A MODULAR SYSTEM FOR DECISION-MAKING SUPPORT IN GENERATION EXPANSION PLANNING (SUPER)

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Abstract - A computer system for generation expansion studies (SUPER) is introduced that in addition to traditional least cost plans produces minimum risk strategies in the presence of several uncertainties, for example, in demand growth. Signals are provided that allow a utility a proper evaluation of cogeneration options and proposals by IPPs (Independent Power Producers). DSM alternatives compete with more traditional supply options in conforming adequate expansion alternatives. Hydro uncertainties are properly modeled. Interconnection lines can be expansion options. Financial and environmental impacts are evaluated and reported.

SUPER has a modular structure, a relational data base and a Graphic User Interface (GUI). Extensive experience exists using **SUPER** in generation expansion studies for all types of power systems.

1.0 INTRODUCTION

Most of existing generation expansion planning programs provide least-cost plans for predominantly thermal systems for what is perceived as the most likely evolution of variables such as demand growth, fuel, and construction costs and schedules. A limited sensitivity analysis is performed afterwards to check that the results remain valid for realizations of the random variables other than expected. In most cases, however, only minor deviations of forecast values are considered and no insights are provided for decision making or further analysis.

Historical developments in the past two decades have rendered inadequate most of existing planning tools, especially for developing countries. Among relevant events we have the oil crises of the seventies, the debt crises of the eighties, demand forecast errors that resulted in excess capacity, and inappropriately low rates that didn't allow utilities to recover their costs and thus strained their financial health. To these factors we should add more recent moves toward privatization and enhanced environmental awareness.

Planning models should then be able to assess the impacts of uncertainties in demand growth, fuel costs and in construction costs and schedules of large projects. Solely minimizing costs for the most likely realization of uncertain parameters without considering risk, does not provide adequate bases for decision-making. Financial constraints should be accounted for, even if this means deviating from the least cost plan. Demand Side Management (DSM) options, interconnections, cogeneration and sales by Independent Power Producers (IPPs) should be economically assessed as valid expansion alternatives. The models should provide simulation capability and produce signals like marginal costs and marginal benefits, useful in determining rates and in evaluating individual projects within an expansion plan. The environmental impact of plans and projects should be estimated at planning time, to determine their viability and any increase in their cost resulting from mitigation measures.

Note: Marginal costs are the increase in operation cost due to a marginal increase in demand. Marginal benefits (or operation gradients) of a given thermal project or interconnection line are defined as the savings in operation costs obtained by adding a unit (kW) of the thermal project or by increasing in one unit the capacity of the interconnection line.

The presence of an important hydro component in a generation mix with significant regulation capability makes operation (and, therefore, generation expansion) decisions dependent on present and future system configuration ([1] and [2]) and introduces the need to account for hydro uncertainties. Not properly modeling the hydro component can produce seriously under (or over) equipped expansion plans.

To provide adequate support in decision making, therefore, a planning tool is needed that has the following characteristics: (i) Accurate modeling of hydro uncertainties, particularly when large, multi-annual regulation reservoirs are present or are considered as expansion options; (ii) Ability to produce expansion strategies that minimize risk in the presence of uncertainties in variables such as demand growth, fuel costs and construction costs and schedules; (iii) Consideration of DSM options (conservation and load management, for example) as alternatives to building additional capacity; (iv) Evaluation of the convenience of interconnections, cogeneration and power purchases from IPPs; (v) Production of marginal costs and marginal benefits of projects and of interconnections; (vi) Analysis of the financial viability of the expansion plan and (vii) Information on environmental impacts and on ways and costs in mitigating them.

This tool (later called **SUPER**) was initially conceptualized by J. Millán, R. Campo and G. Sánchez-Sierra in the mid eighties. A happy coincidence made it possible for these professionals to promote, support and organize its development in the period 1990-1993 by the team of consultants described in the Acknowledgments, where the contribution of each consultant to the final product is indicated. The project was executed under the umbrella of the Latin American Energy Organization (OLADE) with the sponsorship of the Inter American Development Bank (IDB).

SUPER is a modular system and offers the possibility of adding or replacing modules by others that better fit the needs of the particular utility. It is installed in a user-friendly, Windows-based environment. The modules were adapted from programs being used by utilities in OLADE member countries (for example, MSSSE in Brazil, **WASP III**, Financial program in Ecuador, Hydrological Models and Environmental Impacts Program in Colombia, etc.). This fact contributed to lower development cost and time and ensured the usefulness of the final product.

2.0 DESCRIPTION OF SUPER

Figure 1 presents in four levels the modules that make up **SUPER.** Each level provides information to lower levels. Multiple feedbacks are present between levels.

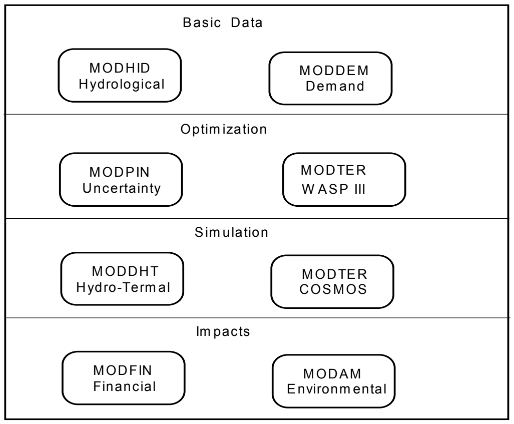

Fig. 1

2.1 Level 1 modules include Demand and Conservation (**DEM**) and Hydrology (**HID**). On the basis of historical hourly demands of up to five years, **DEM** produces demand models to be used by other modules, including Load Duration Curves (LDCs) given as staircases and as fifth degree polynomials and hourly load models. Visual and statistical tests are provided of input data. A pre dispatch is made of generation options like isolated hydro run-of-river, solar, wind, power purchases and sales contracts and cogeneration. An economic evaluation is made of DSM options. Time-of-day marginal energy costs provided by the dispatch (level 3) modules and capacity marginal costs (given as input data) are used to quantify energy and capacity savings of the DSM option. Costs of these alternatives refer to investment and to operating and administrative expenses. A cost-benefit analysis is made of each DSM program, using a variety of economic indicators, for example, present value, benefit-cost ratio, internal rate of return and repayment period. **DEM** accounts for environmental benefits and costs, penetration rates and degradation with time of the DSM option. Graphs are obtained like the one in Figure 2, that indicates up to what levels of system energy marginal costs a given DSM option is competitive. For example, Program 3 (that produces 50 GWH of savings) is economic if the system marginal cost is above 48 US$/MWH.

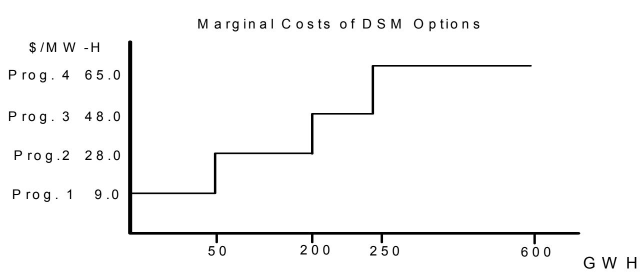

Fig. 2

HID includes four basic functions: (i) Reconstruction of natural inflows for each project site, discounting the effects of system operation and accounting for evaporation and consumptive uses of water; (ii) Filling-in of the historical record of inflows, using available data of all existing posts. A data base of inflows is obtained for all hydro posts that spans the same period of time, using a Kalman filter algorithm. (iii) Operation simulation of the hydro-electric system, maximizing firm hydro energy production and accounting for demand seasonalities. In this way the monthly generation (GWh) and the capacity (MW) of each hydro project for up to five hydro-conditions are produced as required by the **WASP III** component of the Thermal module. Additionally, sequences of available hydro energy of any desired duration and probability of occurrence are calculated, as needed by the expansion module **PIN.** The operation simulation is based on a heuristic algorithm that prevents reservoir depletion, minimizes spillage and avoids trapping water in the largest reservoirs. As an example of the type of outputs produced by HID, a graph of available annual hydroelectric energies is provided in Figure 3, for each historical year of inflows. (iv) Lastly, HID generates of synthetic inflows to be used in dispatch simulations. A mathematical model (Matalas model) is used for inflows that preserves lag one time and spatial correlations ([3], [4] and [5]).

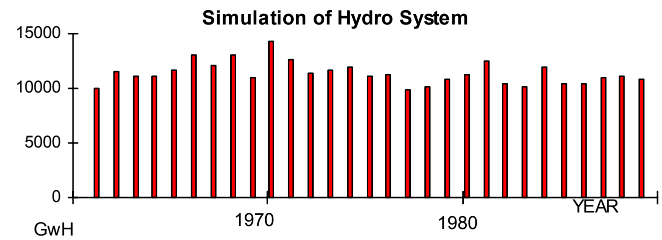

Fig. 3

2.2 There are two level two modules: **PIN** (Planning Under Uncertainty) and **TER** (Thermal). The first is used for predominantly hydro systems and the second one for predominantly thermal systems. **PIN** uses a novel formulation that produces minimum risk strategies, as opposed to least cost plans and makes use of advanced decomposition solution algorithms. Strategies emulate the way planners make decisions, by adapting them as uncertainties unfold. Uncertainties in demand as well as in fuel costs and construction costs and schedules of projects can be explicitly modeled by a decision tree and strategies that minimize the maximum regret (Savage criterion) are provided for each decision node. **PIN** includes a financial formulation that penalizes with higher interest rates loans needed to finance the expansion plan beyond a certain threshold. **PIN** uses an accurate dispatch algorithm based on Stochastic Dual Dynamic Programming (SDDP) (see [6]), that properly accounts for hydro uncertainties, allows an individual representation of the reservoirs and thus avoids the "local feedback problem" of well known successive approximation algorithms (see [7]) and requires reasonable CPU time. As a faster but less accurate alternative, **PIN** has the option to utilize up to five hydro sequences with given probabilities of occurrence. Interconnections are modeled as expansion planning options. Detailed formulation and solution algorithm are found in [1]. The first phase of **PIN** produces tradicional least cost plans. Based on them, the second phase generates minimum risk strategies. (See [8]).

TER includes two sub modules. One of them is the well known **WASP** III (Wien Automatic System Planning) software package ([9]). The second was developed for small thermal systems for which unit size is large compared to demand and, therefore, no Fourier series approximation of the LDC can be used, as required by **WASP.** A direct convolution dispatch algorithm is utilized instead, that like **WASP**'s **MERSIM** program, accounts for uncertainties related to unit forced outages.

2.3 Two dispatch simulation modules are part of **SUPER.** One of them (**DHT**) was developed for predominantly hydro systems and allows modeling of interconnections. The optimal dispatch of each interconnected region is first determined using stochastic dynamic programming with two state variables: energy contents of the equivalent reservoir of each region ([4]) and hydrology tendency, as quantified by the total (energy) natural hydro inflow of the previous period (month). Optimal interchanges are then calculated from regions with lower to regions with higher marginal costs for each hourly period modeled, without exceeding the capacities of interconnection lines. The demand of each region is next increased or decreased to account for its exports or imports. Iterations are performed as needed, until the (expected) total dispatch cost does not change beyond a given tolerance from one iteration to the next. A simulation phase follows that uses either historical or synthetic inflows and calculates useful statistics, including hour-of-day marginal costs and marginal benefits (operation gradients) of thermal projects and of interconnection lines, that can be used to adjust the expansion plan. Energy and capacity reliability indicators are provided, to assess the adequability of the expansion plan. When deciding on optimal operation policies for a region with a given energy state, the corresponding total energy of the region is accounted for, so as to reduce the impact of "local feedback" ([1] and [7]).

The other simulation dispatch module (COSMOS) is used for mainly thermal systems. It is based on the MERSIM module of **WASP** and, for small thermal systems, on a direct convolution algorithm. As in **DHT**, operation gradients and time-of-day marginal costs are calculated.

2.4 The two modules at level 4 measure the impacts of the expansion plan: financial (**FIN**) and environmental (**AMB**). **FIN** does an integrated financial analysis of the utility, including the expansion plan. It produces the following basic statements of accounts: (i) Operational Results, (ii) Sources and Applications of funds and (iii) Balance sheets. It also calculates debt service and asset revalorization and provides cash flows and managerial and financial performance indicators. As options, current or constant money can be used, as well as local and foreign currency.

AMB permits an environmental assessment of individual projects or of expansion plans. It builds an additive multiobjective function formulated to: (i) Minimize the impact on the physical environment; (ii) Minimize the impact on the biological environment; (ii) Minimize displaced population; (iii) Minimize regional costs and (iv) Maximize regional benefits. The preference structure of decision makers is reflected in the weights assigned to the objectives. Combinations of values of specific variables measure each of the objectives. For example, the following variables make up the first objective (impact on the physical environment): stability in the project zone, inflow reduction in the project basin, inflow increase in the receiving basin, water quality and air quality. Projects are prioritized according to their environmental impact. Information is provided on how to mitigate these impacts. (See [10] and [11]).

3.0 SOFTWARE DEVELOPMENT ASPECTS

Since the modules of **SUPER** were developed by part time consultants working in several countries and the budget for traveling and phone and mail communications was very limited, the following decisions were made with respect to software development strategy:

3.1 An Integration team made up of one senior and two junior analysts was set up in the project base at OLADE headquarters in Quito, Ecuador, with responsibility for communication among modules and data-base and MMI (Man-Machine Interface) development.

3.2 From the beginning, there was continuous emphasis on interfaces: the first document produced after the Functional Requirements was an Integration document detailing the interfaces among modules as perceived at the beginning of the project. This document was frequently updated and circulated among the professionals in charge of module development (Module Chiefs).

3.3 Rapid prototyping. A prototype was ready after about five months of work and was circulated among potential users, who provided valuable suggestions. Early versions of documents describing mathematical formulation and solution approaches of all modules were also circulated as soon as they were ready.

3.4 As much as possible, standard commercial software was used: Microsoft Windows and Visual Basic for MMI and off-the-shelf software packages for communication between the MMI, the data base and the applications.

The final product works in a menu-driven, windows environment in which the modules share a relational data base. Extensive use is made of graphical outputs. Reports of several levels of detail are produced by each module for different users, including summary (executive) reports for decision makers. On-line helps illustrate usage of the program and clarify concepts. Detailed consistency checks are performed upon inputting data and error messages are generated as needed.

4.0 EXAMPLES OF USE

The modules of **SUPER** can be used separately or in tandem, according to the objectives of the study. As an illustration, we include partial results of a study made for a utility that has a predominantly hydro system with no multiannual regulation. A reference expansion plan was to be obtained accounting for uncertainties. Based on experience, demand was considered the most important source of risk and forecasts were prepared for two demand scenarios (high and low).

DEM was used first to obtain a fifth degree polynomial and a staircase representations of the LDC, as required by **WASP** and **DHT**, respectively. With the help of **HID**, a common data base was then produced of the historical record of natural inflows for all hydro stations, spanning the period 1957 to 1988. Using the common data base, **HID** performed a simulation of the hydroelectric system to obtain monthly generations (GWh) and capacities (MW) available from each hydroelectric project, for three hydro-conditions, as required by **WASP**. **HID** also obtained three sequences of hydro energies, each with a given probability of occurrence for use by **PIN**. (The probabilities in this case apply to maximum energy production of the hydro-electric system, for a given realization of a sequence of historical inflows. For example, a 30-year sequence that begins in 1985 and wraps around until 1982 is a "dry" one, with .20 probability of occurrence. For this application the SDDP based dispatch was under development and, therefore, could not be used.)

PIN was run next to obtain an (approximate, due to the fact that a simplified dispatch was used) minimum risk expansion strategy under demand uncertainty. The results are provided in Table 1, from which it can be concluded that a hydro-based expansion is preferred and that interesting thermal alternatives for this utility include Low Speed Diesel generators and aeroderivative gas turbines, with and without STIG cycle. With this information, **WASP** was used to obtain several candidate plans under different assumptions regarding the date of introduction to the system of the first major hydro project. The order of incorporation of hydro projects that is required as an input by **WASP** was the one obtained by **PIN**.

Dispatch of the plans produced by **WASP** was analyzed with the help of **DHT**. Some thermal reinforcements were required in certain years to ensure adequate reliability. The type of reinforcement was decided by choosing the thermal project with the highest positive difference between its marginal benefit (operation gradient) and the cost of anticipating 1 kW. **WASP** was then used to check whether it was possible to find more economical plans, based on the reinforcements introduced. An iterative procedure followed that at the end produced least cost reliable plans for several dates of introduction of the first major hydro project, for both the high and the low demand scenarios. Table 2 shows the results. Table 3 was prepared next, containing the regrets for each demand scenario, equal to the difference between the cost corresponding to each decision and the least cost for this scenario. Using Savage criterion, the decision adopted for incorporation of Esthid was 1999, corresponding to the minimum of the maximum regrets.

MINIMUM RISK STRATEGY

1993		
1994		
1995		
1996		
1997		
1998		
1999		
2000		
2001	ESTHID	ESTHID
2002	GUAHID	GUAHID
2003		
2004		
2005		BARHID
2006		
2007		CHANHID
2008	BARHID	
2009		L. SP. DSL
2010		GAS T. L. SP. DSL
2011	CHANHID	
2012		
	AVER. DEMAND SCENAR.	HIGH DEMAND SCENARIO

Table 1

RISK ANALYSIS
SAVAGE CRITERION

COSTS OF PLANS WITH ESTHID IN SEVERAL YEARS

	1999	**2000**	**2001**	**2002**	**2003**
Average Demand	660.3	654.2	655.2	663.3	664.8
High Demand	886.3	896.9	901.4	907.8	916.3

Table 2

REGRETS

	1999	**2000**	**2001**	**2002**	**2003**
Average Demand	6.1	0	1	9.1	10.6
High Demand	0	10.6	15.1	21.5	30
Max Regrets	6.1	10.6	15.1	21.5	30

Table 3

Environmental and financial impacts of the plans obtained above were determined to be acceptable by level 4 modules. The financial analysis proved to be very useful, since it determined the level of new debt needed to finance the expansion, together with acceptable rates to ensure the financial health of the utility. To this end the marginal costs of generation were used, as obtained by **DHT** and displayed in Figure 4.

SUPER was utilized to assess the adequability of an interconnection proposed for six countries. Marginal benefits of two of the interconnections as produced by **SUPER** appear in Figure 5. It can be seen that interconnection C5-C6 is under utilized for several years, which suggests the possibility of reducing its capacity. Interconnections C1-C2 and C2-C3 however, present large marginal benefits for some years, for instance starting in 1997, with very large marginal benefits in 2000 and 2001, which suggests the convenience of anticipating this reinforcement planned for 2003.

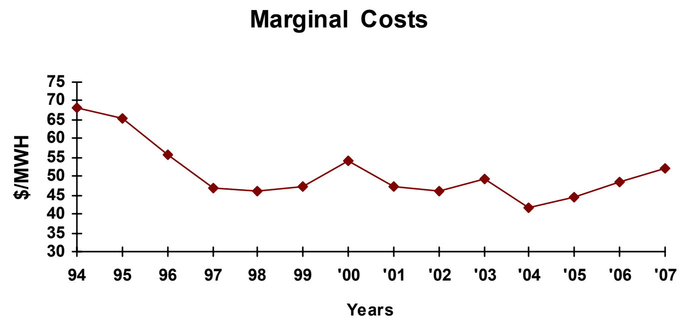

Fig. 4

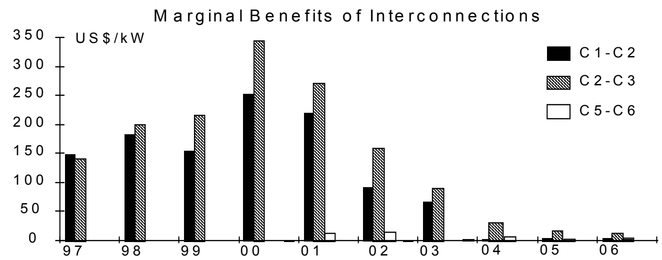

Fig.5

For country C with a rich mixture of available energy sources a minimum risk strategy was obtained that accounted for uncertainties in demand growth (represented by two scenarios), natural gas costs and construction periods of large hydro candidates. The minimum risk strategy of Table 4 was obtained, that utilizes resources of every type (gas, hydro and coal). Due to uncertainties in construction periods, some large hydro projects that appear in the least cost plan for the high demand scenario are not included in the minimum risk strategy. Due to uncertainties in the cost of natural gas, some combined cycle projects of the least cost plan are replaced by coal plants in the minimum risk strategy. To protect against the risk of having the high demand, the strategy for the low demand scenario includes additional projects to the ones that appear in the least cost plan for the same demand scenario.

Table 4 provides for each year and demand scenario the decision that minimizes risk (Savage criterion) from there on under uncertainties in demand, fuel costs and project construction periods.

MINIMUM RISK STRATEGY FOR COUNTRY C

1994		
1999		COMB_CYC150 COMB_CYC150
2001	HYDRO131 COMB_CYC150	COAL150
2002	COMB_CYC300 COMB_CYC150	COMB_CYC150
2003		
2004		
	AVER. DEMAND SCENAR.	**HIGH DEMAND SCENARIO**

Table 4

Several applications to date have been made of **SUPER**, including expansion planning in Brazil (a large, predominantly hydro system with several multi-annual regulation reservoirs, consisting of five interconnected regions) and in Jamaica (a predominantly thermal system, interested in assessing the cost-benefit of several demand side options). In all these cases **SUPER** has proved to be a useful and flexible tool.

CONCLUSIONS

As a decision-making support system for generation expansion studies, **SUPER** has the following desirable characteristics: (i) Produces minimum risk strategies under demand growth and other uncertainties; (ii) Provides accurate modeling of hydro uncertainties; (iii) Models interconnections as expansion options; (iv) Produces least cost plans and simulates the operation of alternative plans; (iv) Performs economic evaluation of demand side options, as alternatives to generation expansion; (v) Provides appropriate signals to assess the convenience of proposals by cogenerators and IPPs and (vi) Evaluates financial and environmental impacts of expansion plans. **SUPER** is a set of integrated tools that share a common relational data base in a user friendly environment. Its modular nature allows for adaptation and growth.

A variety of studies for all types of power systems (from predominantly hydro with large regulating reservoirs and interconnections to single region predominantly thermal systems) have proved its validity and usefulness.

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