variables	REF	MF1	MF2	MF3	MF4	MF5	MF6	MF7	MF8
y1	101300	101300	101300	101300	101300	101300	101300	101300	101300
y2	1107960	1116352	1135289	1128159	1107751	1107960	1123519	1107960	1117532
y3	1074722	1082861	1101231	1083033	1074519	1074722	1089813	1074722	1084006
y4	104411.5	104411	104411	104411	104411	104411	106542	104411	104411
y5	278.15	278.15	278.15	278.15	278.15	278.15	278.15	278.15	278.15
y6	598.811	601.9	608.726	601.964	598.784	598.811	601.08	598.811	600.204
y7	1218.271	1218.27	1218.27	1218.27	1218.27	1218.27	1218.27	1218.27	1218.27
y8	767.3203	766.027	763.158	766	767.353	769.575	767.835	767.32	765.847
y9	393.9435	394.28	395.035	394.287	393.935	394.213	393.81	411.544	394.327
y11	2.366859	2.37481	2.39265	2.37498	2.39106	2.36686	2.39245	2.36686	2.38292
y12	157.2164	158.418	161.131	158.444	157.186	157.216	159.414	157.216	158.587
y13	0.98006	0.98762	1.00467	0.98778	0.97972	0.98006	0.99381	0.98006	0.98864
y14	32585	32585	32585	32585	32585	32172.7	32585	32585	32585
y15	50889.06	51775.5	53780	51794.1	50867	50889.1	51968.1	50889.1	51557.4
y16	33250	33250	33250	33250	33250	32829.3	33250	33250	33592.8
y17	60725.97	60726	60726	60726	60726	61048.8	60726	60726	60726
y18	288.3474	288.347	288.347	288.347	288.347	288.347	288.347	288.347	288.347
y19	343.15	343.15	343.15	343.15	343.15	343.15	343.15	343.15	343.15
y20	393.15	393.15	393.15	393.15	393.15	393.416	393.15	393.15	393.15
y21	11.0479	11.2452	11.3204	11.2493	11.0458	11.0479	11.203	11.0479	11.1433
y22	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
y23	0.833922	0.83435	0.82023	0.83436	0.8339	0.83392	0.83468	0.83392	0.8344
y24	0.835	0.835	0.82	0.835	0.835	0.835	0.835	0.835	0.835
y25	1.267206	1.26721	1.26721	1.26721	1.26721	1.26721	1.26721	1.26721	1.26721
y26	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03
y27	0.98	0.98	0.98	0.98	0.97	0.98	0.98	0.98	0.98
y28	3.030811	3.05377	3.10557	3.05425	3.03024	3.03081	3.07337	3.03081	3.05699
y29	0.84996	0.85036	0.85123	0.85037	0.84995	0.84571	0.85068	0.84996	0.85041
y30	0.851	0.851	0.851	0.851	0.851	0.84675	0.851	0.851	0.851
y31	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.97
y32	0.0298	0.0298	0.0298	0.0298	0.0298	0.0298	0.0492	0.0298	0.0298
y33	0.95	0.94692	0.94015	0.94686	0.95008	0.95	0.93528	0.997	0.94649
y34	0.133913	0.1345	0.13582	0.13451	0.1339	0.13391	0.13368	0.14054	0.13458
y35	2.305707	2.29565	2.27326	2.29544	2.30596	2.30571	2.30971	1.97732	2.29424
y36	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.108	0.12
y37	0.880252	0.87909	0.87647	0.87907	0.88028	0.88025	0.88071	0.83876	0.87893
y38	10.29314	10.3711	10.547	10.3727	10.2912	10.2931	10.2289	10.2931	10.3821

Table. A3.1 - Calculated values of the variables of the model in the reference and the operation conditions corresponding to the eight cases of single malfunction

Variables	MF1	MF2	MF3	MF4	MF5	MF6	MF7	MF8
y1	101300	101300	101300	101300	101300	101300	101300	101300
y2	1108777	1110634	1120425	1104710	1107969	1108203	1107960	1107966
y3	1075514	1077315	1075530	1071568	1074730	1074957	1074722	1074727
y4	104411	104411	104411	104411	104411	106542	104411	104411
y5	278.15	278.15	278.15	278.15	278.15	278.15	278.15	278.15
y6	600.814	605.193	600.856	598.273	598.812	598.851	598.811	598.812
y7	1220.08	1224.2	1220.12	1211.05	1218.29	1218.33	1218.27	1218.28
y8	768.363	770.778	768.385	763.196	769.608	770.248	767.32	767.335
y9	394.064	394.314	394.067	393.45	394.202	394.269	405.985	393.94
y11	2.36686	2.36686	2.36686	2.36686	2.36686	2.36686	2.36686	2.36686
y12	157.216	157.216	157.216	157.216	157.216	157.216	157.216	157.216
y13	0.98006	0.98006	0.98006	0.98006	0.98006	0.98006	0.98006	0.98006
y14	32412.3	32024.4	32408.7	32103.4	32166	32048.9	32585	32248.7
y15	51210.8	51941.4	51217.6	50803.6	50892.3	50900.4	50889.1	50891.1
y16	33073.8	32677.9	33070.1	32758.5	32822.5	32703	33250	33249.6
y17	60873.2	61200.1	60876.3	60135.5	61047.8	61135.7	58626	60725.5
y18	288.347	288.347	288.347	288.347	288.347	288.347	288.347	288.347
y19	343.15	343.15	343.15	343.15	343.15	343.15	343.15	343.15
y20	393.271	393.54	393.274	392.664	393.415	393.487	391.421	393.15
y21	11.1696	11.0746	11.1722	11.0155	11.048	11.0503	11.0479	11.048
y22	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
y23	0.83391	0.8188	0.83391	0.83392	0.8339	0.83388	0.83392	0.83391
y24	0.835	0.82	0.835	0.835	0.835	0.835	0.835	0.835
y25	1.26721	1.26721	1.26721	1.26721	1.26721	1.26721	1.26721	1.26721
y26	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03
y27	0.98	0.98	0.98	0.97	0.98	0.98	0.98	0.98
y28	3.02854	3.02338	3.02849	3.03987	3.03079	3.03132	3.03081	3.0308
y29	0.84996	0.84992	0.84996	0.84996	0.8457	0.84995	0.84996	0.84995
y30	0.851	0.851	0.851	0.851	0.84675	0.851	0.851	0.851
y31	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.97
y32	0.0298	0.0298	0.0298	0.0298	0.0298	0.0492	0.0298	0.0298
y33	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
y34	0.13391	0.13388	0.13391	0.13391	0.1339	0.13388	0.13391	0.13391
y35	2.30581	2.30677	2.30581	2.30571	2.30602	2.30621	2.09138	2.30584
y36	0.12	0.12	0.12	0.12	0.12	0.12	0.108	0.12
y37	0.88026	0.88032	0.88026	0.88025	0.88029	0.88031	0.85186	0.88026
y38	10.3007	10.318	10.3009	10.2629	10.2932	10.0866	10.2931	10.2932

Table A3.2 - Calculated values of the variables of the model in the free conditions corresponding to the eight cases of single malfunction

.MALFUNCTION 1: Variation of the pressure drop of the filter

The results of the thermoeconomic diagnosis problem obtained using all the productive structures are presented. Table A3.3 summarizes the values of the parameters obtained applying the productive structures TG2, TG3, TG5 and TG6 to the *operation vs. reference* procedure.

The results of the productive structure TG3 application do not furnish clear information for the diagnosis: some parameters indicates the malfunction as located in the compressor while others in the heat exchanger. This fact is due to the charge for the exergy loss. All the malfunctions, except the heat transfer coefficient variation, cause an higher temperature of the exhausted gas. The component charged for it becomes more sensitive to the malfunctions, as the presence of an anomaly makes increase its fuel. If the charged component coincides to the malfunctioning component, the effect of the anomaly is amplified, while if another component is charged, an induced malfunction takes place. This means that the choice of the productive structure influences the results of the diagnosis if the operation vs. reference approach is applied.

In this case a clear answer is not possible looking at the parameters relative to different productive structures. The only parameter which indicates the compressor as the malfunctioning component whatever is the chosen productive structure is the ratio between the irreversibility variation and the irreversibility in reference condition. The others are not reliable in this case. It is not acceptable that the answer on the malfunction location is so much dependent on the productive structure, specially if the more suitable structure is not the same for all the possible malfunctions.

The complete $\Delta\mathbf{K}$ matrices, resulting from the application of the FvR method to the productive structures, are shown in table A3.4. All the productive structures give the same result: the malfunction is located in the compressor.

		Combustor	Compressor	Turbine	Heat Exch.	Alternator
TG2	Relative fuel impact	0.661	0.482	-0.085	-0.058	0.000
	Relative irreversibility variation	0.539	0.421	0.071	-0.032	0.000
	ΔI/I	0.005	0.040	0.006	-0.001	0.000
	Malfunction	-130	101	-19	-13	0
	Dysfunction	344	67	47	0	0
TG3	Relative fuel impact	0.079	0.449	-0.079	0.551	0.000
	Relative irreversibility variation	0.180	0.421	0.071	0.328	0.000
	ΔI/I	0.002	0.040	0.006	0.006	0.000
	Malfunction	-272	101	-19	130	0
	Dysfunction	343	67	47	0	0
TG5	Relative fuel impact	0.622	0.499	-0.069	-0.052	0.000
	Relative irreversibility variation	0.539	0.421	0.071	-0.032	0.000
	ΔI/I	0.005	0.040	0.006	-0.001	0.000
	Malfunction	-134	101	-19	-13	0
	Dysfunction	348	67	47	0	0
TG6	Relative fuel impact	0.067	0.466	-0.065	0.532	0.000
	Relative irreversibility variation	0.180	0.421	0.071	0.328	0.000
	ΔI/I	0.002	0.040	0.006	0.006	0.000
	Malfunction	-240	101	-19	130	0
	Dysfunction	312	67	47	0	0

Table A3.3 - Diagnosis parameters using productive structures TG2, TG3, TG5 and TG6

CC	AC	GT	CR	A
-0.002	0	0	0	0
0	0	-1E-04	0.0008	0
0.0007	0	0	0	0
0	0.0027	0	0	0
0	0	0	0	0
0	0	0	0	0

TG2

CC	AC	GT	CR	A
-0.002	0	0	0	0
0	0	-8E-05	0.0005	0
0.0007	0	0	0	0
0	0.0026	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

CC	AC	GT	CR	A
-0.003	0	0	0	0
-1E-05	0	0.0004	0.0008	0
0.0013	0	-5E-04	-8E-05	0
0	0.0027	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-0.003	0	0	0	0
0	0	0.0004	0.0007	0
0.0013	0	-5E-04	-8E-05	0
0	0.0027	0	0	0
0	0	0	0	0
0	0	0	0	0

TG6

Table A3.4 - $\Delta\mathbf{K}$ matrices corresponding to the malfunction MF1

MALFUNCTION 2: Variation of the isentropic efficiency of the compressor

This second malfunction corresponds to a 1.8% reduction of the maximum value of the isentropic efficiency.

Table A3.5 shows the values of the evaluation parameters obtained by applying the classical thermoeconomic diagnosis procedure. Also in this case the induced malfunctions influence the result of the diagnosis, in fact not all the parameters give the same answer. This means that the comparison between operation and reference conditions (OvR) does not allow to correctly locate the anomaly.

		Combustor	Compressor	Turbine	Heat Exch.	Alternator
TG2	Relative fuel impact	0.678	0.463	-0.084	-0.057	0.000
	Relative irreversibility variation	0.541	0.419	0.072	-0.031	0.000
	ΔI/I	0.015	0.128	0.021	-0.003	0.000
	Malfunction	-420	311	-59	-40	0
	Dysfunction	1117	229	152	0	0
TG3	Relative fuel impact	0.096	0.429	-0.077	0.552	0.000
	Relative irreversibility variation	0.182	0.419	0.072	0.327	0.000
	ΔI/I	0.006	0.128	0.021	0.021	0.000
	Malfunction	-867	311	-59	422	0
	Dysfunction	1102	229	152	0	0
TG5	Relative fuel impact	0.639	0.480	-0.068	-0.051	0.000
	Relative irreversibility variation	0.541	0.419	0.072	-0.031	0.000
	ΔI/I	0.015	0.128	0.021	-0.003	0.000
	Malfunction	-430	311	-59	-40	0
	Dysfunction	1127	229	152	0	0
TG6	Relative fuel impact	0.084	0.446	-0.063	0.533	0.000
	Relative irreversibility variation	0.182	0.419	0.072	0.327	0.000
	ΔI/I	0.006	0.128	0.021	0.021	0.000
	Malfunction	-767	311	-59	422	0
	Dysfunction	1002	229	152	0	0

Table A3.5 - Evaluation parameters calculated applying the OvR procedure to the malfunction MF2

As it happens in the case of the filter pressure drop variation, the only parameter able to identify the correct malfunction location whatever is the chosen productive structure is the ratio between the irreversibility variation and the irreversibility in reference condition. It is also possible to notice as the indication made by other parameters is strongly dependent on the component on which the exergy losses are charged. If the structures TG2 and TG5 are used the biggest fuel impact and irreversibility variation takes place in the combustor, due to the assumption of the losses as a combustor fuel. On the contrary, if the structures TG3 and TG5 are used the biggest values of fuel impact, irreversibility variation and malfunction takes place in the heat exchanger, due to the assumption of the losses as heat exchanger fuel. Moreover the magnitude of these parameters is comparable with the values assumed in the compressor. Using these consideration it is possible to hazard the guess that the malfunction is located in the compressor.

The surveys offered by the FvR comparison are coherent, as shown in table A3.6: the element of the matrix Δ***KP*** corresponding to the compressor is by far bigger than the other elements, whatever is the chosen productive structure. If exergy is not split into mechanical and thermal components the difference between the variation of the unit exergy consumption in the compressor and in the other components is generally higher. As this behaviour also takes place in other cases of malfunction analysis, the contemporary use of more than one structure is suggested, in particular a structure described using exergy flows and one where exergy is split into its components.

The combustor is characterized by an high negative value of the unit exergy consumption variation, which means that the exergy efficiency has improved. This is due to the absence of the set point constraint on the inlet turbine temperature, so the combustion gas has an higher specific exergy. This malfunction is characterized by a sign opposite to the total fuel impact, so it must not be taken into account for the direct diagnosis problem.

CC	AC	GT	CR	A
-0.007	0	0	0	0
0	0	-4E-04	0.0032	0
0.0022	0	0	0	0
0	0.009	0	0	0
0	0	0	0	0
0	0	0	0	0

TG2

CC	AC	GT	CR	A
-0.006	0	0	0	0
0	0	-4E-04	0.0026	0
0.0021	0	0	0	0
0	0.009	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

CC	AC	GT	CR	A
-0.011	0	0	0	0
-5E-05	0	0.0012	0.0034	0
0.0042	0	-0.002	-2E-04	0
0	0.009	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-0.011	0	0	0	0
0	0	0.0012	0.0028	0
0.0042	0	-0.002	-2E-04	0
0	0.009	0	0	0
0	0	0	0	0
0	0	0	0	0

TG6

Table A3.6 - Δ**K** matrices corresponding to the malfunction MF2

The calculation of the malfunctions made using the structure TG5, shown in table A3.7, allows to notice as the induced malfunctions are lower than the intrinsic one. An important effect of the anomaly is the increase of the combustor product, which originates a big dysfunction in this component.

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	328	85	49	0	0	462	-623	-161
DI2	319	44	48	0	0	410	420	830
DI3	-47	-25	-15	0	0	-87	-36	-123
DI4	31	1	1	0	0	33	47	80
DI5	0	0	0	0	0	0	0	0
DI	630	104	83	0	0	817		
MF	-623	420	-36	47	0		-191	
Total	8	524	47	47	0			626

Table A3.7 - Malfunction and dysfunction table corresponding to the FvR approach, using TG5

MALFUNCTION 3: Variation of the pressure drop in the combustor

A malfunction corresponding to 33% increase of the per cent pressure drop has been here simulated. The application of the *OvR* methods in this case (see table A3.8) highlights the ineffectiveness of the parameter $\Delta I/I$. On the contrary the fuel impact and the irreversibility variation have the biggest values in correspondence of the combustor, whatever is the productive structure. This fact is related to the high exergy flows processed by the combustor, so that these two parameters alone are not sufficient to locate the malfunction.

		Combustor	Compressor	Turbine	Heat Exch.	Alternator
TG2	Relative fuel impact	1.312	-0.169	-0.085	-0.058	0.000
	Relative irreversibility variation	0.858	0.103	0.071	-0.032	0.000
	ΔI/I	0.008	0.010	0.006	-0.001	0.000
	Malfunction	-5	-36	-19	-13	0
	Dysfunction	353	78	48	0	0
TG3	Relative fuel impact	0.685	-0.158	-0.079	0.551	0.000
	Relative irreversibility variation	0.499	0.103	0.071	0.327	0.000
	ΔI/I	0.005	0.010	0.006	0.006	0.000
	Malfunction	-149	-36	-19	133	0
	Dysfunction	351	78	48	0	0
TG5	Relative fuel impact	1.297	-0.175	-0.070	-0.052	0.000
	Relative irreversibility variation	0.858	0.103	0.071	-0.032	0.000
	ΔI/I	0.008	0.010	0.006	-0.001	0.000
	Malfunction	-8	-36	-19	-13	0
	Dysfunction	357	78	48	0	0
TG6	Relative fuel impact	0.697	-0.164	-0.065	0.532	0.000
	Relative irreversibility variation	0.499	0.103	0.071	0.327	0.000
	ΔI/I	0.005	0.010	0.006	0.006	0.000
	Malfunction	-117	-36	-19	133	0
	Dysfunction	319	78	48	0	0

Table A3.8 - Evaluation parameters calculated applying the OvR procedure to the malfunction MF3

The operation vs. reference approach is not so generally able to locate where the anomaly has happened. On the contrary the free vs. reference procedure give interesting results (see table A3.9): the maximum value among the terms of the matrix ΔK is, whatever productive structure is chosen, the one corresponding to the resources of the combustor coming from the compressor. The use of the structures TG5 and TG6 also suggests that the malfunction has a mechanical cause, as the maximum positive term of the matrix ΔK corresponds to the variation of the mechanical exergy required by the combustor.

TG2

CC	AC	GT	CR	A
-0.002	0	0	0	0
0	0	-1E-04	0.0008	0
0.0018	0	0	0	0
0	-3E-04	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

CC	AC	GT	CR	A
-0.002	0	0	0	0
0	0	-1E-04	0.0006	0
0.0017	0	0	0	0
0	-3E-04	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-0.003	0	0	0	0
-1E-05	0	0.0004	0.0009	0
0.0027	0	-5E-04	-8E-05	0
0	-3E-04	0	0	0
0	0	0	0	0
0	0	0	0	0

TG6

CC	AC	GT	CR	A
-0.003	0	0	0	0
0	0	0.0004	0.0007	0
0.0027	0	-5E-04	-8E-05	0
0	-3E-04	0	0	0
0	0	0	0	0
0	0	0	0	0

Table A3.9 - $\Delta\mathbf{K}$ matrices corresponding to the malfunction MF3

The elements of the matrix ΔKP corresponding to the combustor put on evidence that in this component also takes place a decrease of unit exergy consumption, which absolute value is higher than the term due to the anomaly. This negative term is due to the higher outlet temperature. Such a behaviour can not be noticed by observing the malfunction row in the malfunction and dysfunction table, because its elements takes into account the overall behaviour of the component (see table A3.10). As the combustor is working in the complex better, its malfunction is negative.

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	213	49	32	0	0	294	-62	231
DI2	-9	-1	-1	0	0	-12	-12	-24
DI3	-12	-7	-4	0	0	-24	-8	-32
DI4	7	0	0	0	0	8	11	19
DI5	0	0	0	0	0	0	0	0
DI	198	42	26	0	0	266		
MF	-62	-12	-8	11	0		-71	
Total	136	29	18	11	0			194

Table A3.10 - Malfunction and dysfunction table corresponding to the FvR approach, using TG5

If the malfunctions are split into their contributions it is possible to take into account the complex behaviour of components characterized by more than one fuel. The general contribution MF_{ji} to the component malfunction can be defined according to equation 4.13:

$$MF_i = P_i^0 \cdot \Delta k_i = \sum_{j=0}^{n} P_i^0 \cdot \Delta k_{ji} = \sum_{j=0}^{n} MF_{ji} . \qquad \text{(A3.4)}$$

The malfunction matrix, built calculating all the terms MF_{ji}, relative to the productive structure TG5 is shown in table A3.11. It is possible to notice that two malfunctions happen in the combustor: the first, negative, is due to the higher temperature of the exiting gas and the second positive is due to the increased pressure drop. As the first contribution prevails on the second the total malfunction in the combustor is negative. The results does not change if other productive structures are considered.

Combustor	Compressor	Turbine	Heat Exch.	Alternator
-318	0	0	0	0
0	0	35	10	0
257	0	-43	-1	0
0	-12	0	0	0
0	0	0	0	0
0	0	0	0	0

Table A3.11 - Malfunction matrix corresponding to application of the FvR approach to the TG5

MALFUNCTION 4

The thermodynamic data relative to the operation condition, obtained by simulating a variation of the combustor efficiency of about 1% are shown in figure A3.1. A first look on these data reveals that the malfunction is substantially intrinsic, in fact the only quantity which has an appreciable variation is the fuel mass flow.

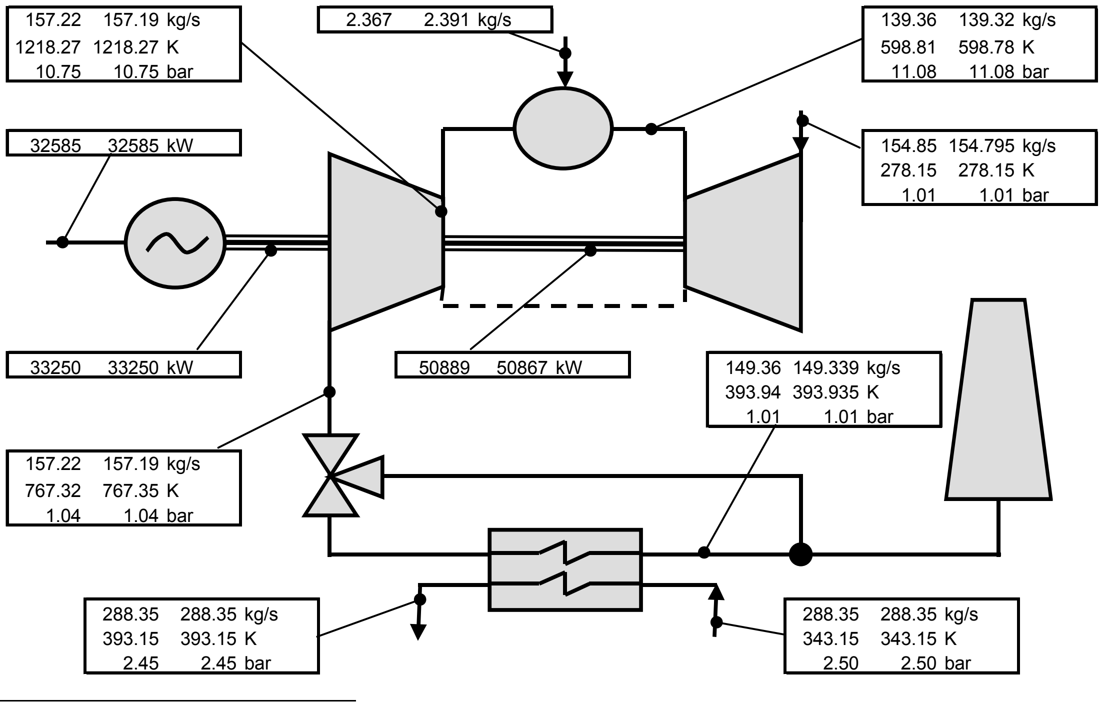

Figure A3.1 - Thermodynamic data corresponding to reference and operation conditions

The application of OvR (see table A3.12) and FvR (see table A3.13) procedures confirms this consideration, in fact whatever is the considered productive structure, the largest variation of the unit exergy consumption takes place in the combustor.

Moreover the intrinsic malfunction is largely bigger than all the induced malfunctions (see table A3.14).

		Combustor	Compressor	Turbine	Heat Exch.	Alternator
TG2	Relative fuel impact	0.998	0.001	0.001	0.000	0.000
	Relative irreversibility variation	1.001	-0.001	-0.001	0.000	0.000
	ΔI/I	0.027	0.000	0.000	0.000	0.000
	Malfunction	1220	1	0	0	0
	Dysfunction	-9	-2	-1	0	0
TG3	Relative fuel impact	1.003	0.001	0.001	-0.005	0.000
	Relative irreversibility variation	1.004	-0.001	-0.001	-0.003	0.000
	ΔI/I	0.030	0.000	0.000	0.000	0.000
	Malfunction	1224	1	0	-3	0
	Dysfunction	-9	-2	-1	0	0
TG5	Relative fuel impact	0.998	0.001	0.001	0.000	0.000
	Relative irreversibility variation	1.001	-0.001	-0.001	0.000	0.000
	ΔI/I	0.027	0.000	0.000	0.000	0.000
	Malfunction	1220	1	0	0	0
	Dysfunction	-9	-2	-1	0	0
TG6	Relative fuel impact	1.003	0.001	0.001	-0.004	0.000
	Relative irreversibility variation	1.004	-0.001	-0.001	-0.003	0.000
	ΔI/I	0.030	0.000	0.000	0.000	0.000
	Malfunction	1223	1	0	-3	0
	Dysfunction	-8	-2	-1	0	0

Table A3.12 - Evaluation parameters calculated applying the OvR procedure to the MF4

CC	AC	GT	CR	A
0.0082	0	0	0	0
0	0	0.0003	-0.003	0
0.0025	0	0	0	0
0	9E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

TG2

CC	AC	GT	CR	A
0.008	0	0	0	0
0	0	0.0003	-0.002	0
0.0025	0	0	0	0
0	9E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

CC	AC	GT	CR	A
0.0134	0	0	0	0
5E-05	0	-0.002	-0.003	0
0.0014	0	0.002	0.0003	0
0	9E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
0.0134	0	0	0	0
0	0	-0.002	-0.002	0
0.0014	0	0.002	0.0003	0
0	9E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

TG6

Table A3.13 - $\Delta\mathbf{K}$ matrices corresponding to the malfunction MF4

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	115	26	16	0	0	157	1393	1550
DI2	3	0	0	0	0	4	4	8
DI3	47	27	18	0	0	91	27	118
DI4	-26	-1	0	0	0	-27	-39	-67
DI5	0	0	0	0	0	0	0	0
DI	139	52	34	0	0	225		
MF	1393	4	27	-39	0		1385	
Total	1532	57	61	-39	0			1610

Table A3.14 - Malfunction and dysfunction table corresponding to the FvR comparison, using TG5

MALFUNCTION 5: Variation of the isentropic efficiency of the turbine

The operation condition corresponds to a 0.5% reduction of the turbine isentropic efficiency. This is a very significant case of the FvR procedure potency.

The results of the OvR comparison, shown in table A3.15, do not allow a correct diagnosis. Once more the answer depends on the productive structure; in particular the maximum malfunction takes place in the combustor or in the heat exchanger, depending on which component is charged for the losses.

		Combustor	Compressor	Turbine	Heat Exch.	Alternator
TG2	Relative fuel impact	0.724	-0.057	0.317	0.017	0.000
	Relative irreversibility variation	0.729	0.041	0.221	0.009	0.000
	ΔI/I	0.016	0.010	0.049	0.001	0.000
	Malfunction	319	-30	175	9	0
	Dysfunction	410	71	46	0	0
TG3	Relative fuel impact	0.034	-0.053	0.294	0.726	0.000
	Relative irreversibility variation	0.307	0.041	0.221	0.431	0.000
	ΔI/I	0.007	0.010	0.049	0.021	0.000
	Malfunction	-182	-30	175	432	0
	Dysfunction	489	71	46	0	0
TG5	Relative fuel impact	0.669	-0.060	0.373	0.018	0.000
	Relative irreversibility variation	0.729	0.041	0.221	0.009	0.000
	ΔI/I	0.016	0.010	0.049	0.001	0.000
	Malfunction	230	-30	175	9	0
	Dysfunction	499	71	46	0	0
TG6	Relative fuel impact	0.010	-0.055	0.347	0.698	0.000
	Relative irreversibility variation	0.307	0.041	0.221	0.431	0.000
	ΔI/I	0.007	0.010	0.049	0.021	0.000
	Malfunction	-137	-30	175	432	0
	Dysfunction	444	71	46	0	0

Table A3.15 - Evaluation parameters calculated applying the OvR procedure to the MF5

On the contrary, the FvR procedure always allows the correct location, as shown in table A3.16.

TG2

CC	AC	GT	CR	A
0.0002	0	0	0	0
0	0	0.0024	0.0017	0
7E-05	0	0	0	0
0	6E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

CC	AC	GT	CR	A
-2E-05	0	0	0	0
0	0	0.0024	0.0013	0
-6E-06	0	0	0	0
0	6E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-3E-05	0	0	0	0
0.0003	0	0.0006	0.0019	0
-3E-06	0	0.0018	-2E-04	0
0	6E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

TG6

CC	AC	GT	CR	A
-3E-05	0	0	0	0
0	0	0.0006	0.0015	0
-3E-06	0	0.0018	-2E-04	0
0	6E-05	0	0	0
0	0	0	0	0
0	0	0	0	0

Table A3.16 - $\Delta\mathbf{K}$ matrices corresponding to the malfunction MF5

The malfunction analysis also shows that the intrinsic malfunction is higher than the induced malfunctions, as shown in table A3.17 in the case of productive structure TG5.

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	16	1	1	0	0	17	21	38
DI2	2	0	0	0	0	3	3	6
DI3	161	31	21	0	0	212	204	416
DI4	17	1	0	0	0	18	26	43
DI5	0	0	0	0	0	0	0	0
DI	195	33	22	0	0	250		
MF	21	3	204	26	0		253	
Total	216	36	226	26	0			503

Table A3.17 - Malfunction and dysfunction table corresponding to the FvR approach, using TG5

The difference between the malfunctions calculated using the operation vs. reference and the free vs. reference approaches puts on evidence that the regulation system intervention induces important malfunctions on the components. The graph in figure shows the malfunctions and dysfunctions caused by the anomaly (FM_i and DI_i calculated using the FvR) and by the regulation system intervention (MF_r and DI_r calculated as difference between the two approaches). It makes clear how the FvR approach allows to avoid some important contributions of induced malfunctions. If the TG5 productive structure is chosen, the regulation system induces a lot of malfunctions and dysfunctions mainly in the combustor. This makes impossible a correct diagnosis using the operation vs. reference approach.

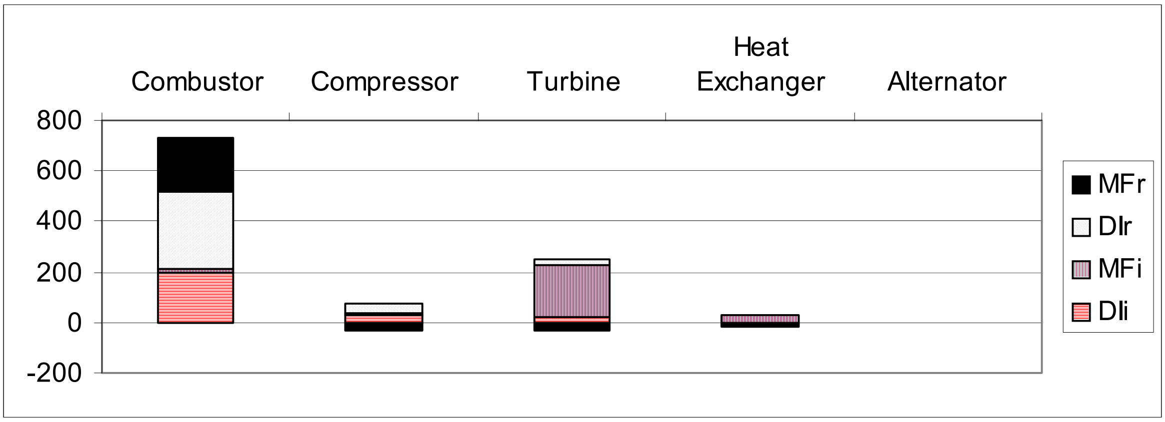

Figure A3.2 - Malfunctions and dysfunctions caused by the anomaly and by the regulation, using TG5

MALFUNCTION 6: Variation of the pressure drop in the heat exchanger

The operation condition corresponds to a 65% increase of the pressure drop in the heat exchanger.

The evaluation parameters calculated applying the OvR approach, reported in table A3.18, show once more the dependence of the results on the choice of the productive structure and, in particular, on the loss charging. All parameters indicate as the malfunctioning component the combustor if the structures TG2 and TG5 are used, or the heat exchanger if the structures TG3 and TG6 are used. This constitutes an important result, in fact the choice of the structures TG2 and TG5 would furnish a wrong answer to the direct diagnosis problem.

		Combustor	Compressor	Turbine	Heat Exch.	Alternator
TG2	Relative fuel impact	0.720	-0.058	-0.048	0.386	0.000
	Relative irreversibility variation	0.727	0.042	0.018	0.213	0.000
	ΔI/I	0.020	0.013	0.005	0.017	0.000
	Malfunction	400	-39	-34	272	0
	Dysfunction	531	92	57	0	0
TG3	Relative fuel impact	0.032	-0.053	-0.045	1.066	0.000
	Relative irreversibility variation	0.306	0.042	0.018	0.634	0.000
	ΔI/I	0.010	0.013	0.005	0.040	0.000
	Malfunction	-238	-39	-34	812	0
	Dysfunction	629	92	57	0	0
TG5	Relative fuel impact	0.665	-0.060	-0.061	0.456	0.000
	Relative irreversibility variation	0.727	0.042	0.018	0.213	0.000
	ΔI/I	0.020	0.013	0.005	0.017	0.000
	Malfunction	288	-39	-34	272	0
	Dysfunction	643	92	57	0	0
TG6	Relative fuel impact	0.009	-0.055	-0.057	1.104	0.000
	Relative irreversibility variation	0.306	0.042	0.018	0.634	0.000
	ΔI/I	0.010	0.013	0.005	0.040	0.000
	Malfunction	-179	-39	-34	812	0
	Dysfunction	571	92	57	0	0

Table A3.18 - Evaluation parameters calculated applying the OvR procedure to the MF6

On the contrary the FvR approach, which results are shown in table A3.19, indicates the heat exchanger as the malfunctioning component, independently on the used structure. Moreover if a more detailed structure, characterized by the split of the exergy components (TG5 or TG6), is used, the cause of the anomaly can be understood: the element of the matrix $\Delta\boldsymbol{K}$ assuming the maximum value corresponds to the consumption of the mechanical exergy by the heat exchanger. This means that the heat exchanger requires a larger amount of mechanical exergy. In all the cases of pure thermal or mechanical malfunction the maximum variation of the unit exergy consumption happens in the element of the matrix $\Delta\boldsymbol{K}$ corresponding to the use of thermal or mechanical exergy.

CC	AC	GT	CR	A
0.0002	0	0	0	0
0	0	-1E-05	0.0195	0
1E-04	0	0	0	0
0	0.0002	0	0	0
0	0	0	0	0
0	0	0	0	0

TG2

CC	AC	GT	CR	A
-6E-05	0	0	0	0
0	0	-1E-05	0.019	0
-4E-06	0	0	0	0
0	0.0002	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

CC	AC	GT	CR	A
-1E-04	0	0	0	0
0.0003	0	0.0008	0.0025	0
2E-05	0	-8E-04	0.017	0
0	0.0002	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-1E-04	0	0	0	0
0	0	0.0008	0.002	0
2E-05	0	-8E-04	0.017	0
0	0.0002	0	0	0
0	0	0	0	0
0	0	0	0	0

TG6

Table A3.19 - Δ**K** matrices corresponding to the malfunction MF6

The malfunction/dysfunction table shows that the malfunction is mainly intrinsic (table A3.20 refers to the productive structure TG5). On the contrary the results obtained using the operation vs. reference approach is affected by the malfunctions induced by the regulation system, which magnitude is comparable with the intrinsic malfunctions.

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	23	2	1	0	0	25	28	53
DI2	0	0	0	0	0	0	0	-1
DI3	-11	-10	-7	0	0	-28	0	-28
DI4	229	49	32	0	0	309	282	592
DI5	0	0	0	0	0	0	0	0
DI	240	40	26	0	0	307		
MF	28	0	0	282	0		309	
Total	268	40	26	282	0			616

Table A3.20 - Malfunction and dysfunction table relative to the FvR approach, using TG5

MALFUNCTION 7: Variation of the heat transfer coefficient of the recuperator

The only sensible effect of the heat transfer coefficient reduction is the reduction of the mass flow of the gas passing through the by-pass.

The use of the OvR approach does not allow to correctly locate the malfunction, as shown in table A3.21. Some parameters are undetermined, because using some particular therm-oeconomic model the resources and the product do not vary.

		Combustor	Compressor	Turbine	Heat Exch.	Alternator
TG2	Relative fuel impact	-2.826E+14	0.000	0.000	2.826E+14	0.000
	Relative irreversibility variation	-3.739E+13	-1.056	2.278	3.739E+13	0.000
	$\Delta I/I$	-0.013	0.000	0.000	0.039	0.000
	Malfunction	-842	0	0	612	0
	Dysfunction	230	0	0	0	0
TG3	Relative fuel impact	1.000	0.000	0.000	0.000	0.000
	Relative irreversibility variation	0.000	-1.158	2.158	0.000	0.000
	$\Delta I/I$	0.000	0.000	0.000	0.000	0.000
	Malfunction	0	0	0	0	0
	Dysfunction	0	0	0	0	0
TG5	Relative fuel impact					
	Relative irreversibility variation	-2.403E+13	-0.714	0.786	2.403E+13	0.000
	$\Delta I/I$	-0.013	0.000	0.000	0.039	0.000
	Malfunction	-612	0	0	612	0
	Dysfunction	0	0	0	0	0
TG6	Relative fuel impact	1.000	0.000	0.000	0.000	0.000
	Relative irreversibility variation	0.000	-20.000	21.000	0.000	0.000
	$\Delta I/I$	0.000	0.000	0.000	0.000	0.000
	Malfunction	0	0	0	0	0
	Dysfunction	0	0	0	0	0

Table A3.21 - Evaluation parameters calculated applying the OvR procedure to the MF7

On the contrary the application of the proposed methodology, which results are shown in table A3.22, evidences the heat exchanger as the malfunctioning component. Moreover the use of the structures TG5 or TG6 allows to identify the cause of the component behaviour, in fact the thermal component of the unit exergy consumption has increased more than the other, so the required thermal resource has increased.

TG2

CC	AC	GT	CR	A
0.0048	0	0	0	0
0	0	0	0.0497	0
0.0019	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

TG3

CC	AC	GT	CR	A
0	0	0	0	0
0	0	0	0.1035	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
0	0	0	0	0
0.0061	0	0	0.0486	0
0	0	0	0.0011	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

TG6

CC	AC	GT	CR	A
0	0	0	0	0
0	0	0	0.1023	0
0	0	0	0.0011	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

Table A3.22 - $\Delta\mathbf{K}$ matrices corresponding to the malfunction MF7

In this case the malfunction/dysfunction table, calculated using the structure TG5 (see table A3.23), highlights an important induced malfunction in the combustor, caused by the charge for the losses. The malfunction/dysfunction table calculated using for example the structure TG6 (see table A3.24) shows only an intrinsic malfunction. This term is therefore the sum of two contribution: the real intrinsic malfunction (about 738 kW) and the malfunction induced on the loss (about 598 kW), which in this productive structure is assigned to the recuperator too. This behaviour suggests the use of different productive structures for the plant diagnosis, characterized by a different definition of fuels and products and a different charge for the losses.

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	387	20	13	0	0	421	569	990
DI2	0	0	0	0	0	0	0	0
DI3	0	0	0	0	0	0	0	0
DI4	504	29	19	0	0	552	738	1290
DI5	0	0	0	0	0	0	0	0
DI	891	50	32	0	0	973		
MF	569	0	0	738	0		1307	
Total	1461	50	32	738	0			2280

Table A3.23 - Malfunction and dysfunction table relative to the FvR approach, using TG5

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	0	0	0	0	0	0	0	0
DI2	0	0	0	0	0	0	0	0
DI3	0	0	0	0	0	0	0	0
DI4	861	54	34	0	0	949	1536	2485
DI5	0	0	0	0	0	0	0	0
DI	861	54	34	0	0	949		
MF	0	0	0	1536	0		1536	
Total	861	54	34	1536	0			2485

Table A3.24 - Malfunction and dysfunction table relative to the FvR approach, using TG6

MALFUNCTION 8: Variation of the efficiency of the alternator

The last single malfunction analysed is the variation of the alternator efficiency. In this case the evaluation parameters calculated using the OvR approach makes possible the anomaly location (see table A3.25).

		Combustor	Compressor	Turbine	Heat Exch.	Alternator
TG2	Relative fuel impact	0.326	-0.057	-0.048	-0.032	0.811
	Relative irreversibility variation	0.509	0.041	0.040	-0.018	0.427
	ΔI/I	0.009	0.008	0.007	-0.001	0.515
	Malfunction	15	-24	-21	-14	343
	Dysfunction	394	57	54	0	0
TG3	Relative fuel impact	0.032	-0.053	-0.044	0.310	0.755
	Relative irreversibility variation	0.307	0.041	0.040	0.185	0.427
	ΔI/I	0.006	0.008	0.007	0.007	0.515
	Malfunction	-146	-24	-21	148	343
	Dysfunction	393	57	54	0	0
TG5	Relative fuel impact	0.289	-0.059	-0.039	-0.029	0.839
	Relative irreversibility variation	0.509	0.041	0.040	-0.018	0.427
	ΔI/I	0.009	0.008	0.007	-0.001	0.515
	Malfunction	11	-24	-21	-14	343
	Dysfunction	399	57	54	0	0
TG6	Relative fuel impact	0.009	-0.055	-0.037	0.300	0.784
	Relative irreversibility variation	0.307	0.041	0.040	0.185	0.427
	ΔI/I	0.006	0.008	0.007	0.007	0.515
	Malfunction	-110	-24	-21	148	343
	Dysfunction	357	57	54	0	0

Table A3.25 - Evaluation parameters calculated applying the OvR procedure to the MF8

The application of the FvR approach puts on evidence the alternator as the malfunctioning component too (see **ΔK** matrix in table A3.26), moreover the induced malfunctions have been completely eliminated in the analysis, as shown in the malfunction/dysfunction table (see table A3.27). Once more the regulation system induces some malfunctions in the system, nevertheless in this case their magnitude is low, so that it does not influence the diagnosis made using the classical approach.

CC	AC	GT	CR	A
-1E-05	0	0	0	0
0	0	-2E-05	0.0001	0
-4E-06	0	0	0	0
0	4E-05	0	0	0.0106
0	0	0	0	0
0	0	0	0	0

TG2

CC	AC	GT	CR	A
-1E-05	0	0	0	0
0	0	-2E-05	0.0001	0
-4E-06	0	0	0	0
0	4E-05	0	0	0.0106
0	0	0	0	0
0	0	0	0	0

TG3

CC	AC	GT	CR	A
-2E-05	0	0	0	0
-2E-06	0	-2E-05	0.0001	0
-2E-06	0	-6E-06	2E-07	0
0	4E-05	0	0	0.0106
0	0	0	0	0
0	0	0	0	0

TG5

CC	AC	GT	CR	A
-2E-05	0	0	0	0
0	0	-2E-05	0.0001	0
-2E-06	0	-6E-06	2E-07	0
0	4E-05	0	0	0.0106
0	0	0	0	0
0	0	0	0	0

TG6

Table A3.26 - $\Delta\mathbf{K}$ matrices corresponding to the malfunction MF8

	Combustor	Compressor	Turbine	Heat Exch.	Alternator	DF	MF	Total
DI1	0	0	0	0	0	0	0	0
DI2	0	0	0	0	0	0	0	0
DI3	0	0	0	0	0	0	0	0
DI4	0	0	0	0	0	0	0	0
DI5	260	32	39	0	0	330	343	673
DI	260	32	39	0	0	330		
MF	0	0	0	0	343		343	
Total	260	32	39	0	343			673

Table A3.27 - Malfunction and dysfunction table relative to the FvR approach, using TG5

ANNEX 4

Diagnosis of the Moncalieri steam turbine plant

In this part the data relative to the cases of single malfunctions examined in chapter 6 are presented. Table A4.1 shows the normalized maximum values of Δk_{ij} in the analysed cases of single malfunctions.

	MF9	MF10	MF11	MF12	MF13	MF14	MF15	MF16	MF17	MF18	MF19	MF20	MF21	MF22
SG	1	1	0	0.13	0.05	0	0	0	0	0.09	0.07	0.39	0.31	0.07
HP0	0.56	0.36	0	0.13	0.05	0	0	0.03	0.09	0.05	0.06	0.29	0.39	0
HP1	0.36	0.16	1	0.04	0.01	0	0	0	0.01	0.02	0.02	0.11	0.12	0.02
HP2	0.01	0.11	0	0.04	0.01	0	0	0.03	0.08	0.02	0.03	0.22	0.22	0.02
MP1	0.27	0.13	0	0.03	0.01	0	0	0	0.01	0.02	0.01	0.09	0.09	0.01
MP2	0.16	0.07	0	1	0.01	0	0	0	0.01	0.01	0.01	0.05	0.06	0
MP3	0.2	0.1	0	0	0.01	0	0	0	0.01	0.01	0.01	0.06	0.08	0
MP4	0.67	0.03	0.08	0	0	0	0	0	0	0	0	0	0	0.34
LP1	0.33	0.16	0	0	0.01	0	0	0.01	0.01	0.02	0.03	0.09	0.13	0
LP2	0	0.12	0	0.06	0.01	0	0	0.15	0.5	0	0.09	0.49	0.9	0
LP3	0.01	0	0	0	1	0	0	0	0	0	0	0	0	0.01
HC	0	0	0.38	0.3	0.06	0.1	1	0	0	0.16	0	0.43	0.25	0
A	0.18	0.1	0.06	0.08	0.01	0	0	0.03	0.03	0.03	0.06	0.12	0.12	0.08
C	0.8	0.31	0	0.07	0.02	1	0	0.01	0.05	0.05	0.05	0.31	0.28	0.06
EP	0.01	0	0	0	0	0	0	0	0	0.02	0.01	0.04	0.1	0
HE1	0	0	0	0.1	0	0	0.01	0.21	0.68	0	0.26	0.29	0.88	0
HE2	0	0	0.1	0	0	0	0	1	0	0	0	0	0	0
HE3	0	0	0.13	0.01	0	0	0	0.33	1	1	0	0	0	0
HE4	0	0	0.16	0	0	0	0	0	0.05	0.18	1	0	0	0.13
D	0	0	0.05	0	0	0	0	0	0	0	0.44	0	0	0
CP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HE6	0	0	0.09	0	0	0	0	0	0	0	0	0	0	0
HE7	0	0	0.09	0	0	0	0	0	0	0	0	1	1	1
HE8	0	0	0.1	0	0	0	0	0	0	0	0	0.45	0	0.41

Table. A4.1 - Normalized maximum values of Δk_{ij} in the analysed cases of single malfunctions

MALFUNCTION 9: Variation of the re-heater pressure drops

The simulation has been made by imposing a 20% increasing of the pressure drop in the re-heater. Table A4.2 shows the thermodynamic data relative to the reference and operation conditions, while the table A4.3 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	98.43	124.5	3450	35	45.74	7	117	46.03	7	117
2	86.54	27.15	3104	86.83	27.86	3109	36	45.74	6.86	230	46.03	6.86	231
3	0.375	27.15	3381	0.369	27.86	3383	37	45.74	6.723	299	46.03	6.723	300
4	86.91	27.15	3105	87.2	27.86	3110	38	45.74	6.588	497	46.03	6.588	497
5	0	27.15	3105	0	27.86	3110	39	80.74	6.588	507	81.04	6.588	507
6	86.91	27.15	3105	87.2	27.86	3110	40	80.74	6.457	580	81.04	6.457	580
7	86.91	24.435	3552	87.2	24.51	3552	41	2.28	3.594	588	2.304	3.599	589
8	39.44	2.2317	2938	39.62	2.229	2937	42	5.92	2.009	505	5.957	2.006	505
9	39.44	1.1859	2938	39.62	1.191	2937	43	6.738	0.361	307	6.78	0.363	308
10	37.01	0.0224	2417	37.25	0.023	2416	44	8.647	0.172	238	8.691	0.173	239
11	1.645	0.1914	2630	1.583	0.193	2629	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.911	0.193	2734	46	8.647	0.172	81.6	8.691	0.173	81.8
13	0.818	0.401	2744	0.823	0.403	2744	47	97.85	5.555	658	98.42	5.575	658
14	3.641	2.2317	2938	3.652	2.229	2937	48	97.85	162.1	681	98.42	162.2	681
15	1.37	3.9928	3062	1.425	3.999	3061	49	97.85	158.8	842	98.42	158.9	842
16	2.28	3.9928	3170	2.304	3.999	3166	50	97.85	155.6	995	98.42	155.8	1001
17	1.443	6.4188	3174	1.446	6.436	3174	51	97.85	152.5	1063	98.42	152.7	1068
18	5.545	13.724	3380	5.544	13.77	3380	52	3.151	35.33	1052	3.107	35.99	1057
19	6.97	27.15	3104	7.283	27.86	3109	53	10.12	27.15	983	10.39	27.86	989
20	3.151	35.325	3162	3.107	35.99	3166	54	15.67	13.72	826	15.93	13.77	827
21	0.628	3.9928	3235	0.606	3.999	3240	56	45.74	7	82	46.03	7	82.2
22	0.029	0.95	3235	0.029	0.95	3240	57	45.74	7	81.9	46.03	7	82.2
23	0.161	1.2	3235	0.204	1.2	3240	59	0.086	0.022	81.1	0.086	0.023	81.3
24	0.029	0.95	3209	0.029	0.95	3208	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.189	1.2	3236	61	4900	1	68.1	4900	1	68.2
26	0.029	0.95	3217	0.028	0.95	3238	63	401.9	4	293	401.8	4	293
27	-0.06	1.2	3217	-0.06	1.2	3238	64	401.9	3.98	504	401.8	3.98	504
31	35	2.2317	2938	35.01	2.229	2937	66	45.74	0.022	81.1	46.03	0.023	81.3
33	35	11	520	35.01	11	520	68	97.09	89.58	3381	97.67	90.34	3383
34	45.74	7	112	46.03	7	112	69	80.74	6.457	580	81.04	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33149	55	2801	2820
29	83684	83592	58	53	54
30	103627	103631	62	101049	101053
32	45	45	67	289797	290286

Table A4.2 - Values of the thermodynamic variables relative to the simulation MF9

Variable	Reference	Operation	
x_1	0.974	0.96682	
x_2	5.795	5.806	kg/s
x_3	35	35.008	kg/s

Table A4.3 - Values of the regulation parameters in reference and operation conditions

These data and the Lagrange multipliers shown in table 6.13 allow to calculate the fluxes of the productive structure in reference, operation and free conditions. The results are shown in table A4.4 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	290286	289755	4b-1	8395.9	8426.9	8386	10s	7.993	8.017	7.909
1s	6297.69	6329.46	6263.3	4s-1	40.501	40.728	39.368	b10	594	597.9	579.9
b1	152708	152830	153158	m4-1	7626.1	7653.7	7636.3	11b	2889	2897	2845
2b-1	8396.42	8215.63	8406.2	4b-2	4871.8	4902	4855.5	11s	29.67	29.71	29.72
2s-1	87.4946	87.2187	86.426	4s-2	18.364	18.418	18.041	b11	2325	2333	2281
m2-1	6733.25	6559.85	6760.4	m4-2	4433.9	4442.2	4428.4	12b	2165	2183	2155
2b-2	23670.2	23601.1	23685	4b-3	10760	10845	10654	12s	14.33	14.41	14.82
2s-2	129.216	128.658	126.61	4s-3	151.59	152.86	149.86	b12	1892	1909	1874
m2-2	21214	21158.6	21274	m4-3	7878.4	7942.8	7800.6	13b	2459	2480	2390
2b-3	6181.79	6083.13	6112.6	5b	30173	30149	30435	13s	13.99	14.13	14.1
2s-3	34.5519	34.3886	33.788	5m	44.592	44.612	44.631	b13	2193	2212	2126
m2-3	5525	5430.29	5469.2	5s	-2866	-2871	-2883	14m	2801	2820	2765
3b-1	15941.8	15994	16021	b5	21751	21749	21927	14s	18.71	18.85	18.44
3s-1	54.3999	54.7248	52.835	6b	-0.124	-0.124	-0.124	b14	1885	1898	1861
m3-1	14907.7	14955	15015	6s	0.0916	0.0917	0.0917	15b	7001	7047	7004
3b-2	17609.2	17685.1	17698	m6	101049	101053	101394	15s	41.54	41.89	43.17
3s-2	49.6442	49.9273	48.947	7b	5716.8	5765.6	5615.4	b15	6211	6252	6186
m3-2	16665.6	16737.2	16765	8s	0.381	0.3838	0.3733	16b	6974	7301	7179
3b-3	9581.47	9637.68	9658.7	8m	53.453	53.786	52.435	16s	20.34	21.86	22.03
3s-3	32.8064	33.053	32.435	b8	32.847	33.054	32.217	b16	6587	6886	6749
m3-3	8957.86	9010.19	9041	9b	6482.5	1197.4	1162	17b	3223	3185	3133
3b-4	10452.7	10536.8	10568	9s	15.98	20.202	19.801	17s	6.237	6.16	6.687
3s-4	41.1731	39.6786	39.529	b9	6185.7	813.9	786.58	b17	3105	3068	3012
m3-4	9670.07	9783.52	9815.5	10b	745.9	750.07	729.82				

Table A4.4 - Fluxes of the productive structure TV2a

The Δ**k** matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.5 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	-0.006	-0.004	-0.002	-6E-05	-0.002	-0.001	-0.001	-0.004	-0.002	-2E-05	-3E-05	0
OvR	0.002	0.005	0	0.001	1E-04	6E-06	3E-05	0	7E-05	0.005	5E-06	0
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	-0.001	-0.005	-4E-05	0	0	0	0	0	-8E-06	0	0	0
OvR	0.001	0.002	1E-05	0.006	0	0	0	7E-06	8E-06	5E-05	0.002	0

Table A4.5 - Maximum values of Δk_{ij} calculated using the structure TV2a

When the free versus reference approach is applied, the negative values of the $\Delta \mathbf{k}$ matrix must be analysed, as the product in free condition is higher than in reference condition, so the plant works better. In this case the most possible location of the anomaly is in the steam generator. On the contrary the plant in working condition is characterized by a lower efficiency than in reference condition. So the positive values of the matrix must be analysed. This approach does not allow to correctly locate the anomaly.

MALFUNCTION 10: Variation of the steam generator efficiency

The simulation has been made by imposing a 1% decreasing of the steam generator efficiency. Table A4.6 shows the thermodynamic data relative to the reference and operation conditions, while the table A4.7 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.85	124.5	3450	35	45.74	7	117	45.74	7	117
2	86.54	27.15	3104	86.54	27.15	3104	36	45.74	6.86	230	45.74	6.86	230
3	0.375	27.15	3381	0.375	27.15	3381	37	45.74	6.723	299	45.74	6.723	299
4	86.91	27.15	3105	86.91	27.15	3105	38	45.74	6.588	497	45.74	6.588	497
5	0	27.15	3105	0	27.15	3105	39	80.74	6.588	507	80.74	6.588	507
6	86.91	27.15	3105	86.91	27.15	3105	40	80.74	6.457	580	80.74	6.457	580
7	86.91	24.435	3552	86.91	24.43	3552	41	2.28	3.594	588	2.28	3.594	588
8	39.44	2.2317	2938	39.44	2.232	2938	42	5.92	2.009	505	5.92	2.009	505
9	39.44	1.1859	2938	39.44	1.186	2938	43	6.738	0.361	307	6.738	0.361	307
10	37.01	0.0224	2417	37.01	0.022	2417	44	8.647	0.172	238	8.647	0.172	238
11	1.645	0.1914	2630	1.645	0.191	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.909	0.191	2711	46	8.647	0.172	81.6	8.647	0.172	81.6
13	0.818	0.401	2744	0.818	0.401	2744	47	97.85	5.555	658	97.85	5.555	658
14	3.641	2.2317	2938	3.641	2.232	2938	48	97.85	162.1	681	97.85	162.1	681
15	1.37	3.9928	3062	1.369	3.993	3062	49	97.85	158.8	842	97.85	158.8	842
16	2.28	3.9928	3170	2.28	3.993	3170	50	97.85	155.6	995	97.85	155.6	995
17	1.443	6.4188	3174	1.443	6.419	3174	51	97.85	152.5	1063	97.85	152.5	1063
18	5.545	13.724	3380	5.545	13.72	3380	52	3.151	35.33	1052	3.151	35.33	1052
19	6.97	27.15	3104	6.97	27.15	3104	53	10.12	27.15	983	10.12	27.15	983
20	3.151	35.325	3162	3.151	35.33	3162	54	15.67	13.72	826	15.67	13.72	826
21	0.628	3.9928	3235	0.628	3.993	3235	56	45.74	7	82	45.74	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.74	7	81.9
23	0.161	1.2	3235	0.161	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.169	1.2	3201	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3217	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.06	1.2	3217	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35	2.232	2938	66	45.74	0.022	81.1	45.74	0.022	81.1
33	35	11	520	35	11	520	68	97.09	89.58	3381	97.09	89.58	3381
34	45.74	7	112	45.74	7	112	69	80.74	6.457	580	80.74	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33472	55	2801	2801
29	83684	83683	58	53	53
30	103627	103621	62	101049	101044
32	45	45	67	289797	292725

Table A4.6 - Values of the thermodynamic variables relative to the simulation MF10

Variable	Reference	Operation	
x_1	0.974	0.974	
x_2	5.795	5.854	kg/s
x_3	35	35	kg/s

Table A4.7 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.8 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	292725	289707	4b-1	8395.9	8396.6	8278.5	10s	7.993	7.992	8.506
1s	6297.69	6297.7	6390.8	4s-1	40.501	40.503	43.359	b10	594	594	632.4
b1	152708	152708	148498	m4-1	7626.1	7626.6	7460.2	11b	2889	2889	2989
2b-1	8396.42	8396.41	8129.7	4b-2	4871.8	4871.5	4820.7	11s	29.67	29.67	29.87
2s-1	87.4946	87.4945	89.974	4s-2	18.364	18.363	19.886	b11	2325	2325	2440
m2-1	6733.25	6733.25	6431.6	m4-2	4433.9	4433.6	4337	12b	2165	2164	2181
2b-2	23670.2	23670.2	22661	4b-3	10760	10760	11076	12s	14.33	14.33	12.98
2s-2	129.216	129.216	132.23	4s-3	151.59	151.59	158.09	b12	1892	1892	1949
m2-2	21214	21214	20166	m4-3	7878.4	7878.8	8092.6	13b	2459	2459	2686
2b-3	6181.79	6181.84	5881.2	5b	30173	30173	29160	13s	13.99	13.99	15.49
2s-3	34.5519	34.5521	35.24	5m	44.592	44.591	44.594	b13	2193	2193	2438
m2-3	5525	5525.05	5216.1	5s	-2866	-2866	-2812	14m	2801	2801	2931
3b-1	15941.8	15941.8	15442	b5	21751	21751	21129	14s	18.71	18.71	19.65
3s-1	54.3999	54.3999	57.79	6b	-0.124	-0.124	-0.121	b14	1885	1885	1975
m3-1	14907.7	14907.7	14352	6s	0.0916	0.0916	0.0888	15b	7001	7001	6954
3b-2	17609.2	17609	17150	m6	101049	101044	97872	15s	41.54	41.54	36.32
3s-2	49.6442	49.6433	51.527	7b	5716.8	5716.8	6004	b15	6211	6211	6269
m3-2	16665.6	16665.3	16177	8s	0.381	0.381	0.4048	16b	6974	6974	7186
3b-3	9581.47	9581.27	9264	8m	53.453	53.453	56.49	16s	20.34	20.34	20.05
3s-3	32.8064	32.8056	33.978	b8	32.847	32.847	34.728	b16	6587	6587	6870
m3-3	8957.86	8957.67	8622.7	9b	6670.9	1180.3	1239.6	17b	3223	3223	3283
3b-4	10452.7	10451.9	10040	9s	14.923	19.729	20.58	17s	6.237	6.237	5.553
3s-4	41.1731	41.1708	40.542	b9	6412.2	805.31	857.93	b17	3105	3105	3203
m3-4	9670.07	9669.29	9274.8	10b	745.9	745.92	787.94				

Table A4.8 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.9 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	0.05	0.018	0.008	0.006	0.007	0.004	0.005	0.001	0.008	0.006	1E-04	0
OvR	0.028	0	4E-09	0	1E-07	6E-07	2E-06	8E-06	4E-05	6E-07	3E-09	1E-05
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	0.005	0.015	6E-05	0	0	0	0	0	2E-05	0	0	0
OvR	5E-09	4E-05	3E-08	1E-05	8E-07	2E-05	3E-06	7E-07	5E-07	3E-07	1E-07	2E-09

Table A4.9 - Maximum values of Δk_{ij} calculated using the structure TV2a

In this case the proposed methodology points out some induced malunctions, in particular in the turbine sections and in the condenser. The outlet steam generator temperature is maintained constant by the control system. If the overall plant fuel is maintained fixed and the efficiency of the steam generator decreases, this temperature decreases too. The efficiency of the turbines is so affected. On the contrary in the operation versus reference approach, the set points are complied, so the working condition of the turbines does not change, so any induced malfunctions takes place. In this case the regulation system intervention induced malfunctions having negative values. They eliminate the induced malfunctions caused by the dysfunctions and a part of the intrinsic malfunction. This fact is pointed out by the unit cost of the regulation, which assumes a value lower than the average cost of the plant products, as shown in figure 6.2.

MALFUNCTION 11: Variation of the efficiency of the first stage of the high pressure turbine

The simulation has been made by imposing a 2% decreasing of the isentropic efficiency of the second stage of the middle pressure turbine. Table A4.10 shows the thermodynamic data relative to the reference and operation conditions. Table A4.11 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	98.27	124.5	3450	35	45.74	7	117	46.09	7	117
2	86.54	27.15	3104	86.91	27.27	3109	36	45.74	6.86	230	46.09	6.86	231
3	0.375	27.15	3381	0.377	27.27	3382	37	45.74	6.723	299	46.09	6.723	300
4	86.91	27.15	3105	87.29	27.27	3110	38	45.74	6.588	497	46.09	6.588	499
5	0	27.15	3105	0	27.27	3110	39	80.74	6.588	507	81.1	6.588	509
6	86.91	27.15	3105	87.29	27.27	3110	40	80.74	6.457	580	81.1	6.457	581
7	86.91	24.435	3552	87.29	24.54	3552	41	2.28	3.594	588	2.275	3.618	589
8	39.44	2.2317	2938	39.76	2.256	2939	42	5.92	2.009	505	5.956	2.03	507
9	39.44	1.1859	2938	39.76	1.196	2939	43	6.738	0.361	307	6.782	0.364	308
10	37.01	0.0224	2417	37.29	0.023	2417	44	8.647	0.172	238	8.719	0.174	239
11	1.645	0.1914	2630	1.688	0.193	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.937	0.193	2705	46	8.647	0.172	81.6	8.719	0.174	81.8
13	0.818	0.401	2744	0.826	0.405	2745	47	97.85	5.555	658	98.28	5.579	658
14	3.641	2.2317	2938	3.681	2.256	2939	48	97.85	162.1	681	98.28	162.2	681
15	1.37	3.9928	3062	1.346	4.02	3062	49	97.85	158.8	842	98.28	158.9	842
16	2.28	3.9928	3170	2.275	4.02	3174	50	97.85	155.6	995	98.28	155.7	996
17	1.443	6.4188	3174	1.439	6.453	3174	51	97.85	152.5	1063	98.28	152.6	1064
18	5.545	13.724	3380	5.578	13.79	3380	52	3.151	35.33	1052	3.164	35.48	1053
19	6.97	27.15	3104	6.994	27.27	3109	53	10.12	27.15	983	10.16	27.27	984
20	3.151	35.325	3162	3.164	35.48	3168	54	15.67	13.72	826	15.74	13.79	827
21	0.628	3.9928	3235	0.641	4.02	3238	56	45.74	7	82	46.09	7	82.2
22	0.029	0.95	3235	0.029	0.95	3238	57	45.74	7	81.9	46.09	7	82.1
23	0.161	1.2	3235	0.15	1.2	3238	59	0.086	0.022	81.1	0.086	0.023	81.3
24	0.029	0.95	3209	0.029	0.95	3210	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.165	1.2	3190	61	4900	1	68.1	4900	1	68.2
26	0.029	0.95	3217	0.029	0.95	3213	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3213	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35.01	2.256	2939	66	45.74	0.022	81.1	46.09	0.023	81.3
33	35	11	520	35.01	11	522	68	97.09	89.58	3381	97.5	89.99	3382
34	45.74	7	112	46.09	7	112	69	80.74	6.457	580	81.1	6.457	581

point	W kW	W kW	point	W kW	W kW
28	33472	33113	55	2801	2815
29	83684	83442	58	53	54
30	103627	103584	62	101049	101007
32	45	45	67	289797	290443

Table A4.10 - Values of the thermodynamic variables relative to the simulation MF11

Variable	Reference	Operation	
x_1	0.974	0.9695	
x_2	5.795	5.809	kg/s
x_3	35	35.0093	kg/s

Table A4.11 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.12 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	290443	289743	4b-1	8395.9	8475.7	8440.9	10s	7.993	8.09	8.037
1s	6297.69	6317.85	6288.4	4s-1	40.501	40.897	40.376	b10	594	601.3	594.6
b1	152708	153053	152800	m4-1	7626.1	7699.2	7673.3	11b	2889	2925	2906
2b-1	8396.42	8299.03	8391.3	4b-2	4871.8	4915.4	4882.7	11s	29.67	30.05	29.95
2s-1	87.4946	87.3791	87.276	4s-2	18.364	18.564	18.429	b11	2325	2354	2336
m2-1	6733.25	6639.94	6732.1	m4-2	4433.9	4479.6	4462.5	12b	2165	2166	2152
2b-2	23670.2	23545.1	23489	4b-3	10760	10871	10786	12s	14.33	14.38	14.42
2s-2	129.216	139.382	138.49	4s-3	151.59	153.13	151.69	b12	1892	1893	1878
m2-2	21214	20898.6	20856	m4-3	7878.4	7963.2	7901.9	13b	2459	2462	2436
2b-3	6181.79	6234.32	6219.4	5b	30173	30265	30311	13s	13.99	14	13.93
2s-3	34.5519	34.7448	34.52	5m	44.592	44.501	44.508	b13	2193	2196	2171
m2-3	5525	5574.61	5563.1	5s	-2866	-2865	-2866	14m	2801	2815	2797
3b-1	15941.8	16006.2	15975	b5	21751	21755	21788	14s	18.71	18.81	18.68
3s-1	54.3999	54.6943	54.251	6b	-0.124	-0.124	-0.124	b14	1885	1895	1882
m3-1	14907.7	14967.7	14944	6s	0.0916	0.0917	0.0914	15b	7001	7042	7011
3b-2	17609.2	17664.3	17624	m6	101049	101007	100837	15s	41.54	41.79	41.89
3s-2	49.6442	49.8524	49.505	7b	5716.8	5772.1	5714.1	b15	6211	6249	6215
m3-2	16665.6	16717.7	16683	8s	0.381	0.3843	0.3805	16b	6974	7019	6970
3b-3	9581.47	9597.14	9575.7	8m	53.453	53.86	53.388	16s	20.34	20.64	20.66
3s-3	32.8064	32.8865	32.649	b8	32.847	33.099	32.807	b16	6587	6627	6578
m3-3	8957.86	8972.71	8955	9b	6634.3	1194.2	1179.6	17b	3223	3247	3223
3b-4	10452.7	10436.3	10410	9s	15.914	19.91	19.667	17s	6.237	6.37	6.411
3s-4	41.1731	41.5795	41.394	b9	6332.4	816.18	805.47	b17	3105	3126	3102
m3-4	9670.07	9646.78	9623.2	10b	745.9	754.86	747.37				

Table A4.12 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.13 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	0	0	0.011	0	0	0	0	9E-04	0	0	0	0.004
OvR	4E-05	0.003	0.011	0	2E-05	3E-06	3E-06	9E-04	9E-07	2E-06	0	0.004
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	7E-04	0	0	0	0.001	0.001	0.002	6E-04	0	1E-03	9E-04	0.001
OvR	9E-04	0.002	1E-05	0	0	5E-06	2E-04	0	6E-06	0	5E-04	5E-04

Table A4.13 - Maximum values of Δk_{ij} calculated using the structure TV2a

In this case the two methodologies furnishes a similar result. The free versus reference approach allows to erase some induced malfunctions. This is confirmed by the value assumed by the unit cost associated to the regulation system, which is higher than the average cost of the plant product.

MALFUNCTION 12: Variation of the second stage of the middle pressure turbine efficiency

The simulation has been made by imposing a 2% decreasing of the isentropic efficiency of the second stage of the middle pressure turbine. Table A4.14 shows the thermodynamic data relative to the reference and operation conditions. Table A4.15 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	98.09	124.5	3450	35	45.74	7	117	45.98	7	117
2	86.54	27.15	3104	86.74	27.21	3104	36	45.74	6.86	230	45.98	6.86	231
3	0.375	27.15	3381	0.376	27.21	3382	37	45.74	6.723	299	45.98	6.723	300
4	86.91	27.15	3105	87.12	27.21	3105	38	45.74	6.588	497	45.98	6.588	498
5	0	27.15	3105	0	27.21	3105	39	80.74	6.588	507	80.94	6.588	508
6	86.91	27.15	3105	87.12	27.21	3105	40	80.74	6.457	580	80.94	6.457	581
7	86.91	24.435	3552	87.12	24.49	3552	41	2.28	3.594	588	2.271	3.609	589
8	39.44	2.2317	2938	39.64	2.25	2942	42	5.92	2.009	505	5.933	2.025	506
9	39.44	1.1859	2938	39.64	1.193	2942	43	6.738	0.361	307	6.756	0.364	308
10	37.01	0.0224	2417	37.21	0.022	2419	44	8.647	0.172	238	8.678	0.174	239
11	1.645	0.1914	2630	1.64	0.193	2633	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.923	0.193	2720	46	8.647	0.172	81.6	8.678	0.174	81.7
13	0.818	0.401	2744	0.823	0.404	2748	47	97.85	5.555	658	98.09	5.568	658
14	3.641	2.2317	2938	3.661	2.25	2942	48	97.85	162.1	681	98.09	162.1	681
15	1.37	3.9928	3062	1.374	4.01	3066	49	97.85	158.8	842	98.09	158.9	842
16	2.28	3.9928	3170	2.271	4.01	3172	50	97.85	155.6	995	98.09	155.7	995
17	1.443	6.4188	3174	1.435	6.439	3179	51	97.85	152.5	1063	98.09	152.6	1063
18	5.545	13.724	3380	5.563	13.76	3380	52	3.151	35.33	1052	3.162	35.41	1053
19	6.97	27.15	3104	6.99	27.21	3104	53	10.12	27.15	983	10.15	27.21	983
20	3.151	35.325	3162	3.162	35.41	3163	54	15.67	13.72	826	15.72	13.76	827
21	0.628	3.9928	3235	0.619	4.01	3236	56	45.74	7	82	45.98	7	82.1
22	0.029	0.95	3235	0.029	0.95	3236	57	45.74	7	81.9	45.98	7	82.1
23	0.161	1.2	3235	0.172	1.2	3236	59	0.086	0.022	81.1	0.086	0.022	81.2
24	0.029	0.95	3209	0.029	0.95	3212	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.174	1.2	3213	61	4900	1	68.1	4900	1	68.2
26	0.029	0.95	3217	0.029	0.95	3224	63	401.9	4	293	402	4	293
27	-0.06	1.2	3217	-0.06	1.2	3224	64	401.9	3.98	504	402	3.98	504
31	35	2.2317	2938	34.96	2.25	2942	66	45.74	0.022	81.1	45.98	0.022	81.2
33	35	11	520	34.96	11	521	68	97.09	89.58	3381	97.32	89.81	3382
34	45.74	7	112	45.98	7	112	69	80.74	6.457	580	80.94	6.457	581

point	W kW	W kW	point	W kW	W kW
28	33472	33502	55	2801	2809
29	83684	83466	58	53	54
30	103627	103595	62	101049	101018
32	45	44	67	289797	290367

Table A4.14 - Values of the thermodynamic variables relative to the simulation MF12

Variable	Reference	Operation	
x_1	0.974	0.9715	
x_2	5.795	5.807	kg/s
x_3	35	34.96	kg/s

Table A4.15 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.16 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	290367	289735	4b-1	8395.9	8464.1	8427.8	10s	7.993	8.059	8.052
1s	6297.69	6317.06	6307.7	4s-1	40.501	40.714	40.582	b10	594	598.9	597.4
b1	152708	153021	152564	m4-1	7626.1	7691	7657	11b	2889	2915	2911
2b-1	8396.42	8342.79	8375.1	4b-2	4871.8	4921.8	4894.6	11s	29.67	30.01	29.89
2s-1	87.4946	87.554	87.726	4s-2	18.364	18.552	18.511	b11	2325	2345	2342
m2-1	6733.25	6680.31	6708.8	m4-2	4433.9	4475.3	4454.5	12b	2165	2159	2153
2b-2	23670.2	23741.3	23635	4b-3	10760	10866	10828	12s	14.33	14.3	14.15
2s-2	129.216	129.694	129.48	4s-3	151.59	153.06	152.38	b12	1892	1888	1884
m2-2	21214	21278.6	21175	m4-3	7878.4	7959.9	7933.5	13b	2459	2459	2463
2b-3	6181.79	6202.09	6171.4	5b	30173	30263	30241	13s	13.99	14.04	14.01
2s-3	34.5519	34.73	34.66	5m	44.592	44.462	44.524	b13	2193	2192	2197
m2-3	5525	5542.64	5513	5s	-2866	-2866	-2865	14m	2801	2809	2809
3b-1	15941.8	15975.3	15921	b5	21751	21756	21753	14s	18.71	18.78	18.76
3s-1	54.3999	54.5582	54.592	6b	-0.124	-0.124	-0.123	b14	1885	1891	1891
m3-1	14907.7	14939.3	14884	6s	0.0916	0.0917	0.0913	15b	7001	7024	7004
3b-2	17609.2	17446.3	17391	m6	101049	101018	100645	15s	41.54	41.7	41.32
3s-2	49.6442	57.3993	57.395	7b	5716.8	5763.4	5747	b15	6211	6232	6219
m3-2	16665.6	16356.4	16300	8s	0.381	0.3833	0.3827	16b	6974	6997	6988
3b-3	9581.47	9614.06	9578.3	8m	53.453	53.726	53.656	16s	20.34	20.43	20.24
3s-3	32.8064	32.8464	32.815	b8	32.847	33.017	32.973	b16	6587	6609	6604
m3-3	8957.86	8990.37	8955	9b	6628.7	1195.2	1189.8	17b	3223	3236	3228
3b-4	10452.7	10451.7	10406	9s	15.581	20.055	19.954	17s	6.237	6.274	6.174
3s-4	41.1731	40.6497	40.499	b9	6332.9	814.41	811.33	b17	3105	3117	3111
m3-4	9670.07	9679.86	9636.8	10b	745.9	751.91	750.16				

Table A4.16 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.17 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	0.001	0.001	4E-04	4E-04	3E-04	0.01	2E-06	0	2E-07	6E-04	0	0.003
OvR	3E-04	0.001	4E-04	9E-05	1E-04	0.009	0.001	0.002	0.004	9E-04	3E-07	8E-04
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	8E-04	7E-04	0	1E-03	8E-06	8E-05	0	0	4E-06	0	0	0
OvR	2E-05	0.002	8E-07	0.001	4E-04	0.003	9E-04	2E-04	2E-04	1E-04	1E-04	0.001

Table A4.17 - Maximum values of Δk_{ij} calculated using the structure TV2a

MALFUNCTION 13: Variation of the third stage of the low pressure turbine efficiency

The simulation has been made by imposing a 2% decreasing of the isentropic efficiency of the third stage of the low pressure turbine. Table A4.18 shows the thermodynamic data relative to the reference and operation conditions. Table A4.19 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	98.07	124.5	3450	35	45.74	7	117	45.91	7	117
2	86.54	27.15	3104	86.72	27.21	3104	36	45.74	6.86	230	45.91	6.86	231
3	0.375	27.15	3381	0.376	27.21	3382	37	45.74	6.723	299	45.91	6.723	300
4	86.91	27.15	3105	87.1	27.21	3105	38	45.74	6.588	497	45.91	6.588	498
5	0	27.15	3105	0	27.21	3105	39	80.74	6.588	507	80.92	6.588	508
6	86.91	27.15	3105	87.1	27.21	3105	40	80.74	6.457	580	80.92	6.457	581
7	86.91	24.435	3552	87.1	24.49	3552	41	2.28	3.594	588	2.277	3.606	589
8	39.44	2.2317	2938	39.58	2.245	2938	42	5.92	2.009	505	5.94	2.021	506
9	39.44	1.1859	2938	39.58	1.191	2938	43	6.738	0.361	307	6.76	0.362	308
10	37.01	0.0224	2417	37.15	0.022	2421	44	8.647	0.172	238	8.679	0.173	238
11	1.645	0.1914	2630	1.644	0.192	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.918	0.192	2715	46	8.647	0.172	81.6	8.679	0.173	81.7
13	0.818	0.401	2744	0.821	0.403	2745	47	97.85	5.555	658	98.07	5.567	658
14	3.641	2.2317	2938	3.663	2.245	2938	48	97.85	162.1	681	98.07	162.1	681
15	1.37	3.9928	3062	1.375	4.007	3062	49	97.85	158.8	842	98.07	158.9	842
16	2.28	3.9928	3170	2.277	4.007	3170	50	97.85	155.6	995	98.07	155.7	995
17	1.443	6.4188	3174	1.44	6.436	3174	51	97.85	152.5	1063	98.07	152.6	1063
18	5.545	13.724	3380	5.561	13.75	3380	52	3.151	35.33	1052	3.161	35.41	1053
19	6.97	27.15	3104	6.989	27.21	3104	53	10.12	27.15	983	10.15	27.21	983
20	3.151	35.325	3162	3.161	35.41	3163	54	15.67	13.72	826	15.71	13.75	827
21	0.628	3.9928	3235	0.622	4.007	3236	56	45.74	7	82	45.91	7	82.1
22	0.029	0.95	3235	0.029	0.95	3236	57	45.74	7	81.9	45.91	7	82
23	0.161	1.2	3235	0.168	1.2	3236	59	0.086	0.022	81.1	0.086	0.022	81.2
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.172	1.2	3207	61	4900	1	68.1	4900	1	68.2
26	0.029	0.95	3217	0.029	0.95	3221	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3221	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35.01	2.245	2938	66	45.74	0.022	81.1	45.91	0.022	81.2
33	35	11	520	35.01	11	521	68	97.09	89.58	3381	97.31	89.79	3382
34	45.74	7	112	45.91	7	112	69	80.74	6.457	580	80.92	6.457	581

point	W kW	W kW	point	W kW	W kW
28	33472	33499	55	2801	2808
29	83684	83757	58	53	54
30	103627	103634	62	101049	101056
32	45	45	67	289797	290325

Table A4.18 - Values of the thermodynamic variables relative to the simulation MF13

Variable	Reference	Operation	
x_1	0.974	0.9717	
x_2	5.795	5.807	kg/s
x_3	35	35.005	kg/s

Table A4.19 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.20 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	290325	289735	4b-1	8395.9	8432.5	8407.5	10s	7.993	8.042	8.035
1s	6297.69	6314.9	6307.5	4s-1	40.501	40.698	40.635	b10	594	597.2	596.7
b1	152708	152996	152564	m4-1	7626.1	7659.6	7635.6	11b	2889	2909	2907
2b-1	8396.42	8346.67	8375.7	4b-2	4871.8	4894.3	4874.3	11s	29.67	29.9	29.82
2s-1	87.4946	87.5302	87.71	4s-2	18.364	18.452	18.438	b11	2325	2341	2340
m2-1	6733.25	6684.34	6709.7	m4-2	4433.9	4452	4437	12b	2165	2162	2156
2b-2	23670.2	23736	23635	4b-3	10760	10806	10785	12s	14.33	14.28	14.15
2s-2	129.216	129.646	129.48	4s-3	151.59	160.22	159.82	b12	1892	1891	1887
m2-2	21214	21273.8	21176	m4-3	7878.4	7763.7	7749.7	13b	2459	2460	2465
2b-3	6181.79	6200.39	6171.3	5b	30173	30226	30168	13s	13.99	14	13.97
2s-3	34.5519	34.7024	34.645	5m	44.592	44.54	44.544	b13	2193	2194	2200
m2-3	5525	5541.34	5513.2	5s	-2866	-2867	-2863	14m	2801	2808	2809
3b-1	15941.8	15974.1	15922	b5	21751	21753	21722	14s	18.71	18.77	18.77
3s-1	54.3999	54.5543	54.604	6b	-0.124	-0.124	-0.124	b14	1885	1890	1891
m3-1	14907.7	14938	14885	6s	0.0916	0.0917	0.0914	15b	7001	7022	7003
3b-2	17609.2	17636.4	17583	m6	101049	101056	100725	15s	41.54	41.68	41.32
3s-2	49.6442	49.7641	49.754	7b	5716.8	5755.5	5748.5	b15	6211	6230	6218
m3-2	16665.6	16691.3	16638	8s	0.381	0.386	0.3826	16b	6974	6995	6988
3b-3	9581.47	9589.15	9555.3	8m	53.453	53.652	53.645	16s	20.34	20.43	20.24
3s-3	32.8064	32.8569	32.836	b8	32.847	32.907	32.966	b16	6587	6607	6604
m3-3	8957.86	8965.15	8931.6	9b	6627.6	1188.8	1185.8	17b	3223	3235	3228
3b-4	10452.7	10436.1	10393	9s	15.579	19.904	19.826	17s	6.237	6.271	6.175
3s-4	41.1731	40.8485	40.712	b9	6331.8	810.77	809.36	b17	3105	3116	3111
m3-4	9670.07	9660.28	9619.3	10b	745.9	749.88	749.31				

Table A4.20 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.21 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	0.001	0.001	4E-04	4E-04	3E-04	2E-04	2E-04	0	3E-04	3E-04	0.026	0.002
OvR	3E-04	0.001	4E-04	8E-05	1E-04	9E-05	1E-04	5E-06	0.003	5E-04	0.026	0.002
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	8E-04	7E-04	0	1E-03	8E-06	8E-05	0	0	4E-06	0	0	0
OvR	6E-04	5E-04	0.002	6E-04	1E-05	0.001	4E-04	1E-04	2E-04	2E-04	1E-04	1E-04

Table A4.21 - Maximum values of Δk_{ij} calculated using the structure TV2a

Both the structures allow to correctly locate the anomaly, but the operation versus reference approach is characterized by lower malfunctions.

MALFUNCTION 14: Variation of the condenser heat transfer coefficient

In a separate routine the effectiveness-NTU model of the condenser has been made in order to simulate a malfunction condition in this component. The disposal data in design condition allow to determine the value of the heat transfer coefficient, by mean of the following steps. The known data are:

heat transfer area	A	6540 m^2;
condensate temperature	T_c	26.4°C;
inlet water temperature	T_{in}	12 °C;
outlet water temperature	T_{out}	20.4°C;
water mass flow	G	4900 kg/s;
water specific heat capacity	c_p	4.184 kJ/kgK.

The condensate is a fluid which specific heat capacity at constant pressure is infinite, so that water is the fluid characterized by the lower heat capacity, moreover the heat capacity ratio *r* is zero. In this way the effectiveness can be written:

$$\varepsilon = \frac{(T_{out} - T_{in})}{(T_c - T_{in})} \tag{A4.1}$$

$$\varepsilon = 1 - e^{-NTU} . \tag{A4.2}$$

Equations A4.1 and A4.2 allow to calculate the number of transfer units. Using its definition the heat transfer coefficient can be determined:

$$K = \frac{G \cdot c_p \cdot NTU}{A} . \tag{A4.3}$$

The calculated value of the heat transfer coefficient is 2.75 kW/m^2K.

A variation of this coefficient produces a variation of water mass flow and outlet water temperature, once the equations A4.1 - A4.3 are applied and the heat flow

$$\Phi = G \cdot c_p \cdot (T_{out} - T_{in}) \tag{7.10}$$

is kept constant. In this way the malfunction can be simulated simply by a water mass flow variation.

The simulation has been made by imposing a 5% decreasing of the heat transfer coefficient. Table A4.22 shows the thermodynamic data relative to the reference and operation conditions. Table A4.23 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G	p	h	G	p	h	point	G	p	h	G	p	h
	kg/s	bar	kJ/kg	kg/s	bar	kJ/kg		kg/s	bar	kJ/kg	kg/s	bar	kJ/kg
1	97.85	124.54	3450	97.85	124.5	3450	35	45.74	7	117	45.74	7	117
2	86.54	27.15	3104	86.54	27.15	3104	36	45.74	6.86	230	45.74	6.86	230
3	0.375	27.15	3381	0.375	27.15	3381	37	45.74	6.723	299	45.74	6.723	299
4	86.91	27.15	3105	86.91	27.15	3105	38	45.74	6.588	497	45.74	6.588	497
5	0	27.15	3105	0	27.15	3105	39	80.74	6.588	507	80.74	6.588	507
6	86.91	27.15	3105	86.91	27.15	3105	40	80.74	6.457	580	80.74	6.457	580
7	86.91	24.435	3552	86.91	24.43	3552	41	2.28	3.594	588	2.28	3.594	588
8	39.44	2.2317	2938	39.44	2.232	2938	42	5.92	2.009	505	5.92	2.009	505
9	39.44	1.1859	2938	39.44	1.186	2938	43	6.738	0.361	307	6.738	0.361	307
10	37.01	0.0224	2417	37.01	0.022	2417	44	8.647	0.172	238	8.647	0.172	238
11	1.645	0.1914	2630	1.645	0.191	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.909	0.191	2711	46	8.647	0.172	81.6	8.647	0.172	81.6
13	0.818	0.401	2744	0.818	0.401	2744	47	97.85	5.555	658	97.85	5.555	658
14	3.641	2.2317	2938	3.641	2.232	2938	48	97.85	162.1	681	97.85	162.1	681
15	1.37	3.9928	3062	1.37	3.993	3062	49	97.85	158.8	842	97.85	158.8	842
16	2.28	3.9928	3170	2.28	3.993	3170	50	97.85	155.6	995	97.85	155.6	995
17	1.443	6.4188	3174	1.443	6.419	3174	51	97.85	152.5	1063	97.85	152.5	1063
18	5.545	13.724	3380	5.545	13.72	3380	52	3.151	35.33	1052	3.151	35.33	1052
19	6.97	27.15	3104	6.97	27.15	3104	53	10.12	27.15	983	10.12	27.15	983
20	3.151	35.325	3162	3.151	35.33	3162	54	15.67	13.72	826	15.67	13.72	826
21	0.628	3.9928	3235	0.628	3.993	3235	56	45.74	7	82	45.74	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.74	7	81.9
23	0.161	1.2	3235	0.161	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	5401	1	50.5
25	0.169	1.2	3201	0.169	1.2	3201	61	4900	1	68.1	5401	1	66.5
26	0.029	0.95	3217	0.029	0.95	3217	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.06	1.2	3217	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35	2.232	2938	66	45.74	0.022	81.1	45.74	0.022	81.1
33	35	11	520	35	11	520	68	97.09	89.58	3381	97.09	89.58	3381
34	45.74	7	112	45.74	7	112	69	80.74	6.457	580	80.74	6.457	580

point	W	W	point	W	W
	kW	kW		kW	kW
28	33472	33472	55	2801	2801
29	83684	83684	58	53	53
30	103627	103627	62	101049	101049
32	45	45	67	289797	289797

Table A4.22 - Values of the thermodynamic variables relative to the simulation MF14

Variable	Reference	Operation	
x_1	0.974	0.974	
x_2	5.795	5.795	kg/s
x_3	35	35	kg/s

Table A4.23 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.24 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289797	289797	4b-1	8395.9	8395.9	8395.9	10s	7.993	7.888	7.888
1s	6297.69	6215.08	6215.1	4s-1	40.501	39.97	39.97	b10	594	594	594
b1	152708	152708	152708	m4-1	7626.1	7626.1	7626.1	11b	2889	2889	2889
2b-1	8396.42	8396.42	8396.4	4b-2	4871.8	4871.8	4871.8	11s	29.67	29.28	29.28
2s-1	87.4946	86.3469	86.347	4s-2	18.364	18.123	18.123	b11	2325	2325	2325
m2-1	6733.25	6733.25	6733.2	m4-2	4433.9	4433.9	4433.9	12b	2165	2165	2165
2b-2	23670.2	23670.2	23670	4b-3	10760	10760	10760	12s	14.33	14.15	14.15
2s-2	129.216	127.521	127.52	4s-3	151.59	149.6	149.6	b12	1892	1892	1892
m2-2	21214	21214	21214	m4-3	7878.4	7878.4	7878.4	13b	2459	2459	2459
2b-3	6181.79	6181.79	6181.8	5b	30173	30173	30173	13s	13.99	13.81	13.81
2s-3	34.5519	34.0987	34.099	5m	44.592	44.592	44.592	b13	2193	2193	2193
m2-3	5525	5525	5525	5s	-2866	-2829	-2829	14m	2801	2801	2801
3b-1	15941.8	15941.8	15942	b5	21751	21751	21751	14s	18.71	18.46	18.46
3s-1	54.3999	53.6863	53.686	6b	-0.124	-0.124	-0.124	b14	1885	1885	1885
m3-1	14907.7	14907.7	14908	6s	0.0916	0.0904	0.0904	15b	7001	7001	7001
3b-2	17609.2	17609.2	17609	m6	101049	101049	101049	15s	41.54	41	41
3s-2	49.6442	48.993	48.993	7b	5716.8	5716.8	5716.8	b15	6211	6211	6211
m3-2	16665.6	16665.6	16666	8s	0.381	0.376	0.376	16b	6974	6974	6974
3b-3	9581.47	9581.47	9581.5	8m	53.453	53.453	53.453	16s	20.34	20.07	20.07
3s-3	32.8064	32.3761	32.376	b8	32.847	32.847	32.847	b16	6587	6587	6587
m3-3	8957.86	8957.86	8957.9	9b	6610.7	1180.3	1180.3	17b	3223	3223	3223
3b-4	10452.7	10452.7	10453	9s	15.444	19.469	19.469	17s	6.237	6.155	6.155
3s-4	41.1731	40.6331	40.633	b9	6314	805.32	805.32	b17	3105	3105	3105
m3-4	9670.07	9670.07	9670.1	10b	745.9	745.9	745.9				

Table A4.24 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.25 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	0	0	0	0	0	0	0	0	0	0	0	0.002
OvR	0	0	0	0	0	0	0	0	0	0	0	0.002
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	0	0.018	0	0	0	0	0	0	0	0	0	0
OvR	0	0.018	0	0	0	0	0	0	0	0	0	0

Table A4.25 - Maximum values of Δk_{ij} calculated using the structure TV2a

Both the structures allow to correctly locate the anomaly. The values assumed by the elements of the matrix of unit exergy consumption variations are the same. The only induced effect takes place in the hot condenser. It is due to the variation of negentropy produced. In the thermoeconomic diagnosis this contribution must be neglected.

MALFUNCTION 15: Variation of heat transfer coefficient of the hot condenser

The simulation has been made by imposing a 3% decreasing of the heat transfer coefficient of the hot condenser. Table A4.26 shows the thermodynamic data relative to the reference and operation conditions. Table A4.27 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G	p	h	G	p	h	point	G	p	h	G	p	h
	kg/s	bar	kJ/kg	kg/s	bar	kJ/kg		kg/s	bar	kJ/kg	kg/s	bar	kJ/kg
1	97.85	124.54	3450	97.85	124.5	3450	35	45.74	7	117	45.74	7	117
2	86.54	27.15	3104	86.54	27.15	3104	36	45.74	6.86	230	45.74	6.86	230
3	0.375	27.15	3381	0.375	27.15	3381	37	45.74	6.723	299	45.74	6.723	299
4	86.91	27.15	3105	86.91	27.15	3105	38	45.74	6.588	497	45.74	6.588	497
5	0	27.15	3105	0	27.15	3105	39	80.74	6.588	507	80.74	6.588	507
6	86.91	27.15	3105	86.91	27.15	3105	40	80.74	6.457	580	80.74	6.457	580
7	86.91	24.435	3552	86.91	24.43	3552	41	2.28	3.594	588	2.28	3.594	588
8	39.44	2.2317	2938	39.44	2.232	2938	42	5.92	2.009	505	5.92	2.009	505
9	39.44	1.1859	2938	39.44	1.186	2938	43	6.738	0.361	307	6.738	0.361	307
10	37.01	0.0224	2417	37.01	0.022	2417	44	8.647	0.172	238	8.647	0.172	238
11	1.645	0.1914	2630	1.645	0.191	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.909	0.191	2711	46	8.647	0.172	81.6	8.647	0.172	81.6
13	0.818	0.401	2744	0.818	0.401	2744	47	97.85	5.555	658	97.85	5.555	658
14	3.641	2.2317	2938	3.641	2.232	2938	48	97.85	162.1	681	97.85	162.1	681
15	1.37	3.9928	3062	1.369	3.993	3062	49	97.85	158.8	842	97.85	158.8	842
16	2.28	3.9928	3170	2.28	3.993	3170	50	97.85	155.6	995	97.85	155.6	995
17	1.443	6.4188	3174	1.443	6.419	3174	51	97.85	152.5	1063	97.85	152.5	1063
18	5.545	13.724	3380	5.545	13.72	3380	52	3.151	35.33	1052	3.151	35.33	1052
19	6.97	27.15	3104	6.97	27.15	3104	53	10.12	27.15	983	10.12	27.15	983
20	3.151	35.325	3162	3.151	35.33	3162	54	15.67	13.72	826	15.67	13.72	826
21	0.628	3.9928	3235	0.628	3.993	3235	56	45.74	7	82	45.74	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.74	7	81.9
23	0.161	1.2	3235	0.161	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.169	1.2	3201	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3217	63	401.9	4	293	411.8	4	293
27	-0.06	1.2	3217	-0.06	1.2	3217	64	401.9	3.98	504	411.8	3.98	499
31	35	2.2317	2938	35	2.232	2938	66	45.74	0.022	81.1	45.74	0.022	81.1
33	35	11	520	35	11	520	68	97.09	89.58	3381	97.09	89.58	3381
34	45.74	7	112	45.74	7	112	69	80.74	6.457	580	80.74	6.457	580

point	W	W	point	W	W
	kW	kW		kW	kW
28	33472	33472	55	2801	2801
29	83684	83683	58	53	53
30	103627	103621	62	101049	101044
32	45	45	67	289797	289797

Table A4.26 - Values of the thermodynamic variables relative to the simulation MF15

Variable	Reference	Operation	
x_1	0.974	0.974	
x_2	5.795	5.795	kg/s
x_3	35	35	kg/s

Table A4.27 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.28 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289797	289797	4b-1	8395.9	8396.6	8396.6	10s	7.993	7.992	7.992
1s	6297.69	6297.7	6297.7	4s-1	40.501	40.503	40.503	b10	594	594	594
b1	152708	152708	152708	m4-1	7626.1	7626.6	7626.6	11b	2889	2889	2889
2b-1	8396.42	8396.41	8396.4	4b-2	4871.8	4871.5	4871.5	11s	29.67	29.67	29.67
2s-1	87.4946	87.4945	87.494	4s-2	18.364	18.363	18.363	b11	2325	2325	2325
m2-1	6733.25	6733.25	6733.2	m4-2	4433.9	4433.6	4433.6	12b	2165	2164	2164
2b-2	23670.2	23670.2	23670	4b-3	10760	10760	10760	12s	14.33	14.33	14.33
2s-2	129.216	129.216	129.22	4s-3	151.59	151.59	151.59	b12	1892	1892	1892
m2-2	21214	21214	21214	m4-3	7878.4	7878.8	7878.8	13b	2459	2459	2459
2b-3	6181.79	6181.84	6181.8	5b	30173	30173	30173	13s	13.99	13.99	13.99
2s-3	34.5519	34.5521	34.552	5m	44.592	44.591	44.591	b13	2193	2193	2193
m2-3	5525	5525.05	5525	5s	-2866	-2866	-2866	14m	2801	2801	2801
3b-1	15941.8	15941.8	15942	b5	21751	21652	21652	14s	18.71	18.71	18.71
3s-1	54.3999	54.3999	54.4	6b	-0.124	-0.124	-0.124	b14	1885	1885	1885
m3-1	14907.7	14907.7	14908	6s	0.0916	0.0916	0.0916	15b	7001	7001	7001
3b-2	17609.2	17609	17609	m6	101049	101044	101044	15s	41.54	41.54	41.54
3s-2	49.6442	49.6433	49.643	7b	5716.8	5716.8	5716.8	b15	6211	6211	6211
m3-2	16665.6	16665.3	16665	8s	0.381	0.381	0.381	16b	6974	6974	6974
3b-3	9581.47	9581.27	9581.3	8m	53.453	53.453	53.453	16s	20.34	20.34	20.34
3s-3	32.8064	32.8056	32.806	b8	32.847	32.847	32.847	b16	6587	6587	6587
m3-3	8957.86	8957.67	8957.7	9b	6610.7	1180.3	1180.3	17b	3223	3223	3223
3b-4	10452.7	10451.9	10452	9s	15.608	19.729	19.729	17s	6.237	6.237	6.237
3s-4	41.1731	41.1708	41.171	b9	6314	805.31	805.31	b17	3105	3105	3105
m3-4	9670.07	9669.29	9669.3	10b	745.9	745.92	745.92				

Table A4.28 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.29 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	3E-07	0	4E-09	0	4E-10	0	0	2E-06	0	6E-07	0	0.006
OvR	2E-07	0	4E-09	0	1E-07	6E-07	2E-06	8E-06	4E-05	6E-07	3E-09	0.005
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	1E-05	0	4E-09	4E-05	0	1E-05	0	0	7E-09	2E-07	2E-07	1E-07
OvR	1E-05	2E-09	5E-09	4E-05	3E-08	1E-05	8E-07	3E-06	7E-07	5E-07	3E-07	1E-07

Table A4.29 - Maximum values of Δk_{ij} calculated using the structure TV2a

Both the structures allow to correctly locate the anomaly, but the operation versus reference approach is characterized by lower malfunctions.

MALFUNCTION 16: Variation of the TTD in the second feed water heater

The simulation has been made by imposing a 50% increasing of the TTD of the feed water heater HE2. Table A4.30 shows the thermodynamic data relative to the reference and operation conditions. Table A4.31 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.89	124.5	3450	35	45.74	7	117	45.74	7	117
2	86.54	27.15	3104	86.57	27.16	3104	36	45.74	6.86	230	45.74	6.86	230
3	0.375	27.15	3381	0.374	27.16	3381	37	45.74	6.723	299	45.74	6.723	291
4	86.91	27.15	3105	86.94	27.16	3105	38	45.74	6.588	497	45.74	6.588	497
5	0	27.15	3105	0	27.16	3105	39	80.74	6.588	507	80.75	6.588	507
6	86.91	27.15	3105	86.94	27.16	3105	40	80.74	6.457	580	80.75	6.457	580
7	86.91	24.435	3552	86.94	24.44	3552	41	2.28	3.594	588	2.297	3.586	588
8	39.44	2.2317	2938	39.21	2.221	2937	42	5.92	2.009	505	6.084	1.999	505
9	39.44	1.1859	2938	39.21	1.178	2937	43	6.738	0.361	307	6.73	0.361	307
10	37.01	0.0224	2417	37.03	0.022	2417	44	8.647	0.172	238	8.624	0.172	238
11	1.645	0.1914	2630	1.57	0.192	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.895	0.192	2734	46	8.647	0.172	81.6	8.624	0.172	81.6
13	0.818	0.401	2744	0.646	0.401	2744	47	97.85	5.555	658	97.87	5.555	658
14	3.641	2.2317	2938	3.787	2.221	2937	48	97.85	162.1	681	97.87	162.1	681
15	1.37	3.9928	3062	1.448	3.984	3061	49	97.85	158.8	842	97.87	158.8	842
16	2.28	3.9928	3170	2.297	3.984	3162	50	97.85	155.6	995	97.87	155.7	995
17	1.443	6.4188	3174	1.453	6.414	3174	51	97.85	152.5	1063	97.87	152.5	1063
18	5.545	13.724	3380	5.547	13.73	3380	52	3.151	35.33	1052	3.153	35.34	1052
19	6.97	27.15	3104	6.973	27.16	3104	53	10.12	27.15	983	10.13	27.16	983
20	3.151	35.325	3162	3.153	35.34	3162	54	15.67	13.72	826	15.67	13.73	826
21	0.628	3.9928	3235	0.586	3.984	3236	56	45.74	7	82	45.74	7	82
22	0.029	0.95	3235	0.029	0.95	3236	57	45.74	7	81.9	45.74	7	82
23	0.161	1.2	3235	0.204	1.2	3236	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3208	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.188	1.2	3237	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3236	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3236	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35.01	2.221	2937	66	45.74	0.022	81.1	45.74	0.022	81.1
33	35	11	520	35.01	11	520	68	97.09	89.58	3381	97.13	89.61	3381
34	45.74	7	112	45.74	7	112	69	80.74	6.457	580	80.75	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33479	55	2801	2802
29	83684	83778	58	53	53
30	103627	103622	62	101049	101045
32	45	45	67	289797	289850

Table A4.30 - Values of the thermodynamic variables relative to the simulation MF16

Variable	Reference	Operation	
x_1	0.974	0.9736	
x_2	5.795	5.797	kg/s
x_3	35	35.005	kg/s

Table A4.31 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.32 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289850	289730	4b-1	8395.9	8301	8297	10s	7.993	7.728	7.717
1s	6297.69	6302.89	6302.3	4s-1	40.501	40.081	40.091	b10	594	514.2	514.4
b1	152708	152768	152671	m4-1	7626.1	7539.4	7535.2	11b	2889	3000	3000
2b-1	8396.42	8391.18	8394.9	4b-2	4871.8	4875.7	4872.5	11s	29.67	31.83	31.82
2s-1	87.4946	87.6967	87.746	4s-2	18.364	18.308	18.312	b11	2325	2395	2396
m2-1	6733.25	6724.78	6727.6	m4-2	4433.9	4418.8	4416.2	12b	2165	2170	2169
2b-2	23670.2	23683.2	23661	4b-3	10760	10772	10771	12s	14.33	14.23	14.2
2s-2	129.216	129.327	129.32	4s-3	151.59	151.78	151.76	b12	1892	1899	1899
m2-2	21214	21225.7	21203	m4-3	7878.4	7887.6	7887.4	13b	2459	2469	2471
2b-3	6181.79	6189.2	6182.6	5b	30173	30138	30118	13s	13.99	14.06	14.06
2s-3	34.5519	34.7836	34.778	5m	44.592	44.643	44.638	b13	2193	2202	2204
m2-3	5525	5528.25	5521.8	5s	-2866	-2869	-2868	14m	2801	2802	2803
3b-1	15941.8	15953	15941	b5	21751	21751	21739	14s	18.71	18.72	18.72
3s-1	54.3999	54.4246	54.453	6b	-0.124	-0.124	-0.124	b14	1885	1886	1886
m3-1	14907.7	14918.8	14907	6s	0.0916	0.0916	0.0916	15b	7001	7003	6999
3b-2	17609.2	17635.9	17624	m6	101049	101045	100972	15s	41.54	41.57	41.48
3s-2	49.6442	49.7441	49.755	7b	5716.8	5722.5	5723.6	b15	6211	6213	6211
m3-2	16665.6	16690.6	16679	8s	0.381	0.3811	0.3813	16b	6974	6978	6978
3b-3	9581.47	9610.48	9603	8m	53.453	53.451	53.472	16s	20.34	20.36	20.32
3s-3	32.8064	32.9315	32.935	b8	32.847	32.846	32.859	b16	6587	6591	6592
m3-3	8957.86	8984.72	8977.2	9b	6613.8	1186.3	1186.2	17b	3223	3225	3224
3b-4	10452.7	10498.5	10489	9s	15.597	20.023	20.012	17s	6.237	6.244	6.219
3s-4	41.1731	39.4732	39.445	b9	6317.4	805.77	805.94	b17	3105	3106	3106
m3-4	9670.07	9748.45	9739.3	10b	745.9	661.03	661.29				

Table A4.32 - Fluxes of the productive structure TV2a

The Δ**k** matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.33 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	4E-05	8E-04	1E-04	8E-04	4E-05	6E-05	1E-04	0	2E-04	0.005	4E-06	0
OvR	3E-05	6E-04	6E-05	6E-04	4E-07	6E-05	2E-04	0	0.004	0.004	4E-06	2E-06
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	8E-04	4E-04	3E-06	0.006	0.03	0.01	0	0	4E-06	0	0	0
OvR	8E-04	3E-04	5E-06	0.007	0.029	0.009	3E-04	4E-04	4E-06	2E-06	2E-05	2E-05

Table A4.33 - Maximum values of Δk_{ij} calculated using the structure TV2a

Both the structures allow to correctly locate the anomaly, but the operation versus reference approach is characterized by lower malfunctions.

MALFUNCTION 17: Variation of the TTD in the third feed water heater

The simulation has been made by imposing a 50% increasing of the TTD of the feed water heater HE3. Table A4.34 shows the thermodynamic data relative to the reference and operation conditions. Table A4.35 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.89	124.5	3450	35	45.74	7	117	45.74	7	117
2	86.54	27.15	3104	86.57	27.16	3104	36	45.74	6.86	230	45.74	6.86	230
3	0.375	27.15	3381	0.374	27.16	3381	37	45.74	6.723	299	45.74	6.723	299
4	86.91	27.15	3105	86.94	27.16	3105	38	45.74	6.588	497	45.74	6.588	489
5	0	27.15	3105	0	27.16	3105	39	80.74	6.588	507	80.75	6.588	502
6	86.91	27.15	3105	86.94	27.16	3105	40	80.74	6.457	580	80.75	6.457	580
7	86.91	24.435	3552	86.94	24.44	3552	41	2.28	3.594	588	2.436	3.586	588
8	39.44	2.2317	2938	39.38	2.23	2937	42	5.92	2.009	505	5.911	2.007	505
9	39.44	1.1859	2938	39.38	1.183	2937	43	6.738	0.361	307	6.727	0.361	307
10	37.01	0.0224	2417	37.03	0.022	2417	44	8.647	0.172	238	8.622	0.172	238
11	1.645	0.1914	2630	1.57	0.192	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.895	0.192	2734	46	8.647	0.172	81.6	8.622	0.172	81.6
13	0.818	0.401	2744	0.816	0.401	2744	47	97.85	5.555	658	97.87	5.555	658
14	3.641	2.2317	2938	3.475	2.23	2937	48	97.85	162.1	681	97.87	162.1	681
15	1.37	3.9928	3062	1.587	3.984	3061	49	97.85	158.8	842	97.87	158.8	842
16	2.28	3.9928	3170	2.436	3.984	3156	50	97.85	155.6	995	97.87	155.7	995
17	1.443	6.4188	3174	1.453	6.414	3174	51	97.85	152.5	1063	97.87	152.5	1063
18	5.545	13.724	3380	5.547	13.73	3380	52	3.151	35.33	1052	3.153	35.34	1052
19	6.97	27.15	3104	6.973	27.16	3104	53	10.12	27.15	983	10.13	27.16	983
20	3.151	35.325	3162	3.153	35.34	3162	54	15.67	13.72	826	15.67	13.73	826
21	0.628	3.9928	3235	0.586	3.984	3236	56	45.74	7	82	45.74	7	82
22	0.029	0.95	3235	0.029	0.95	3236	57	45.74	7	81.9	45.74	7	82
23	0.161	1.2	3235	0.204	1.2	3236	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.188	1.2	3237	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3236	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3236	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35.01	2.23	2937	66	45.74	0.022	81.1	45.74	0.022	81.1
33	35	11	520	35.01	11	520	68	97.09	89.58	3381	97.13	89.61	3381
34	45.74	7	112	45.74	7	112	69	80.74	6.457	580	80.75	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33479	55	2801	2802
29	83684	83699	58	53	53
30	103627	103610	62	101049	101033
32	45	45	67	289797	289850

Table A4.34 - Values of the thermodynamic variables relative to the simulation MF17

Variable	Reference	Operation	
x_1	0.974	0.9736	
x_2	5.795	5.797	kg/s
x_3	35	35.005	kg/s

Table A4.35 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.36 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289850	289730	4b-1	8395.9	8370.2	8366.2	10s	7.993	7.972	7.972
1s	6297.69	6302.98	6302.3	4s-1	40.501	40.402	40.411	b10	594	592.7	592.9
b1	152708	152768	152671	m4-1	7626.1	7602.5	7598.3	11b	2889	2764	2764
2b-1	8396.42	8391.18	8394.9	4b-2	4871.8	4876.3	4873.1	11s	29.67	29.29	29.26
2s-1	87.4946	87.698	87.747	4s-2	18.364	18.31	18.314	b11	2325	2208	2208
m2-1	6733.25	6724.78	6727.6	m4-2	4433.9	4419.3	4416.7	12b	2165	2293	2292
2b-2	23670.2	23683.2	23661	4b-3	10760	10773	10772	12s	14.33	15.26	15.24
2s-2	129.216	129.329	129.32	4s-3	151.59	151.79	151.77	b12	1892	2003	2002
m2-2	21214	21225.7	21203	m4-3	7878.4	7888.2	7887.9	13b	2459	2469	2471
2b-3	6181.79	6189.2	6182.6	5b	30173	30175	30156	13s	13.99	14.06	14.06
2s-3	34.5519	34.7841	34.779	5m	44.592	44.605	44.6	b13	2193	2202	2204
m2-3	5525	5528.25	5521.8	5s	-2866	-2868	-2866	14m	2801	2802	2803
3b-1	15941.8	15953.2	15942	b5	21751	21753	21742	14s	18.71	18.72	18.72
3s-1	54.3999	54.439	54.466	6b	-0.124	-0.124	-0.124	b14	1885	1886	1886
m3-1	14907.7	14918.8	14907	6s	0.0916	0.0916	0.0916	15b	7001	7003	6999
3b-2	17609.2	17635.9	17624	m6	101049	101033	100960	15s	41.54	41.57	41.48
3s-2	49.6442	49.7448	49.755	7b	5716.8	5723.1	5724.2	b15	6211	6213	6211
m3-2	16665.6	16690.6	16679	8s	0.381	0.3811	0.3813	16b	6974	6978	6978
3b-3	9581.47	9610.49	9603	8m	53.453	53.451	53.472	16s	20.34	20.36	20.32
3s-3	32.8064	32.932	32.935	b8	32.847	32.846	32.859	b16	6587	6591	6592
m3-3	8957.86	8984.73	8977.2	9b	6613.8	1186.4	1186.4	17b	3223	3225	3224
3b-4	10452.7	10413.1	10403	9s	15.597	20.028	20.016	17s	6.237	6.245	6.22
3s-4	41.1731	39.1244	39.098	b9	6317.4	805.81	805.98	b17	3105	3106	3106
m3-4	9670.07	9669.71	9660.5	10b	745.9	744.16	744.38				

Table A4.36 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.37 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	4E-05	8E-04	1E-04	8E-04	6E-05	6E-05	1E-04	0	1E-04	0.005	4E-06	0
OvR	3E-05	6E-04	6E-05	6E-04	1E-05	6E-05	1E-04	0	0.001	0.004	4E-06	5E-05
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	3E-04	4E-04	3E-06	0.006	0	0.009	5E-04	0	4E-06	0	0	0
OvR	3E-04	3E-04	5E-06	0.007	2E-06	0.009	0.002	4E-04	5E-06	2E-06	2E-05	2E-05

Table A4.37 - Maximum values of Δk_{ij} calculated using the structure TV2a

Both the structures allow to correctly locate the anomaly, although some important induced effects take place in the system.

MALFUNCTION 18: Pressure drop at the steam side in the third feed water heater

The simulation has been made by imposing a 2% pressure drop at the steam side of the feed water heater HE3. Table A4.38 shows the thermodynamic data relative to the reference and operation conditions. Table A4.39 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.85	124.5	3450	35	45.74	7	117	45.74	7	117
2	86.54	27.15	3104	86.54	27.15	3104	36	45.74	6.86	230	45.74	6.86	230
3	0.375	27.15	3381	0.375	27.15	3381	37	45.74	6.723	299	45.74	6.723	300
4	86.91	27.15	3105	86.91	27.15	3105	38	45.74	6.588	497	45.74	6.588	491
5	0	27.15	3105	0	27.15	3105	39	80.74	6.588	507	80.74	6.588	504
6	86.91	27.15	3105	86.91	27.15	3105	40	80.74	6.457	580	80.74	6.457	580
7	86.91	24.435	3552	86.91	24.43	3552	41	2.28	3.594	588	2.392	3.594	588
8	39.44	2.2317	2938	39.47	2.239	2938	42	5.92	2.009	505	5.891	1.914	499
9	39.44	1.1859	2938	39.47	1.188	2938	43	6.738	0.361	307	6.727	0.361	307
10	37.01	0.0224	2417	37.02	0.022	2417	44	8.647	0.172	238	8.638	0.172	238
11	1.645	0.1914	2630	1.649	0.191	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.911	0.191	2711	46	8.647	0.172	81.6	8.638	0.172	81.6
13	0.818	0.401	2744	0.836	0.401	2745	47	97.85	5.555	658	97.85	5.555	658
14	3.641	2.2317	2938	3.498	2.239	2938	48	97.85	162.1	681	97.85	162.1	681
15	1.37	3.9928	3062	1.482	3.993	3062	49	97.85	158.8	842	97.85	158.8	842
16	2.28	3.9928	3170	2.392	3.993	3165	50	97.85	155.6	995	97.85	155.6	995
17	1.443	6.4188	3174	1.443	6.419	3174	51	97.85	152.5	1063	97.85	152.5	1063
18	5.545	13.724	3380	5.545	13.72	3380	52	3.151	35.33	1052	3.151	35.33	1052
19	6.97	27.15	3104	6.97	27.15	3104	53	10.12	27.15	983	10.12	27.15	983
20	3.151	35.325	3162	3.151	35.33	3162	54	15.67	13.72	826	15.67	13.72	826
21	0.628	3.9928	3235	0.628	3.993	3235	56	45.74	7	82	45.74	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.74	7	82
23	0.161	1.2	3235	0.161	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.169	1.2	3201	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3218	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3218	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35	2.239	2938	66	45.74	0.022	81.1	45.74	0.022	81.1
33	35	11	520	35	11	521	68	97.09	89.58	3381	97.09	89.58	3381
34	45.74	7	112	45.74	7	112	69	80.74	6.457	580	80.74	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33472	55	2801	2801
29	83684	83620	58	53	53
30	103627	103583	62	101049	101007
32	45	45	67	289797	289797

Table A4.38 - Values of the thermodynamic variables relative to the simulation MF18

Variable	Reference	Operation	
x_1	0.974	0.974	
x_2	5.795	5.796	kg/s
x_3	35	35	kg/s

Table A4.39 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.40 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289797	289729	4b-1	8395.9	8413	8410.9	10s	7.993	7.811	7.82
1s	6297.69	6297.98	6300.2	4s-1	40.501	40.578	40.637	b10	594	594.2	595.1
b1	152708	152708	152620	m4-1	7626.1	7641.7	7638.6	11b	2889	2795	2798
2b-1	8396.42	8396.41	8391.1	4b-2	4871.8	4875.1	4874.1	11s	29.67	29.43	29.4
2s-1	87.4946	87.4984	87.566	4s-2	18.364	18.379	18.396	b11	2325	2236	2238
m2-1	6733.25	6733.25	6726.9	m4-2	4433.9	4437.7	4435.9	12b	2165	2264	2264
2b-2	23670.2	23670.2	23649	4b-3	10760	10768	10774	12s	14.33	15.16	15.13
2s-2	129.216	129.222	129.29	4s-3	151.59	151.67	151.77	b12	1892	1976	1977
m2-2	21214	21214	21192	m4-3	7878.4	7884.8	7889.8	13b	2459	2459	2464
2b-3	6181.79	6181.84	6175.5	5b	30173	30204	30180	13s	13.99	13.99	13.99
2s-3	34.5519	34.5535	34.57	5m	44.592	44.56	44.561	b13	2193	2193	2198
m2-3	5525	5525.05	5518.5	5s	-2866	-2865	-2864	14m	2801	2801	2804
3b-1	15941.8	15942	15932	b5	21751	21753	21739	14s	18.71	18.71	18.73
3s-1	54.3999	54.415	54.494	6b	-0.124	-0.124	-0.124	b14	1885	1885	1887
m3-1	14907.7	14907.6	14896	6s	0.0916	0.0916	0.0915	15b	7001	7001	7000
3b-2	17609.2	17609	17600	m6	101049	101007	100935	15s	41.54	41.54	41.42
3s-2	49.6442	49.6456	49.694	7b	5716.8	5719.2	5725.8	b15	6211	6211	6212
m3-2	16665.6	16665.3	16655	8s	0.381	0.3843	0.3848	16b	6974	6974	6979
3b-3	9581.47	9581.27	9574.6	8m	53.453	53.453	53.522	16s	20.34	20.34	20.29
3s-3	32.8064	32.8071	32.836	b8	32.847	32.785	32.827	b16	6587	6587	6594
m3-3	8957.86	8957.68	8950.5	9b	6612.3	1180.8	1182.1	17b	3223	3223	3225
3b-4	10452.7	10383.1	10374	9s	15.575	19.736	19.748	17s	6.237	6.238	6.204
3s-4	41.1731	40.8948	40.882	b9	6316.3	805.64	806.82	b17	3105	3105	3107
m3-4	9670.07	9605.81	9597.4	10b	745.9	742.68	743.61				

Table A4.40 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.41 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	7E-04	4E-04	2E-04	1E-04	2E-04	8E-05	1E-04	2E-05	2E-04	1E-06	0	0.001
OvR	3E-06	6E-07	3E-07	2E-07	2E-05	6E-07	3E-05	3E-04	8E-04	0	4E-06	0.001
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	2E-04	4E-04	1E-04	0	0	0.007	0.001	0	1E-06	0	0	0
OvR	2E-04	8E-06	0.002	0	0	0.007	0.001	3E-06	2E-06	7E-07	4E-07	2E-07

Table A4.41 - Maximum values of Δk_{ij} calculated using the structure TV2a

Both the structures allow to correctly locate the anomaly. The induced effects are very little in this simulation. The two matrices are very close the one to the other, as a very low regulation has been necessary for the operation condition determination.

MALFUNCTION 19: Pressure drop at the steam side in the fourth feed water heater

The simulation has been made by imposing a 2% pressure drop at the steam side of the feed water heater HE4. Table A4.42 shows the thermodynamic data relative to the reference and operation conditions. Table A4.43 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.85	124.5	3450	35	45.74	7	117	45.5	7	116
2	86.54	27.15	3104	86.53	27.14	3104	36	45.74	6.86	230	45.5	6.86	230
3	0.375	27.15	3381	0.375	27.14	3381	37	45.74	6.723	299	45.5	6.723	299
4	86.91	27.15	3105	86.91	27.14	3105	38	45.74	6.588	497	45.5	6.588	496
5	0	27.15	3105	0	27.14	3105	39	80.74	6.588	507	80.5	6.588	507
6	86.91	27.15	3105	86.91	27.14	3105	40	80.74	6.457	580	80.5	6.457	572
7	86.91	24.435	3552	86.91	24.43	3552	41	2.28	3.594	588	2.03	3.408	580
8	39.44	2.2317	2938	39.45	2.221	2937	42	5.92	2.009	505	5.653	1.999	505
9	39.44	1.1859	2938	39.45	1.187	2937	43	6.738	0.361	307	6.487	0.361	307
10	37.01	0.0224	2417	37.01	0.022	2416	44	8.647	0.172	238	8.402	0.172	238
11	1.645	0.1914	2630	1.642	0.191	2629	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.915	0.191	2713	46	8.647	0.172	81.6	8.402	0.172	81.5
13	0.818	0.401	2744	0.834	0.401	2743	47	97.85	5.555	658	97.85	5.538	657
14	3.641	2.2317	2938	3.623	2.221	2937	48	97.85	162.1	681	97.85	162.1	680
15	1.37	3.9928	3062	1.129	3.986	3061	49	97.85	158.8	842	97.85	158.8	841
16	2.28	3.9928	3170	2.03	3.986	3182	50	97.85	155.6	995	97.85	155.6	995
17	1.443	6.4188	3174	1.671	6.402	3174	51	97.85	152.5	1063	97.85	152.5	1063
18	5.545	13.724	3380	5.558	13.71	3380	52	3.151	35.33	1052	3.152	35.32	1052
19	6.97	27.15	3104	6.974	27.14	3104	53	10.12	27.15	983	10.13	27.14	983
20	3.151	35.325	3162	3.152	35.32	3162	54	15.67	13.72	826	15.68	13.71	826
21	0.628	3.9928	3235	0.622	3.986	3235	56	45.74	7	82	45.5	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.5	7	81.9
23	0.161	1.2	3235	0.167	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3208	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.171	1.2	3206	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3220	63	401.9	4	293	401.8	4	293
27	-0.06	1.2	3217	-0.07	1.2	3220	64	401.9	3.98	504	401.8	3.98	504
31	35	2.2317	2938	35	2.221	2937	66	45.74	0.022	81.1	45.5	0.022	81.1
33	35	11	520	35	11	520	68	97.09	89.58	3381	97.09	89.57	3381
34	45.74	7	112	45.5	7	111	69	80.74	6.457	580	80.5	6.457	572

point	W kW (Reference)	W kW (Operation)	point	W kW (Reference)	W kW (Operation)
28	33472	33478	55	2801	2801
29	83684	83731	58	53	53
30	103627	103660	62	101049	101082
32	45	45	67	289797	289798

Table A4.42 - Values of the thermodynamic variables relative to the simulation MF19

Variable	Reference	Operation	
x_1	0.974	0.974	
x_2	5.795	5.796	kg/s
x_3	35	35	kg/s

Table A4.43 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.44 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289798	289729	4b-1	8395.9	8401	8398.8	10s	7.993	7.827	7.834
1s	6297.69	6297.89	6300.2	4s-1	40.501	40.566	40.625	b10	594	590.7	591.5
b1	152708	152713	152624	m4-1	7626.1	7629.8	7626.7	11b	2889	2861	2863
2b-1	8396.42	8397.53	8392.2	4b-2	4871.8	4868	4866.9	11s	29.67	29.33	29.32
2s-1	87.4946	87.5287	87.596	4s-2	18.364	18.341	18.357	b11	2325	2303	2306
m2-1	6733.25	6733.7	6727.3	m4-2	4433.9	4427.7	4425.8	12b	2165	1948	1949
2b-2	23670.2	23674	23653	4b-3	10760	10752	10759	12s	14.33	13.61	13.54
2s-2	129.216	129.239	129.31	4s-3	151.59	151.49	151.59	b12	1892	1689	1690
m2-2	21214	21217.3	21195	m4-3	7878.4	7872.8	7877.9	13b	2459	2684	2690
2b-3	6181.79	6184.7	6178.4	5b	30173	30118	30094	13s	13.99	15.72	15.75
2s-3	34.5519	34.5942	34.611	5m	44.592	44.637	44.637	b13	2193	2386	2391
m2-3	5525	5527.1	5520.5	5s	-2866	-2869	-2867	14m	2801	2801	2804
3b-1	15941.8	15953.5	15943	b5	21751	21749	21735	14s	18.71	18.71	18.73
3s-1	54.3999	54.4056	54.49	6b	-0.124	-0.124	-0.124	b14	1885	1885	1887
m3-1	14907.7	14919.3	14907	6s	0.0916	0.0916	0.0916	15b	7001	7015	7014
3b-2	17609.2	17645.1	17636	m6	101049	101082	101010	15s	41.54	41.67	41.55
3s-2	49.6442	49.7598	49.807	7b	5716.8	5714.8	5721.4	b15	6211	6223	6224
m3-2	16665.6	16699.2	16689	8s	0.381	0.3822	0.3827	16b	6974	6978	6983
3b-3	9581.47	9528.29	9521.6	8m	53.453	53.164	53.233	16s	20.34	20.35	20.3
3s-3	32.8064	32.632	32.661	b8	32.847	32.607	32.65	b16	6587	6591	6597
m3-3	8957.86	8907.98	8900.8	9b	6614.3	1175.6	1176.9	17b	3223	3224	3226
3b-4	10452.7	10505.5	10497	9s	15.572	19.726	19.738	17s	6.237	6.236	6.203
3s-4	41.1731	41.1213	41.104	b9	6318.3	800.57	801.76	b17	3105	3106	3108
m3-4	9670.07	9723.86	9715.4	10b	745.9	739.46	740.41				

Table A4.44 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.45 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	6E-04	5E-04	2E-04	2E-04	1E-04	1E-04	1E-04	0	3E-04	8E-04	3E-05	0
OvR	0	8E-05	3E-06	1E-04	0	2E-05	2E-05	0	1E-04	7E-04	3E-05	0
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	5E-04	4E-04	1E-04	0.002	0	0	0.009	0.004	3E-06	0	0	0
OvR	5E-04	5E-05	1E-04	0.003	0	0	0.009	0.004	3E-06	1E-04	4E-06	0

Table A4.45 - Maximum values of Δk_{ij} calculated using the structure TV2a

Both the structures allow to correctly locate where the anomaly has taken place.

MALFUNCTION 20: Pressure drop at the steam side in the seventh feed water heater

The simulation has been made by imposing a 2% pressure drop at the steam side of the feed water heater HE7. Table A4.46 shows the thermodynamic data relative to the reference and operation conditions. Table A4.47 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.86	124.5	3450	35	45.74	7	117	45.79	7	117
2	86.54	27.15	3104	86.65	27.18	3104	36	45.74	6.86	230	45.79	6.86	230
3	0.375	27.15	3381	0.374	27.18	3381	37	45.74	6.723	299	45.79	6.723	300
4	86.91	27.15	3105	87.02	27.18	3105	38	45.74	6.588	497	45.79	6.588	498
5	0	27.15	3105	0	27.18	3105	39	80.74	6.588	507	80.79	6.588	508
6	86.91	27.15	3105	87.02	27.18	3105	40	80.74	6.457	580	80.79	6.457	580
7	86.91	24.435	3552	87.02	24.46	3552	41	2.28	3.594	588	2.272	3.6	589
8	39.44	2.2317	2938	39.46	2.242	2938	42	5.92	2.009	505	5.927	2.018	506
9	39.44	1.1859	2938	39.46	1.187	2938	43	6.738	0.361	307	6.744	0.361	307
10	37.01	0.0224	2417	37.06	0.022	2417	44	8.647	0.172	238	8.651	0.173	238
11	1.645	0.1914	2630	1.623	0.192	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.908	0.192	2719	46	8.647	0.172	81.6	8.651	0.173	81.6
13	0.818	0.401	2744	0.817	0.402	2745	47	97.85	5.555	658	97.86	5.558	658
14	3.641	2.2317	2938	3.654	2.242	2938	48	97.85	162.1	681	97.86	162.1	681
15	1.37	3.9928	3062	1.381	4	3062	49	97.85	158.8	842	97.86	158.8	842
16	2.28	3.9928	3170	2.272	4	3168	50	97.85	155.6	995	97.86	155.7	983
17	1.443	6.4188	3174	1.441	6.426	3174	51	97.85	152.5	1063	97.86	152.5	1062
18	5.545	13.724	3380	5.604	13.73	3380	52	3.151	35.33	1052	3.701	35.26	1052
19	6.97	27.15	3104	6.316	27.18	3104	53	10.12	27.15	983	10.02	25.82	970
20	3.151	35.325	3162	3.701	35.26	3162	54	15.67	13.72	826	15.62	13.73	826
21	0.628	3.9928	3235	0.615	4	3235	56	45.74	7	82	45.79	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.79	7	82
23	0.161	1.2	3235	0.175	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.175	1.2	3213	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3224	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.06	1.2	3224	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35	2.242	2938	66	45.74	0.022	81.1	45.79	0.022	81.1
33	35	11	520	35	11	521	68	97.09	89.58	3381	97.1	89.56	3381
34	45.74	7	112	45.79	7	112	69	80.74	6.457	580	80.79	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33419	55	2801	2802
29	83684	83616	58	53	54
30	103627	103582	62	101049	101006
32	45	45	67	289797	289883

Table A4.46 - Values of the thermodynamic variables relative to the simulation MF20

Variable	Reference	Operation	
x_1	0.974	0.974	
x_2	5.795	5.798	kg/s
x_3	35	35	kg/s

Table A4.47 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.48 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289883	289729	4b-1	8395.9	8404.4	8399.5	10s	7.993	8.014	8.028
1s	6297.69	6302.19	6307.3	4s-1	40.501	40.531	40.665	b10	594	594.6	596.5
b1	152708	152760	152559	m4-1	7626.1	7634.2	7627	11b	2889	2902	2907
2b-1	8396.42	8403.08	8391.1	4b-2	4871.8	4881.4	4878.9	11s	29.67	29.83	29.82
2s-1	87.4946	87.6382	87.79	4s-2	18.364	18.379	18.417	b11	2325	2335	2341
m2-1	6733.25	6737.7	6723.4	m4-2	4433.9	4436.6	4432.5	12b	2165	2156	2157
2b-2	23670.2	23708.6	23661	4b-3	10760	10783	10798	12s	14.33	14.22	14.12
2s-2	129.216	129.499	129.66	4s-3	151.59	151.91	152.14	b12	1892	1886	1889
m2-2	21214	21247.7	21198	m4-3	7878.4	7896	7907.4	13b	2459	2455	2467
2b-3	6181.79	6082.31	6068.1	5b	30173	30217	30163	13s	13.99	13.96	13.97
2s-3	34.5519	34.1409	34.185	5m	44.592	44.547	44.548	b13	2193	2190	2202
m2-3	5525	5433.53	5418.7	5s	-2866	-2865	-2862	14m	2801	2802	2808
3b-1	15941.8	15971.9	15948	b5	21751	21752	21720	14s	18.71	18.71	18.76
3s-1	54.3999	54.5066	54.687	6b	-0.124	-0.124	-0.124	b14	1885	1886	1890
m3-1	14907.7	14936.1	14909	6s	0.0916	0.0916	0.0915	15b	7001	7001	6998
3b-2	17609.2	17610.8	17589	m6	101049	101006	100843	15s	41.54	41.44	41.19
3s-2	49.6442	49.6655	49.775	7b	5716.8	5727.3	5742.2	b15	6211	6213	6217
m3-2	16665.6	16667	16644	8s	0.381	0.3848	0.386	16b	6974	6410	6424
3b-3	9581.47	9574.31	9559.1	8m	53.453	53.511	53.667	16s	20.34	19.95	19.67
3s-3	32.8064	32.7885	32.854	b8	32.847	32.821	32.917	b16	6587	6031	6044
m3-3	8957.86	8951.23	8935	9b	7726.4	1184.8	1187.8	17b	3223	3780	3782
3b-4	10452.7	10417.6	10398	9s	18.597	19.872	19.897	17s	6.237	7.702	7.762
3s-4	41.1731	40.4682	40.44	b9	7378.5	807.21	809.89	b17	3105	3634	3640
m3-4	9670.07	9648.6	9629.4	10b	745.9	746.88	749.04				

Table A4.48 - Fluxes of the productive structure TV2a

The Δ**k** matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.49 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	0.001	0.001	4E-04	8E-04	3E-04	2E-04	2E-04	0	3E-04	0.002	4E-06	0.002
OvR	2E-05	2E-04	3E-05	5E-04	2E-07	2E-06	7E-07	0	0	0.001	0	0.002
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	4E-04	0.001	1E-04	0.001	0	0	0	0	4E-06	0	0.004	0.002
OvR	4E-04	3E-04	1E-04	0.002	3E-04	3E-04	0	0	2E-06	0	0.004	0.002

Table A4.49 - Maximum values of Δk_{ij} calculated using the structure TV2a

Both the structures allow to correctly locate where the anomaly has taken place. In this case the regulation system only operates on the throttles, so the steam mass flow varies respect to the reference condition. A light regulation is sufficient to reduce the malfunctions induced by the anomaly on some turbine stages, on the steam generator and on the condenser. The effect of the regulation system is confirmed by the value assumed by its unit cost, which is lower than the average unit cost of the products.

MALFUNCTION 21: Variation of the pressure drop at the liquid side in the seventh feed water heater

The simulation has been made by imposing a 2% variation of the pressure drop at the liquid side of the feed water heater HE7. Table A4.50 shows the thermodynamic data relative to the reference and operation conditions. Table A4.51 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.86	124.5	3450	35	45.74	7	117	45.75	7	117
2	86.54	27.15	3104	86.55	27.15	3104	36	45.74	6.86	230	45.75	6.86	230
3	0.375	27.15	3381	0.375	27.15	3381	37	45.74	6.723	299	45.75	6.723	299
4	86.91	27.15	3105	86.92	27.15	3105	38	45.74	6.588	497	45.75	6.588	497
5	0	27.15	3105	0	27.15	3105	39	80.74	6.588	507	80.75	6.588	507
6	86.91	27.15	3105	86.92	27.15	3105	40	80.74	6.457	580	80.75	6.457	580
7	86.91	24.435	3552	86.92	24.44	3552	41	2.28	3.594	588	2.28	3.594	588
8	39.44	2.2317	2938	39.42	2.233	2938	42	5.92	2.009	505	5.922	2.01	505
9	39.44	1.1859	2938	39.42	1.184	2938	43	6.738	0.361	307	6.739	0.361	307
10	37.01	0.0224	2417	37.02	0.022	2417	44	8.647	0.172	238	8.645	0.172	238
11	1.645	0.1914	2630	1.627	0.191	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.906	0.191	2717	46	8.647	0.172	81.6	8.645	0.172	81.6
13	0.818	0.401	2744	0.817	0.401	2745	47	97.85	5.555	658	97.86	5.555	658
14	3.641	2.2317	2938	3.642	2.233	2938	48	97.85	162.1	681	97.86	162.1	681
15	1.37	3.9928	3062	1.386	3.993	3062	49	97.85	158.8	842	97.86	158.8	842
16	2.28	3.9928	3170	2.28	3.993	3168	50	97.85	155.6	995	97.86	154.1	995
17	1.443	6.4188	3174	1.443	6.42	3174	51	97.85	152.5	1063	97.86	151	1063
18	5.545	13.724	3380	5.546	13.73	3380	52	3.151	35.33	1052	3.152	35.33	1052
19	6.97	27.15	3104	6.968	27.15	3104	53	10.12	27.15	983	10.12	27.15	983
20	3.151	35.325	3162	3.152	35.33	3162	54	15.67	13.72	826	15.67	13.73	826
21	0.628	3.9928	3235	0.617	3.993	3235	56	45.74	7	82	45.75	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.75	7	82
23	0.161	1.2	3235	0.172	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.174	1.2	3211	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3223	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3223	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35	2.233	2938	66	45.74	0.022	81.1	45.75	0.022	81.1
33	35	11	520	35	11	520	68	97.09	89.58	3381	97.1	89.58	3381
34	45.74	7	112	45.75	7	112	69	80.74	6.457	580	80.75	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33473	55	2801	2802
29	83684	83681	58	53	53
30	103627	103612	62	101049	101035
32	45	45	67	289797	289812

Table A4.50 - Values of the thermodynamic variables relative to the simulation MF21

Variable	Reference	Operation	
x_1	0.974	0.9739	
x_2	5.795	5.796	kg/s
x_3	35	35	kg/s

Table A4.51 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.52 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289812	289729	4b-1	8395.9	8385.4	8382.5	10s	7.993	7.994	7.998
1s	6297.69	6298.62	6300.2	4s-1	40.501	40.458	40.505	b10	594	593.8	594.5
b1	152708	152734	152641	m4-1	7626.1	7616.4	7612.7	11b	2889	2891	2892
2b-1	8396.42	8395.14	8392	4b-2	4871.8	4874.2	4872.4	11s	29.67	29.69	29.68
2s-1	87.4946	87.5479	87.612	4s-2	18.364	18.357	18.37	b11	2325	2326	2328
m2-1	6733.25	6731.13	6726.9	m4-2	4433.9	4431.7	4429.5	12b	2165	2162	2162
2b-2	23670.2	23673	23651	4b-3	10760	10766	10771	12s	14.33	14.28	14.23
2s-2	129.216	129.243	129.29	4s-3	151.59	151.66	151.73	b12	1892	1891	1892
m2-2	21214	21216.5	21194	m4-3	7878.4	7883.8	7887.4	13b	2459	2459	2463
2b-3	6181.79	6183.29	6176.7	5b	30173	30184	30162	13s	13.99	13.99	13.99
2s-3	34.5519	34.6098	34.621	5m	44.592	44.586	44.586	b13	2193	2193	2198
m2-3	5525	5525.47	5518.8	5s	-2866	-2866	-2865	14m	2801	2802	2804
3b-1	15941.8	15943.8	15933	b5	21751	21751	21738	14s	18.71	18.71	18.73
3s-1	54.3999	54.4027	54.472	6b	-0.124	-0.124	-0.124	b14	1885	1886	1887
m3-1	14907.7	14909.7	14898	6s	0.0916	0.0916	0.0915	15b	7001	7002	7000
3b-2	17609.2	17611.4	17601	m6	101049	101035	100960	15s	41.54	41.55	41.43
3s-2	49.6442	49.6555	49.696	7b	5716.8	5719.1	5724.2	b15	6211	6212	6213
m3-2	16665.6	16667.6	16657	8s	0.381	0.3844	0.3848	16b	6974	6988	6992
3b-3	9581.47	9582.74	9575.7	8m	53.453	53.459	53.516	16s	20.34	20.88	20.82
3s-3	32.8064	32.8142	32.837	b8	32.847	32.788	32.824	b16	6587	6591	6596
m3-3	8957.86	8959.04	8951.6	9b	6613.7	1182.1	1183.1	17b	3223	3224	3225
3b-4	10452.7	10447.2	10438	9s	15.559	19.807	19.813	17s	6.237	6.229	6.197
3s-4	41.1731	40.6799	40.662	b9	6317.9	805.67	806.59	b17	3105	3106	3107
m3-4	9670.07	9673.98	9665.2	10b	745.9	745.75	746.51				

Table A4.52 - Fluxes of the productive structure TV2a

The Δ**k** matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.53 for the two diagnosis approaches.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	4E-04	5E-04	2E-04	0.0003	1E-04	8E-05	1E-04	0	2E-04	0.001	0	3E-04
OvR	0	2E-04	5E-07	0.0002	0	3E-07	4E-07	0	8E-06	0.001	0	5E-04
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	2E-04	4E-04	1E-04	0.0011	0	0	0	0	1E-06	0	0.0013	0
OvR	6E-05	7E-05	1E-04	0.0016	8E-05	5E-05	0	6E-07	1E-06	7E-07	0.0015	0

Table A4.53 - Maximum values of Δk_{ij} calculated using the structure TV2a

In this case, as discussed in chapter 6, the operation versus reference approach does not allow to correctly locate the anomaly, while the free versus reference approach does. In both cases an high induced effect has occurred in the HE1, having the same magnitude as the intrinsic effect. The regulation system intervention increase this effect (and reduces some other ones, as indicated by the value assumed by the unit cost associated to the intervention itself), and makes it higher than the intrinsic effect.

MALFUNCTION 22: Variation of the TTD in the seventh feed water heater
The simulation has been made by imposing a 50% increasing of the TTD of the feed water heater HE7. Table A4.54 shows the thermodynamic data relative to the reference and operation conditions. Table A4.55 shows the values of the regulation parameters.

	Reference			Operation				Reference			Operation		
point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg	point	G kg/s	p bar	h kJ/kg	G kg/s	p bar	h kJ/kg
1	97.85	124.54	3450	97.85	124.5	3450	35	45.74	7	117	45.71	7	117
2	86.54	27.15	3104	86.51	27.14	3104	36	45.74	6.86	230	45.71	6.86	230
3	0.375	27.15	3381	0.375	27.14	3381	37	45.74	6.723	299	45.71	6.723	299
4	86.91	27.15	3105	86.88	27.14	3105	38	45.74	6.588	497	45.71	6.588	497
5	0	27.15	3105	0	27.14	3105	39	80.74	6.588	507	80.71	6.588	507
6	86.91	27.15	3105	86.88	27.14	3105	40	80.74	6.457	580	80.71	6.457	580
7	86.91	24.435	3552	86.88	24.43	3552	41	2.28	3.594	588	2.28	3.591	588
8	39.44	2.2317	2938	39.39	2.23	2937	42	5.92	2.009	505	5.918	2.007	505
9	39.44	1.1859	2938	39.39	1.183	2937	43	6.738	0.361	307	6.734	0.361	307
10	37.01	0.0224	2417	36.99	0.022	2417	44	8.647	0.172	238	8.637	0.172	238
11	1.645	0.1914	2630	1.625	0.191	2630	45	0.086	0.95	411	0.086	0.95	411
12	1.909	0.1914	2711	1.903	0.191	2716	46	8.647	0.172	81.6	8.637	0.172	81.6
13	0.818	0.401	2744	0.816	0.401	2745	47	97.85	5.555	658	97.85	5.553	658
14	3.641	2.2317	2938	3.638	2.23	2937	48	97.85	162.1	681	97.85	162.1	681
15	1.37	3.9928	3062	1.386	3.991	3062	49	97.85	158.8	842	97.85	158.8	841
16	2.28	3.9928	3170	2.28	3.991	3168	50	97.85	155.6	995	97.85	155.6	1004
17	1.443	6.4188	3174	1.441	6.416	3174	51	97.85	152.5	1063	97.85	152.5	1063
18	5.545	13.724	3380	5.543	13.72	3380	52	3.151	35.33	1052	2.751	35.38	1053
19	6.97	27.15	3104	7.404	27.14	3104	53	10.12	27.15	983	10.15	27.14	983
20	3.151	35.325	3162	2.751	35.38	3163	54	15.67	13.72	826	15.7	13.72	826
21	0.628	3.9928	3235	0.617	3.991	3235	56	45.74	7	82	45.71	7	82
22	0.029	0.95	3235	0.029	0.95	3235	57	45.74	7	81.9	45.71	7	81.9
23	0.161	1.2	3235	0.172	1.2	3235	59	0.086	0.022	81.1	0.086	0.022	81.1
24	0.029	0.95	3209	0.029	0.95	3209	60	4900	1	50.5	4900	1	50.5
25	0.169	1.2	3201	0.174	1.2	3211	61	4900	1	68.1	4900	1	68.1
26	0.029	0.95	3217	0.029	0.95	3223	63	401.9	4	293	401.9	4	293
27	-0.06	1.2	3217	-0.07	1.2	3223	64	401.9	3.98	504	401.9	3.98	504
31	35	2.2317	2938	35	2.23	2937	66	45.74	0.022	81.1	45.71	0.022	81.1
33	35	11	520	35	11	520	68	97.09	89.58	3381	97.09	89.6	3381
34	45.74	7	112	45.71	7	112	69	80.74	6.457	580	80.71	6.457	580

point	W kW	W kW	point	W kW	W kW
28	33472	33506	55	2801	2801
29	83684	83702	58	53	53
30	103627	103611	62	101049	101033
32	45	45	67	289797	289742

Table A4.54 - Values of the thermodynamic variables relative to the simulation MF22

Variable	Reference	Operation	
x_1	0.974	0.9739	
x_2	5.795	5.795	kg/s
x_3	35	35.004	kg/s

Table A4.55 - Values of the regulation parameters in reference and operation conditions

The corresponding fluxes of the productive structure in reference, operation and free conditions are shown in table A4.56 for the structure TV2a.

flux	ref	op	free	flux	ref	op	free	flux	ref	op	free
1b	289797	289742	289730	4b-1	8395.9	8375.1	8375.2	10s	7.993	7.984	7.982
1s	6297.69	6296.55	6295.9	4s-1	40.501	40.407	40.398	b10	594	593	592.9
b1	152708	152690	152689	m4-1	7626.1	7607	7607.2	11b	2889	2886	2886
2b-1	8396.42	8390.64	8392.9	4b-2	4871.8	4869.3	4869.1	11s	29.67	29.65	29.65
2s-1	87.4946	87.4858	87.482	4s-2	18.364	18.337	18.335	b11	2325	2323	2322
m2-1	6733.25	6727.57	6729.9	m4-2	4433.9	4427.3	4427.4	12b	2165	2162	2162
2b-2	23670.2	23640.5	23640	4b-3	10760	10754	10753	12s	14.33	14.28	14.28
2s-2	129.216	129.02	129	4s-3	151.59	151.48	151.47	b12	1892	1891	1890
m2-2	21214	21187.9	21188	m4-3	7878.4	7874.2	7873.5	13b	2459	2458	2458
2b-3	6181.79	6254.49	6254.5	5b	30173	30179	30178	13s	13.99	13.99	13.99
2s-3	34.5519	34.947	34.942	5m	44.592	44.602	44.597	b13	2193	2193	2192
m2-3	5525	5590.16	5590.2	5s	-2866	-2866	-2866	14m	2801	2801	2801
3b-1	15941.8	15936.4	15936	b5	21751	21754	21753	14s	18.71	18.71	18.7
3s-1	54.3999	54.3699	54.357	6b	-0.124	-0.124	-0.124	b14	1885	1885	1885
m3-1	14907.7	14902.9	14903	6s	0.0916	0.0916	0.0916	15b	7001	7000	6999
3b-2	17609.2	17604.9	17604	m6	101049	101033	101035	15s	41.54	41.54	41.55
3s-2	49.6442	49.6303	49.621	7b	5716.8	5712.6	5711.6	b15	6211	6210	6209
m3-2	16665.6	16661.4	16661	8s	0.381	0.384	0.3839	16b	6974	7387	7386
3b-3	9581.47	9581.41	9581.2	8m	53.453	53.412	53.403	16s	20.34	20.51	20.51
3s-3	32.8064	32.806	32.8	b8	32.847	32.759	32.754	b16	6587	6997	6996
m3-3	8957.86	8957.79	8957.7	9b	5799.7	1180.3	1180.1	17b	3223	2818	2817
3b-4	10452.7	10450.2	10450	9s	13.705	19.776	19.772	17s	6.237	5.281	5.29
3s-4	41.1731	40.6938	40.691	b9	5539.4	804.41	804.24	b17	3105	2718	2717
m3-4	9670.07	9676.68	9676.5	10b	745.9	744.81	744.66				

Table A4.56 - Fluxes of the productive structure TV2a

The $\Delta\mathbf{k}$ matrices corresponding to the operation versus reference comparison and to the free versus reference comparison can be calculated. The maximum (negative) values of the variation of the unit exergy consumptions of every component, required for the anomaly location, are shown in table A4.57 for the two diagnosis approaches. Negative values of the matrix have been analysed as the anomaly have improved the system behaviour. The reference condition does not coincide with the design condition. In this state the feed water heaters do not work in a optimal condition. The anomaly create a different distribution of the average temperature levels in the heat exchangers, corresponding to a better resources use.

Δk_{ijmax}	SG	HP0	HP1	HP2	MP1	MP2	MP3	MP4	LP1	LP2	LP3	HC
FvR	2E-04	0	4E-05	5E-05	3E-05	8E-06	9E-06	1E-03	7E-08	2E-07	4E-05	0
OvR	1E-04	0	2E-04	9E-05	2E-05	1E-05	1E-05	6E-04	0.001	4E-08	4E-05	9E-06
Δk_{ijmax}	A	C	EP	HE1	HE2	HE3	HE4	D	CP	HE6	HE7	HE8
FvR	2E-04	2E-04	0	0	0	0	4E-04	0	0	0	0.003	0.001
OvR	2E-04	1E-04	3E-06	0	0	9E-05	5E-04	2E-04	3E-05	1E-04	0.0026	0.002

Table A4.57 - Maximum values of Δk_{ij} calculated using the structure TV2a

In this case both the structures allow to correctly determine the malfunctioning component.

NOMENCLATURE

Abbreviatures-Symbols-Acronyms

a_0, a_1, ...	constancts in empirical expressions (compressor efficiency and specific heat capacity);
A	alternator;
A	heat transfer area;
A^t	is the total internal available energy;
AC	Air compressor;
A_u	nozzle outlet flowing area;
b_{ch}	chemical component of specific exergy;
$b_{ch}{}^c$	concentration term of the chemical component of specific exergy;
$b_{ch}{}^r$	reaction term of the chemical component of specific exergy;
b_M	mechanical component of specific exergy;
bpg	opening grade of the by-pass valve;
b_T	thermal component of specific exergy;
BPV	By-pass valve;
c	velocity;
c	thermoeconomic unit cost in monetary units;
c	constancts in the semplified model of the gas turbine plant;
c_F	thermoeconomic unit cost of a fuel;
c_p, c_v	specific heats;
c_p	thermoeconomic unit cost of a product;
$c_p(Z)$	thermoeconomic unit cost associated to the capital cost rate;
C	condenser;
C	cost of a system/component;
CC	combustion chamber;
CP	circulation pump;
CGRV	cogeneration grade regulation valve;
CR	*Casinghini* recuperator;
D	deareator;
DF_i	total dysfunction in the i^{th} component;
DF_{ij}	dysfunction generated in the i^{th} component by the j^{th} component;
EP	extraction pump;
f	specific Helmoltz function;
f_i	characteristic equation of the i^{th} component/system;
f_p	exergoeconomic factor;
F	component fuel;
F*	cost of the fuel;
F_T	total fuel of the system;
FvR	diagnosis approach consisting on the comparison between free and reference conditions;
g	malfunction grade (used for graphs obtained by varying the values of the malfunctions);
G	mass flow;

G_b	exergy flow associated to fluid mass flows;
G_c	Fuel consumption;
GLSC	Gland leakage steam condenser;
G_s	entropy flow;
GT	Gas turbine;
h	Specific enthalpy;
h	working hours a year;
HC	*Hot* condenser;
HE	Heat exchanger;
H_i	lower heating value;
HPT	high pressure turbine;
i	effective rate of return;
I	irreversibility;
igv	inlet guided vanes opening grade;
k	ratio of the specific heats;
k	unit exergy consumption;
k_{ij}	unit consumption a flux, resouce of the j^{th} component and product of the i^{th} component;
k*	exergy unit cost;
$\overline{k}*$	average exergetic cost;
$k*_r$	unit cost associated to the regulation system;
L	component loss;
L	Lagrangian function;
LPT	low pressure turbine;
m	exponent in a politropic transformation;
m	number of components of a system;
MF_i	total malfunction generated in the i^{th} component;
MF_i*	cost of the malfunction in the i^{th} component;
$\tilde{MF}_i*$	cost of the malfunction in the i^{th} component, calculated as comparison between free and reference conditions;
MF_r	total malfunction generated by the regulation system intervention;
m_{mol}	molecular mass;
MPT	Middle pressure turbine;
n	number of fluxes in a productive structure;
n	useful life of a system (in years);
N	negentropy flux;
n_{mol}	number of moles;
NTU	Number of transfer units;
OvR	diagnosis approach consisting on the comparison between operation and reference conditions;
p	pressure;
P	fraction of gas mass flow entering the recuperator;
P	component product;
pp	per cent pressure drop;
pp_{cc}	per cent pressure drop in the combustion chamber;
pp_f	per cent pressure drop in the filter;
pp_{he}	per cent pressure drop in the Casinghini recuperator;

pp_S	per cent pressure drop at the steam side of a feed water heater;
pp_W	per cent pressure drop at the liquid side of a feed water heater;
P*	cost of the product;
r	heat capacity ratio;
R	specific gas constanct;
S	entropy;
s	specific entropy;
SG	steam generator;
T	temperature;
TDCA	temperature drain cooling advantage;
TTD	terminal temperature difference;
u	specific internal energy;
v	specific volume;
V	control volume;
W	mechanical power;
W_{el}	electric power;
W_c	mechanical power at the compressor;
W_t	mechanical power at the alternator;
x	mole fraction;
x	characteristic variable of the regulation system;
y	mass fraction;
y	general variable of the model (thermodynamic or thermoeconomic);
$\bar{y}$	set-point value;
Z	capital cost rate of a system/component;

Greeks

α	coefficient in the expression of the steam turbine efficiency;
α	coefficient of the characteristic equation;
α	known value associated to the environmental condition (in the semplified gas turbine model);
β	pressure ratio;
Δ	quantity variation between two states;
ΔF_i	contribution of the i^{th} component to the total fuel impact;
$\Delta F_{i_{int}}$	fuel impact associated to the intrinsic effect in the i^{th} component (predict fuel impact)
ΔF_T	total fuel impact;
ΔF_{Tr}	total fuel impact associated to a regulation system intervention;
$\Delta F_{\Delta P}$	fuel impact associated to the variation of the total production;
$\Delta F_{\Delta k}$	fuel impact associated to the variation of the unit exergy consumption;
Δg_0	molar Gibbs function;
ΔI	irreversibility variation;
ε	heat exchanger effectiveness;
ε	partialization grade;
ε	exergy efficiency;
Φ	thermal flux (thermal load of a plant);
Φ_{ij}	element of the operator irreversibility;
Φ_T	recuperated thermal flow;

Γ cost of the resources entering a component;
η efficiency;
η known value associated to a characteristic parameter (in the semplified model of the gas turbine plant);
η_{alt} alternator efficiency;
η_c compressor efficiency;
η_{cc} combustor efficiency;
η_g steam generator efficiency;
η_{H2} recuperation system efficiency;
η_p pump efficiency;
η_t turbine efficiency;
η_{td} turbine efficiency;
η_θ total to static turbine efficiency;
η_Θ total to total turbine efficiency;
λ Lagrange multipliers;
Λ whole of the Lagrange multipliers;
Π monetary cost of an exergy flow;
ρ density;
Σ_i entropy distruction;
υ stoichiometric coefficient of the considered reference substance;
Ψ exergy flow;
Ψ_i destroyed exergy flow;
Ψ_q exergy flow associated to the thermal flows;
Ψ^*_s exergetic cost rate associated to the system;

Arrays-Matrices

A incidence matrix;
$\langle$**EG**$\rangle$ Jacobian of the characteristic functions;
D coefficient matrix in the calculation of the Lagrange multipliers;
$\mathbf{E_j}$ vector containing the exergy flows exiting the components of the system;
F vector containing the fuels of the component;
G vector of mass flows;
$\mathbf{G_h}$ vector of energy flows;
$\mathbf{G_b}$ vector of exergy flows;
$\mathbf{G_{B^*}}$ vector of the exergetic costs of the flows;
$\mathbf{G_\Pi}$ vector of the thermoeconomic costs of flows;
I vector of the irreversibilties;
|**I**> operator irreversibility;
$\mathbf{I_u}$ whole of the component inputs;
$\mathbf{I_0}$ whole of the environment inputs;
K matrix of unit exergy consumptions;
k* vector containing the marginal costs associated to every flux;
$\mathbf{K_D}$ diagonal matrix of the total unit exergy consumptions;
$\mathbf{K_{ext}}$ vector of unit exergy consumptions associated to the external resources;
$\mathbf{K_{ext}}^*$ vector of the evaluation of the unit cost of the fluxes entering the system from the external environment;
$\mathbf{K_{in}}^*$ vector of the unit cost of the fluxes entering the components of the system;

$\mathbf{k}_{out}^*$	vector of the unit cost of the fluxes exiting from the components of the system;
$<\mathbf{KP}>$	matrix of unit exergy consumptions associated to internal fluxes;
$\mathbf{N}$	whole of components;
$\mathbf{N}$	vector of known terms in the Lagrange multipliers calculation;
$\mathbf{O}_u$	whole of the component outputs;
$\mathbf{O}_0$	whole of the environment outputs;
$\mathbf{P}$	vector of the products of the components;
$\|\mathbf{P}>$	operator product;
$\mathbf{P}_{ext}$	vector of the overall system production;
$\mathbf{U}_D$	identity matrix;
$\mathbf{X}$	matrix of the regulation system variables;
$\mathbf{Y}$	vector of the system model variables (thermodynamic or thermoeconomic)
$\mathbf{Z}$	vector of the capital cost rate of the components;
$\mathbf{z_e}$	vector containing the unit costs of the entering resources and the component costs;
$\Delta\mathbf{F_T}$	vector of the fuel impact in every component;
$\Delta\mathbf{F}_{\Delta\mathbf{P}}$	vector of the fuel impact in every component associated to the variation of the total production;
$\Delta\mathbf{F}_{\Delta\mathbf{k}}$	vector of the fuel impact in every component associated to the variation of the unit exergy consumption;
$\Delta\mathbf{K}$	matrix of the unit exergy consumtions variation;
$\Delta\mathbf{K}_{ind}$	matrix of the unit exergy consumtions variation, associated to the induced effects;
$\Delta\mathbf{K}_{int}$	matrix of the unit exergy consumtions variation, associated to the intrinsic effects;
Λ	vector of the Lagrange multipliers;
χ_u	vector containing the characteristic parameters of the component u;
$\Psi_\mathbf{i}$	vector of destroyed exergy flows in each component;
$\mathbf{0}$	null vector or matrix;

Subscripts

0	reference environment
a	air;
c	compressor;
cc	combustion chamber;
ch	chimney;
cr	critical point;
d	design condition;
D	diagonal matrix;
el	electric;
ext	extraction (in physical structures);
ext	external (in productive structures);
f	filter;
F	fuel;
free	free condition;
g	gas;
h2	alternator refrigeration system;

in	district heating water flux entering a recuperator;
in	entering flux;
is	property at the outlet of an isentropic process;
k	downstream point;
l	reaction products;
L	loss;
M	mechanical component of exergy;
o	upstream point;
op	operation condition;
out	district heating water flux exiting a recuperator;
out	exiting flux;
ox	oxidizer;
P	product;
p	mechanical exergy flow associated to the liquid water (in productive structure);
pv	mechanical exergy flow associated to the steam (in productive structures);
r	regulation system;
ref	reference condition;
rh	re-heater;
s	appropriate function of entropy, (entropy flow or negentropy);
sat	fluid in saturated condition;
t	turbine;
T	thermal component of exergy;
th	thermal;
w	district heating water flux;

Superscripts

t	total quantity;
t	transpose;
*	cost of a flux;
-	average value;

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