

INTRODUCTION TO THE WASP-IV MODEL

1. BACKGROUND INFORMATION

The Wien Automatic System Planning Package (WASP) was originally developed by the Tennessee Valley Authority (TVA) and Oak Ridge National Laboratory (ORNL) of the United States of America to meet the needs of the IAEA's Market Survey for Nuclear Power in Developing Countries conducted by the Agency in 1972-1973^[1, 2].

Based on the experience gained in using the program, many improvements were made to the computer code by IAEA Staff, which led in 1976 to the WASP-II version. Later, the needs of the United Nations Economic Commission for Latin America (ECLA) to study the interconnection of the electrical grids of the six Central American countries, where a large potential of hydroelectric resources is available, led to a joint ECLA/IAEA effort from 1978 to 1980 to develop the WASP-III version^[3].

The WASP-III version has been distributed to several Member States for use in electric expansion analysis. In addition, other computer models have been added to the IAEA's catalogue of planning methodologies to complement the WASP analysis. Firstly, in 1981, the Model for Analysis of Energy Demand (MAED) was developed in order to allow the determination of electricity demand, consistently with the overall requirements for final energy, and thus, to provide a more adequate forecast of electricity needs to be considered in the WASP study^[4]. Later in 1992, the VALORAGUA model for determination of the optimal operating strategy for mixed hydro-thermal power systems was completed as a means of improving the determination of the characteristics of hydroelectric power stations to be fed into WASP^[5]. Microcomputers (PC) versions of WASP-III and MAED have also been developed as stand alone programs^[6, 7] and as part of an integrated package for energy and electricity planning called ENPEP (Energy and Power Evaluation Program)^[8]. A PC version of the VALORAGUA model has also been completed in 1992^[9]. More recently, following the recommendations of an IAEA Advisory Group on WASP Experience in Member States convened in 1990 and 1991, additional enhancements were incorporated in the WASP model, further increasing its capabilities for modelling additional aspects of electricity generation system, handling larger number of fuel types, adding flexibility to capital cost distribution during construction period and for generating additional information. This version has been called WASP-III Plus, and has been released to interested Member States.

With all these improvements, the WASP model has been enhanced to facilitate the work by electricity planners and is currently accepted as a powerful tool for electric system expansion planning. Nevertheless, experienced users of the program have indicated the need to introduce more enhancements within the WASP model in order to cope with the problems constantly faced by the planners owing to the increasing complexity of the system particularly with emerging environmental and other issues.

The inter-agency international symposium on Electricity and the Environment, Helsinki, 1991^[10], also recommended incorporation of environmental and health impacts of electricity sector into comparative assessment of various electricity generation options for making realistic evaluation of different strategies for future development of the sector.

In order to meet the needs of electricity planners and following the recommendations of Helsinki symposium, development of a new version of WASP was initiated in 1992 with cooperation of some member states (Hungary and Greece). Advisory Group and Consultancy meetings on the subject convened during 1992-1996 focused on identifying necessary enhancements to the model and suggesting appropriate methodological approaches to address new issues. The new version of the model with a number of new features has been completed and named as WASP-IV.

Like its predecessor, WASP-IV is designed to find the economically optimal generation expansion policy for an electric utility system within user-specified constraints. It utilizes probabilistic estimation of system -production costs, -unserved energy cost, and -reliability, linear programming technique for determining optimal dispatch policy satisfying exogenous constraints on environmental emissions, fuel availability and electricity generation by some plants, and the dynamic method of optimization for comparing the costs of alternative system expansion policies.

The modular structure of WASP-IV permits the user to monitor intermediate results, avoiding waste of large amounts of computer time due to input data errors. It operates under DOS environment and uses magnetic disc files to save information from iteration to iteration, thus avoiding repetition of calculations that have been previously done.

The new features and enhancements incorporated in WASP-IV are:

- *Option for introducing constraints on environmental emissions, fuel usage and energy generation:* WASP-IV allows user to introduce limits on environmental emissions (up to 2 types of pollutants) by a set of plants; on fuel usage by a set of plants; and/or on energy generation by a set of plants. These constraints are handled by multiple group-limitation technique wherein a group of plants may take role in a constraint and some plants can be involved in more than one type of constraints. Linear programming method is employed to determine an optimal policy for dispatch of plants satisfying these constraints. This option can be extremely useful for real life planning in view of increasing importance of environmental concerns as well as due to the fact that in many cases availability of some fuels for power generation may be limited or energy generation from some plants may be limited.
- *Representation of pumped storage plants:* Such an option was available in WASP-II but was taken out in WASP-III to accommodate more flexibility for hydro plants representation. However, in view of increasing importance of pumped storage plants and other energy storage technologies under development (e.g. large batteries or compressed air storage systems) this option has been included in WASP-IV.
- *Fixed maintenance schedule:* Due to some practical considerations the user may like to specify a certain schedule for annual maintenance of some of the plants in the system. WASP-IV allows for this option.
- *Environmental emission calculations:* WASP-IV calculates environmental emissions from electricity generation, for each year and for each period within a year, based on estimates of electricity generated by each plant and the user specified characteristics of fuels used.

- *Expanded dimensions* for handling up to 90 types of plants and larger number of configurations (up to 500 per year and up to 5000 for the study period).

2. METHODOLOGY OF THE WASP-IV MODEL

2.1. Formulation of the Problem

The WASP-IV code permits finding the optimal expansion plan for a power generating system over a period of up to thirty years, within constraints given by the planner. The optimum is evaluated in terms of minimum discounted total costs. A simplified description of the model follows.

Each possible sequence of power units added to the system (expansion plan or expansion policy) meeting the constraints is evaluated by means of a cost function (the objective function) that is composed of:

- Capital investment costs (I)
- Salvage value of investment costs (S)
- Fuel costs (F)
- Fuel inventory costs (L)
- Non-fuel operation and maintenance costs (M)
- Cost of the energy not served (O)

The cost function to be evaluated by WASP can be represented by the following expression:

$$B_j = \sum_{t=1}^T [\overline{I_{j,t}} - \overline{S_{j,t}} + \overline{F_{j,t}} + \overline{L_{j,t}} + \overline{M_{j,t}} + \overline{O_{j,t}}] \quad (1.1)$$

where:

- B_j is the **objective function** attached to the expansion plan j ,
- t is the time in years (1, 2, ..., T),
- T is the length of the study period (total number of years), and
- the bar over the symbols has the meaning of discounted values to a reference date at a given discount rate i .

The optimal expansion plan is defined by:

$$\text{Minimum } B_j \text{ among all } j \quad (1.2)$$

A minimum cost criterion does not in and of itself capture robustness. Recall that robustness is a very important part of the MISO plan.

The WASP analysis requires as a starting point the determination of alternative expansion policies for the power system. If $[K_t]$ is a vector containing the number of all generating units which are in operation in year t for a given expansion plan, then $[K_t]$ must satisfy the following relationship:

$$[K_t] = [K_{t-1}] + [A_t] - [R_t] + [U_t] \quad (1.3)$$

where:

- $[A_t]$ = vector of committed additions of units in year t ,
- $[R_t]$ = vector of committed retirements of units in year t ,
- $[U_t]$ = vector of candidate generating units added to the system in year t , $[U_t] \geq [0]$

Seems to be a 1x1 "vector" given it gives "the number". Regardless, the point is clear: this year's units must be last year's units plus certain additions less certain retirements, plus number of candidate units added.

$[A_t]$ and $[R_t]$ are given data, and $[U_t]$ is the unknown variable to be determined; the latter is called the system configuration vector or, simply, the system configuration.

Defining the critical period (p) as the period of the year for which the difference between the corresponding available generating capacity and the peak demand has the smallest value, and if $P(K_{t,p})$ is the installed capacity of the system in the critical period of year t , the following constraints should be met by every acceptable configuration:

$$(1 + a_t)D_{tp} \geq P(K_{tp}) \geq (1 + b_t)D_{tp} \quad (1.4)$$

Reserve margin for every period. Periods are modeled monthly.

which simply states that the installed capacity in the critical period must lie between the given maximum and minimum reserve margins, a_t and b_t respectively, above the peak demand D_{tp} in the critical period of the year.

The reliability of the system configuration is evaluated by WASP in terms of the Loss-of-Load Probability index (LOLP). This index is calculated in WASP for each period of the year and each hydro-condition defined. The LOLP of each period is determined as the sum of LOLP's for each hydro-condition (in the same period) weighted by the hydro-condition probabilities, and the average annual LOLP as the sum of the period LOLP's divided by the number of periods.

If $LOLP(K_{t,a})$ and $LOLP(K_{t,i})$ are the annual and the period's LOLP's, respectively, every acceptable configuration must respect the following constraints:

$$LOLP(K_{t,a}) \leq C_{t,a} \quad (1.5)$$

$$LOLP(K_{t,i}) \leq C_{t,p} \quad (\text{for all periods}) \quad (1.6)$$

where $C_{t,a}$ and $C_{t,p}$ are limiting values given as input data by the user.

If an expansion plan contains system configurations for which the annual energy demand E_t is greater than the expected annual generation G_t of all units existing in the configuration for the corresponding year t , the total costs of the plan should be penalized by the resulting cost of the energy

not served. Obviously, this cost is a function of the amount of energy not served N_t , which can be calculated as:

$$N_t = E_t - G_t \quad (1.7)$$

The user may also impose tunnel constraints on the configuration vector $[U_t]$ so that every acceptable configuration must respect:

Tunnel constraints:
To force a certain number of units to be built in year t.

$$[U_t^0] \leq [U_t] \leq [U_t^0] + [\Delta U_t] \quad (1.8)$$

where $[U_t^0]$ is the smallest value permitted to the configuration vector $[U_t]$ and $[\Delta U_t]$ is the tunnel constraint or tunnel width.

The generation by each plant for each period of the year is estimated based on an optimal dispatch policy which, in turn, is dependent on availability of the plants/units, maintenance requirements, spinning reserves requirements and any exogenous constraints imposed by the user on environmental emissions, fuel availability and/or generation by some plants. The user may impose constraints on environmental emissions, fuel usage and energy generation for a set of power plants through the new feature introduced in this version, i.e. through multiple group-limitations. Such constraints take the form:

$$\sum_{i \in I_j} COEF_{ij} \cdot G_i \leq LIMIT_j \quad \text{for } j = 1, \dots, M \quad (1.9)$$

where G_i is generation by plant i , $COEF_{ij}$ is per unit emission (for emission constraints) or per unit fuel usage (for fuel availability constraint), etc by plant i in group limitation j , $LIMIT_j$ is the user specified value for the limit and I_j is the set of plants taking role in group limitation j . These special constraints are handled by a new algorithm incorporated in WASP-IV, which determines dispatch of plants in such a way that these constraints are respected with minimum production cost.

WASP-IV uses prob. production costing, LP (dispatch), and DP (to decide). Tunnel constraints are handled awkwardly.

The problem as stated here corresponds to finding the values of the vector $[U_t]$ over the period of study which satisfy expressions (1.1) to (1.9). This will be the "best" system expansion plan within the constraints given by the user. The WASP code finds this best expansion plan using the dynamic programming technique. In doing so, the program also detects if the solution has hit the tunnel boundaries of expression (1.8) and gives a message in its output. Consequently, the user should proceed to new iterations, relaxing the constraints as indicated in the WASP output, until a solution free of messages is found. This will be the "optimum expansion plan" for the system.

2.2. Calculation of Costs

The calculation of the various cost components in expression (1.1) is done in WASP with certain models in order to account for:

- (a) Characteristics of the load forecast;
- (b) Characteristics of thermal and nuclear plants;

- (c) Characteristics of hydroelectric plants;
- (d) Stochastic nature of hydrology (hydrological conditions); and
- (e) Cost of the energy not served.

In the above list, the word plant is used when referring to a combination of one or more units (for thermal) or to one or more projects (for hydro or pumped storage).

The load is modelled by the peak load and the energy demand for each period (up to 12) for all years (up to 30), and their corresponding inverted load duration curves. The latter represents the probability that the load will equal or exceed a value taken at random in the period (for computational convenience, the inverted load duration curves are expanded in Fourier Series by the computer program).

The models for thermal and nuclear plants are described, each of them, by:

- Maximum and minimum capacities;
- Heat rate at minimum capacity and incremental heat rate between minimum and maximum capacity;
- Maintenance requirements (scheduled outages);
- Failure probability (forced outage rate);
- Emission rates and specific energy use;
- Capital investment cost (for expansion candidates);
- Variable fuel cost;
- Fuel inventory cost (for expansion candidates);
- Fixed component and variable component of (non-fuel) operating and maintenance costs; and
- Plant life (for expansion candidates).

The models for hydroelectric projects are for run-of-river, daily peaking, weekly peaking and seasonal storage regulating cycle. They are defined by identifying for each project:

- Minimum and maximum capacities;
- Energy storage capacity of the reservoirs;

- Energy available per period;
- Capital investment cost (for projects considered as expansion candidates);
- Fixed operating and maintenance (O & M) costs; and
- Plant life (for projects considered as expansion candidates).

The hydroelectric plants are assumed to be 100% reliable and have no associated cost for the water. The stochastic nature of the hydrology is treated by means of hydrological conditions (up to 5), each one defined by its probability of occurrence and the corresponding available capacity and energy of each hydro project in the given hydro-condition.

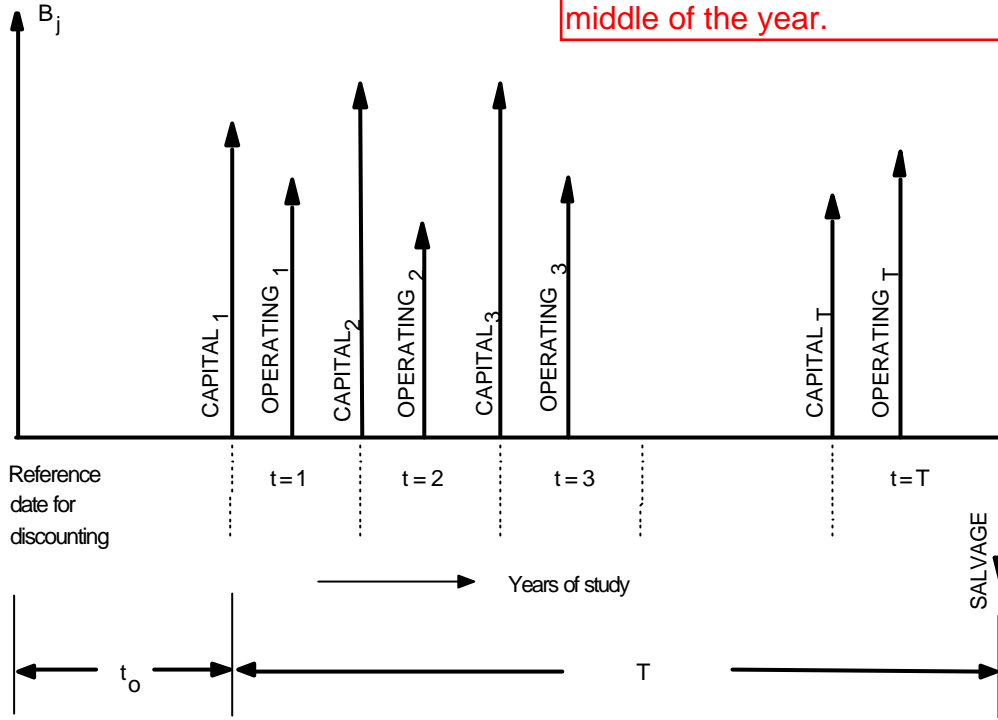
The pumped storage plants are modelled by specifying

- Installed capacity;
- Cycle Efficiency;
- Pumping capacity (for each period);
- Generation capacity (for each period);
- Maximum feasible energy generation (for each period).

The cost of energy not served reflects the expected damages to the economy of the country or region under study when a certain amount of electric energy is not supplied. This cost is modelled in WASP through a quadratic function relating the incremental cost of the energy not served to the amount of energy not served. In theory at least, the cost of the energy not served would permit automatic definition of the adequate amount of reserve capacity in the power system.

In order to calculate the present-worth values of the cost components of Eq. (1.1), the present-worth factors used are evaluated assuming that the full capital investment for a plant added by the expansion plan are made at the beginning of the year in which it goes into service and that its salvage value is the credit at the horizon for the remaining economic life of the plant. Fuel inventory costs are treated as investment costs, but full credit is taken at the horizon (i.e. these costs are not depreciated). All the other costs (fuel, O&M, and energy not served) are assumed to occur in the middle of the corresponding year. These assumptions are illustrated in Figure 1.

Notice that investment costs are modeled at the beginning of the year whereas production costs are modeled at the middle of the year.



Notes:

B_j = objective function (total cost) of the expansion plan

$CAPITAL_1$ = sum of the investment costs of all units added in the first year of study

$OPERATING_1$ = sum of all system operating costs (fuel, O&M, and energy not served) in the first year of study

$SALVAGE$ = sum of the salvage values at horizon of all plants added during the study period

t_0 = number of years between the reference date for discounting and the first year of study

T = length (in number of years) of the study period

Figure 1. Schematic diagram of cash flows for an expansion program

According to the above, the cost components of B_j in expression (1.1) are calculated as follows:

(a) Capital investment cost and salvage values:

$$\overline{I_{j,t}} = (1+i)^{-t} \times \sum [UI_k \times MW_k] \tag{1.10}$$

$$\overline{S_{j,t}} = (1+i)^{-T} \times \sum [d_{k,t} \times UI_k \times MW_k] \tag{1.11}$$

where:

- Σ = sum calculated considering all (thermal, hydro or pumped storage) units k added in year t by expansion plan j,
- UI_k = capital investment cost of unit k, expressed in monetary units per MW,
- MW_k = capacity of unit k in MW,

- $\delta_{k,t}$ = salvage value factor at the horizon for unit k,
 i = discount rate,
 t' = $t + t_0 - 1$
 T' = $T + t_0$

and t , t_0 , and T follow the same definitions given in Figure 1.

(b) Fuel costs:

$$\overline{F_{j,t}} = (1+i)^{-t'-0.5} \times \sum_{h=1}^{NHYD} [\alpha_h \times \Psi_{j,t,h}] \quad (1.12)$$

where α_h is the probability of hydro-condition h , $\Psi_{j,t,h}$ the total fuel costs (sum of fuel costs for thermal and nuclear units) for each hydro-condition, and NHYD represents the total number of hydro-conditions defined.

The energy generated by each unit in the system is calculated by probabilistic simulation. In this approach the forced outages of thermal units are convolved with the inverted load duration curve and, consequently, the effect of unexpected outages of thermal units upon other units is accounted for in a probabilistic way. The net effect is an increase of peaking units generation in order to make up the reduction of base units generation due to scheduled outages for maintenance and unit failures. Thus, increasing the expected generating costs of the system. Obviously the fuel cost of a particular block of energy generated by a unit is calculated as the amount of generation times the unit fuel cost times its heat rate.

If special constraints on a set(s) of plants are imposed for maximum amount of emissions, fuel usage and/or energy generation, linear programming technique is used for determining an optimal dispatch strategy for the plants satisfying these constraints.

(c) Fuel inventory cost:

$$\overline{L_{j,t}} = \left[(1+i)^{-t'} - (1+i)^{-T'} \right] \times \sum [UFIC_{kt} \times MW_{kt}] \quad (1.13)$$

where the indicated sum (\sum) is calculated over all thermal units kt added to the system in year t , and $UFIC_{kt}$ is the unitary full inventory cost of unit kt (in monetary units per MW).

(d) Operation and maintenance costs:

$$\overline{M_{j,t}} = (1+i)^{-t'-0.5} \times \sum [UFO \& M_l \times MW_l + UVO \& M_l \times G_{l,t}] \quad (1.14)$$

where:

- \sum = sum over all units (l) existing in the system in year t ,
 $OFO \& M_l$ = unitary fixed O&M cost of unit l , expressed in monetary units per MW-year,
 $OVO \& M_l$ = unitary variable O&M cost of unit l , expressed in monetary units per kWh,

$G_{l,t}$ = expected generation of unit l in year t , in kWh, which is calculated as the sum of the energy generated by the unit in each hydro-condition weighted by the probabilities of the hydro-conditions.

(e) Energy not served costs:

$$\overline{O}_{j,t} = (1+i)^{-t'-0.5} \times \sum_{h=1}^{NHYD} \left[a + \frac{b}{2} \times \left(\frac{N_{t,h}}{EA_t} \right) + \frac{c}{3} \times \left(\frac{N_{t,h}}{EA_t} \right)^2 \right] \times N_{t,h} \times \mathbf{a}_h \quad (1.15)$$

where: a , b , and c are constants (\$/kWh) given as input data, and:

$N_{t,h}$ = amount of energy not served (kWh) for the hydro-condition h in year t ,

EA_t = energy demand (kWh) of the system in year t .

The cost components of the objective function (B_j) are presented in expressions (1.10) to (1.15) in a simplified form. In fact, the above expressions have been derived considering each expansion candidate as one single unit (P-S, hydro, thermal or nuclear) whereas in WASP-IV the expansion candidates are defined as plants and the number of units (or projects) from each plant to be added in each year is to be determined by the WASP study. Besides, WASP-IV:

- combines capital investment cost and associated salvage value with the fuel inventory cost and its salvage value;
- aggregates operating costs by types of (fuel) plant;
- separates all expenditures (capital or operating) into local and foreign components;
- permits escalating all costs over the study period;
- has provisions to apply different discount rates and escalation ratios for each year, for the local and foreign cost components, and to change the constants (a , b , and c) for evaluating the energy not served cost from year to year.

Finally, the units of the different variables in Eqs. (1.10) to (1.15) and the variable names used in the above discussion do not correspond to the units and terminology used in the WASP modules. Table 1 summarises the capabilities of the WASP-IV computer code.

Table 1. Principal Capabilities of WASP-IV

Parameters	Maximum allowable
Years of study period	30
Periods per year.	12
Load duration curves (one for each period and for each year).	360
Cosine terms in the Fourier representation of the inverted load duration curve of each period.	100
Types of plants grouped by "fuel" types of which: 10 types of thermal plants; and 2 composite hydroelectric plants and one pumped storage plants.	12
Thermal plants of multiple units. This limit corresponds to the total number of plants in the Fixed System plus those thermal plants considered for system expansion which are described in the Variable System (87 if P-S is used).	88
Types of plants candidates for system expansion, of which: 12 types of thermal plants (11 if P-S is used); 2 hydroelectric plant types, each one composed of up to 30 projects; and 1 pumped storage plant type with up to 30 composed projects.	15
Environmental pollutants (materials)	2
Group limitations	5
Hydrological conditions (hydrological years).	5
System configurations in all the study period (in one single iteration involving sequential runs of modules 4 to 6).	5000

2.3. Dimensions of the WASP-IV computer program

Table 1 provides a listing of the more important capabilities of the WASP-IV code. Other characteristics and limitations of second order of importance are explained in the description of the various modules of the program along the chapters of the WASP manual.

3. WASP-IV MODULES

Figure 2 shows a simplified flow chart of WASP-IV illustrating the flow of information from the various WASP modules and associated data files. The numbering of the first three modules is symbolic, since they can be executed independently of each other in any order. For convenience, however, these

three modules have been given numbers here. Modules 4, 5, and 6, however, must be executed in order, after execution of Modules 1, 2, and 3. There is also a seventh module, REPROBAT, which produces a summary report of the first six modules, in addition to its own results.

- Module 1, **LOADSY (Load System Description)**, processes information describing period peak loads and load duration curves for the power system over the study period.
- Module 2, **FIXSYS (Fixed System Description)**, processes information describing the existing generation system and any pre-determined additions or retirements, as well as information on any constraints imposed by the user on environmental emissions, fuel availability or electricity generation by some plants.
- Module 3, **VARSYS (Variable System Description)**, processes information describing the various generating plants which are to be considered as candidates for expanding the generation system.
- Module 4, **CONGEN (Configuration Generator)**, calculates all possible year-to-year combinations of expansion candidate additions which satisfy certain input constraints and which in combination with the fixed system can satisfy the loads. CONGEN also calculates the basic economic loading order of the combined list of FIXSYS and VARSYS plants.
- Module 5, **MERSIM (Merge and Simulate)**, considers all configurations put forward by CONGEN and uses probabilistic simulation of system operation to calculate the associated production costs, energy not served and system reliability for each configuration. In the process, any limitations imposed on some groups of plants for their environmental emissions, fuel availability or electricity generation are also taken into account. The dispatching of plants is determined in such a way that plant availability, maintenance requirement, spinning reserve requirements and all the group limitations are satisfied with minimum cost. The module makes use of all previously simulated configurations. MERSIM can also be used to simulate the system operation for the best solution provided by the current DYNPRO run and in this mode of operation is called REMERSIM. In this mode of operation detailed results of the simulation are also stored on a file that can be used for graphical representation of the results.
- Module 6, **DYNPRO (Dynamic Programming Optimization)**, determines the optimum expansion plan based on previously derived operating costs along with input information on capital costs, energy not served cost and economic parameters and reliability criteria.
- Module 7, **REPROBAT (Report Writer of WASP in a Batched Environment)**, writes a report summarizing the total or partial results for the optimum or near optimum power system expansion plan and for fixed expansion schedules. Some results of the calculations performed by REPROBAT are also stored on the file that can be used for graphical representation of the WASP results (see REMERSIM above).

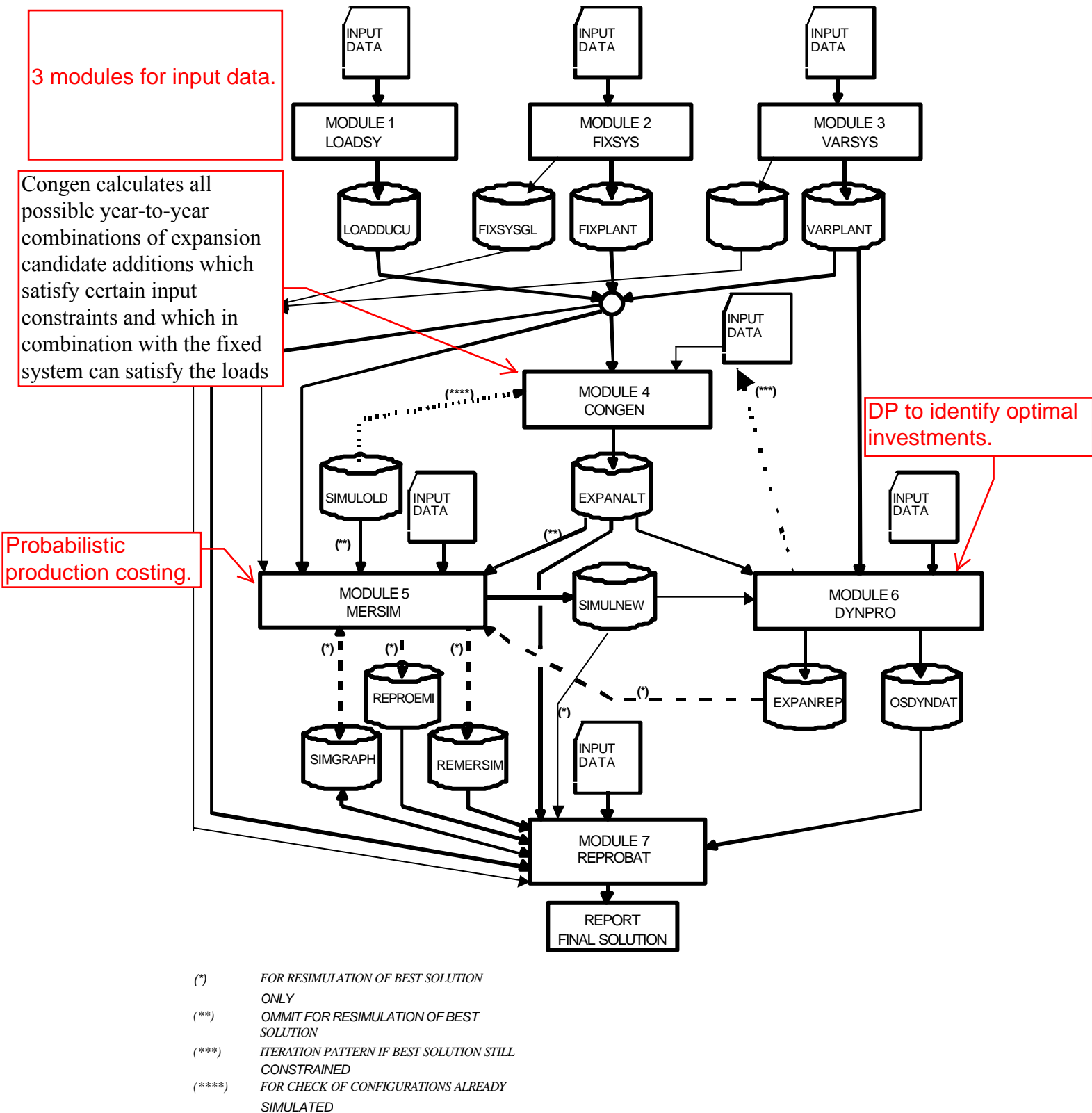


Figure 2. Simplified flow chart of the WASP-IV computer code

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