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Abstract: In this paper, we introduce an optimization strategy in order to comprehensively quantify the impact of availability and maintenance notions during the early stages of synthesis and design of a new natural gas combined cycle power plant. A detailed state-space approach is thoroughly discussed, where influence of maintenance funds on each component's repair rate is directly assessed.

In this context, analysis of the reliability characteristics of the system is centered at two designer-adopted parameters, which largely influence the obtained results: the number of components which may fail independently at the same time, and the number of simultaneous failure/repair events.

Then, optimal solutions are evaluated as the availability-related parameters and the amount of resources assigned for maintenance actions are varied across a wide range of feasible values, which enable obtaining more accurate and detailed estimations of the expected economic performance for the project when compared with traditional economic evaluation approaches.

Highlights

>> A MINLP optimization strategy for a NGCC power plant is introduced.
>> The state-space method is used for identifying availability characteristics.
>> Influence of maintenance funds on each component's repair rate is directly assessed.
>> Impact of designer-adopted characteristics is thoroughly analyzed.
>> Accurate and detailed estimations are obtained for the expected economic performance.

An optimization model for evaluating the economic impact of availability and maintenance notions during the synthesis and design of a power plant

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Abstract

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Keywords: *NGCC* power plant, optimal design, availability, maintenance, economic optimization, state-space approach

Nomenclature

Acronyms

BW	boiler water
CW	cooling water
CNF	conjunctive normal form

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F	fuel
GT	gas turbine
$HRSG$	heat recovery steam generator
$MINLP$	mixed integer non-linear programming
$NGCC$	natural gas combined cycle
NLP	non-linear programming
ST	steam turbine

Availability related symbols

$MFIR_{AS}$	maintenance factor improvement rate of component
N_{AS}	number of components
N_{FM}	number of possible functional modes
N_{FM^f}	number of feasible functional modes
$N_{Op,FM}$	number of operative components at possible functional mode
N_{Op,FM^f}	number of operative components at feasible functional mode
N_{SIFC}	number of simultaneously and independently failed components
N_{SE}	number of simultaneous events
POT_{FM^f}	plant operative time associated to feasible functional mode
Pr_{FM^f}	probability of the system being at feasible functional mode
Pr_{FS}	probability of the system being at feasible functional status
$TRM_{FM_i^f,FM_j^f}$	transition rate matrix between state FM_i^f and state FM_j^f
$TRMsum_{FM_i^f}$	transition rate matrix for state FM_i^f - auxiliary parameter
$\hat{x}$	expected value of variable
x_{FM^f}	value of variable at feasible functional mode
$y_{AS,FM}$	component operative status at possible functional mode
y_{AS,FM^f}	component operative status at feasible functional mode
y_{PP,FM^f}	section operative status at feasible functional mode
z_{AS,FM_i^f,FM_j^f}	component transition rate between state FM_i^f and state FM_j^f

Economic variables and parameters

AC	total additional cost	$MUS\$/y$
a_{PE}	exponential factor for the acquisition cost	-
$CAPEX$	capital expenditures	$MUS\$$
C_{Inv}	total equipment acquisition cost	$MUS\$$
$C_{Inv,PE}$	equipment acquisition cost	$MUS\$$
C_{Mant}	maintenance cost	$MUS\$/y$
C_{MP}	man power cost	$MUS\$/y$
COE	cost of electricity	$US\$/MWh$
C_{PE}	acquisition cost of each piece of equipment	$US\$/kW$ or $US\$/m^2$
C_{PS}	unit cost of raw materials	$US\$/GJ$ or $US\$/m^3$
CRF	capital recovery factor	y
C_{RM}	raw materials cost	$MUS\$/y$
DMC	direct manufacturing cost	$MUS\$$
F_{Inv}	investment factor	-
F_{Mant}	maintenance factor	-
$F_{Mant,Min}$	minimum maintenance factor	-
$F_{Mant,Max}$	maximum maintenance factor	-
F_{O1}	man power operative factor	-
F_{O2}	investment operative factor	-
GE	generated energy	MWh/y
i	interest rate	$1/y$
IFC	investment on fix capital	$MUS\$$
IMC	indirect manufacturing cost	$MUS\$$
n	life cycle length	y
N_{MP}	equivalent number of power cost	-
$OPEX$	operative expenditures	$MUS\$/y$
PC	total production cost	$MUS\$/y$
P_{Elec}	electricity price	$US\$/MWh$
POT_0	standard operative time	h/y

$Sales$	energy sales	$MUS\$/y$
TAC	total annual cost	$MUS\$/y$
$\dot{W}_{Net}$	net generation capacity	MW
X_{PE}	capacity factor for the acquisition cost	kW or m^2
X_{PS}	consumption of raw materials	GJ or m^3

Greek symbols

γ_{AS}	exponential factor for repair rate - maintenance funds relation
λ_{AS}	component failure rate
μ_{AS}	component repair rate
$\mu_{AS,0}$	base component repair rate
$\mu_{AS,Min}$	minimum component repair rate
$\mu_{AS,Max}$	maximum component repair rate

Optimization formulation

f	objective function
$\underline{h}$	set of equality constraints
$\underline{g}$	set of inequality constraints
$\underline{x}$	set of design and operative variables
$\underline{y}$	set of integer variables

Sets

AS	set - components
FS	set - functional statuses
FM	set - possible functional modes
FM^d	subset - functional status for probabilities accounting
FM^f	subset - feasible functional modes
PE	set - process equipment

PP	set - sections
PS	set - process streams

1. Introduction

The synthesis and design of a power plant are determinant stages of its life cycle, as they expose diverse degrees of freedom which can be manipulated in order to achieve significant improvements in the overall project economics. In this context, availability and maintenance notions play a key role even in these early phases as they directly impact on the ability of the plant to fulfill the desired generation goal.

Therefore, a comprehensive approach should be implemented to account for the consequences in the performance of the power plant, of achieving a desired availability level while assigning given resources for maintenance actions to accomplish such requirement. This task has proven to be a challenging one within an optimization context due to the large space of feasible solutions that needs to be analyzed, considering the wide array of design and operative decisions that could potentially improve the economic indicators of the power plant.

1.1. Availability and maintenance in process design

In order to consider the effects of availability and maintenance in the plant economics, Goel et al. (2002, 2003) indicated that revenues and operative costs must be affected by the system inherent availability, while an exponential relationship between investment and availability is used to compute the capital cost of each piece of equipment (if the inherent availability of each piece of equipment is considered explicitly as a continuous decision variable). Nevertheless, it could result quite challenging to obtain real-world data on how inherent availability is linked to capital cost for a given process equipment.

Frangopoulos and Dimopoulos (2004) introduced reliability aspects in the thermoeconomic model of a cogeneration system by means of the state-space method, so that redundancy is embedded in the optimal solution; thus obtaining more realistic values of the system profit. They applied such approach to the determination of the number of cogeneration packages necessary for achieving the desired production goal with a given availability level. In a three levels optimization problem, including synthesis and design, operation under time-varying conditions, and operation under partial failure, characteristics of a cogeneration plant were compared when solving the optimization formulation with and without reliability considerations. If reliability is taken into account, they observed that an extra cogeneration package is necessary in order to satisfy the minimum availability requirements, and proved that profits are overestimated when reliability aspects are ignored.

Luo et al. (2013) presented a methodology to minimize the total cost under normal conditions while reserving enough flexibility and safety for unexpected equipment failure conditions for the interconnected steam power plants that supply utility energy to a petrochemical complex. The proposed optimization strategy transforms the unexpected equipment failure scenarios into virtual periods which are inserted in between the normal scenarios, thus minimizing the total cost for real periods and reserving enough redundancy for the virtual periods (even though it requires a set of extra constraints for handling these last ones).

Aguilar et al. (2008) incorporated reliability and availability into the design (configuration and redundancy allocation) and operation (maintenance schedule) of flexible utility plants; and observed that two different tradeoffs may arise: capital investment versus contractual penalties for not fulfilling the power demand (which can be computed as profit losses during the plant down time); and capital investment versus costs originated by different failure scenarios (while evaluating if the plant is able to cope with the demand). It is observed that both tradeoffs present the advantage that can be implemented by using data commonly available in the literature and industry.

Haghifam and Manbachi (2011) concluded that improving repair rates exhibit a direct relation with the number of operators and their ability to undertake repairs, which is directly related with the annual budget assigned to maintenance. In their analysis, Iyer and Grossmann (1997) also computed the changeover costs for startup/shutdown of units between periods of operation. Moreover, these costs are the ones that link the different periods through binary variables. According to Tan and Kramer (1997), costs for operation at a derated state can be included in the analysis if a model can be determined for component degradation as a function of time, if quality can be modeled as a function of component performance, and if revenue can be modeled as a function of quality.

Erguina (2004) described a prototype model for nuclear power plant maintenance economics, aiming at understanding the impact of maintenance funds allocation on reliability and performance considering the plant life cycle. In the prototype model, it is considered that allocation of funds for preventive maintenance actions has an asymptotic effect on the system reliability, as beyond a given point, no significant performance improvement will be achieved even if additional resources are assigned to such effort. Tan and Kramer (1997) stated that there are four feedback mechanisms used to control and improve equipment reliability in a manufacturing plant: (1) corrective maintenance and failed equipment restoration, (2)development of preventive maintenance strategies for improving plant safety and economics, (3) predictive maintenance followed by implementation of preventive maintenance actions, and (4) design and/or operative modifications for reliability improvement.

Mc Leod et al. (2007) addressed the optimization of nuclear power plant designs based on global risk reduction, focusing in two aspects of the problematic: design considering components quality and redundancy levels, and maintenance scheduling and human reliability. Resolution of the generated problem was pursued by means of an evolutionary algorithm (i.e. a combination of evolutionary strategies and genetic algorithms), which allowed obtaining a balanced design where the future maintenance and test schedules are established from a risk point of view for minimum total cost.

Sun and Liu (2014) proposed a stochastic model for determining the system configuration and operating scheduling of a steam and power plant, considering equipment selection and operation mode (normal, standby, or failure), as well as including compensation adjustments and penalties. Then, the obtained system design is able to cope with both normal operation and emergency scenarios, while a more accurate representation of the economic factors is obtained.

In a short-term combined economicenvironmental dispatch problem, Gjorgiev et al. (2013) introduced a measure of the availability of the generating units present in the system by means of a risk index which is a function of the generating units power level. As result, the authors observed that an increase of the availability of power generation was followed by a small increase of the fuel cost and the gaseous emissions, due to the opposed nature of the newly added objective function with respect to the two commonly considered ones.

1.2. Space of possible operative states

Applying the state-space method consists of three steps, as identified by El-Nashar (2008): first, identification of functional and failure modes of the system by making an inventory of all possible states; second, establishment of rules for transition between states and formulation of the transition rate matrix; and third, evaluation of expected values of the interest variables, by using the states probabilities as weights. For Markov modeling, with n component lifetimes divided into d time discretizations, steady-state solution of the Markov model requires storing $d.2^n$ elements of M for matrix calculations, if only binary states are considered for each component. Independence of events allows decoupling the component lifetimes, although this assumption may not be valid for multiple interacting components (Tan and Kramer, 1997).

As observed by Lisnianski et al. (2012), multi-state models are widely used in the field of power system reliability assessment, since using two-state models for large generating units usually yield pessimistic appraisals. Then, they presented a multi-state Markov model for a coal power unit, where the transition rates between the different generating capacity levels of the unit are estimated based on field observations, by means of an embedded Markov chain. As consequence, they observed that the values of the associated reliability indices are different from those calculated for a long-term range, while events as scheduled outages or planned maintenance cannot be taken into account. A disadvantage of this method is that the designer should perform capacity quantization if the actual derated operating states of the power plant are unknown.

Terrazas-Moreno et al. (2010) proved that it is possible to optimize over the state-space in the last level of the tree, even if the optimal flowsheet contains less units than those present in the last level; as the states in the last level of the tree that are derived from the same node are identical in terms of feasibility/infeasibility, and also, the sum of the probabilities of the states in the last level of the tree is equal to the probability of the state from which they are derived. They also observed that there are two ways for reducing the number of possible states: first, the failures with the same related rate reduction that occur in the same plant can be aggregated as one equivalent failure; and in second place, only the most probable states can be considered (as for example, those ones that cover 99% of the long term operative horizon).

Vassiliadis and Pistikopoulos (2001) presented a MINLP optimization framework for deriving optimal maintenance policies in continuous process operations in the presence of parametric uncertainty. To overcome the highly non-linear and combinatorial nature of the resultant model, availability threshold values of components (which are the minimum acceptable values of their availability, and therefore, determine the time at which maintenance actions need to be performed) were used to propose a two-steps resolution strategy. In addition, to describe the possible states of the process, they used a (operative-failed) state-space, where each possible state for the process has a given probability of occurrence, related to the time-varying availability of each component (as determined by its inherent characteristics and the maintenance policies).

Failure of a component in a cooling, heating and power (BHCP) system may result in failure of a sub-system or the whole system, as observed by Wang et al. (2013). For such a large system, the authors proposed to divide it into three parts in order to apply the state-space method: electricity (either from the gas turbine or from the grid), heat (which can be recovered through the steam generator of produced at the auxiliary boiler), and cool (obtained by means of the electric and/or absorption chillers). This procedure allows to more easily obtain expressions for each sub-system failure and repair rates.

1.3. Aim and outline

In this work, implications of considering availability and maintenance tradeoffs during the synthesis and design stages of a new project for a *NGCC* power plant are thoroughly analyzed by means of a flexible equations-oriented mathematical formulation which accounts for the most important economic characteristics of the system. Meanwhile, every solution here presented is an optimal one, obtained when successfully achieving the resolution of a MINLP mathematical optimization model.

A state-space approach is used to account for the availability of the generation plant, thus facilitating a complete overview of the system operative condition across the entire time horizon (here adopted as annualized one given by the standard operative time), which also enables computing the optimal economic performance of the project more accurately. Moreover, impact of the amount of resources assigned for maintenance actions is evaluated through its influence on the repair rate of each major component which constitutes the power plant. The resultant MINLP model efficiently provides economic optimal solutions considering every feasible scenario that the plant has to deal with.

In addition, benefits of this strategy are evaluated by comparison against a traditionally designed power plant (i.e. a generation facility which does not contemplate these notions, obtained according to Godoy et al. (2010, 2011)). In this context, it is here found that the proposed approach allows obtaining more realistic design options when farther exploring the space of optimal solutions.

2. Formulation of the economic optimization problem: state-space modeling of availability and component-based assessment of maintenance resources impact

2.1. Process configuration

The flow diagram for the $NGCC$ power plant is presented in Figure 1. A 2 GTs + 1 ST multi-shaft power plant is selected as the generation driver (note that the second gas turbine and its associated steam generator are not presented in this figure).

A summary of the modeling assumptions and technical constraints is presented in Appendix A.

2.2. Optimization model

The mathematical formulation for the economic optimization of the $NGCC$ power plant is presented at Figure 2. In this optimization problem, the cost of the generated electricity is selected as objective function $f\left(\underline{x},\underline{y}\right)$; which implies simultaneously minimizing the total expenditures of the project and maximizing the net energy output of the plant. Here, $\underline{x}$ are the sets of design and operative variables and $\underline{y}$ are the sets of integer variables; while $\underline{h}\left(\underline{x},\underline{y}\right)$ and $\underline{g}\left(\underline{x},\underline{y}\right)$ refer to the equality and inequality constraints which configure the mathematical model of the whole project.

2.3. Objective function: cost of electricity

The cost of the generated electricity COE gets computed according to Eq. (1) as the annualized cost TAC per unit of generated energy GE.

$$COE = \frac{TAC}{GE} = \frac{\frac{CAPEX}{CRF} + OPEX}{GE} \tag{1}$$

The annualized economic performance of the project is evaluated through its total cost, which includes capital expenditures $CAPEX$ annualized by a given recovery rate CRF, and annual operative expenditures $OPEX$. A description of the equations used for computing the capital and operative expenditures is presented in Appendix B.

2.4. State-space modeling framework

2.4.1. Number of functional modes and their interrelations

A functional mode is defined as the overall operative status of a system, which is here assumed as fully operational or failed. Each functional mode depends upon the set of operative statuses of its components, which impact on the ability of the system to fulfill its design purpose.

The number of functional modes and their interrelations depend upon the values of two parameters: the number of simultaneously and independently failed components N_{SIFC} and the number of simultaneous events N_{SE}. In order to illustrate this concept, Figure 3 depicts an application example for a system constituted by three components, where it is observed that:

- Each possible functional mode is defined by the set of binary variables associated to every component, where an operative status is represented by a 1, while a 0 depicts a failed status
- The maximum number of zeros at each feasible functional mode is given by N_{SIFC}. Therefore, modes with 0 or 1 failed components may exist at state-space of Figures 3a and 3b, where a value of 1 is adopted for N_{SIFC}; meanwhile, modes with 0, 1 or 2 failed components may exist at state-space of Figures 3c and 3d, where a value of 2 is adopted for N_{SIFC}. Although not here graphically presented, a state-space with $N_{SIFC} = 3$ will additionally include a mode where all three components are failed (totalizing 8 feasible functional modes)
- Transitions between modes occur as the operative condition of one or more components change from operative to failed, or viceversa; where the maximum number of allowable simultaneous events is given by the value fixed by the designer for N_{SE}. When a value of 1 is adopted, transitions where only one component fails or is repaired are allowed, as shown in Figures 3a and 3c. If N_{SE} equals 2, the state-space will also include transitions between feasible modes which imply simultaneously changing the operative status of two components (i.e. two failures, two repair actions, or a failure and a repair action), as illustrated in Figures 3b and 3d. Similar conclusions are drawn for $N_{SE} = 3$

For different values of N_{SIFC} and N_{SE}, Figures 3e and 3f present the number of feasible functional modes and the number of interconnections between them, respectively. It is here observed that:

- the number of feasible functional modes depends on the value adopted for N_{SIFC}, while is independent of N_{SE}
- the number of interconnections between modes increases as N_{SIFC} and N_{SE} do
- while N_{SIFC} is lower than the number of components, the state-space method is not able to represent every possible functional mode

Considering the aforementioned remarks, mathematical expressions for obtaining the space of feasible operative modes for the $NGCC$ power plant, as function of N_{SIFC} and N_{SE}, are derived below.

2.4.2. Identification of possible functional modes

The state-space method (i.e. a Markov-type approach, see for example Ibe (2009); Kuo and Zuo (2003)) is used to evaluate the probability of the system being at each functional mode. These probabilities can be used for computing the operability indices of the system, as well as evaluating its technical and economical performance indicators.

The logically arranged subsystems, also referred as components, are listed in Eq. (2).

$$AS = \{AS_1, AS_2, \cdots, AS_{N_{AS}}\} \tag{2}$$

The number of components is determined by means of Eq. (3).

$$N_{AS} = card(AS) \tag{3}$$

If only operative and failed statuses are considered for each of the components, the number of possible functional modes is given in Eq. (4).

$$N_{FM} = 2^{N_{AS}} \tag{4}$$

Therefore, the space of the possible functional modes is listed in Eq. (5).

$$FM = \{FM_1, FM_2, \cdots, FM_{N_{FM}}\} \tag{5}$$

Then, a binary variable gets associated to each component, according to Eq. (6), in order to describe its status at each possible functional mode.

$$y_{AS,FM} = \begin{cases} 0 & failed \\ 1 & operative \end{cases} \tag{6}$$

The number of operative components at a given possible functional mode can be computed as the summation of the values of the binary variables for such functional mode, as described in Eq. (7).

$$N_{Op,FM} = \sum_{AS} y_{AS,FM} \tag{7}$$

2.4.3. Differentiation of feasible functional modes

Functional modes can be differentiated according to a pre-specified criterion adopted by the designer, regarding the number of units that can independently fail at the same time N_{SIFC}. Consequently, for a system with N_{AS} components, the number of feasible functional modes is given in Eq. (8).

$$N_{FM^f} = 2^{N_{AS}} - \sum_{k=0}^{(N_{AS}-N_{SIFC})} \frac{N_{AS}!}{k!\,(N_{AS}-k)!} \tag{8}$$

The space of the feasible functional modes is listed in Eq. (9).

$$FM^f = \left\{FM_1^f, FM_2^f, \cdots, FM_{N_{FM^f}}^f\right\} \quad , \quad FM^f \subseteq FM \tag{9}$$

The binary variable associated to each component, which describes its status at each feasible functional mode, is given in Eq. (10).

$$y_{AS,FM^f} = y_{AS,FM} \quad if \quad N_{AS} - N_{SIFC} \leq N_{Op,FM} \leq N_{AS} \tag{10}$$

The number of operative components at a given feasible functional mode is given in Eq. (11).

$$N_{Op,FM^f} = N_{Op,FM} \quad if \quad N_{AS} - N_{SIFC} \leq N_{Op,FM} \leq N_{AS} \tag{11}$$

2.4.4. Establishment of transition rules

Each component has a transition rate between its two statuses (operative and failed), as given by its failure and repair rates. Then, the component transition rate is given in Eq. (12).

$$z_{AS,FM_i^f,FM_j^f} = \begin{cases} \mu_{AS} & if \quad y_{AS,FM_i^f} = 0 \quad and \quad y_{AS,FM_j^f} = 1 \\ \lambda_{AS} & if \quad y_{AS,FM_i^f} = 1 \quad and \quad y_{AS,FM_j^f} = 0 \\ 0 & if \quad y_{AS,FM_i^f} = 0 \quad and \quad y_{AS,FM_j^f} = 0 \\ 0 & if \quad y_{AS,FM_i^f} = 1 \quad and \quad y_{AS,FM_j^f} = 1 \end{cases} \tag{12}$$

Failure and repair rates to be used in Eq. (12) are those associated to components defined in Eq. (2). Note that each component is constituted by several pieces of process equipment; so, their logical arrangement (series, parallel, redundancies) should be used to compute overall failure and repair rates associated to a given component (NERC, 2011; OREDA Participants, 2002; Alber et al., 1995).

The overall transition rate from state FM_i^f to state FM_j^f is given by the transition rate matrix, as described in Eq. (13) and Eq. (14), considering the number of simultaneous events N_{SE}.

$$TRM_{FM_i^f,FM_j^f} = \begin{cases} \sum\limits_{AS} z_{AS,FM_i^f,FM_j^f} & \forall i \neq j \quad if \quad 0 < \sum\limits_{AS} \left| y_{AS,FM_i^f} - y_{AS,FM_j^f} \right| \leq N_{SE} \\ -TRMsum_{FM_i^f} & \forall i = j \end{cases} \tag{13}$$

$$TRMsum_{FM_i^f} = \sum_{FM_j^f} TRM_{FM_i^f,FM_j^f} \quad \forall i \neq j \quad if \quad 0 < \sum_{AS} \left| y_{AS,FM_i^f} - y_{AS,FM_j^f} \right| \leq N_{SE} \tag{14}$$

2.4.5. Evaluation of probabilities

The probability of the system being at every given feasible functional mode is obtained by solving the homogenous linear system of equations given in Eq. (15). Solving this system of equations implies finding the steady-state probabilities of an irreducible Markov process.

$$\sum_{FM_i^f} Pr_{FM_i^f} \; TRM_{FM_i^f,FM_j^f} = 0 \quad \forall j \tag{15}$$

An additional constraint is implemented when considering that the sum of state probabilities is always equal to one, as given in Eq. (16).

$$\sum_{FM_i^f} Pr_{FM_i^f} = 1 \tag{16}$$

2.4.6. Expected values of variables and operative span

The expected value of a given variable can be computed as the weighted sum of the values for every feasible functional mode, as given in Eq. (17).

$$\hat{x} = \sum_{FM^f} Pr_{FM^f} \; x_{FM^f} \tag{17}$$

Within a given time horizon, the operative time associated to each functional mode is computed according to Eq. (18) as the standard operative time affected by the probability of occurrence of such functional mode. This follows from the fact that Pr_{FM^f} can be interpreted as the average long-run proportion of the time that the system spends in the functional mode FM^f.

$$POT_{FM^f} = POT_0 \; Pr_{FM^f} \tag{18}$$

Then, it is here observed that the state-space method accounts for every operative condition of the system across the entire time horizon (as probabilities of functional modes add up to 1). Note that the standard operative time POT_0 is here selected as the annualized time horizon, in order to account for the annualized plant maintenance schedule. Also, in this context, availability may be computed as the probability of the system of being at certain desired functional modes, where the process is able to fulfill the expected demand.

2.5. Description of functional modes of the NGCC power plant

The reliability block diagram associated to the power plant is introduced in Figure 4.

At the power plant, the following components are identified according to Eq. (2) for purposes of availability analysis:

- Auxiliary services for both gas turbines (AS_1)
- Each gas turbine plus its associated generator (AS_2 and AS_3)
- Auxiliary services for both heat recovery steam generators and the steam turbine (AS_4)
- The steam turbine and its associated generator (AS_5)
- Each heat recovery steam generator (AS_6 and AS_7)

The number of availability-related components equals 7, according to Eq. (3). Then, the number of possible functional modes equals $2^7 = 128$, as stated in Eq. (4).

2.6. Overall energy generation and resources consumption for each functional status

Altogether, the overall functional status of the power plant can be determined as the conjunction of the operative condition of every component, as defined in Eq. (19) and described in Table 2 regarding the delivered energy (and eventually, the consumed resources).

$$FS = \{P1, P2, P3, P4, P5, P6\} \tag{19}$$

Therefore, functional statuses of the power plant can be determined by specifying which of the sections, defined in Eq. (20) and introduced in Figure 4, operate at full capacity, at a derated condition, or are down.

$$PP = \{GT1, GT2, ST1, ST2\} \tag{20}$$

It is then noted that:

- The functional status of each gas turbine can be determined on its own, thus requiring one element associated to each of them ($GT1$ and $GT2$)
- The description of the functional status of the steam turbine requires two elements ($ST1$ and $ST2$), as it depends upon the steam generated at each $HRSG$ and the operative condition of each associated gas turbine

A binary variable gets associated to each section, which describes its status at each feasible functional mode, as given in Eq. (21).

$$y_{PP,FM^f} = \begin{cases} 0 & failed \\ 1 & operative \end{cases} \tag{21}$$

As consequence, it becomes necessary to determine the functional statuses of the gas and steam turbines in terms of the operative condition of each component for every feasible functional mode. This is accomplished by analyzing the logical relations between them, which are presented in text notation and in conjunctive normal form in Appendix C, and afterwards transformed into the corresponding linear constraints, as described in Eqs. (22-29).

$$y_{GT1,FM^f} \geq y_{AS1,FM^f} + y_{AS2,FM^f} - 1 \tag{22}$$

$$y_{GT2,FM^f} \geq y_{AS1,FM^f} + y_{AS3,FM^f} - 1 \tag{23}$$

$$y_{GT1,FM^f} \leq y_{j,FM^f} \ , \ j = AS1, AS2 \tag{24}$$

$$y_{GT2,FM^f} \leq y_{j,FM^f} \ , \ j = AS1, AS3 \tag{25}$$

$$y_{ST1,FM^f} \geq y_{AS4,FM^f} + y_{AS5,FM^f} + y_{AS6,FM^f} + y_{GT1,FM^f} - 3 \tag{26}$$

$$y_{ST2,FM^f} \geq y_{AS4,FM^f} + y_{AS5,FM^f} + y_{AS7,FM^f} + y_{GT2,FM^f} - 3 \tag{27}$$

$$y_{ST1,FM^f} \leq y_{j,FM^f} \ , \ j = AS4, AS5, AS6, GT1 \tag{28}$$

$$y_{ST2,FM^f} \leq y_{j,FM^f} \ , \ j = AS4, AS5, AS7, GT2 \tag{29}$$

Finally, the probabilities associated to each functional status of the $NGCC$ power plant are computed as stated in Eq. (30), considering their interrelations with the operative statuses of the gas and steam turbines as listed in Table 3 (where only those combinations which are feasible in accordance to Eqs. (22-29) are listed).

$$Pr_{FS} = \sum_{FM^d} Pr_{FM^f} \quad , \quad FM^d \subseteq FM^f \tag{30}$$

2.7. Component-based assessment of maintenance resources impact

Allocation of extra resources on maintenance has a directly measurable effect on upholding or improving the repair time of a given piece of equipment, as a positive influence on the following aspects (among others) is observed:

- Fasten repairing equipment to acceptable standards
- Keeping inventory strategically, to ensure necessary materials are readily available
- Effectively applying manufacturers' recommendations and ensuring compliance with contractual requirements
- Maintenance staff training to improve their skills and capabilities
- Implementing methods to improve workplace security
- Systematizing maintenance actions and keeping personnel aware of applied policies
- Managing maintenance wastes

Enhancing any of these factors involves assigning extra resources for maintenance actions. As stated in Eq. (31), it is assumed that an exponential relationship exists between the mean time to repair of a piece of equipment and the maintenance funds assigned for such task: assigning more resources for equipment maintenance actions will improve its repair time, up to the point where technical difficulties constitute a speed limitation at which repairs can be performed (i.e. a point of diminishing return).

$$\mu_{AS} = \mu_{AS,0} \ \left(F_{Mant}\right)^{\gamma_{AS}} \tag{31}$$

The variables $\mu_{AS,0}$ and γ_{AS} depend upon the values of the minimum and maximum funds available for maintenance, and the associated values of the repair rates for such scenarios, as introduced in Eqs. (32-33).

$$\mu_{AS,0} = \frac{\mu_{AS,Min} - \mu_{AS,Max}}{\left(F_{Mant,Min}\right)^{\gamma_{AS}} - \left(F_{Mant,Max}\right)^{\gamma_{AS}}} \tag{32}$$

$$\gamma_{AS} = \frac{\ln \mu_{AS,Min} - \ln \mu_{AS,Max}}{\ln F_{Mant,Min} - \ln F_{Mant,Max}} \tag{33}$$

Parameters to be used in Eqs. (32-33) can be computed from industry historic data on assigned maintenance funds versus achieved mean repair times (NERC, 2011; OREDA Participants, 2002; Alber et al., 1995). Moreover, when the funds assigned for maintenance actions are increased from the minimum value $F_{Mant,Min}$ up to the maximum one $F_{Mant,Max}$, it can be assumed that the repair rate per component improves by a given percentage $MFIR_{AS}$, as introduced in Eq. (34) and listed in Table 4.

$$\mu_{AS,Max} = MFIR_{AS} \ \mu_{AS,Min} \tag{34}$$

2.8. Implementation

The mathematical program is implemented in the optimization software GAMS (Rosenthal, 2008) and solved through the algorithms CONOPT (Drud, 1996) and SBB (Drud, 2001). The proposed model comprises continuous and discrete variables, as well as highly non-linear constraints which configure a non-convex solutions space (including logarithmic mean temperature differences, correlations for water and steam properties according to IAPWS (1992, 2007), polytropic expansion at turbines, among others). Due to such characteristics, global optimal solutions cannot be guaranteed.

The initialization strategy of the optimization problem is outlined at Figure 5, and implies:

- Common practical values are assigned to the power plant variables, when considering the design and operative characteristics of an actual one (García and Moñux, 2006; Kehlhofer et al., 2009; Rapún Jiménez, 1999)

- The discrete variables associated to each component are set to 1 for the functional mode which represents nominal operative capacity, while they are assumed as 0 at every other one

- For a given amount of resources assigned for maintenance actions, a preliminary evaluation of each component repair rate is achieved

- At this point, the economic performance of the project can be preliminarily computed, as if the system operated at full load across the whole time span

This initial solution is then passed to the software GAMS, which starts the optimization procedure, and ultimately delivers optimal values for every continuous and discrete variable within the mathematical formulation, as summarized in Figure 6 and including:

- Power plant variables (according to Appendix A): effective fuel consumption and operative load of the gas turbine, design capacity and operative load of the steam turbine, exchange area and logarithmic temperature differences at each section of the $HRSGs$, pinch and approach points, boiler and cooling water consumption, pumps power requirement, characteristics (flow rate, temperature, pressure, composition) of each process stream

- Economic performance (according to Section 2.3 and Appendix B): capital investment (including the main pieces of process equipment), operative expenditures (fuel, auxiliary services, maintenance, manpower, etc.), energy sales, total annual cost, electricity cost

- Availability modeling (according to Sections 2.4, 2.5 and 2.6): feasible functional modes (considering the value adopted for $NSIFC$), operative condition of each component at every feasible functional mode, transition rates (considering the value adopted for NSE), probabilities of functional modes, operative span for each functional mode, operative condition of each section, probabilities of functional statuses

- Evaluation of maintenance funds impact (according to Section 2.7): repair rate of each component as function of assigned maintenance funds

3. Optimal designs: results and discussion

Three case studies are hereafter solved and discussed, as summarized in Table 1 and briefly outlined below. As consequence, the economic optima of the $NGCC$ power plant is obtained when solving the resultant MINLP formulation.

Case study 1 introduces the optimal design for the project while the availability and maintenance-related parameters are adopted at values usually adopted in the literature (as suggested by Frangopoulos and Dimopoulos (2004)). Results here obtained are compared against a *Reference plant* designed for a pre-specified annualized operative horizon and a fixed maintenance budget (see Godoy et al. (2011)).

Case study 2 discusses the modifications of the optimal generation project as the availability-related parameters are varied across the whole range of feasible values; while the effect of varying the amount of resources assigned for maintenance actions is thoroughly analyzed in *Case study 3*.

In addition, a sensitivity analysis regarding the adopted economic parameters is presented, including fuel cost, investment on process equipment, as well as interest rate and life cycle span.

3.1. Case study 1: the simplest implementation of the state-space approach

Optimal designs for the $NGCC$ power plant are here obtained by solving the economic optimization formulation previously detailed in Section 2.2. *Case study 1* represents the simplest implementation of the state-space approach, as the availability and maintenance-related parameters are fixed at values usually adopted in the literature, which configure a back and forth radial feasible solutions region (i.e. where the system can only migrate from a fully operative state to one where at most a single component has failed, as exemplified in Figure 3a).

Table 5 lists the probabilities of occurrence for every feasible functional status of the generation facility. A priori, when selecting $NSIFC = 1$ and $NSE = 1$, it is found that the model predicts a large time span for operative at full capacity, even with moderate values of the resources assigned for maintenance actions (adopted as 2% of the capital investment).

The obtained optimal values of the economic performance indicators of the project are presented in Table 6, and also compared against a *Reference plant* designed for a pre-specified annualized operative horizon and a fixed maintenance budget (obtained according to Godoy et al. (2011)).

It is observed that a 5.9% increment on the estimation of the total delivered energy, as the computation also includes the one generated at derated operative conditions. For similar reasons, the total annual cost increases by 3.0% as the operative expenditures are 4.3% larger (driven by the extra fuel consumed for electricity generation). On the other hand, the capital expenditures remain invariant since no relation is here considered between the equipment acquisition cost and the availability related parameters.

Therefore, it is here concluded that this first approach yields improvements over the evaluation of the project economics since the electricity cost diminishes by 2.8%, given that the delivered energy increases at a higher rate than the total annual cost.

Every component of the total expenses is disaggregated in Figure 7. On an annual basis, the fuel consumption broadens 87.3% of the total raw material and utility costs, followed by the expenses on boiler and cooling water (9.0% and 3.7%, respectively).

The acquisition of the gas turbines requires 58.5% of the investment on process equipment, while the remaining 41.5% goes to the steam turbine and $HRSGs$. The construction of the facilities and other investment related factors take about 30% of the annualized expenditures.

In addition, Table 7 introduces the optimal values of key decision variables of the $NGCC$ power plant, including design and operative ones.

Note that the gas turbine design characteristics have been tuned to reproduce the performance of a commercially available one (GE PG9351FA). On the other hand, the steam cycle is specifically tailored for this application. Even so, optimal values for flow rates, temperatures, operative pressures, exchange areas, temperatures differences, etc. are in accordance with values previously reported in the literature (Kotowicz and Bartela, 2010; Srinivas, 2009; Edris, 2010; Woudstra et al., 2010; Franco and Giannini, 2006).

Moreover, it is here noted that the operative variables of the $NGCC$ power plant are allowed to adjust their values within wide ranges (as set by the selected minimum and maximum bounds on the technical constraints), which allows exploring a wider space of feasible solutions and enables attaining further improvement of the system performance.

3.1.1. Comparison with other authors

Frangopoulos and Dimopoulos (2004) introduced some simplifications when modeling the cogeneration plant (which are consistent with the ones at *Case study 1*) in order to obtain a formulation with a manageable size. In this context, they observed that an extra cogeneration package is necessary in order to satisfy the minimum availability requirements if reliability is taken into account, and proved that profits are overestimated when reliability aspects are ignored. In turn, El-Nashar (2008) utilized a single-transition structure to represent the feasible solutions space of a multistage desalination plant coupled to a cogeneration facility, which also allowed them to obtain a mathematical expression for the system availability. Then, they found that the water and power costs are higher when reliability considerations are considered during the design of the joint plant. Under similar modeling assumptions, improvement on economic indexes is here obtained, as no new equipment gets installed in order to increase the availability level of the system, while a more detailed evaluation of the project performance is achieved. It is also confirmed that the adoption of $NSIFC = 1$ and $NSE = 1$ generates a small and manageable optimization formulation.

Haghifam and Manbachi (2011) implemented a state-space and continued Markov model to study the reliability and availability of combined heat and power systems, where three subsystems are identified: electricity-generation, fuel-distribution and heat-generation. In turn, El-Nashar (2008) divided a cogeneration plant for power and desalination into three main components: gas turbine, $HRSG$ and multistage flash plant. Likewise, Wang et al. (2013) proposed a multi-state model for a BHCP system while identifying three main supplies: electricity, heat and cold. Identification of key subsystems allowed these authors, and also in this work, to narrow down the number of logically arranged components (here listed in Eq. (2)), which is a reasonable assumption when analyzing the system as a whole during the synthesis and design stages of its life cycle.

Improving the reliability of each component implies attaining a higher level for the overall availability of the power plant, as demonstrated by Haghifam and Manbachi (2011). Meanwhile, repair rates are here improved as the necessary amount of maintenance resources are optimally assigned, while also evaluating their impact on the economic performance of the generation project. The parameters needed for the here proposed functionalities between repair rates and maintenance budget can be attained from industry historic data (NERC, 2011; OREDA Participants, 2002; Alber et al., 1995); whereas other proposals (Goel et al., 2002, 2003) for assessing the impact of maintenance actions on the system availability would require not-easily-procurable data (which should be provided by equipment manufacturers in non-standard format).

When the operative status of each component is described by a zero-one variable, Vassiliadis and Pistikopoulos (2001) observed that the use of criteria that do not explicitly relate to process profitability as optimization objectives does not allow for the quantification of the balance between maintenance benefits and costs. This problem is here overcome as operative related financial flows (given by Eqs. (B.6-B.11)) are explicitly evaluated for every functional status when considering the associated optimal values of the operative variables (fuel consumption, auxiliary services, etc.), and afterwards weighted through Eq. (17).

3.2. Case study 2: influence of availability related parameters $NSIFC$ and NSE

Optimal designs for the $NGCC$ power plant are here obtained by solving the economic optimization formulation previously detailed in Section 2.2. *Case study 2* analyzes the influence of modifications on the values adopted for the availability related parameters over the optimal economics of the generation project. Then, the number of simultaneously and independently failed components $NSIFC$ is varied from 1 to 7, while the number of simultaneous events NSE is varied from 1 to 4. Consequently, the behavior of the system needs to be weighted across a broader span of feasible operative scenarios in order to evaluate its optimal economic performance.

Figure 8 shows the main characteristics of the optimization formulation (as stated in Figure 2) due to the modification of parameters $NSIFC$ and NSE. Firstly, it is observed that the number of feasible functional modes (defined in Eq. (8)) grows exponentially along the value of $NSIFC$ (see Figure 8a), as does the number of continuous and discrete variables (see Figure 8b), which is inherently linked to the size of the mathematical problem that needs to be solved.

Figure 8c exhibits the computational cost for successfully achieving the resolution of each optimization problem, as the ratio against the resources needed for solving *Case study 1.* Note that a nested successive initialization strategy is used: for a given value of NSE, each optimal solution is used as starting point for the next problem where $NSIFC$ is incremented in one unit; while NSE is increased by one unit in the outer loop. Even though, it is here observed that the resolution effort becomes several times larger than the requirements at the base case, thus imposing limitations to the selection of values for parameters $NSIFC$ and NSE in order to efficiently solve the optimization problem.

For each pair of values of $NSIFC$ and NSE, Figure 8d shows the number of significant probability terms, i.e. the number of feasible functional modes which probability of occurrence is larger than 0.01%. For a given value of NSE, is is here found that an increasingly larger number of feasible functional modes do not significantly contribute to the overall performance of the project as the value of $NSIFC$ increases:

- For $NSE = 1$, the number of significant probability terms equals 8 for $NSIFC = 1$, and 28 for $NSIFC \geq 2$
- For $NSE = 2$, the number of significant probability terms flattens at 64 for $NSIFC \geq 3$. Even though, the number of feasible functional modes reach 128 for $NSIFC = 7$ (according to Eq. (8))
- Similar behavior is observed for $NSE = 3$ and $NSE = 4$

Then, it is concluded that some combinations of $NSIFC$ and NSE do not significantly contribute to improving the accuracy on the evaluation of the economic performance of the generation project, even though they imply an increment on the required computational resources as previously discussed.

The probabilities of occurrence of each feasible functional mode for every optimization problem are introduced at Figure 9. It is here observed that:

- When $NSIFC = 1$, the functional status $P5$ cannot occur since it would require two components failing at the same time
- For $NSE = 1$, the probabilities remain almost invariant for the whole range of values of $NSIFC$
- As NSE adopts a value equal or greater than 2, the functional statuses which represent derated operative conditions become increasingly more common, while the probability of operative at full capacity falls exponentially

Figure 10 presents the optimal economic indicators of the project for each pair of values for $NSIFC$ and NSE. The total annual cost decreases as the value of $NSIFC$ increases, for a given value of NSE, as shown in Figure 10a. The main cost components exhibit similar trends, as illustrated for the fuel consumption in Figure 10b. Moreover, the total delivered energy also becomes smaller, as plotted in Figure 10c.

Since the total annual cost decreases at a lower rate than the delivered energy's, it is observed in Figure 10d that the cost of the generated electricity increases as the value of $NSIFC$ does, for a given value of NSE. In addition, at first sight, the evolution of the objective function follows a similar trend that the one exhibited by the number of significant probability terms.

Thus, these trends regarding the evolution of the objective function can then be explained when considering the probability of occurrence of each feasible functional mode, since operative at a derated condition is more economically inefficient, and consequently implies a larger average (or weighted) cost per unit of delivered energy.

3.3. Case study 3: influence of resources assigned for maintenance actions

Optimal designs for the $NGCC$ power plant are here obtained by solving the economic optimization formulation previously detailed in Section 2.2. *Case study 3* evaluates the modifications on the optimal performance of the generation project as the resources assigned for maintenance actions are varied from the minimum recommended budget (adopted as 0.5% of the capital investment), and up to the maximum available one (adopted as 4% of the capital investment).

Regarding the values of $NSIFC$ and NSE, four feasible combinations are here adopted as listed in Table 1, and denoted as sub-cases *3.A*, *3.B*, *3.C* and *3.D*.

Figure 11 introduces the evolution of the probability of occurrence of each functional status as the maintenance resources are varied. It is here observed that:

- The probability of operative at nominal capacity increases as the maintenance funds do, for every feasible scenario
- For *Case study 3.A*, which represents the simplest implementation of the state-space approach (i.e. when $NSIFC = 1$ and $NSE = 1$), the functional status probabilities exhibit only a slight dependence on the maintenance budget. Similar conclusions are drawn for those scenarios where $NSE = 1$ and independently of the value of $NSIFC$
- Increasing the maintenance resources has a positive and more pronounced effect over the economic performance of the generation project when NSE is equal or greater than 2, as shown for *Case studies 3.B*, *3.C* and *3.D*

Figure 12 presents the optimal economic indicators for each sub-case within *Case study 3*, for the whole range of assigned maintenance resources.

As an increasing maintenance budget implies a larger time span where the power plant operates at nominal capacity or at a derated condition with a higher operative load, the total annual expenditures present a positive slope, according to Figure 12a, since the main cost components also exhibit a similar trend, as exemplified in Figure 12b for the fuel consumption. Consequently, an increment on the delivered energy is also attained, as Figure 12c indicates.

Regarding the evolution of the electricity cost versus the assigned maintenance resources, Figure 12d shows that the delivered electricity becomes cheaper as consequence of the positive effect exerted by an increasing maintenance budget.

3.3.1. Economic Sensitivity Analysis

As expected, the optimal values of the economic performance indicators of the project are critically dependent on the adopted values of the economic parameters. Thus, the sensitivity of the obtained optima is here discussed as several financial parameters are varied across a ±20% range, for each sub-case included in *Case study 3*, while the maintenance factor has been fixed at 0.020. Then, Figure 13 reflects the relative influence of variations on the economic parameters over the electricity cost (i.e. the objective function).

It is observed that the fuel cost exerts the largest negative impact on the electricity cost, followed in order of importance by the investment factor and the interest rate. On the contrary, increasing the life cycle length exposes a favorable (quasi) linear trend on the economic performance indicators of the project (as the capital expenditures get depreciated across a longer time span).

These economic parameters should then be carefully balanced considering the different available alternatives (turbines manufacturers, fuel sources, type of provision contract, etc.), so the newly designed generation plant results more appealing to potential investors.

Figure 13 represents the economic sensitivity of the project as one economic parameter is varied at a time (while the other ones are kept at their expected values), which intends to configure a representative or average case. It is noted that the simultaneous increase of all the economic parameters (even including several others here not considered) would set a worst case scenario where the economic performance indicators get severely impacted and the electricity cost gets increased far beyond the values here reported; while a best case scenario could be obtained if the economic parameters are varied in the opposite direction, thus obtaining a minimum optimal value of the objective function.

A more rigorous and in-depth economic analysis should consider the uncertainty distribution (in a deterministic or stochastic way) of each economic parameter, which would enable finding the most likely scenarios that the project would have to face; although such analysis is beyond the scope of this work.

4. Conclusions

A comprehensive strategy has been here discussed in order to successfully achieve the economic optimization of a $NGCC$ power plant, while considering the availability of the system through its wide array of feasible operative statuses, as well as the assignment of maintenance resources and its implications on the financial performance of the project.

Implications of a state-space approach are thoroughly discussed, where influence of maintenance funds on each component's repair rate is directly assessed. In this context, availability-related parameters $NSIFC$ and NSE must be carefully selected in order to more accurately represent the actual characteristics of the region of economic optimal solutions for this type of generation plants, where it is observed that:

- A priori, utilizing $NSIFC = 1$ and $NSE = 1$, as illustrated in *Case study 1* and usually adopted in the literature, may render an improvement of the economic indexes. At *Case study 2*, similar conclusions are obtained when $NSIFC = 1$ for any value of NSE, or when $NSE = 1$ for any value of $NSIFC$

- When both $NSIFC$ and NSE are equal or greater than 2, *Case study 2* shows that the power plant operates during an increasingly larger time span at different derated conditions, where the estimated value for the delivered energy cost results higher than for the *Reference plant*. It is also observed that functional status $P5$ cannot be represented by the state-space method if $NSIFC$ equals 1, since it requires two components failing independently at the same time

- An increasingly larger budget for maintenance actions improves the availability of the system, as quantified at *Case study 3*, whereas such behavior is more noticeable when both $NSIFC$ and NSE are equal or greater than 2

Therefore, it is here found that values of parameters $NSIFC$ and NSE are critical for the successful evaluation of the optimal economic performance of the generation plant. It is then observed that the value for both $NSIFC$ and NSE should be carefully selected in order to better depict the actual characteristics of $NGCC$ power plants across the full span of functional statuses under a component-based policy for assessment of the impact of assigned maintenance resources; although restraint should be exercised since the size of the resultant optimization mathematical problem becomes larger as $NSIFC$ does, also requiring extra computational resources in order to promptly achieve convergence.

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A. Considerations about the modeling strategy of the *NGCC* power plant

A.1. General considerations

Regarding the power plant, the following modeling aspects are taken into account:

- The design of the power plant implies determining the size and operating characteristics of every exchange section at the *HRSGs*. A fixed configuration is adopted at both *HRSGs* (considering the ones used by Bassily (2007); Franco and Casarosa (2002); Franco and Giannini (2006)). Thus, their optimization implies maximizing the recovered heat while considering the pinch and approach temperatures of the system

- The steam turbine is designed for the flow rate that effectively circulates through every pressure level. Performance maps provided by turbine manufacturers are used to correlate the isentropic efficiency and the flow capacity as a function of the compression ratio and rotational speed (Bahadori and Vuthaluru, 2010; Martelli et al., 2011), for given turbine size

A.2. Technical constraints

In order to circumscribe a feasible operating region, technical limits and manufacturers recommendations are considered by means of inequality constraints:

- Minimum and maximum approach point (5 K and 15 K, respectively), to guarantee no water evaporation in the economizers and to avoid thermal shock at evaporator entries, respectively

- Minimum and maximum pinch point (5 K and 15 K, respectively), to secure reasonable practical values of the *HRSG* heat transfer area

- Maximum steam pressure for each operating pressure level at the *HRSG* (120 atm for high pressure, 45 atm for intermediate pressure, 5 atm for low pressure, 1.5 atm for deaerator, 0.15 atm for condenser), to assure operation within normal parameters

- Minimum operating pressure of the condenser (0.05 atm), fixed by minimum temperature of available cooling water

- Maximum gas temperature at *HRSG* inlet (900 K), to prevent materials deterioration

- Minimum gas pressure at $HRSG$ discharge (1.005 atm), to secure adequate operating parameters
- Minimum gas temperature at $HRSG$ discharge (360 K), to prevent corrosion due to water condensation
- Minimum temperature difference at superheater exit (30 K), to secure adequate operating parameters
- Minimum temperature difference at condenser (4 K), to avoid excessive cooling water consumption
- Minimum temperature difference at regenerator exit (40 K), to secure adequate operating parameters
- Minimum and maximum steam quality at steam turbine discharge (0.92 and 0.97, respectively), to secure adequate operating parameters at the steam turbine

A.3. Technical parameters

The technical parameters are listed in Table 8.

B. $CAPEX$ and $OPEX$ calculation

A description of the equations used for computing the capital and operating expenditures is here presented.

B.1. Capital expenditures

The main pieces of process equipment are considered when computing the necessary capital investment, as listed in Eq. (B.1).

$$PE = \{GT, ST, HRSG\} \tag{B.1}$$

The acquisition cost of a given piece of equipment $C_{Inv,PE}$ depends upon its size X_{PE} and constructive characteristics, and is computed by Eq. (B.2).

$$C_{Inv,PE} = C_{PE}(X_{PE})^{a_{PE}} \tag{B.2}$$

The exponential coefficient a_{PE} is assumed equal to one for turbines and equal to 0.6 for $HRSGs$. Reference costs C_{PE} are computed by correlations reported in the literature (Seider et al., 2009; Henao, 2005; Nye Thermodynamics Corporation, 2013; U.S. Energy Information Administration, 2010; Matches, 2013), while Table 10 lists adopted characteristics for all the pieces of equipment considered in the capital investment computation.

The total investment cost C_{Inv} is determined as the sum of individual equipment costs $C_{Inv,PE}$, according to Eq. (B.3).

$$C_{Inv} = \sum_{PE} C_{Inv,PE} \tag{B.3}$$

The total investment on fix capital $CAPEX$ is also related (besides equipment acquisition) to the design and construction of the necessary facilities and auxiliary services; thus the total equipment acquisition cost is affected by an investment factor F_{Inv} in order to consider such expenditures, as given at Eq. (B.4). Specific values here assumed for the economic indexes when computing capital expenditures are listed in Table 9 according to the guidelines given at Abu-Zahra et al. (2007); Rao and Rubin (2002).

$$CAPEX = F_{Inv}\, C_{Inv} \tag{B.4}$$

The recovery factor CRF which affects the investment on fix capital is computed by Eq. (B.5), for a given interest rate i and life span n.

$$CRF = \frac{(i+1)^n - 1}{i\ (i+1)^n} \tag{B.5}$$

B.2. Operating expenditures

Operating expenditures $OPEX$ get computed as given at Eq. (B.6). The calculation includes raw materials and utilities C_{RM}, maintenance C_{Mant}, man power C_{MP}, and other costs related to these previous ones. Specific values here assumed for the economic indexes F_{O1} and F_{O2} are listed in Table 11 according to the guidelines given at Abu-Zahra et al. (2007); Rao and Rubin (2002).

$$OPEX = C_{RM} + C_{Mant} + F_{O1}\ C_{MP} + F_{O2}\ C_{Inv} \tag{B.6}$$

The main process streams are considered when computing the cost of raw materials and utilities, as listed in Eq. (B.7).

$$PS = \{F, CW, BW\} \tag{B.7}$$

Total cost of raw materials and utilities C_{RM} is computed by Eq. (B.8), where POT is the plant operating time; C_{PS} refers to the raw material or utility price and $\dot{m}_{PS}$ denotes the flow rate (annual basis) of each process stream.

$$C_{RM} = \sum_{PS} POT\ C_{PS} X_{PS} \tag{B.8}$$

Up-to-date fuel cost is obtained from U.S. Department of Energy (2013). Utilities costs are estimated according to the guidelines introduced by Ulrich and Vasudevan (2006), as unit costs C_{PS} are computed from Eq. (B.9).

$$C_{PS} = a_{PS} + b_{PS}\ C_F \tag{B.9}$$

where a_{PS} and b_{PS} coefficients are computed according to Table 12.

A traditional economic evaluation approach estimates maintenance costs C_{Mant} as a fix percentage F_{Mant} of the capital investment, according to Eq. (B.10).

$$C_{Mant} = F_{Mant}\ C_{Inv} \tag{B.10}$$

Man power costs C_{MP} consider the administrative, technical and operating personnel necessary at both plants, according to Eq. (B.11).

$$C_{MP} = F_{MP}\, N_{MP} \tag{B.11}$$

B.3. Energy sales

Energy sales $Sales$ get computed by Eq. (B.12), as the price of the delivered electricity P_{Elec} times the total generated energy GE.

$$Sales = P_{Elec}\, GE \tag{B.12}$$

B.4. Economic parameters

The economic parameters are listed in Table 13.

C. Derivation of functional statuses for the *NGCC* power plant

The logical relations for every feasible functional mode between the gas and steam turbines and each availability-related component are here introduced in text notation and in conjunctive normal form.

C.1. Gas turbines

$$\begin{cases} if\ \ \big(y_{AS1,FM^f}=1\ and\ y_{AS2,FM^f}=1\big)\ \ then\ \ \big(y_{GT1,FM^f}=1\big) \\ \qquad CNF:\ \neg y_{AS1,FM^f}\vee\neg y_{AS2,FM^f}\vee y_{GT1,FM^f} \\ \qquad\qquad Implies:\ Eq.\ (22) \end{cases} \tag{C.1}$$

$$\begin{cases} if\ \ \big(y_{AS1,FM^f}=1\ and\ y_{AS3,FM^f}=1\big)\ \ then\ \ \big(y_{GT2,FM^f}=1\big) \\ \qquad CNF:\ \neg y_{AS1,FM^f}\vee\neg y_{AS3,FM^f}\vee y_{GT2,FM^f} \\ \qquad\qquad Implies:\ Eq.\ (23) \end{cases} \tag{C.2}$$

$$\begin{cases} if\ \ \big(y_{AS1,FM^f}=0\ or\ y_{AS2,FM^f}=0\big)\ \ then\ \ \big(y_{GT1,FM^f}=0\big) \\ CNF:\ \ \big(y_{AS1,FM^f}\vee\neg y_{GT1,FM^f}\big)\wedge\big(y_{AS2,FM^f}\vee\neg y_{GT1,FM^f}\big) \\ \qquad\qquad Implies:\ Eq.\ (24) \end{cases} \tag{C.3}$$

$$\begin{cases} if\ \ \big(y_{AS1,FM^f}=0\ or\ y_{AS3,FM^f}=0\big)\ \ then\ \ \big(y_{GT2,FM^f}=0\big) \\ CNF:\ \ \big(y_{AS1,FM^f}\vee\neg y_{GT2,FM^f}\big)\wedge\big(y_{AS3,FM^f}\vee\neg y_{GT2,FM^f}\big) \\ \qquad\qquad Implies:\ Eq.\ (25) \end{cases} \tag{C.4}$$

C.2. Steam turbine

$$\begin{cases} if\ \ \big(y_{AS4,FM^f}=1\ and\ y_{AS5,FM^f}=1\ and\ y_{AS6,FM^f}=1\ and\ y_{GT1,FM^f}=1\big)\ \ then\ \ \big(y_{ST1,FM^f}=1\big) \\ \qquad CNF:\ \neg y_{AS4,FM^f}\vee\neg y_{AS5,FM^f}\vee\neg y_{AS6,FM^f}\vee\neg y_{GT1,FM^f}\vee y_{ST1,FM^f} \\ \qquad\qquad Implies:\ Eq.\ (26) \end{cases} \tag{C.5}$$

$$\begin{cases} if\ \ \big(y_{AS4,FM^f}=1\ and\ y_{AS5,FM^f}=1\ and\ y_{AS7,FM^f}=1\ and\ y_{GT2,FM^f}=1\big)\ \ then\ \ \big(y_{ST2,FM^f}=1\big) \\ \qquad CNF:\ \neg y_{AS4,FM^f}\vee\neg y_{AS5,FM^f}\vee\neg y_{AS7,FM^f}\vee\neg y_{GT2,FM^f}\vee y_{ST2,FM^f} \\ \qquad\qquad Implies:\ Eq.\ (27) \end{cases} \tag{C.6}$$

$$\begin{cases} if \;\; \big(y_{AS4,FM^f} = 0 \; or \; y_{AS5,FM^f} = 0 \; or \; y_{AS6,FM^f} = 0 \; or \; y_{GT1,FM^f} = 0\big) \;\; then \;\; \big(y_{ST1,FM^f} = 0\big) \\ \qquad CNF: \; \begin{matrix} \big(y_{AS4,FM^f} \vee \neg y_{ST1,FM^f}\big) \wedge \big(y_{AS5,FM^f} \vee \neg y_{ST1,FM^f}\big) \wedge \\ \big(y_{AS6,FM^f} \vee \neg y_{ST1,FM^f}\big) \wedge \big(y_{GT1,FM^f} \vee \neg y_{ST1,FM^f}\big) \end{matrix} \\ \qquad\qquad\qquad Implies: \;\; Eq.\ (28) \end{cases} \tag{C.7}$$

$$\begin{cases} if \;\; \big(y_{AS4,FM^f} = 0 \; or \; y_{AS5,FM^f} = 0 \; or \; y_{AS7,FM^f} = 0 \; or \; y_{GT2,FM^f} = 0\big) \;\; then \;\; \big(y_{ST2,FM^f} = 0\big) \\ \qquad CNF: \; \begin{matrix} \big(y_{AS4,FM^f} \vee \neg y_{ST2,FM^f}\big) \wedge \big(y_{AS5,FM^f} \vee \neg y_{ST2,FM^f}\big) \wedge \\ \big(y_{AS7,FM^f} \vee \neg y_{ST2,FM^f}\big) \wedge \big(y_{GT2,FM^f} \vee \neg y_{ST2,FM^f}\big) \end{matrix} \\ \qquad\qquad\qquad Implies: \;\; Eq.\ (29) \end{cases} \tag{C.8}$$

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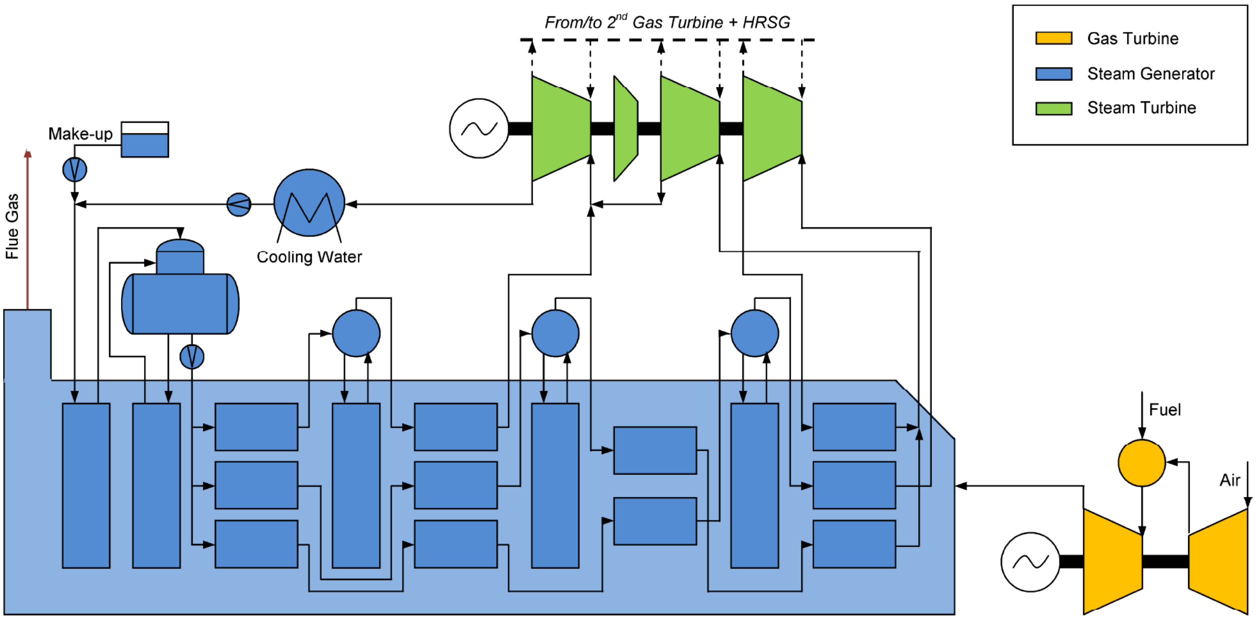


Figure 1: Flow diagram for the *NGCC* power plant

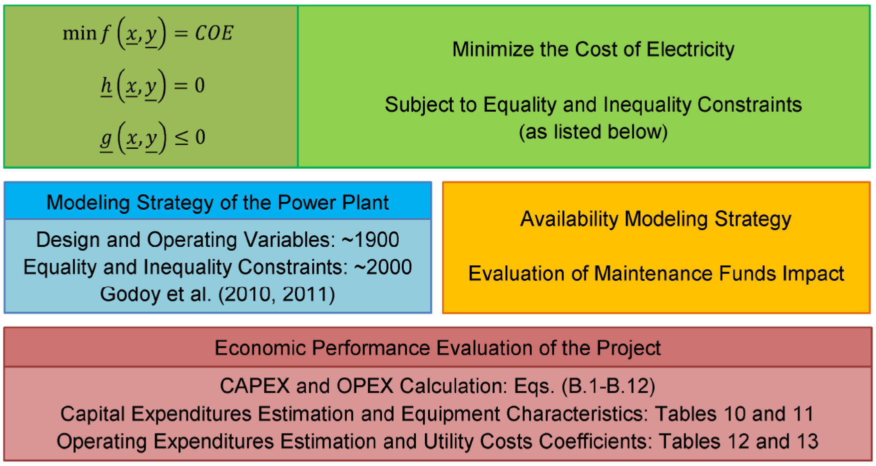
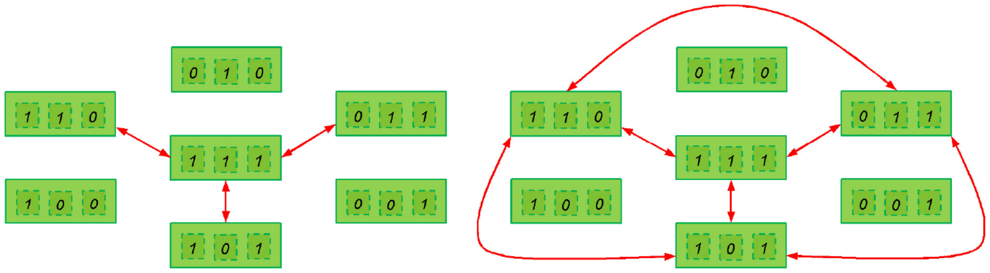
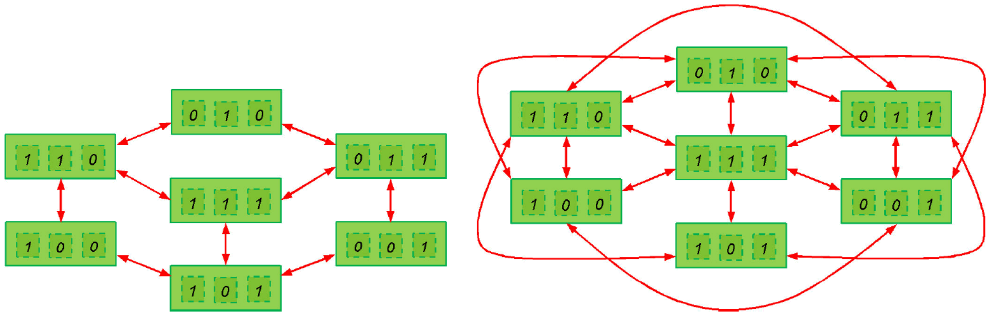


Figure 2: Economic optimization problem



(a) $NSIFC = 1$, $NSE = 1$

(b) $NSIFC = 1$, $NSE = 2$ or $NSIFC = 1$, $NSE = 3$



(c) $NSIFC = 2$, $NSE = 1$

(d) $NSIFC = 2$, $NSE = 2$

	NSIFC		
NSE	1	2	3
1	4	7	8
2	4	7	8
3	4	7	8

(e) Number of feasible functional modes

	NSIFC		
NSE	1	2	3
1	3	9	12
2	6	18	24
3	6	21	28

(f) Number of interconnections

Figure 3: $NSIFC$ and NSE application example

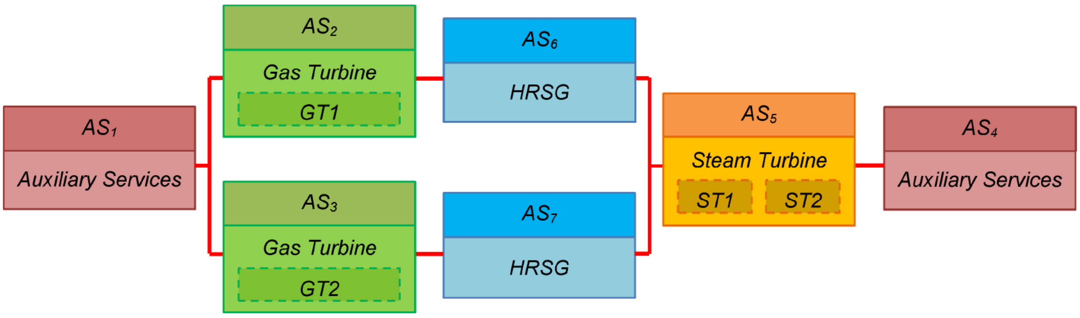


Figure 4: Reliability block diagram for the *NGCC* power plant

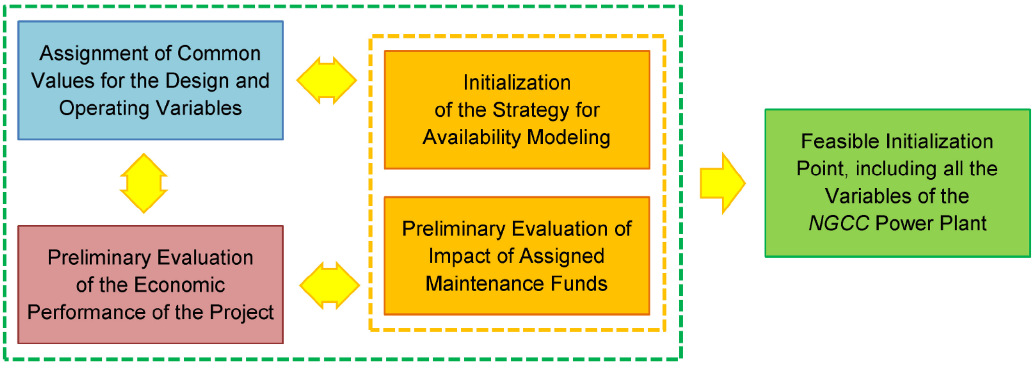


Figure 5: Initialization strategy

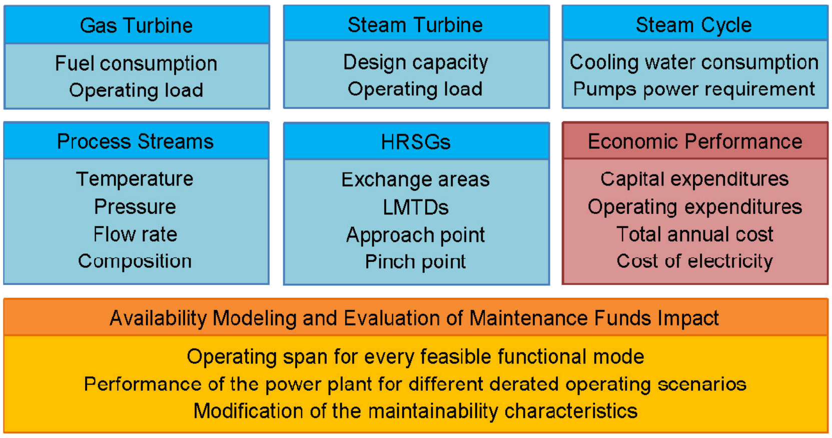
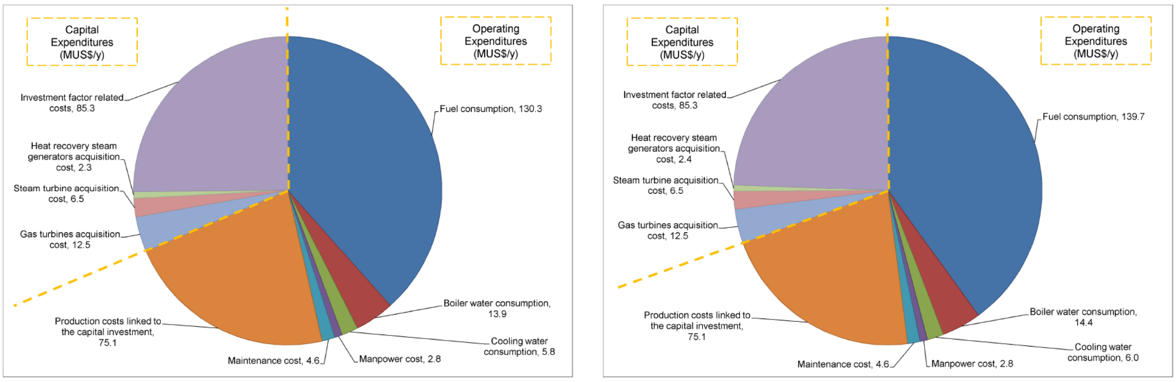


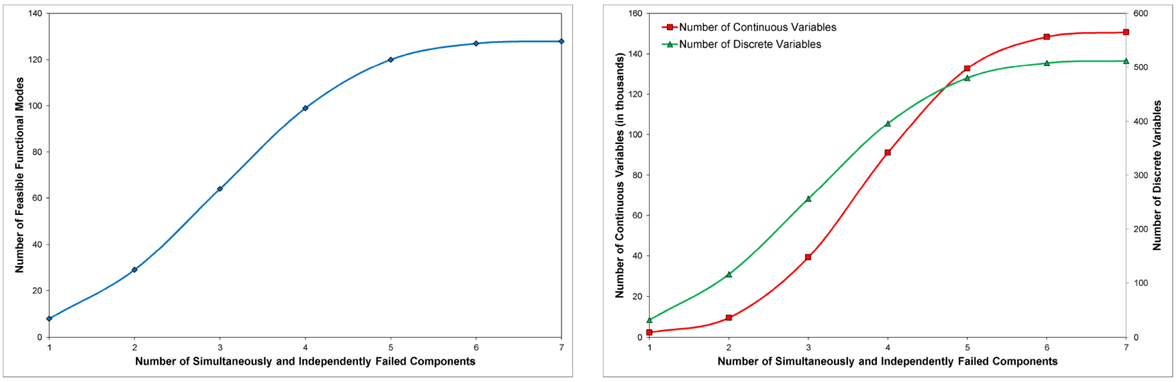
Figure 6: Decision variables for the power plant



(a) Reference Plant

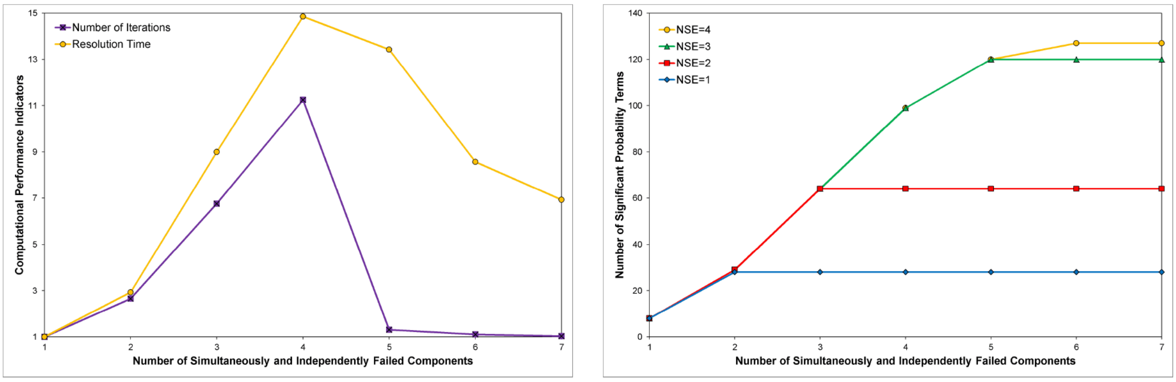
(b) Case Study 1

Figure 7: Case study 1. Costs distribution for the project



(a) Number of feasible functional modes

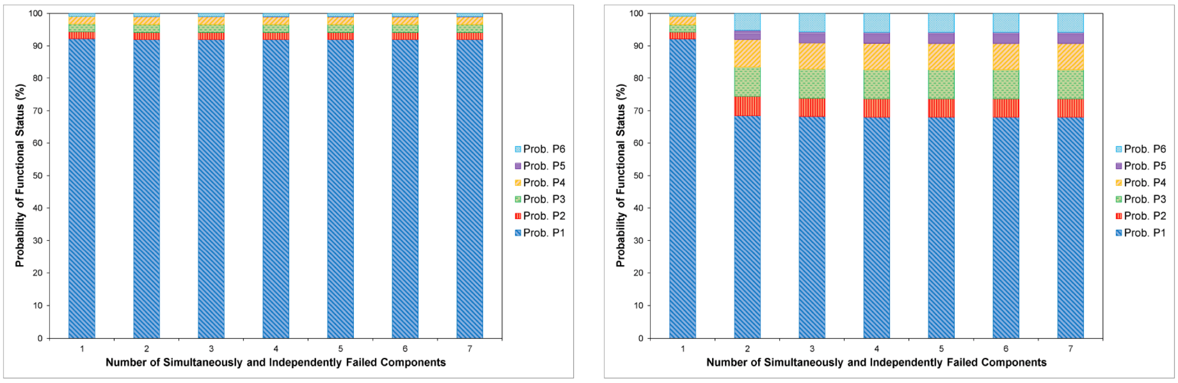
(b) Number of variables



(c) Computational performance indicators

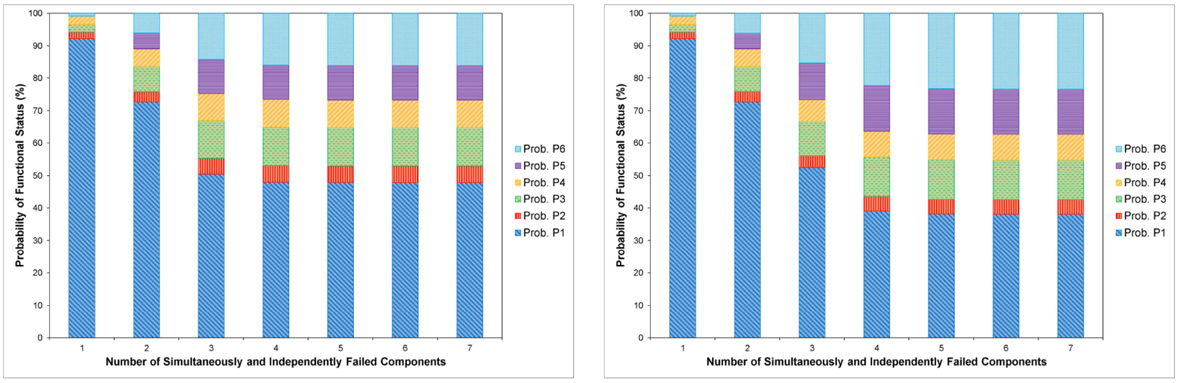
(d) Number of significant probability terms

Figure 8: Case study 2. Characteristics of the resultant mathematical problem for different $NSIFC$ and NSE values



(a) Probabilities for $NSE = 1$

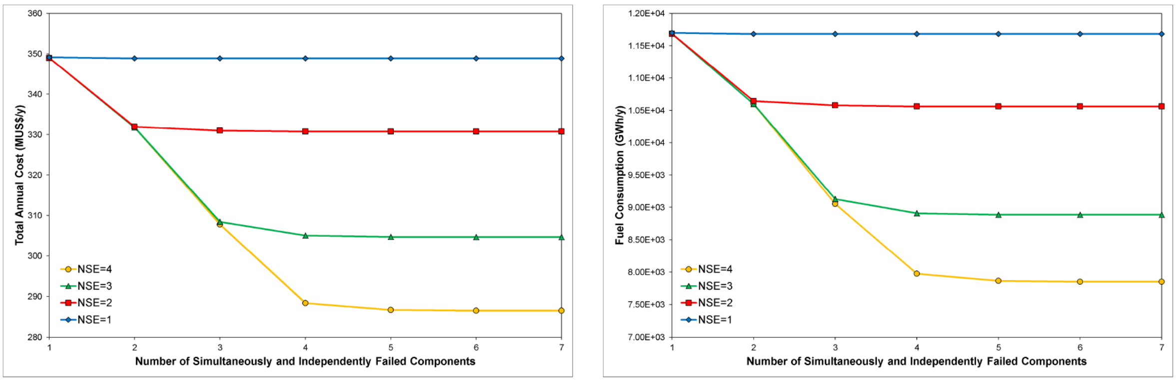
(b) Probabilities for $NSE = 2$



(c) Probabilities for $NSE = 3$

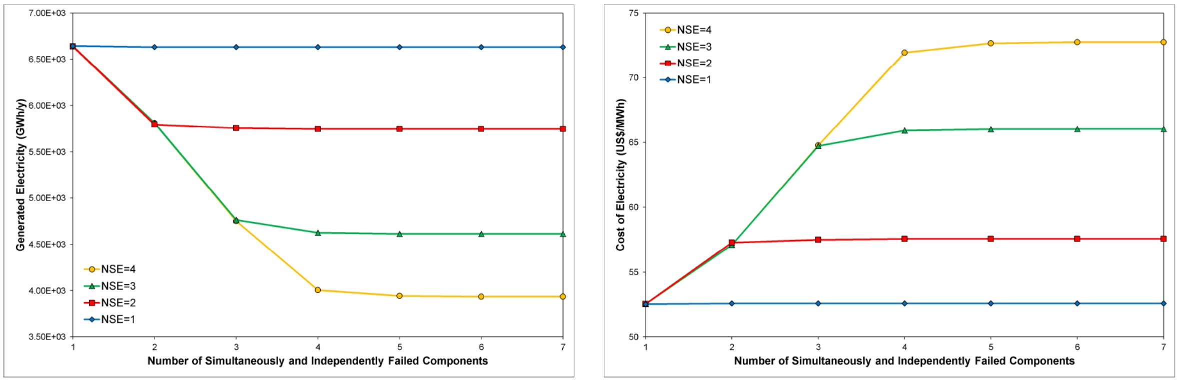
(d) Probabilities for $NSE = 4$

Figure 9: Case study 2. Probability of functional statuses for different $NSIFC$ and NSE values



(a) Total annual cost

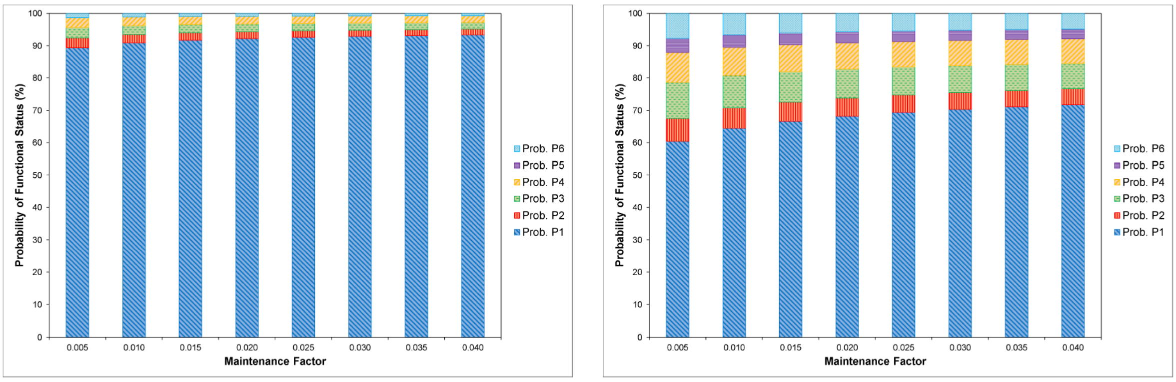
(b) Fuel consumption



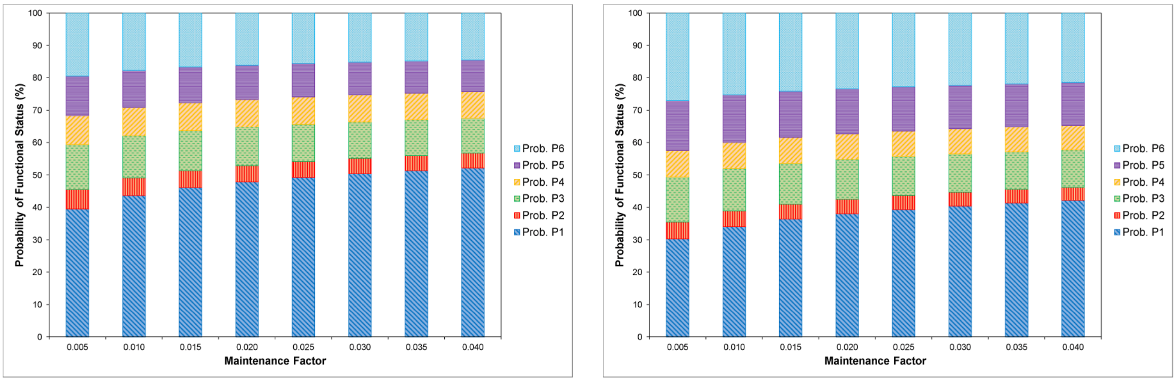
(c) Generated electricity

(d) Cost of electricity

Figure 10: Case study 2. Economic indicators for different $NSIFC$ and NSE values

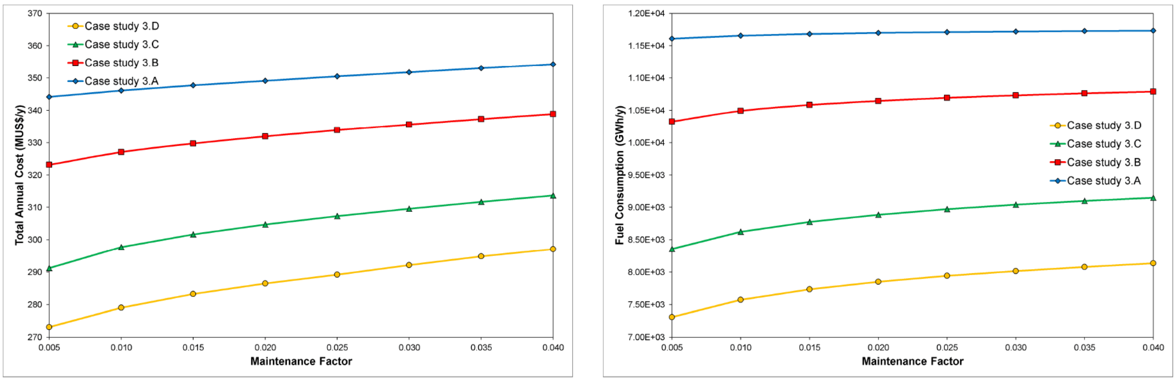


(a) Probabilities for Case study 3.A (b) Probabilities for Case study 3.B



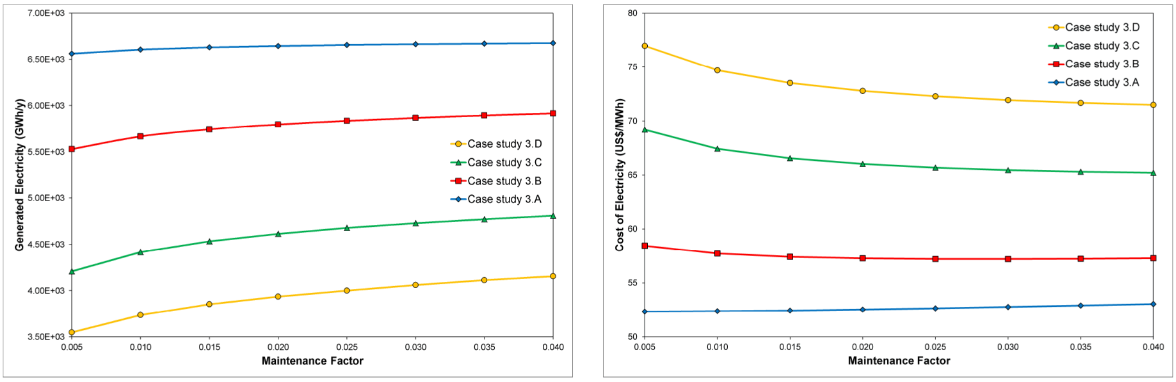
(c) Probabilities for Case study 3.C (d) Probabilities for Case study 3.D

Figure 11: Case study 3. Probability of functional statuses for different amount of resources assigned for maintenance actions



(a) Total annual cost

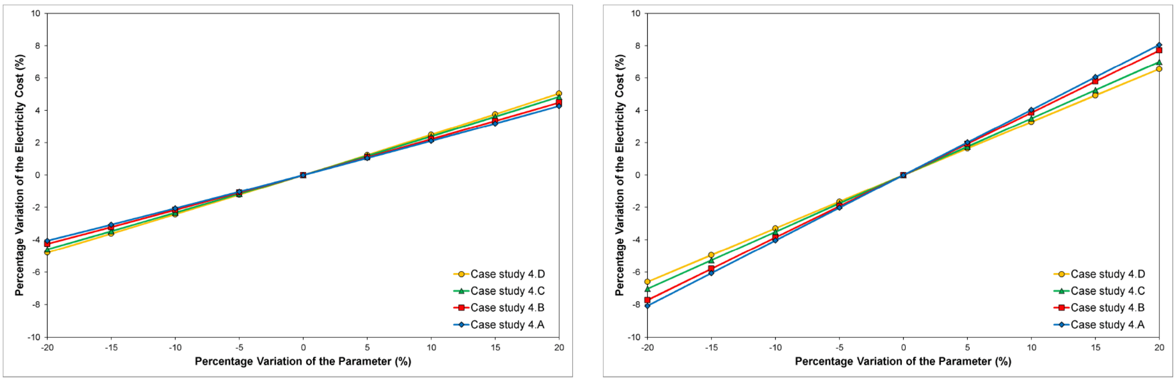
(b) Fuel consumption



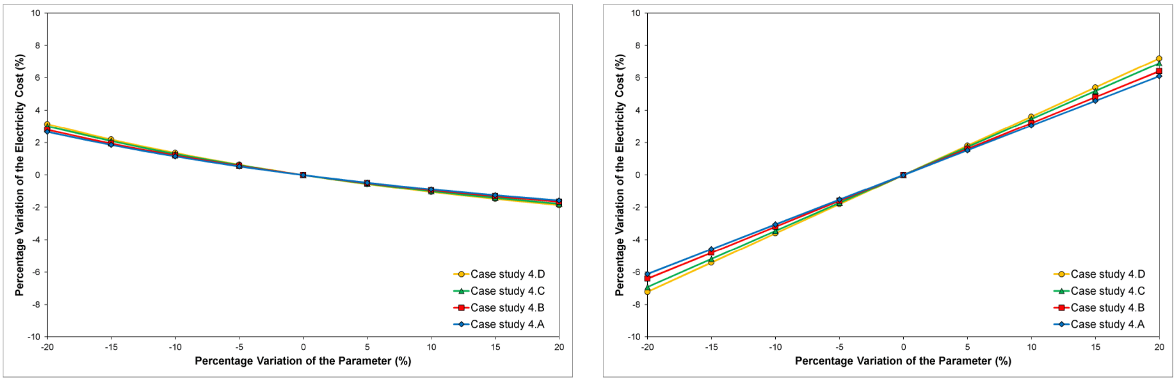
(c) Generated electricity

(d) Cost of electricity

Figure 12: Case study 3. Economic indicators for different amount of resources assigned for maintenance actions



(a) Interest rate (b) Fuel cost



(c) Life cycle length (d) Investment factor

Figure 13: Case study 3. Economic sensitivity analysis

List of Tables

Table 1: Description of case studies

	Reference plant	Case study 1	Case study 2	Case study 3
Type of mathematical problem	NLP	MINLP	MINLP	MINLP
Strategy for availability modeling	Fixed annual operating horizon	State-space approach	State-space approach	State-space approach
NSE - $NSIFC$	N/A - N/A	1 - 1	1 to 4 - 1 to 7	A: 1 - 1 B: 2 - 2 C: 3 - 5 D: 4 - 7
Assessment of maintenance funds impact	Fixed amount	Component-based policy	Component-based policy	Component-based policy
F_{Mant}	0.02	0.02	0.02	0.005 to 0.04

Table 2: Description of functional statuses for the *NGCC* power plant

Item	Description
$P1$	The power plant operates at full capacity
$P2$	Both gas turbines operate at full capacity, the steam turbine operates at half capacity
$P3$	Both gas turbines operate at open loop
$P4$	Only one gas turbine operates at full capacity, the other gas turbine is down, the steam turbine operates at half capacity
$P5$	Only one gas turbine operates at open loop, the other gas turbine and the steam turbine are down
$P6$	The power plant is down

Table 3: Relation between binary variables for each section and functional status for the power plant

Binary variable associated to each section				Power plant functional status
$GT1$	$GT2$	$ST1$	$ST2$	
1	1	1	1	$P1$
1	1	1	0	$P2$
1	1	0	1	$P2$
1	1	0	0	$P3$
1	0	1	0	$P4$
0	1	0	1	$P4$
1	0	0	0	$P5$
0	1	0	0	$P5$
0	0	0	0	$P6$

Table 4: Maintainability factor improvement rates

Item	Units	Value
Auxiliary services for the gas turbines (AS_1)	-	1.9
Gas turbine plus its associated generator (AS_2, AS_3)	-	1.5
Auxiliary services for both $HRSGs$ and the steam turbine (AS_4)	-	1.9
Steam turbine and its associated generator (AS_5)	-	1.5
Heat recovery steam generators (AS_6, AS_7)	-	1.8

Table 5: Case study 1. Probabilities of functional statuses

Functional status	Units	Value
$P1$	%	92.25
$P2$	%	2.15
$P3$	%	2.34
$P4$	%	2.39
$P6$	%	0.87

Table 6: Case study 1. Optimal economic indicators for the project

Item	Units	Reference Plant	Case Study 1
Total annual cost (TAC)	$MUS\$/y$	339.07	349.14
Operative expenditures ($OPEX$)	$MUS\$/y$	232.47	242.54
Capital expenditures ($CAPEX/CRF$)	$MUS\$/y$	106.60	106.60
Generated energy (GE)	GWh/y	531.60	541.04
Energy sales ($Sales$)	$MUS\$/y$	6.27	6.64
Cost of electricity (COE)	$US\$/MWh$	54.06	52.54

Table 7: Case study 1. Optimal design and operating variables for the power plant

	Units	Value
Power plant net generation capacity	MW	783.9
Gas turbine	MW	257.8
Steam turbine	MW	268.3
Thermal efficiency	-	0.5748
Gas turbine parameters		
Fuel flow rate	$kmol/s$	0.82
Compression ratio	-	15.8
Turbine inlet temperature	K	1560
Steam turbine flow rate		
Low pressure section	kg/s	98.3
Intermediate pressure section	kg/s	88.2
High pressure section	kg/s	68.8
HRSG exchange area		
Deaerator section	dam^2	33.06
Low pressure section	dam^2	35.80
Intermediate pressure section	dam^2	43.94
High pressure section	dam^2	80.54
HRSG operative pressure		
Deaerator section	MPa	0.152
Low pressure section	MPa	0.237
Intermediate pressure section	MPa	1.788
High pressure section	MPa	12.16
Reheater section	MPa	1.788
Utilities consumption		
Cooling water	kg/s	2847
Boiler water	kg/s	98.3

Table 8: Technical parameters

Item	Units	Value
Air	-	
Temperature	K	298
Oxygen molar fraction	%	20.59
Nitrogen molar fraction	%	77.48
Water molar fraction	%	1.93
Fuel	-	
Temperature	K	298
Pressure	MPa	4.05
Methane molar fraction	%	91.41
Ethane molar fraction	%	4.73
Propane molar fraction	%	0.83
Butane molar fraction	%	0.29
Hexane molar fraction	%	0.09
Nitrogen molar fraction	%	0.07
Oxygen molar fraction	%	0.89
Temperature of fresh process water	K	298
Cooling water inlet temperature	K	298

Table 9: Capital expenditures estimation

Equipment acquisition cost	C_{Inv}	
Installation		$0.53\ C_{Inv}$
Instrumentation and control		$0.20\ C_{Inv}$
Piping		$0.40\ C_{Inv}$
Electrical		$0.11\ C_{Inv}$
Building and services		$0.10\ C_{Inv}$
Land and yard improvements		$0.15\ C_{Inv}$
Services facilities		$0.20\ C_{Inv}$
Total direct manufacturing cost	DMC	$2.69\ C_{Inv}$
Engineering		$0.10\ DMC$
Construction expenses		$0.10\ DMC$
Contractors fee		$0.01\ DMC$
Contingencies		$0.16\ DMC$
Total indirect manufacturing cost	IMC	$0.37\ DMC$
Investment on fix capital	IFC	$DMC + IMC$
Working investment		$0.25\ IFC$
Start-up cost		$0.10\ IFC$
Capital expenditures	$CAPEX$	$1.35\ IFC = 5\ C_{Inv}$

Table 10: Equipment characteristics used for computing capital costs

Item	Type	Units	Value	Reference
Gas turbines (GT)	GE PG9351FA	$US\$/kW$	2.583 x 10^2	Nye TC (2013)
Steam turbine (ST)	3 Pressure Levels	$US\$/kW$	2.583 x 10^2	Nye TC (2013)
Generators ($HRSG$)	Horizontal, unfired	$US\$/m^2$	1.115 x 10^4	U.S. EIA (2010)

Table 11: Operating expenditures estimation

Raw material and utility	C_{RM}	
Operative manpower	C_{MP}	
Maintenance	C_{Mant}	
Local taxes		$0.02\ IFC$
Insurance		$0.01\ IFC$
Supervision and support labor		$0.30\ C_{MP}$
Laboratory charges		$0.10\ C_{MP}$
Operative supplies		$0.015\ IFC$
Plant overhead		$0.60\ C_{MP} + 0.045\ IFC$
Total production cost	PC	$C_{RM} + C_{Mant} + 2\ C_{MP} + 0.09\ IFC$
Administrative		$0.15\ C_{MP}$
Distribution and marketing		$0.015\ C_{MP}$
Research and development		$0.035\ C_{MP}$
Total additional cost	AC	$0.2\ C_{MP}$
Operative expenditures	$OPEX$	$PC + AC = C_{RM} + C_{Mant} + 2.2\ C_{MP} + 0.33\ C_{Inv}$

Table 12: Utility cost coefficients

Item	Units	a_{PS} coefficient	b_{PS} coefficient
Cooling water (CW)	$US\$/m^3$	$0.5589 + 0.0168\ X_{PS}^{1}$	0.003
Boiler water (BW)	$US\$/m^3$	$2.7945 + 0.1118\ X_{PS}^{0.6}$	0.04

Table 13: Economic parameters

Item	Units	Value
Standard operative time (POT_0)	h/y	8000
Interest rate (i)	%	8.0
Life cycle span (n)	y	25
Maintenance factor (F_{Mant})	-	0.020
Maintenance factor - minimum value ($F_{Mant,Min}$)	-	0.005
Maintenance factor - maximum value ($F_{Mant,Max}$)	-	0.040
Fuel cost (C_F)	$US\$/GJ$	3.318
Manpower equivalent factor (F_{MP})	-	$3.0\ x\ 10^5$
Manpower equivalent number (N_{MP})	-	75.75
Electricity price (P_{Elec})	$US\$/MWh$	80.00