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A new approach to optimization of generation expansion planning using multi-period multi-objective framework

M. Ghaffari rad H. Barati B. Mouaref

Department of Electrical Engineering, dezful branch, islamic azad University, dezful, Iran,

Corresponding Author email: m_ghaffari@hotmail.com

ABSTRACT: This paper describes using a new approach to solve multi-period multi-objective optimization of generation expansion planning (MMGEP) problem in deregulated power systems over a long term planning horizon. The model optimises simultaneously multiple objectives (i.e. minimization of total costs, expected energy not served and emissions of generation units and maximisation of system reliability). The mixed-integer programming (MIP) is used for the proposed optimization and an efficient linearisation technique is proposed to convert the non-linear reliability metrics into a set of linear expressions. The proposed solution for multi objective mathematical programming (MMP) framework includes a hybrid augmented–weighted epsilon constraint and lexicographic optimisation approach to obtain the Pareto optimal or efficient solutions for the MMGEP problem. Finally, fuzzy decision making is implemented to select the most preferred solution among Pareto solutions based on the goals of decision makers (DMs). A synthetic test system including five types of candidate units is considered here for GEP in a 6-year planning horizon. The effectiveness of the proposed modifications is illustrated in detail.

Nomenclature

The main mathematical symbols used are given below.

Sets

C: total cost;
U_t: vector of newly introduced unit in the stage (one stage= 2years) ;
$U_{t,i}$: ith element of the newly introduced unit in stage t;
X_{t-1}: cumulative capacity vector of existing units in stage (t-1);
X_t: cumulative capacity vector of existing units in stage (t);
d: discount rate;
δ_i : salvage factor of the th unit;
T: Length of planning horizon (t = 1, 2,.., T)
N: Generating units (existing and newly added)

Variables

S': variable used to indicate that the maintenance cost is calculated at the middle of each year;
u_k: 1 if generating unit k is selected at time period t and 0 otherwise
σ_j : 1 if the forced outage of unit j causes some loss-of-load and 0 otherwise.
σ_{jk} : 1 if the forced outage of units *j,k* causes some
loss-of-load and 0 otherwise.
y_{jt}: Amount of imported fuels of type *j* in time period *t* (units)
μ_i: Individual membership functions of the objective function *i*
P_j: Probability of single contingency that the unit *j* in the time period *t* is selected but it is unavailable
P_{jk}: Probability of double contingency that units j and *k* are selected in the time period *t* but they are unavailable

Parameters

i_{nt}: Investment cost of newly added generating unit n in time period t ($/MW)
s_{nt}: Salvage values of newly added generating unit n in time period t ($/MW)
M^j_{min}: minimum fuel mix ratio of the th type;
M^j_{max}: maximum fuel mix ratio of the th type;

j: type of the unit (type of fuel used: Oil, LNG, Coal, Nuclear)
R_{min} :minimum reserve margin
R_{max}:maximum reserve margin
D_t: demand at the th stage in megawatts
$X_{t,i}$:cumulative capacity of th unit at stage i

Abbreviations
GEP: Generation expansion planning
LOLP: Loss of load probability
EENS: Expected energy not served
DSM: Demand Side Management
DMs: Decision makers
MMP: Multiobjective mathematical programming
FOR: Forced outage rate
MIP: Mixed integer programming
RES: Renewable energy sources

INTRODUCTION

Generation expansion planning (GEP) is one of the most important decision-making activities in electric utilities and defines the optimal schemes of sizing, placement and specially the dynamics (i.e. timing) of investments on generation units to meet the expected energy demand over the long-term horizon [1, 2]. It is known that the GEP problem is a constrained, non-linear and discrete optimisation problem. Mostly, GEP has been considered as a single-objective (may consist of a single term, e.g. [3, 4] or multiobjective, e.g. [5, 6]) optimization problem with constraints. This approach only results in a single optimal solution where tradeoffs between different components of the objective function must be fixed in advance of solution. However, the GEP problem inherently involves multiple, conflicting and incommensurate objectives that should be considered simultaneously.

Least-cost GEP is to determine the minimum-cost capacity addition plan (i.e., the type and number of candidate plants) that meets forecasted demand within a prespecified reliability criterion over a planning horizon. The major objectives of the GEP problem are to minimize costs, environmental impacts and maximisation of the system reliability. No single Pareto optimal solution is adequate to be claimed as an optimum solution of a problem with multiple conflicting objectives. Thus, the resulting multiobjective optimisation problem involves number of trade-off solutions. Therefore a multiobjective optimisation method is desirable to solve the GEP problem. Recently, environmental issues have been changed as an important issue in the worldwide. Carbon dioxide (CO2) is one of the main greenhouse gases that are responsible for global warming and climate changes. The combustion of fossil fuels has played an important role in the generation of CO2 in the atmosphere. Many countries are committed to the Kyoto Protocol [7] and aimed for significant reduction in greenhouse gas emissions within the next decade. Subsequently, problems concerning production of atmospheric emissions by fossil fuel resources and scarcity of them in the near future lead to increased interests in 'energy saving' and 'environmental protection' issues [8]. One strategy to reduce dependence to fossil fuel resources is based on reducing 'energy consumption' by applying energy savings programmes focused on energy demand reduction and energy efficiency in industrial [9] and domestic [10] loads. Another strategy to achieve this goal is the implementation of RES, not only for large-scale energy production, but also for stand-alone systems [11]. It is widely believed that RES is more expensive than conventional technologies so that expanding their use will only increase the cost of generating electricity. However, finance theory provides a very different viewpoint, suggesting that generating alternatives should be valued not only on their stand-alone cost, but also on the basis of their contribution to portfolio cost with respect to their contribution to 'portfolio risk' [12, 13]. Modern mean variance portfolio theory further predicts that adding RES will reduce overall generating costs at any given level of risk, even where RES cost more on a 'stand-alone' basis. Environmental benefits and operating cost saving can be used to the advantage of renewable energy sources (RES) to compete with the less costly conventional sources. Also, the renewable energy credit market assigns monetary values to the environmental benefits obtained from offsetting conventional fuel [14–16]. Another point in this area, recently few studies have undertaken the challenge of optimisation problems for power system studies faced with uncertainty, when there is an explicit desire to accommodate multiple objectives within the decision framework. In other words, a drawback of the most existing energy planning models is that they do not consider uncertainty associated with fossil fuel prices and their increasing trend [17]. Fossil fuel price fluctuation depresses economic activity in fossil fuel consumption nations.

Even small percentage increases in fossil fuel prices can yield sizable economic losses through unemployment and income losses, as well as losses in the value of financial and other assets [12,18]. Efficient generating portfolios minimise national exposure to such fluctuations, commensurate with creating optimal overall generating costs. Efficient generating portfolios expose society to the minimum level of risk needed to attain given energy cost objectives.

Besides, reliability is another important factor in the power system planning for future system capacity expansion. The plan must satisfy a desired level of reliability. Usually, measurement of reliability or adequacy to make sure that total generation system capacity is sufficient to meet the system demand requirements, provided by two commonly used indices: (1) loss of load probability (LOLP) and (2) expected energy not served (EENS) [19, 20]. These indices set the reserve requirements and are sensitive to unit size, type, number and forced outage rate (FOR). To the best of our knowledge, the contributions of this work with respect to the previous researches in the area can be summarised as follows:

Many concerns of DM in the area of the GEP procedure are considered as the extra objective functions in the linear constrained multiobjective optimisation problem. In the proposed GEP scheme, cost, emissions, energy consumption, portfolio investment risk and reliability are treated as competing objective functions. Moreover, the benefits associated with utilisation of RES and demand side management (DSM) programmes are considered in the GEP process for efficient generating portfolio.

The lexicographic optimisation and hybrid augmented–weighted ε-constraint method is proposed to solve the multiobjective optimisation problem. The lexicographic optimisation is used to determine the range of objective functions more effectively compared with the conventional ε-constraint method. Moreover, the augmented ε-constraint method generates only efficient Pareto optimal solutions and avoids inefficient ones. In order to select the ‘best’ compromised solution among the Pareto optimal solutions of multiobjective optimisation problem, a fuzzy decision making tool is adopted.

The rest of this paper is organised as follows: In Section 2, the proposed multiperiod multiobjective generation expansion planning (MMGEP) model is introduced in the form of a mixed-integer programming (MIP) problem [35]. Section 3, introduces the proposed solution approach for the multiobjective mathematical programming (MMP) problem. In the next section, obtained results for a test system are presented and discussed to demonstrate the effectiveness of the proposed scheme. Some relevant conclusions are drawn in Section 5.

Mathematical model

The aim of problem is to determine an optimal generation expansion plan incorporating RES over a planning period that minimises simultaneously relevant costs, expected energy not serve, CO2 emission and energy price risks as well as maximises reliability, subject to several constraints.

objective functions

The objective functions in MMGEP can be formulated as follows

Total cost (O_1): Mathematically, solving a least-cost GEP problem is equivalent to finding a set of optimal decision vectors over a planning horizon that minimizes an objective function under several constraints. The GEP problem to be considered is formulated as follows [6]:

$$\min C = \sum_{t=1}^{T}[I(U_t)+M(X_t)+O(X_t)-S(U_t)] \tag{1}$$

Including:

cumulative capacity vector:

$$X_t = X_{t-1}+U,(t=1,2,3..T) \tag{2}$$

investment cost:

$$I(U_t)=(1+d)^{-2t}\sum_{i=1}^{N}(CI_i \times U_{t,i}) \tag{3}$$

salvage value of the newly added unit:

$$S(U_t)=(1+d)^{-T'}\sum_{i=1}^{N}(CI_i \times \delta_i \times U_{t,i}) \tag{4}$$

operation and maintenance cost:

$$M(X_t)=\sum_{s'=0}^{1}((1+d)^{1.5+t'+s'}(\sum(X_t \times FC)+MC)) \tag{5}$$

outage cost:

$$O(X_t) = OC \times \sum_{s'=0}^{1} ((1+d)^{1.5+t'+s'}) \qquad (6)$$

$$t' = 2(t-1) \qquad (7)$$

$$T' = 2 \times T - t' \qquad (8)$$

Reliability (O2): This objective function expresses the outage cost. Outage cost is evaluated using EENS index. The minimisation of outage cost (or maximisation of reliability) is represented by the following expression:

$$LOLP = \sum_{j=1}^{n} \sigma_j P_j^1 + \sum_{j=1}^{n} \sum_{k>j}^{n} \sigma_{jk} P_{jk}^2 \qquad (9)$$

The EENS can be evaluated using a probabilistic approach [24]. An upper bound on probabilities of LOLP and EENS because of single and double unit contingencies is used to define reliability indices. The main advantage of this method is that the reliability indices can be formulated as a linear function of the MMGEP integer and continuous variables. This is achieved through formulations explained in Appendix that express the non-linear indices into mathematically equivalent linear equalities and inequalities over the decision variables.

EENS (O3): the cost of reliability (for instance EENS) will depend on many factors, when a failure to supply energy occurs, including the types of customers interrupted, actual load demand at the time of outage, duration of outage and the time in which the outage occurs.

$$EENS = \sum_{j=1}^{n} \sigma_j \rho_j^1 (P_{gi} - R) + \sum_{j=1}^{n} \sum_{k>j}^{n} \sigma_{jk} \rho_{jk}^2 \times (P_{gi} + P_{gk} - R) \qquad (10)$$

There are several ways to approximate EENS cost including gross national product/total energy consumption, survey method, case studies of blackouts, preparation cost of customer, direct and indirect methods. More details about this matter can be found in [25].

CO2 emission (O4): The amount of CO2 emission by generating units should be minimised. This objective can be determined by the emission rates of the different type of generating units as follows:

$$O_4 = \sum_{t \in T} \sum_{n \in N} E_n g n_{nt} \qquad (11)$$

Note that other emission of gases like SO_X and NO_X can be also considered [21- 23].

Constraints

Upper construction limit: This physical constraint reflects the maximum allowable number/capacity (or investment) for each unit of the fuel type j to be committed during period t; because of natural reasons (i.e. space, resources etc.).

$$0 \le U_t \le U_{\max, t} \qquad (12)$$

where $U_{\max,t}$ is the maximum construction capacity of the units at stage t .

2.2.2. Reserve Margin: The selected units must satisfy the minimum and maximum reserve margin

$$(1+R_{\min}) \times D_t \le \sum_{i=1}^{N} X_{t,i} \le (1+R_{\max}) \times D_t \qquad (13)$$

2.2.3. Fuel Mix Ratio: The GEP has different types of generating units such as Coal, Liquefied Natural Gas (LNG), Oil, and Nuclear. The selected units along with the existing units of each type must satisfy the fuel mix ratio

$$M^j{}_{\min} \le X_{t,j} \Big/ \sum_{i=1}^{N} X_{t,j} \le M^j \max \qquad (14)$$

2.2.4. Reliability Criterion(lolp): The selected units along with the existing units must satisfy the reliability criterion, Loss of Load Probability (LOLP)

$$LOLP(X_t) \le \varepsilon \qquad (15)$$

where ε is the reliability criterion expressed in LOLP.

Multi objective mathematical programming (MMP)

In MMP there is more than one objective function and there is no single optimal solution that simultaneously optimises all the objective functions. In these cases, the DMs are looking for the ‘most preferred’ solution. In MMP, the concept of optimality is replaced with that of efficiency or Pareto optimality. The efficient (or Pareto optimal, non-dominated, non-inferior) solution is the solution that cannot be improved in one objective function without deteriorating its performance in at least one of the rest. A well organized technique to solve MMP problems owning one main objective function among all objective functions is the ε-constraint method which belongs to posteriori or generation methods [27]. The ε-constraint method has several important advantages over the traditional weighting method, which combines the objective functions of the MMP problem by weighted sum to construct a single objective function [27]. Despite its advantages over the weighting method, the ε-constraint method has two points that need attention. At first, the range of the objective functions over the efficient set is not optimised. To solve this problem, lexicographic optimisation technique is proposed here.

Secondly, the generated Pareto optimal solutions by the ε-constraint method may be dominated or inefficient solutions. Augmented ε-constraint technique is suggested to remedy this deficiency. The augmented ε-constraint method does not consider the importance of the objective functions in generating the Pareto solutions, which is inconsistent with the decision maker policy. Therefore augmented–weighted ε-constraint approach is proposed here such that the relative importance of the objective functions is explicitly modelled in the generation of the Pareto solutions.

The proposed MMP solution method incorporating lexicographic optimisation and hybrid augmented–weighted ε-constraint technique is implemented to solve the MMP model of GEP including five objective functions O_1, O_2, O_3 and O_4. The mentioned MMP solution method is detailed in the next subsection.

Solution methodology of MMGEP problem

The formulation of the MMP based on the augmented ε-constraint technique is as follows, more details can be found in [26–29]

$$\min/\max\left[O_1(x)+dir_1 r_1\sum_{i=2}^{m}s_i/r_i\right] \quad (16)$$

$$O_i(x)-dir_i s_i=e_i, i=2,3,...,m$$

where m is the number of objective functions. dir_i is the direction of the ith objective function, that it is equal to +1 when the ith objective function should be minimised, and equal to +1, when it should be maximised. By parametrical iterative variations in the e_i the efficient solutions of the problem are obtained. s_i is the introduced slack or surplus variables for the constraints of the MMP problem. In order to avoid any scaling problem, $r_1 s_i/r_i$ (i=1,2,…,m) is used in the second term of the objective function. The formulation of (16) is known as the augmented ε-constraint method because of the augmentation of the objective function O_1 by the second term. It can be shown that the augmented ε-constraint method generates only efficient solutions [28]. Its proof can be found in [27].

In order to apply the ε-constraint method, the range of each objective function (r_i) should be determined. The most common approach is to calculate these ranges from the payoff table. In the conventional approach to construct payoff table, there is no guarantee that the obtained solutions from the individual optimisation of the objective functions are Pareto optima or efficient solutions. In order to overcome this deficiency, the lexicographic optimization is proposed here in order to construct the payoff table including only efficient solutions. In general, the lexicographic optimisation of a series of objective functions is to optimise the first objective function and then among the possible alternative optima optimise for the second objective function and so on. The flowchart of computing payoff table for the MMP problem is shown in Fig.1, [28].

The payoff table has m rows and columns. The ith column of the payoff table includes the obtained values for the objective function O_i among which the minimum and maximum values indicate the range of the objective function O_i for the ε-constraint method.

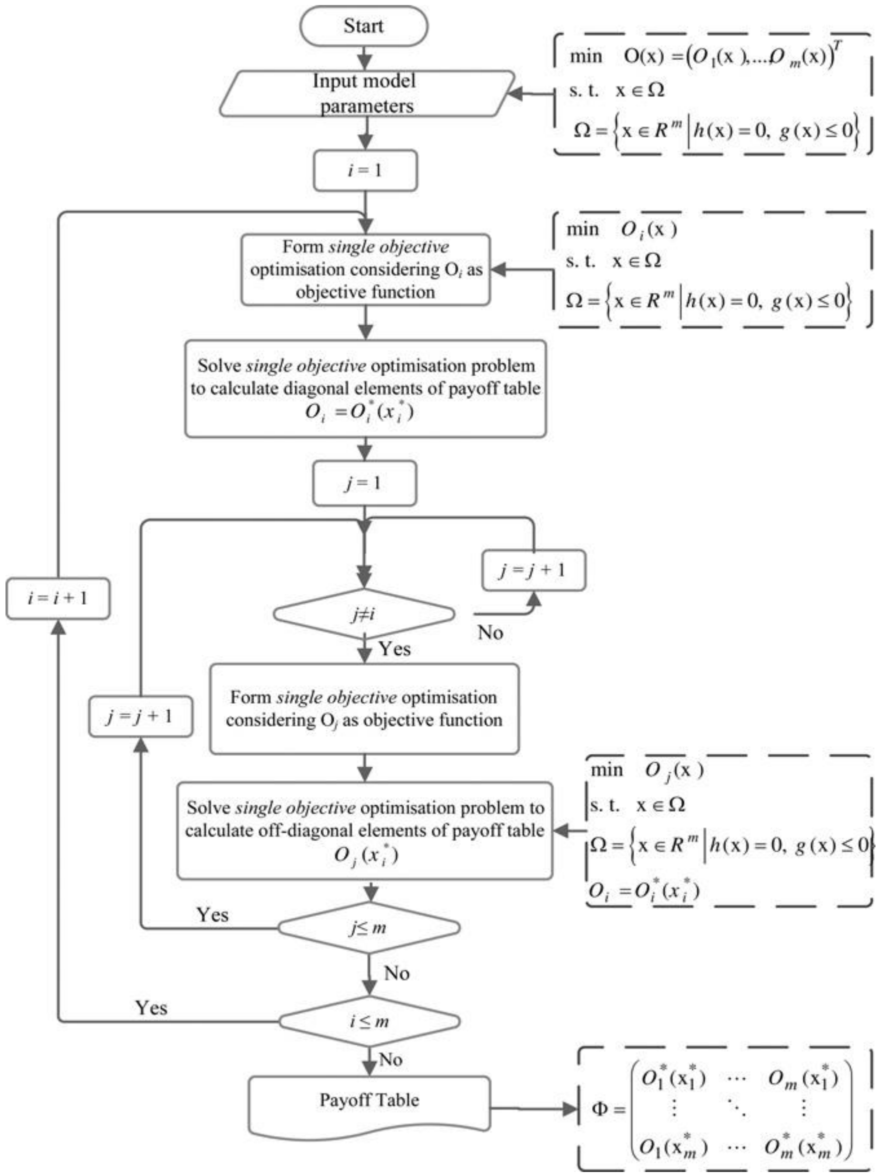

Figure1. Flowchart of the lexicographic optimisation for calculation of payoff table [28]

Then, the range of each objective function can be calculated using:

$$r_i = O_i^{\max} - O_i^{\min}, i = 1, 2, ..., m \tag{17}$$

After finding the range (r_i) of all objective functions from payoff table, the augmented ε-constraint technique divides the range of m-1 objective functions $O_2, \dots, O_m$ to $q_2, \dots, q_m$ equal intervals using $(q_2\text{-}1), \dots, (q_m\text{-}1)$ intermediate equidistant grid points, respectively. Considering the minimum and maximum values of the range, we have in total $(q_2 + 1), \dots, (q_m + 1)$ grid points for $O_2, \dots, O_m$, respectively. So, we should solve $N_{SP}=(q_2 + 1) \times (q_3 + 1) \times \dots \times (q_m + 1)$ optimisation sub-problems to obtain Pareto optimal solutions.

The augmented ε-constraint method does not consider the importance of the objective functions in generating the Pareto solutions, which is inconsistent with the DMs policy. Therefore augmented–weighted ε-constraint approach is proposed here such that the relative importance of the objective functions is explicitly modelled in the generation of the Pareto solutions. Consequently, in the proposed augmented–weighted ε-constraint method, the objective function of (16) is changed as follows:

$$\min/\max\left[w_1 O_1(x) + dir_1 r_1 \sum_{i=2}^{m} w_i s_i / r_i \right] \tag{18}$$
$$O_i(x) - dir_i s_i = e_i$$

where w_i is the weight factor of a DMs for the *i*th objective function. It should be noted that although the proposed augmented–weighted ε-constraint framework includes weight factors, it is different from the weighting methods which generate a single solution for a set of weights without any guarantee to be an efficient solution. For generating Pareto optimal solution in each sub-problem the following formulation should be solved

$$\min/\max\left[O_1(x)+dir_1r_1/w_1\sum_{i=2}^{m}w_is_i^{ni}/r_i\right]$$
$$\begin{cases}O_i(x)-dir_is_i^{ni}=e_i^{ni}\\ i=2,3,...,m;ni=0,1,...q_i\end{cases} \qquad (19)$$

$$\begin{aligned}&e_i^{ni}=O_i^{\min}(dir_i+1)/2-O_i^{\max}(dir_i-1)/2+(dir_ir_ini)/q_i\\ &i=2,3,...,m, \qquad ni=0,1,...,q_i\end{aligned} \qquad (20)$$

Although there are many efficient solutions obtained by MMP solution methods, one of these solutions is the most preferred for the MMP problem considering the importance of its objective functions. The fuzzy decision maker is used to softly select the most preferred compromise solution among the Pareto optimal solutions of each case. For this purpose, the fuzzy decision maker calculates a linear membership function for each objective function in each Pareto optimal solution, which measures the relative distance between the value of the objective function in the Pareto optimal solution from its values in the respective utopia and pseudo nadir points. The closer value of the objective function to its individual optimum value (utopia) (farther from its pseudo nadir) results in the higher membership function (higher degree of optimality) for the objective function in the Pareto optimal solution. The mathematical formulation of these membership functions for the MMP GEP problem is as follows [28–30] (see (21) that h=1,2,...,N_{SP} and i=1,2,…,m).

The total membership function (total degree of optimality) of each Pareto optimal solution is computed considering the individual membership functions (μ_i^h) and the relative importance of the objective functions (w_i)

$$\mu_{tot}^h=\sum_{i=1}^{m}w_i\mu_i^h \qquad (22)$$

$$\mu_i^h=\begin{cases}1;O_i^h\geq O_i^{\min}(dir_i-1)/2+O_i^{\max}(dir_i+1)/2\\ \dfrac{1}{2r_i}\begin{bmatrix}(O_i^{\max}-O_i^h)(1-dir_i)\\ +(O_i^h-O_i^{\min})(1+dir_i)\end{bmatrix} & ;O_i^{\min}\leq O_i^h\leq O_i^{\max}\\ 0;O_i^h\leq O_i^{\max}(dir_i-1)/2+O_i^{\min}(dir_i+1)/2\end{cases} \qquad (21)$$

The most preferred solution refers to the Pareto solution with the highest value of mtot or the highest preference for the MMP problem. This solution more optimises the objective functions of the MMP problem, considering their relative importance, than the other Pareto solutions.

The efficiency of implementing posteriori methods with respect to the priori and interactive methods has been described in [27]. It can be inferred from [27] that in the posteriori methods, for example, the proposed augmented– weighted ε-constraint method, the Pareto set of solutions are generated and then fuzzy decision maker can be implemented to select among them. Indeed, in these methods, decision maker can do his/her most-preferred solution while he/she have access to all the Pareto set which helps decision maker to have a better selection based on your preferences. In other words, in the posteriori methods, the decision maker, firstly, obtains a good sense of the Pareto solutions and then he/she can make his/her final decision to specify the most-preferred solution. By combining the augmented–weighted ε-constraint method with the lexicographic optimisation the proposed MMP solution method is obtained. The proposed framework can be summarised as the following steps:

Step 1: Calculate the payoff table for an MMP problem using lexicographic optimisation method.

Step 2: Determine the range of the ith objective function (i = 2, 3, . . . , m) from the payoff table, refer to (17).

Step 3: Divide the range of at least m-1 objective functions into q_i (i = 2, 3, . . . , m) equal intervals, respectively, by using (20).

Step 4: Generate the Pareto efficient solutions by solving feasible optimisation sub-problems in (19) by proposed MMP solution method, and discard infeasible ones.

Step 5: Select the most preferred Pareto optimal solution among the efficient solutions obtained in step 4 by the fuzzy decision maker process, (21) and (22).

In the implementation of the above algorithm for generating Pareto optimal solutions of each sub-problem (19), an innovative addition to algorithm has been proposed in [27] which refer to the early exit from the nested loop when the sub-problem becomes infeasible for some combination of e^{ni}_{i}. This matter has been implemented in the simulation phase of the paper. Detailed description of the early exit from the nested loop can be found in [27].

Relevant simulations of the numerical examples are carried out in the GAMS software package [31]. Large-scale commercial CPLEX solver [32] is used to solve the MIP based MMGEP. All the test results were performed in PC with a 2 GHz Pentium(R) Dual-Core CPU under the Windows 7 operating system.

Test system description

The proposed framework of MMGEP problem was applied to a test system for a 6-year planning horizon. The planning horizon is divided into three 2-year time periods. The expansion decision for each period means that the expansion will be made at the beginning of the period and the new technology will be available for that 2-year period as well as the following time periods. Generation technology options for capacity additions include: conventional oil units, coal units, LNG, nuclear units. In this paper, hourly variation(s) of demand/generation is not considered. The associated fuel data of the units were estimated from [6]. Demand was assumed to be constant throughout the time period. The maintenance costs were assumed to occur in the middle of the year and other costs were assumed to occur in the beginning of the year. Some of the input data was taken from [6, 16, 20, 23, 33, 34], and the rest was estimated using different sources. The forecasted peak demand over the study period is given in Table 1. The technical and economic data of the existing plants and candidate plant types for future additions are shown in Tables 2 and 3, respectively.

Parameters of the MMGEP

There are several parameters to be pre-determined, which are related to the MMGEP problem. This paper considers 10% as the discount rate, 0.01 as the acceptable LOLP level. The unserved energy, or EENS cost is set at 0.05 $/kWh [4, 20]. The considered lower bounds of capacity mix are 60, 30 and 10% for the base, medium and peak load type power plants, respectively. FOR for various units is in the range of 2–10%. Generation (after considering FOR) is assumed to be constant throughout the period. The lower and upper bounds for reserve margin are set as 20% and 40%. The salvage factor is additionally added.

Implementing MMP solution algorithm

Using the ε-constraint method for the proposed formulation of the MMGEP, the payoff table obtained. According to the payoff table (F), the range of objective functions O1 to O4 is determined as the minimum and maximum values of columns 1–4, respectively.

Payoff table (F) and limits of objective functions are given in Table 4.Two different solution methods were implemented to solve the MMP problem, including the augmented (denoted by Aug) and proposed augmented–weighted ε-constraint (denoted by Aug-wei) methods. In order to compare the performance of the MMP solution methods, all methods were solved considering three different sets of weight factors as shown in Table 5. Considering q2 = q3 = q4 = 2, will results in 81 optimisation sub-problems for the MMP generation expansion problem. Among the 81 optimisation subproblems, there are 22, 25 and 11 infeasible sub-problems for all solution methods in cases I–IV, respectively.

RESULTS AND DISCUSSION

For the sake of a fair comparison between the results of the MMP solution methods, the same range for each objective function was considered (in all cases) for the fuzzification process. A detailed comparison based on the most preferred solution between two solution methods for cases I–III is presented in Table 6. The 2nd to 8th columns of the Table 6 show the values of each objective function and their corresponding individual membership functions obtained from three MMP solution methods. The 9th column of this table shows the total membership function (total degree of optimality).

Comparing Table 6 with payoff table (F), it is obvious that all of the most solutions are between the best value (minimum) and the nadir value (maximum) for each objective function. By investigating the results of Table 6 and corresponding payoff table, it is observed that the objective O1 has conflicting manner with respect to other three objectives, that is, O2–O4. The objectives O2, O3 and O4, relatively have the same behaviour. For instance, in case II, decreasing the importance of cost function, O1 (w_1 = 0.2), the value of O1 is deteriorated. In contrast, the CO2 emission function, O4 with w_4 = 0.5 is improved because of its conflicting manner with O1. As seen, the most preferred solution of the proposed augmented–weighted ε-constraint method obtains higher total membership value than the augmented ε-constraint methods with reasonable CPU time as shown in the last column of Table 6. Thus, the proposed MMP solution method has a higher degree of preference for the MMGEP than the other MMP solution methods in all cases. Although the augmented ε-constraint method obtains the most preferred solution with the low execution time, its degree of preference is lower than the other method.

Table 1 . Forecasted peak demand

Period, year	Period 1	Period 2	Period 3
Peak, MW	7000	9000	10000

The augmented ε-constraint method, however, achieves the higher degree of preference than the conventional approach with cost of higher execution time. Table 7 summarises generation expansion plans of cases I–III obtained by the proposed MMP method for 6-year planning horizon. In this expansion plan, the type of generation unit needs to be decided for the remaining 6750 MW of the expected electricity demand. As shown in Table 6 proposed solution has the minimum cost solution, but with higher emission, loss of load probability and expected energy not served among other solution methods with all constraints satisfied in case I.

In this case, the proposed solution has capacity addition of 3700 MW in period 1, 950 MW in period 2 and 1000 MW in period 3, resulting in a cost of 1.090445×10^{10} \$. Note that, the highest and most important investment is made at the beginning of the planning horizon in all cases. Moreover, the investment decisions are changed based on the relative weight factors of objective functions as shown in Table 7. As this table indicates, for the second case where the objective is to find the least emission units of the expansion plan, more investing are assigned for

Table 2. Characteristics and costs of the existing generation units

Type	Capacity, MW	FOR, %	Var. cost, \$/KWH	Fixed O&M cost,\$/KW-mon	CO2 ,kg/MW	No. of units
Oil 1	200	7	0.024	2.25	743	1
Oil 2	200	6.8	0.027	2.25	743	1
Oil 3	150	6	0.030	2.13	618	1
LNG G/T	50	3	0.043	4.52	423	3
LNG C/C 1	400	10	0.038	1.63	403	1
LNG C/C 2	400	10	0.040	1.63	403	1
LNG C/C 3	450	11	0.035	2	403	1
Coal 1	250	15	0.023	6.65	834	2
Coal 2	500	9	0.019	2.81	848	1
Coal 3	500	8.5	0.015	2.81	848	1
Nuclear1 pwr	1000	9	0.005	4.94	0	1
Nuclear2 pwr	1000	8.8	0.005	4.63	0	1

the LNG and nuclear units because of their lower emission for construction. When the weight factor for the cost function is decreased (case III), the expansion decisions changes towards environmental friendly technologies. Thus, the RES or nuclear are installed at their maximum number of construction as it can be seen in Table 6. A high percentage of LNG C/C are initially introduced in the investment plan in all cases, except for case III. This is mainly because of this fact that in this case the weight factors of the reliability and eens objective functions are higher than cases I and II and weight factor cost is lower than other cases.

Table 3 . Characteristics and costs of the candidate generation units

Type	Capacity, MW	FOR, %	Var. cost, \$/KWH	Fixed O&M cost,\$/KW-mon	Capital cost, \$/kw	CO2 ,kg/MW	Construction upper limit
Oil	200	7	0.021	2.2	812.5	743	5
LNG C/C	450	10	0.035	0.9	500	403	4
Coal	500	9.5	0.014	2.75	1062.5	876	3
Nuclear pwr	1000	9	0.004	4.6	1625	0	3
Nuclear phwr	700	7	0.003	5.5	1750	0	3

Table 4. Payoff table (F) and limits of objective functions

	O1 (10^{10} \$)	O2 (%)	O3 (MWh)	O4 (kg)
O_1	1.03675	0.048	95.76	12933.95
O_2	1.24137	0	0	10732.012
O_3	1.24137	0	0	10732.012
O_4	1.20792	0.161	321.12	8807.403
O_{min}	1.03675	0	0	8807.403
O_{max}	1.24137	0.161	321.12	12933.95

Table 5. Weight combinations for cases

Cases	Cost (O_1)	Reliability(O_2)	EENS(O_3)	CO2(O_4)
Case 1	0.25	0.25	0.25	0.25
Case 2	0.3	0.1	0.1	0.5
Case 3	0.1	0.3	0.3	0.3

Table 6. Results of the most preferred solution obtained by the proposed method and other MMP methods for cases I–III

	O_1 (10^{10} \$)	μ_1	O_2(%)	μ_2	O_3(Mwh)	μ_3	O_4(kg)	μ_4	μ	Time,min
Case 1										
Aug	1.22405	0.61	0.01	0.81	27.31	0.703	12231.02	0.57	0.673	24.12
Aug-wei.	1.090445	0.74	0	1	0	1	10091.24	0.69	0.86	24.29
Case 2										
Aug	1.103322	0.723	0.051	0.691	113.12	0.61	10110.52	0.66	0.677	21.43
Aug-wei.	1.082856	0.77	0.05	0.7	96.12	0.7	9909.53	0.73	0.736	25.12
Case 3										
Aug	1.223111	0.25	0.23	0.811	67.12	0.799	9901.86	0.912	0.781	25.011
Aug-wei.	1.182285	0.29	0.02	0.85	47.88	0.85	8807.4	1	0.9	25.15

Additionally, as it can be seen from Table 3, coal units have the highest emission level that is, 876 kg/MW, with respect to the other types of units. Additionally, the fuel price volatility of gas fuel is assumed higher than other fuel types in this study.

Therefore the LNG CC units are not deserved to be selected for the case II. Consequently to consider fixed costs in this units are more intended in the case II with respect to the case II because of the lower levels of eens and reliability for these units as well as higher importance of
O4 in the case III. DSM options are presented in all cases. In the first case (the most importance for O1), DMS1 is selected in all periods because of its low initial cost.

Table 7. Number of newly introduced plans in case I–III by proposed method for 6-year planning horizon

Candidate type (capacity in MW)	No. of unit selected								
	Case 1			Case 2			Case 3		
	Period1	Period2	Period3	Period1	Period2	Period3	Period1	Period2	Period3
Oil	1	0	0	1	1	2	0	0	0
LNG C/C	0	3	0	3	2	2	0	0	1
Coal	1	1	0	1	1	0	1	1	0
Nuclear pwr	3	0	1	1	0	0	1	0	0
Nuclear phwr	0	0	0	0	1	0	3	2	1

CONCLUSIONS

In this paper, a MMGEP model has been presented. A framework to solve the MMGEP model is proposed to obtain the Pareto optimal solutions. Also, the fuzzy decision maker is utilised to select the most-preferred solution among the Pareto solutions. Moreover, the GEP problem is formulated as a fourobjective problem. The objectives include minimisation of cost, CO2 emission, expected energy not served, maximisation of reliability (or minimisation of force outage rate of network).

To cope with the MMGEP problem, the hybrid augmented ε-constraint method and weighting approach, named as augmented–weighted ε-constraints method, is proposed. The efficiency of the proposed framework has been illustrated on three cases with different sets of weight factors for objective functions and compared with the augmented ε-constraints method. The results show the superiority of the proposed approach over the augmented ε-constraint technique. The research work is under way in order to incorporate uncertainties, for example, demand forecast, the construction time and price uncertainty into the GEP problem. Also, including the risk of delay in construction time can be considered as an extension to this work in the future research to highlight the benefits of RES in the GEP problem.

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