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

E. Godoy, S.J. Benz, N.J. Scenna*

CAIMI (Centro de Aplicaciones Informáticas y Modelado en Ingeniería), Facultad Regional Rosario, Universidad Tecnológica Nacional, Rosario, Argentina[1]

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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.

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

[1] http://www.frro.utn.edu.ar/investigacion/caimi.

* Corresponding author.
E-mail addresses: ezgodoy@frro.utn.edu.ar (E. Godoy), sbenz@frro.utn.edu.ar (S.J. Benz), nscenna@santafe-conicet.gob.ar (N.J. Scenna).

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Nomenclature

Acronyms

BW	boiler water
CW	cooling water
CNF	conjunctive normal form
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

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).