*World Conference Series with Virtual Participation™:*
*2009 Interdisciplinary Conference on Chemical, Mechanical and Materials Engineering (2009 ICCMME)*
*Hosted by Australian Institute of High Energetic Materials in Melbourne, Australia*
*07-20 December 2009*

# Life cycle oriented design of a GT + 1PSH HRSG type CCGT power plant

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## **Abstract:**

In the present work, a life cycle oriented approach is used for designing power plants in a way they can satisfy the desired demand along the whole time horizon, while selected economic indicators of the project are optimized. As case study, optimal design characteristics as well as optimal values of long term operation parameters of a GT + 1PSH HRSG Type CCGT power plant (*GT*: gas turbine, *1PSH*: 1 pressure with superheater, *HSRG*: heat recovery steam generator, *CCGT*: combined cycle gas turbine) are obtained by means of a multiperiod mathematical model, seeing that the net present value of the facility is maximized. In addition, advantages of the life cycle oriented approach are discussed when compared with a power plant design obtained by traditional methods.

*Keywords: power plant, life cycle, economic optimization*

## 1. INTRODUCTION

A life cycle oriented approach, which makes decisions based on economic indicators that refer to the whole CCGT power plant life cycle, is critical under today's business conditions due to increased competition and market uncertainties, among others. Usually, a plant life cycle consists of several phases such as synthesis and design, construction, operation, and eventually disposal (Ishii et al., 1997). From the economic point of view, decisions made during the early stages of synthesis and design largely determine the economic performance of the plant across its entire life cycle. So, it becomes necessary to consider not only the capital investment and annual operative costs but also, for example, costs associated with the construction phase, start-up and shut-down periods, maintenance operations, etc.

Then, a multiperiod framework has to be used to make decisions considering dynamic changes of external conditions through time, as risks associated to unforeseeable situations will became reduced by considering future scenarios within the model. The aim of the present work is to determine characteristics of the equipment to be installed (design power of gas and steam turbines, exchange area of HRSG, etc.), and the operating conditions of the whole system (pressures, temperatures, flows, etc.) which represent the most effective way of meeting the expected demands over the entire life cycle of the facility.

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## 2. MULTIPERIOD MATHEMATICAL MODEL OF A POWER PLANT

### *2.1. Core Model of the Power Plant*

The mathematical model of the power plant is implemented in GAMS through a series of modules, as presented in Figure 1 (for further details, see Godoy et al., 2009), which comprise the main characteristics of such systems (see for example: Valdés and Rapún, 2006).

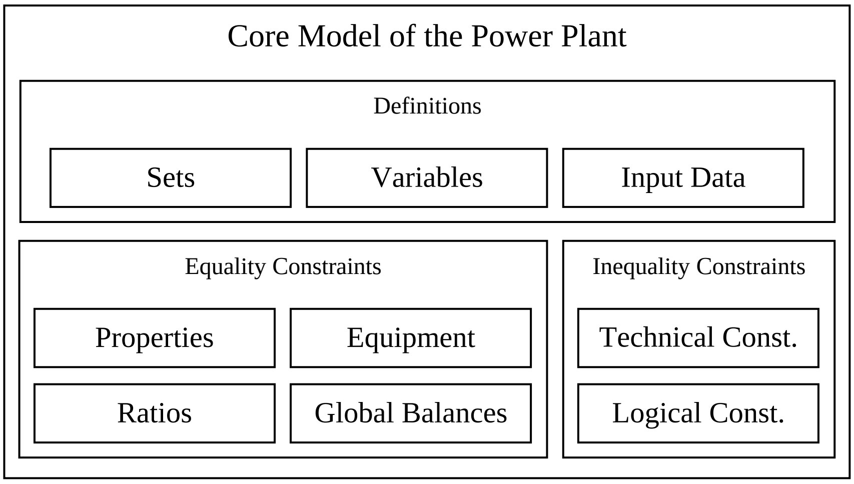

Figure 1: Modules that form the Core Model of the Power Plant

### *2.2. Multiperiod Modelling Framework*

#### *Time Periods*

The multiperiod modelling framework is defined as a set of periods *ti* which comprises the main stages of the plant life cycle (pre-operative phase, when all the construction tasks are carried out; operative phase, when the plant is operated at base and peak load; post-operative phase, when the plant is dismantled) and account for the number of years the life cycle of the plant is intended to last.

In addition, each year is divided into four seasonal sub-periods *sti*, which allow modelling the variations some variables incur because of the seasons shift (Aguilar et al., 2007). As an example, Eq. (1) models the time-dependent trend of the power demand, as the real world variability of such variable is assimilated to vary in a discrete way (it is assumed that the mean annual power demand *Wo* increases a fixed percentage *ADG* each year, while seasonal variations *Woe* are also introduced).

$$Wo_{ti} = Wo_{ti-1} \, . \left(1 + ADG\right) . \left(1 + Woe_{sti}\right) \tag{1}$$

Similarly, variability of the parameters that define the multiperiod modelling framework is also considered, including for example seasonal changes of the ambient temperature, annualized increments of electricity prices and fuel costs, and so on.

As the life cycle of the facility is intended to last up to 30 years, and since each year is divided into 4 seasons, the multiperiod modelling framework includes 120 different scenarios which need to be optimized in order to obtain the optimal value of the objective function over the whole time horizon.

### *Coupling Constraints*

A set of equality constraints is defined to couple the values of the design variables through the multiple scenarios included within the time horizon.

Transfer areas of the HRSG sections (ECO: economizer; EVA: evaporator; SH: superheater) get coupled in a way optimal values of these surfaces is selected, enabling to operate the combined cycle at its optimal performance.

Gas and steam turbines are dimensioned in a way they can deliver the desired amount of power while operating within feasible technical limits. Also, an upper limit to the design power of gas and steam turbines is in place. Although in practice discrete sets of gas and steam turbines are available, in the present model it is allowed that each turbine adopts any size below such upper bound.

## *2.3. Optimization Formulation for Life Cycle Costing*

The mathematical statement of the economic problem linked to the evaluation of the profitability of investment options, that allows selecting the project which yields optimal values of the financial indicators, here evaluated through its net present value *NPV*, is given by Eq. (2) trough Eq. (4).

$$\max_{x} NPV = \sum_{ti,sti} \frac{\left(Sales + SVFC + Dep\right)_{ti,sti} - \left(C_{Op} + IFC + IWC + NIT\right)_{ti,sti}}{\left(1 + ADR\right)^{ti}} \quad \text{: Objective Function} \qquad (2)$$

$$s.t. \quad f\left(x^{Op}_{ti,sti}\ , x^{Des}\right) = 0 \quad \text{: Equality Constraints} \qquad (3)$$

$$g\left(x^{Op}_{ti,sti}\ , x^{Des}\right) \leq 0 \quad \text{: Inequality Constraints} \qquad (4)$$

$$x^{Op}_{ti,sti}\ , x^{Des} \in \Re \quad , \quad ti = \left\{ \underbrace{1\,,2}_{Pre-Operative}\ , \underbrace{3\,,\cdots,29}_{Operative}\ , \underbrace{30}_{Post-Operative} \right\} \quad , \quad sti = \left\{ Au\,, Wi\,, Sp\,, Su \right\}$$

*NPV* of the project is the summation of discounted cash flows; i.e. it is the summation of net cash flows discounted to present value according to the annual discount rate *ADR* desired by the investor. The net cash flow of the *ti-th* year of the project life cycle is the difference between financial inputs and outputs that occur during such period, including sales of electricity *Sales*, operative costs $C_{Op}$, investment on fix capital *IFC*, investment on working capital *IWC*, salvage value of fix capital *SVFC*, depreciations *Dep*, and taxes *NIT*.

## 3. OPTIMIZATION OF A POWER PLANT: RESULTS AND DISCUSSION

Design and operation of a GT + 1PSH HRSG Type CCGT power plant are here optimized considering the life cycle approach by using the multiperiod optimization model.

One of the main obstacles in any optimization problem is finding a first feasible initialization point (Iyer and Grossmann, 1997). For a multiperiod optimization model, it is necessary to find a feasible initialization point also for the coupled periods, in particular for the coupled design variables. Thus, an optimization procedure is here applied, which allows obtaining optimal multiperiod solutions for the system, through a three step sequential strategy:

- *Step I – Finding a feasible initialization point with de-coupled periods*: a simple Linear Model (Godoy et al., 2009), constituted by mathematical correlations of single period optimal values of decision variables is used to compute feasible values of design and operative variables for each scenario included within the power plant life cycle.

- *Step II – Finding a feasible initialization point with coupled periods*: the de-coupled solution found in Step I constitutes a feasible initialization point for easily solving the multiperiod problem, when the design variables get coupled (i.e. their values get linked by technical constraints) over the whole time horizon.

- *Step III – Economic optimization of the CCGT power plant*: by addressing the net present value as objective function, a solution which yields optimal values of the project financial indicators (in each scenario that the plant faces along its whole life cycle) is found with no effort by using the coupled solution found in Step II as feasible initialization point.

Economic optimization is performed via the software GAMS, using CONOPT as NLP solver, in a personal computer with an AMD Athlon™ 64 Dual Core 4000+ 2.11 GHz processor and 1 GB DDR2 RAM memory. It can be observed that all the steps of the optimization procedure feature acceptable values of the resolution time (totalizing around 850 seconds to pass through all three steps) and the iteration count (Steps I, II and III of the optimization procedure required 438, 378 and 704 iterations, respectively), in spite of the complexity of the mathematical problem, as the number of variables and equations exceeds 15000 in all cases and many constraints are highly non-linear.

Table 1: Optimal Values of the Decision Variables

| Variable | Life Cycle Approach | Traditional Approach |
|---|---|---|
| GT Design Power (MW) | 250.9 | 196.9 |
| ST Design Power (MW) | 76.2 | 130.2 |
| Power Plant Design Power (MW) | 327.1 | 327.1 |
| Economizer Area ($m^2$) | 12241 | 22185 |
| Evaporator Area ($m^2$) | 36489 | 45702 |
| Superheater Area ($m^2$) | 3870 | 5444 |
| HRSG Exchange Area ($m^2$) | 52600 | 73331 |
| Area Distribution ECO : EVA : SH | 0.233 : 0.694 : 0.073 | 0.303 : 0.623 : 0.074 |
| Average Thermal Efficiency (%) | 52.04 | 46.70 |
| Net Present Value (M$) | 142.0 | 113.9 |

Optimal values of design variables associated to the multiperiod economic optima are reported in Table 1, including the power production distribution and the HRSG area distribution. These values are pared with the ones corresponding to the traditional approach, evidencing this way the improvements for the design and operation of power plants obtained with life cycle approach.

Traditionally, power plants are designed for the maximum value of the expected demand, or even over-dimensioned with respect to such value, trying this way to secure they will be able to fulfil the power production requirement at any feasible scenario. Then, values of obtained results by means of the traditional approach are also presented in Table 1, in order to identify improvements for the design and operation of power plants offered by the here proposed multiperiod optimization model.

The design power ratio varies from 1.51 in the traditional solution to 3.29 in the economic optima, although the total power production capacity remains the same in both solutions. The HRSG exchange area associated to the economic optima is 28.3 % lower than the one obtained for a traditional based plant design. Then, a design based on a power ratio of 3.29 with gas and steam turbines of 250.9 MW and 76.2MW, respectively, and a HRSG of 52600 m$^2$ with an economizer:evaporator:superheater area ratio of 0.233:0.694:0.073, secure the best economic performance will be accomplished along the whole time horizon while maintaining the capital investment at the lowest feasible amount.

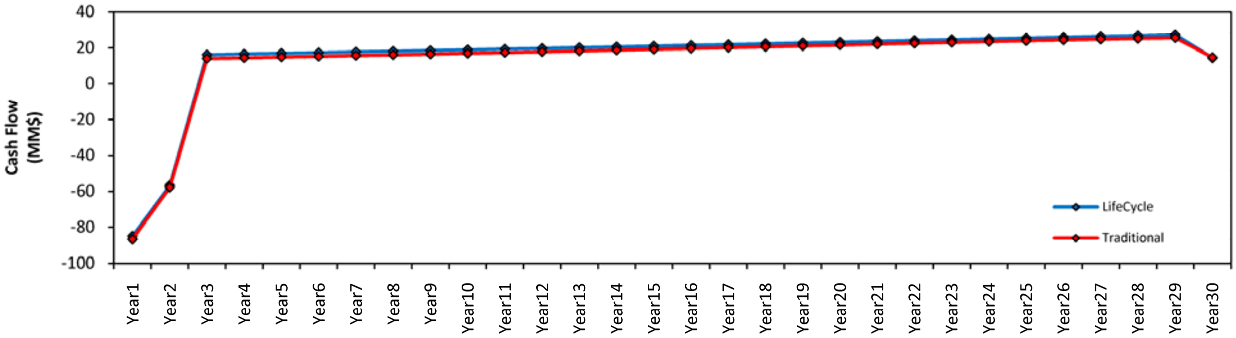

Figure 2: Cash Flows

When the economic multiperiod optimization of the power plant is performed, an optimal net present value of 142.0 M$ is obtained, as can be seen in Table 1. Since the value of the NPV corresponding to a traditional approach is 19.8 % lower, extra 28.1 M$ are gained when designing and operating the CCGT on its multiperiod economic optima.

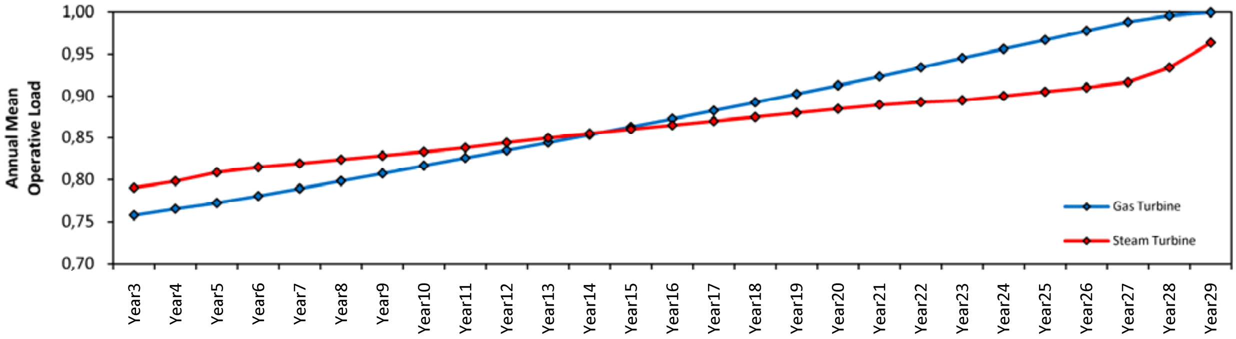

Figure 3: Gas and Steam Turbines Annual Mean Operative Loads

Cash flows within each year along the plant life cycle are presented in Figure 2. During the pre-operative phase, negative cash flows occur because of investment on fix capital as the plant is built. Across the operative phase, increasing positive cash flows are obtained while satisfying the power demand; optimal economic results let state that the cash flow increases about 2.4 % on yearly basis in the first operative years, although such percentage decreases up to 1.7 % in the last ones. Finally, in the last year of the plant life cycle, the salvage value of the fixed capital investment originates a positive cash flow as the plant is dismantled.

The optimal economic solution is also constituted by optimal values of the operative variables, including pressures, temperatures, flow rates, and so on. As example, in Figure 3, optimal profiles of (annual mean) operative loads for the gas and steam turbines is presented, which assure an optimal performance from an economic aim is achieved in each scenario that the plant faces along its whole life cycle while satisfying the predicted increase on the energy demand.

## 4. CONCLUSIONS

The design and operation of a GT + 1PSH HRSG Type CCGT power plant is here optimized to meet the expected demands over the entire life cycle of the facility, applying a long term multiperiod optimization model. This procedure constitutes a flexible tool that provides insight of the multiperiod power plant design from an economic point of view along the whole time horizon. Comparison with optimal results obtained by the traditional approach (optimization for a nominal condition) shows improvements for the design of power plants offered by the here proposed life cycle oriented approach.

In addition, a short term operative model for determining optimal operative conditions according to dynamic changes of market conditions will be also pursued in future works.

## ACKNOWLEGEMENTS

The authors gratefully acknowledge the financial support of the Agencia Nacional de Promoción Cientifica y Tecnológica (ANPCyT) and the Universidad Tecnológica Nacional (UTN) from Argentina.

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