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Three Multiple Criteria Models for Power Generation Expansion Planning: A Review

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Abstract

In this paper, we have summarized three inter-related multiple criteria models for power generation expansion planning that we have published recently. These papers also present different solution or algorithmic approaches for solving these models and use the same case study involving realistic data for the power generation expansion planning problem. The models, and their solution approaches, emphasize different aspects of the power generation expansion planning problem and the need for solution methods that utilize the model characteristics. A general conclusion from this review of the three models/methods is that there is no one "best" model or a "best" solution approach. Considerations of problem granularity level impact the complexity of the resultant model. Modeling complexity and limitations of algorithms and computing power mean that one over-arching model or a solution method is not a practical approach to this problem. We also identify here further research areas for extending the proposed models.

Keywords
Multiple Criteria Decision Making, Power Generation Expansion Planning, Fuzzy Solution Approach,

1. Introduction and Background

Power generation expansion planning (GEP) is an important and much studied problem. The complexity of this problem arises from the considerations of: multiple time horizons; multiple fuel sources; multiple generation technologies; fuzziness or uncertainty in data and in constraints and criteria; multiple conflicting constraints and criteria; and, the granularity in the model details. GEP problems have usually been modeled as single-objective programming problems which usually consider only the total cost (minimize) or system reliability (maximize) as the objective function [1]. In recent years, powerful and attractive multiple criteria decision making analysis approaches have been developed and applied to power systems planning. In some of these approaches, the alternatives (i.e., expansion plans) are generated through the model/process itself and in others the expansion plans are known (or developed using other approaches) before their comparison and final selection process through the multiple criteria decision model/process. In order to consider the GEP problem from a more realistic perspective, we have (with other co-authors) explored three different modeling frameworks, some of which necessitated the development of solution processes to make them solvable in realistic computational times. To demonstrate the applicability of these models (and the proposed solution methods), we have used variations of a basic case study of a realistic size. In this paper, we will compare and contrast the basic modeling frameworks and solution methods used in these papers. For details about these models, solution methods used and major results, the readers can consult the original papers [1-3]. For an overview of multiple criteria decision methods see [4 and 5]. For surveys of GEP models and their solutions, interested readers may consult [6-9].

2. Core Model Structures and Case Study Overview

The general multiple criteria GEP (MGEP) model can be written as:

$$\begin{aligned} \min \quad & \left[f_1(y), f_2(y), f_3(y), f_4(y) \right] \\ s.t. \quad & y \in Y \end{aligned} \tag{1}$$

where, $y \in Y$ is the feasible solution space and $f_l(y)$ is the l^{th} objective function (l = 1, 2, 3, 4).

Core Model Structures

MGEP model one (MGEP-1), presented in [1], has the following basic features:

- Multiple criteria - investment, operation, and transmission costs (minimize); environmental impact, i.e., total aggregate carbon dioxide emission from non-renewable energy sources, (minimize); amount of imported fuel (minimize); and, energy price risks (minimize). Note, additional criteria can be added if felt necessary.
- Model represents generation-transmission supply chain as a network, where nodes represent power demand or supply points.
- Power flow through an arc is expressed considering only one of two Kirchhoff's laws (current conservation law).
- Modeled as a multi-time period, multiobjective linear programming problem that has continuous decision variables and is deterministic.
- Seven groups of decision variables are used in the model - generation amount of each new or existing unit type at each node in each time period; power generation from new or existing units of each unit type at each node in each time period; cumulative capacity of each unit type at each node in each time period; power flow through each arc in each time period ; additional transmission capacity in each arc in each time period; cumulative capacity in each arc in each time period; and amount of imported fuel of each type in each time period .
- Eight types of constraints in the model – node balance equation for each node in each time period; network transmission capacity on each arc in each time period; generation capacity of each type of generation plants in each node in each time period; maximum investment amount available for each unit type in each node in each time period; fuel demand (local market, domestic production, and imported) for each fuel type in each period; cumulative generation capacity for each unit type in each node during each time period; cumulative transmission capacity on each arc in each time period; and, nonnegativity of the decision variables.
- The model is a multiobjective linear programming problem with (3*N*θ*T)+(3*A*T)+(F*T) variables, and (T*[N+2*A+3*N*θ+F]) constraints; where, N=set of (energy demand/supply) nodes, T=set of periods in planning time horizon, A=set of transmission lines or arcs, θ=set of generation unit types, and F=set of fuel types. For the case study problem, N=26, T=10, A=37, θ=8, and F=4 resulting in 7390 variables and 7280 constraints.
- The proposed solution approach of this model consists of three phases.
    - Phase One - a set of nondominated[1] solutions (expansion plans) are found using four multicriteria programming methods: max-min, min-max, compromise programming, and weighting approach [5]. These methods do not require any preference information from the decision maker (DM). The first three methods provide one solution each.
    - Phase Two – since the fourth method in Phase One can generate a very large number of solutions, these are reduced to a smaller set by using a K-means clustering algorithm[2]. Thus, a total of no more than K+3 nonodominated solutions (expansion plans) remain after Phase Two.
    - Phase Three - the set of nondominated solutions after Phase Two are ranked-ordered by using the Analytical Hierarchy Process (AHP) [10]. To use AHP[3], the four criteria are first arranged in a hierarchy: at hierarchy one are the four original criteria; at hierarchy two, criterion one (cost) is subdivided into three sub-criteria (investment cost, operation cost, and transmission cost) and criterion four (risk) is divided into two sub-criteria (potential fuel price fluctuation and nuclear risk). Next, pair-wise judgments/comparisons between criteria and sub-criteria are provided by the decision maker. Finally, the pair-wise judgments are used to develop weighing factors for the four original objectives to compute overall ranking scores for the alternate expansion plans.

MGEP model two (MGEP-2), presented in [2], has the following basic features:

- Multiple criteria - investment and operation costs (minimize); environmental impact, i.e., total aggregate carbon dioxide emission from non-renewable energy sources, (minimize); imported fuel (minimize); and, energy price risks due to exposure to fuel price volatility in the expansion decisions (minimize). While the objective descriptions in MGEP-2 and MGEP-3 (described below) look similar, the actual mathematical equations are quite different because of the way planning horizon has been modeled and the different variables involved.

- Model represents generation-transmission supply chain as a network, where nodes represent power demand or supply points.
- The power flow through an arc is expressed in terms of both the voltage phase angle at each node and the circuit susceptance.
- Modeled as a single-period, deterministic, multiobjective, mixed-integer, and non-linear generation expansion planning problem.
- Five groups of decision variables are used in the model: the set of new units of different types at each node; generation amount from each unit type (new and existing) at each node; the number of new circuits on each arc; the voltage phase angle at each node; and, the amount of imported fuel of each type. All variables are non-negative and the investment decision variables must be integers.
- Seven types of constraints are in the model – node balance equation for each node; transmission capacity of each arc; generation capacity of each type of generation plants in each node; investment capacity of each unit type in each node; fuel demand (local market, domestic production, and imported) for each fuel type; cumulative limit on the number of new generation units of each type; total power generation capacity (existing and new) in the system must be higher than the total demand by the system operating reserve factor; and, cumulative limit on total investment in new transmission lines.
- The model has $(2*N*\theta)+A+N+F$ variables of which $(N*\theta)+A$ are integers, and $N+(2*A)+(N*\theta)+F+\theta+1$ constraints, of which, N+A are non-linear. For the case study problem, N=7, A=7, θ=8, and F=4, resulting in 130 variables (of which 63 are integers) and 89 constraints (of which 14 are non-linear).
- The solution method proposed to solve this model consists of the following three steps: (1) generate a set of non-dominated (Pareto optimum, noninferior or efficient) solutions for the model; (2) group similar solutions via the K-Means algorithm in order to reduce the number of alternatives (nondominated solutions) to be considered; and, (3) use Analytical Hierarchy Process (AHP) to identify the most preferred alternative. The hierarchy used here is the same one used in MGEP-1.

  A new evolutionary computation concept based algorithm (EA) was developed (see [11] for more detail) to determine the set of the non-dominated solutions, or the Pareto front, in step (1). In EA, there are no assumptions of convexity of the objective functions like in traditional methods, and in one iteration of the algorithm, it is possible to get more than one non-dominated solution. With the aid of evolutionary algorithm, it may be possible to obtain an approximation to the true Pareto front of non-dominated solutions for multiobjective optimization problems. EA is a stochastic optimization technique inspired by the process of natural evolution. The creation of descendants is a stochastic procedure that includes competition and performance-based selection from a population of parents and children. Through simulated generations the survival of the most apt individuals allows one to find good approximations of complex optimization problems.

MGEP model three (MGEP-3), presented in [3], has the following basic features:

- Multiple criteria - four fuzzy objectives: investment, transmission and operation cost (minimize); environmental impact in the form of the aggregate carbon dioxide emissions from fossil-fuel plants (minimize); amount of imported fuel (minimize); and the exposure to fuel price volatility risk (minimize).
- Model represents generation-transmission supply chain as a network, where nodes represent power demand or supply points.
- Planning horizon is represented as a single time period with fuzzy objectives and fuzzy constraints (because of fuzzy parameters).
- Five groups of decision variables in the model are: power generation from the existing units of each type at each node; power generation from new units of each type at each node; power flow through each arc; additional amount of new power transmission capacity in each arc; and, amount of imported fuel of each type.
- The fuzzy multiobjective linear programming model has five types of constraints: flow balance constraints (involving fuzzy demand in each node); transmission capacity limits on each arc; generation capacity of existing plants; generation capacity limits on new units; and, availability of domestic and imported fuel.

- The model has $(2N*\theta)+2A+F$ variables (which are all non-negative) and $2N*(1+\theta)+A+F+4$ constraints (of which N are fuzzy). For the case study problem, N=7, A=7, $\theta=8$, and F=4 resulting in 130 variables and 141 constraints (of which 7 are fuzzy).
- The solution method proposed to solve this problem involves the following major steps:
  - Fuzzy objectives are converted into fuzzy goal constraints using triangular membership functions.
  - The problem is transformed into a single objective linear programming problem through the use of a degree of satisfaction variable (which becomes the objective function of the transformed maximizing LP).
  - Several scenarios are developed and sensitivity to variations in significant model characteristics and assumptions by manipulating different factors are investigated. For the case study problem, six scenarios were investigated to show the applicability of the MGEP-3 model to a realistic size problem.

Table 1 provides a side-by-side review of the similarities and differences among the three models. Note that while the descriptions of objectives and constraints may appear to be the same, the actual equations are quite different because of how the variables have been defined and other factors involved.

Table 1: Principal Features of the Three Models.

Features		MGEP-1 [1]	MGEP-2 [2]	MGEP-2 [3]
Objectives	Description	Investment, operation and transmission costs; Total CO_2 emission; Amount of imported fuel; Energy price risks	Investment and operation costs; Total CO_2 emission; Amount of imported fuel; Energy price risks	Investment, operation and transmission costs; Total CO_2 emission; Amount of imported fuel; Energy price risks
	Type	Linear, deterministic	Linear, deterministic	Linear, fuzzy (with fuzzy goals)
Variables	Type	Continuous, deterministic	Mixed integer, deterministic	Continuous, deterministic
	Number#	$(3*N*\theta*T)+(3*A*T)+(F*T)$	$(2*N*\theta)+A+N+F$; $(N*\theta)+A$ integers	$(2N*\theta)+2A+F$
Parameters	Type	Deterministic	Deterministic	Deterministic and fuzzy
Constraints	Type	Linear, deterministic	Linear and non-linear, deterministic	Linear, deterministic and fuzzy
	Number	$(T*[N+2*A+3*N*\theta+F])$	$N+(2*A)+(N*\theta)+F+\theta+1$; $(N+A)$ non-linear	$2N*(1+\theta)+A+F+4$, N fuzzy
Model representation	Type	Generation-transmission supply chain as a network	Generation-transmission supply chain as a network	Generation-transmission supply chain as a network
	Nodes	Power demand and/or supply points	Power demand and/or supply points	Power demand and/or supply points
	Arcs	Transmission lines	Transmission lines	Transmission lines
	Power flow	Considers the circuit susceptance	Considers voltage phase angle at each node and the circuit susceptance	Considers the circuit susceptance
	Planning horizon	Multiple time periods	Single time period	Single time period
Solution method		Multicriteria programming methods; K-means clustering algorithm; AHP	Estimate Pareto frontier using evolutionary algorithm; K-means clustering algorithm; AHP	Use triangular membership functions for fuzzy goals and parameters; convert to a single objective LP; use scenarios to identify potential solutions

#N=number of nodes, T=number of time periods, A=number of arcs (transmission lines), F=number of fuel types, θ=number of generation unit types

Case Study Problem Overview

Table 2 provides the key features of the variations of the case study problem used to illustrate the models and the proposed solution methods.

Table 2: Case Study Problem Features

Features		MGEP-1 [1]	MGEP-2 [2]	MGEP-3 [3]
Model	Number of nodes	N=26	N=7	N=7
	Number of arcs	A=37	A=7	A=7
	Number of time periods	T=10	T=1	T=1
	Number of power generation types	θ=8	θ=8	θ=8
	Number of fuel types	F=4	F=4	F=4
Constraints	Number	7280, all linear	89, of which 14 are non-linear	141 (all linear), of which 7 are fuzzy
Variables	Number	7390, all continuous	130, of which 63 are integers and the rest are continuous	130, all continuous
Objective functions (Goals)	Number/type	All 4 are linear and deterministic	All 4 are linear and deterministic	All 4 are linear and have fuzzy goals

The case study models were solved using GAMS/CPLEX software for MGEP-1 and MGEP-3 models (which are linear programs) and evolutionary algorithm for MGEP-2 programmed in C++. All problems were solved using a Intel core i7 2.80 GHZ CPU computer with 500GB of hard disk and 8 GB of memory, it took less than 1 minute of computational time to generate a Pareto front for MGEP-1, MGEP-2 and MGEP-3 problems.

3. Concluding Remarks

In this paper, we have summarized the key features and characteristics of three multicriteria power generation expansion planning problems. While the models are similar, they, however, address different aspects of a realistic problem of this nature. Table 1 provides a succinct summary of the similarities among and differences between the three models – each model introduces a different emphasis in the model. In addition, the papers have proposed solution methods specific to each model. A common case study is used to illustrate the model, proposed solution methods, and issues involved in the execution of these models. A general conclusion from this review of the three methods is that there is no one "best" model or a "best" solution approach. Considerations of problem granularity level impact the complexity of the resultant model. A common recurring problem was the inability to solve a realistic size problem in a reasonable computation time because all the problems are NP-hard and, therefore, grow in size exponentially. This appears to be critical if one wishes to combines features of the three models in one encompassing model formulation or wants to add other features. So, a fertile area of future research would be in developing very efficient solution techniques even if that involves some trade-off in the model granularity. The models can also be extended by considering other relevant objectives, using multiple time periods (in MGEP-2 and MGEP-3), more explicit consideration of non-linearity (in objectives and constraints) and integrality of variables, and adding additional variables and/or constraints that make the problem more realistic in nature. However, all these will add to the problem complexity and size, making it even more difficult to solve in a realistic time frame. Another area of emerging research is the potential impact of Smart Grid Technology on generation expansion transmission problems.

Footnotes

[1]A non-dominated solution is a feasible solution to the multiobjective problem for which no improvement in any objective function is possible without sacrificing at least one of the other objective functions.

[2]K-means algorithm is one of the simplest unsupervised learning algorithms that solve the clustering (grouping) problem. The procedure follows a simple and easy way to classify a given data set through a certain number of clusters fixed a priori.

[3]AHP is a Multiple Criteria Selection Method that is represented in terms of levels of a hierarchy. At the top-level is the goal or over-all purpose of the problem. The subsequent levels represent criteria, sub-criteria, etc. The last level represents the decision alternatives.

References

1. Ceciliano-Meza, J. L., Yildirim, M. B., and Masud, A. S. M., 2007, "A Model for the Multiperiod Multiobjective Power Generation Expansion Problem," IEEE Transactions on Power Systems, 22(2), 871-878.
2. Ceciliano-Meza, J. L., Yildirim, M. B., and Masud, A. S. M., 2009, "A Multiobjective Evolutionary Programming Algorithm and Its Applications to Power Generation Expansion Planning," IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans," 39(5), 1086-1096.
3. Yildirim, M. B., Nezami, F. G., Masud, A. S. M., and Ceciliano-Meza, J. L., 2011, "A Fuzzy Multicriteria Generation Expansion Planning Model," International Journal of Multicriteria Decision Making, 1(2), 133-154.
4. Masud, A. S. M.and Ravindran, A., 2008, "Multiple Criteria Decision Making," in Operations Research and Management Handbook, A. Ravindran (ed.), CRC Press, Boca Raton, Florida, Chapter 5: 1-41.
5. Hwang, C. L. and Masud, A. S. M., 1979, Multiple Objective Decision Modeling-Methods and Applications, Springer-Verlag, New York.
6. Latorre, G., Cruz, R.D., Areiza, J.M., and Villegas, A., 2003, "Classification of publications and models on transmission expansion planning," IEEE Transactions on Power Systems, 18(2), 938 – 946.
7. Kannan, S., Slochanal, S.M.R., Padhy, N.P., 2005, "Application and comparison of metaheuristic techniques to generation expansion planning problem," IEEE Transactions on Power Systems, 20(1), 466 – 475.
8. Voropai, N., and Ivanova, E., 2002, "Multi-Criteria Decision Analysis Techniques in Electric Power System Expansion Planning," International Journal of Electrical Power Energy Systems, 24(1), 71-78.
9. Zhu, J., and Chow, M., 1997, "A Review of Emerging Techniques on Generation Expansion Planning," IEEE Transactions on Power Systems, 12(4), 1722-1728.
10. Saaty, T., 1980, The Analytical Hierarchy Process, John Wiley, New York.
11. Ceciliano-Meza, J.L., 2006, Multicriteria Analysis of Power Generation Expansion Planning, PhD Dissertation, Department of Industrial and Manufacturing Engineering, Wichita State University.