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A multi-step multi-objective generation expansion planning model-A case study in Mexico

Rodrigo Palacios[a, a*], Eduardo Valdes[b], Rafael Batres[a]

[a] *Laboratorio Binacional para la gestión inteligente de la sustentabilidad energética y la formación tecnológica. Tecnológico de Monterrey. Campus Cuernavaca. Morelos, Mexico*

[b] *Universidad Autonoma de Nuevo Leon. Nuevo Leon, Mexico*

Abstract

Planning in the energy sector implies multiple and conflicting objectives. Multi-objective models allow the analysis of the inter-relationships and trade-off solutions to be obtained. This paper presents a mixed integer linear model for multi-step multi-objective generation expansion planning (MMGEP). The MMGEP problem is defined as the problem of determining the answers to the following questions: What types of generation technologies are to be added to the grid? What is the capacity of each new generation plant? Where will the plant be located? When will the plant be located? The MMGEP objectives are to minimize the global cost of the system, minimize the environmental impact and maximize the social profits. The proposed model is based on a real power system in Mexico for the planning period between 2017 and 2037. The problem was solved using the NSGA-II algorithm.

Keywords: Energy planning, generation expansion planning, capacity expansion planning, Generation expansion planning

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1. Introduction

Generation expansion planning (GEP) is the problem of finding an additional capacity schedule that satisfies the forecasted load demand with a given reliability criteria over a planning horizon of typically 10–30 years [1]. It has been one of the most studied problems in operation research. This problem appears with different alternative terms such as follows: power system planning, capacity expansion planning, GEP, power system expansion planning, least cost electricity planning, and energy supply planning [2].

Multi-objective optimization models have received considerable attention in the GEP problem because of the need to include multiple and opposing aspects [3,4]. Solving multi-objective optimization considers multiple objectives that are optimized simultaneously, thus obtaining a set of non-dominated solutions. Previous studies consider the cost and other objectives such as the environmental impact [5] or emissions [6,7], but the problems are solved as single-objective problems. In [8], the authors presented a comparison of the different development plans used for the Mexican system in the period between 2005 and 2014 and concluded that the energy supply system should not be expanded solely in terms of minimizing the cost. In [9], the problem has been modeled with four objective functions, three relating to cost and one to CO_2 emissions, for the same period. The same authors compared their model with a bi-objective one in which they considered three cost elements using the AHP methodology [10].

Multi-step multi-objective generation expansion planning (MMGEP) involves finding the optimal plan for the construction of new capacity, according to different economic, environmental and social objectives, and is subject to diverse and complex constraints for each stage of the planning period. This problem is currently at a turning point, mainly owing to the following three reasons: the integration of renewable sources, the liberalization of the sector, and the increase in interest in social and environmental

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Corresponding author. Tel.: +34 699 791764; *E-mail address*: rodrigopalacios@itesm.mx.

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aspects.

The World Energy Council has developed the concept *Energy Trilemma* to address the triple challenge of obtaining safe, affordable and environmentally sustainable energy [11]. This concept achieves high performance in all three areas and involves the assessment of the complex interlocking links between the public and private sectors, governments and regulators, economic and social factors, national resources, environmental concerns, and individual behavior.

The main contribution of this paper is the development of a model based on a holistic methodological approach to collect the global effects of energy planning in three dimensions. The proposed model has been applied to a real case study concerning the Mexican GEP problem for the period between 2017 and 2037. The following sections describe the model, case study, results, conclusions, and future work.

2. Multi-step Multi-Objective Generation Expansion Planning Model

In the MMGEP problem, the goal is to find the optimal plan for the construction of new generation capacity according to different economic, environmental, and social objectives. The problem comprises generating the best expansion plan in terms of the type of generation technology, location, time, and size with the purpose of satisfying the energy demand. The multi-step approach ensures a compromise between the optimality of the solutions for each planning period and the whole of the planning process.

It is important to note that although the decision problem involves the new generation plants, to complete the integration to the energy system, we need to consider the addition of new transmission lines. The following four characteristics of decision variables are considered, which are common for plants and lines: Where the element will be located? When the element will be located? What type of elements will be added? What will be the capacity of each element? The main characteristics of the MMGEP model are presented in Table 1.

Table 1. The main characteristics of the MMGEP model.

Characteristic	MMGEP model
Time horizon	Large Term (21 years)
Geographical coverage	National
Systemic approach	Top down
Type	Deterministic
Time perception	Dynamic
Data	Quantitative and qualitative

2.1. Sets and variables

The transmission network is represented by a graph, $G = (N, A)$, where N represents the set of demand and supply regions and A represents the set of existing transmission lines. The other given data are: Q, F, and Y. Q is a set of technologies, F is a set of fuels, and Y is a set of years within the planning horizon.

In the model, eight variables are considered: Three related to the plants, three related to the lines, one related to the import of fuel and one related to the operative reserve margin. For each region i, for each technology q, and for each year of planning y, the new generation capacity added (MW), the cumulative capacity (MW), and the generation (MWh) are represented by the variables $NewCap_{i,q,y}$, $Cap_{i,q,y}$, and $Gen_{i,q,y}$, respectively. The new transmission capacity (MW), the cumulative transmission capacity (MW), and the energy flow (MWh) for the transmission lines joining the regions (i,j) in each year y are represented by the variables $NewLin_{i,j,y}$, $Lin_{i,j,y}$, and $Flo_{i,j,y}$, respectively. The last two variables represent the amount of imported fuel of type f ($FueImp_{f,y}$) and the operative reserve margin for each region i ($ResMar_{i,y}$) both for the year of planning y.

2.2. Objective functions

The objective functions considered in the multi-objective optimization problem are as follows: to minimize the global cost of the energy system, to minimize environmental impact, and to maximize the social profits. It is worth mentioning that the last objective has not been explicitly considered in the literature regarding multi-objective formulations for the generation expansion problem.

2.2.1. Minimizing the global cost

This objective function seeks to minimize the total cost, which is composed of the investment cost for additional generation and transmission capacity, the operational cost of the generation plants and transmission lines, and the importation cost of fuel. $NewCapCos_{i,q,y}$ and $GenCos_{i,q,y}$ are the investment and operational cost per MW, respectively.

$$Min.\ f_1 = \sum_{y\in Y}\left(\sum_{i\in N, q\in Q}\left(NewCapCos_{i,q,y}\cdot NewCap_{i,q,y} + GenCos_{i,q,y}\cdot Gen_{i,q,y}\right) + \sum_{(i,j)\in A}\left(NewLinCos_{i,j,y}\cdot NewLin_{i,j,y} + FloCos_{i,j,y}\cdot Flo_{i,j,y}\right) + \sum_{f\in F}\left(FueImpCos_{f,y}\cdot FueImp_{f,y}\right)\right) \tag{1}$$

2.2.2. Minimizing the environmental impact

This objective function is to minimize the environmental impact of new generation capacity and the emissions generated during the operation of the newly added plants. The emissions are measured in tons of CO_2 equivalent to simply collect the emissions of CO, CO_2, NO_x, SO_2, and CH_4.

$$Min. f_2 = \sum_{i\in N, q\in Q, y\in Y}\left(EnvImpCos_q\cdot NewCap_{i,q,y} + Emi_{i,q,y}\cdot Gen_{i,q,y}\right) \tag{2}$$

2.2.3. Maximizing social profit

This objective function is defined as the total employment generated by the construction of new capacity and transmission lines and by the operation of all capacity plants and transmission lines.

$$Max.\ f_3 = \sum_{y\in Y}\left(\sum_{i\in N, q\in Q}\left(NewCapEmp_{i,q,y}\cdot NewCap_{i,q,y} + GenEmp_{i,q,y}\cdot Gen_{i,q,y}\right) + \sum_{(i,j)\in A}\left(NewLinEmp_{i,j,y}\cdot NewLin_{i,j,y} + FloEmp_{i,j,y}\cdot Flo_{i,j,y}\right)\right) \tag{3}$$

2.3. Constraints

In the MMGEP problem the following constraints are considered.

Equation (4) assures the coverage of the demand with its corresponding reserve margin for each region, in each planning period.

$$\sum_{(j,i)\in A} Flo_{j,i,y} - \sum_{(i,j)\in A} Flo_{i,j,y} + \sum_{q\in Q} Gen_{i,q,y} = Dem_{i,y}\cdot\left(1 + ResMar_{i,y}\right);\forall i\in N, y\in Y \tag{4}$$

Equations (5) and (6) ensure that the generation in plants and flow of energy in the lines does not exceed the cumulative capacity each year. $EffCap_{i,q}$ and $EffLin_{i,j}$ are the efficiency of the plants and lines, respectively.

$$Gen_{i,q,y} \le EffCap_{i,q}\cdot Cap_{i,q,y};\qquad \forall\ i\in N, q\in Q, y\in Y \tag{5}$$

$$Flo_{i,j,y} \le EffLin_{i,j}\cdot Lin_{i,j,y};\qquad \forall\ (i,j)\in A, y\in Y \tag{6}$$

Equations (7) and (8) update the installed capacity for each type of technology in each region and the installed capacity of transmission in each line, for each planning period.

$$Cap_{i,q,y} = Cap_{i,q,y-1} + NewCap_{i,q,y} \; ; \; \forall\, i \in N, q \in Q, y \in Y \tag{7}$$

$$Lin_{i,j,y} = Lin_{i,j,y-1} + NewLin_{i,j,y} \; ; \; \forall\, (i,j) \in A, y \in Y \tag{8}$$

Equation (9) ensures that the amount of fuel to cover the generation is consistent with the amount of fuel that is either available in the country or imported. *FueCon*$_q$ is the fuel consumption of each technology per MW, and *FueNat*$_{f,y}$ is the national fuel production *f* per year.

$$\sum_{i\in N, q\in Q} FueCon_q \cdot Gen_{i,q,y} = FueImp_{f,y} + FueNat_{f,y} \; ; \; \forall\, f \in F, y \in Y \tag{9}$$

Equation (10) establishes the operating reserve margin necessary to cover any possible errors in the forecast of the demand and in the forecast of the generation of renewable sources. *DemFor*$_{i,y}$ and *RenFor*$_{i,y}$ are the margin forecasts of the demand and generation of renewable sources, respectively.

$$ResMar_{i,y} = RenFor_{i,y} + DemFor_{i,y} \; ; \; \forall\, i \in N, y \in Y \tag{10}$$

Equation (11) prevents the use of a greater capacity than what is available in each region, for each type of resource.

$$ResAva_{i,q} \geq Cap_{i,q,y-1} + NewCap_{i,q,y} \; ; \; \forall\, i \in N, q \in Q, y \in Y \tag{11}$$

3. Case Study: Mexico

The proposed model has been evaluated using the Mexico power system. This system is represented by 50 nodes (regions) and 66 arcs (transmission lines); the capacities of the regions and lines are shown in Figure 1. The planning horizon consists of a period of 21 years (2017–2037) using 2016 as the base year, which has a current capacity of 73,510 MW. The generation technology options considered for the capacity additions are as follows: coal units, conventional steam units, gas turbines, gas combined cycle, nuclear, wind, solar, geothermal, and hydro units. In terms of the non-renewable fuels, coal, gas, oil, and uranium were considered.

The data used to construct the model coefficients were gathered from several sources with a strong emphasis to be in a good agreement with the real values observed in the Mexican case study. For this system, the resulting MMGEP model had 21 • (3 • 50 • 9 + 3 • 66 • 2 + 4 + 50) = 37,800 variables and 21 • (3 • 50 • 9 + 2 • 50 + 2 • 66 • 2 + 4) = 36,078 constraints. The parameters are available from https://github.com/CYBERneticSYNergic/Mexico_2017_2037.

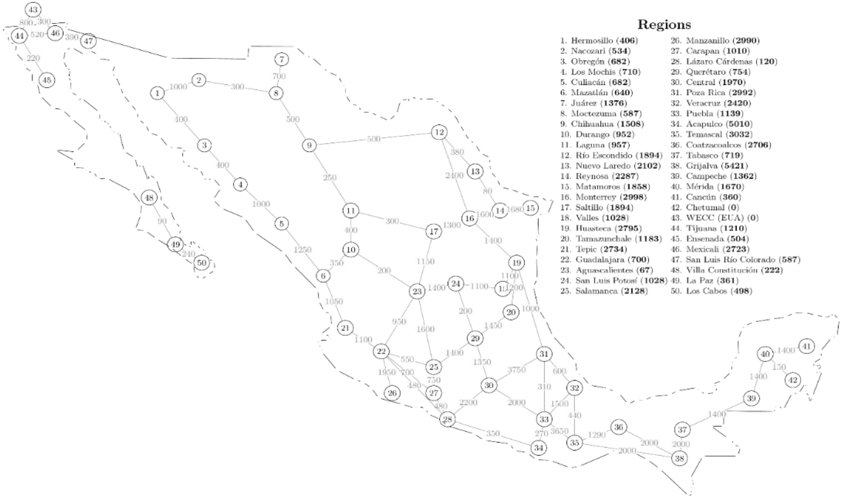

Fig. 1. The generation and transmission capacity for each region and transmission line, respectively.

4. Methodology

The application of metaheuristic algorithms has been widely used and developed for the GEP problem. Among them, the most used have been genetic algorithms in their multiple variants [12]. Genetic algorithms are metaheuristic procedures based on the theory of natural selection for a species. In a manner similar to that in which a population of individuals adapts to their environment through their competence, reproduction, and mutations through the passage of generations, a set of solutions to an optimization problem are improved by procedures that emulate these evolutionary operators.

In the case of multi-objective optimization problems, the adaptation or fitness of the population refers to the closeness and similarity to the Pareto front. The manner in which this adaptation is achieved is typical of each algorithm. In particular, the NSGA-II algorithm [13] favors individuals according to their level of non-dominance [14]. The algorithm begins with an initial population P of N individuals. According to their fitness, the individuals are selected to reproduce and a new offspring population R of size N is generated. Optionally, some individuals of R can mutate according to the probability of mutation P_m. Then, the individuals from P and R compete with each other for inclusion in the next generation.

In the area of energy, the NSGA-II algorithm has been widely used in the reactive power planning problem [15,16,17,18,19], the optimal power flow problem [20,21,22] and the GEP problem [6,23].

An individual can be represented by two three-dimensional matrices. The first one, stores the generation of each region and technology for each year, and the second one, a node arc matrix, stores the energy flow between the regions for each year. The rest of the MMGEP variables can be calculated from these matrices.

Building a feasible individual comprises three steps. First, the capacity of the network is increased by iteratively selecting a region and technology to open a new plant until the total generation exceeds the demand of the first year, the reserve margin and a surplus S, which is a parameter. The selection of new plants can be random or in favor of any of the three objectives considered. In the second step, the regions that generate more energy than the amount required send their excess to those that do not meet their demand. The surplus S ensures that the demand of each region is satisfied despite the loss of energy during transport between the regions. Finally, in the third step, the excess generation of the plants was eliminated to satisfy the amount of energy required by each region. Similarly, the selection of plants that decrease their generation can be random or in favor of any of the three objectives considered. We call these steps IncreaseCapacity, SendFlow, and RemoveExcess, respectively. This process allows one to make feasible any individual whose distribution network does not comply with MGEP constraints, which from now on will be called the MakeFeasible process.

The crossover operator constructs two offsprings from a pair of parents. For each region, one child inherits the technologies in common while the other inherits the technologies used for both parents in that region. In other words, one child inherits the intersection of the technologies from both parents in one region and the other the union of these. The capacity of a technology of a child is the greatest for the same technology in both parents. Then, both offsprings are made feasible using the MakeFeasible procedure.

The mutation operator consists of randomly eliminating a technology used in some regions. Then, we use the MakeFeasible procedure on the resultant individual.

With the procedures described, the NSGA-II algorithm allows one to find a set of non-dominated solutions that represent the planning of the first year after the passage of G generations. To plan the following year, MakeFeasible is first applied to all the individuals in the front so that they meet the new demand and then proceeds with the evolution of another G generations. Successively, we get the planning for each year of the planning horizon in the MMGEP problem.

5. Results

The NSGA-II algorithm was implemented in Python 3.6 using parallel computing on a PC equipped with an Intel Core-i7 processor having 3.4 GHz speed and 16 GB of RAM. A statistical analysis was performed to set the parameters of the algorithm for the case study using the hypervolume of the Pareto front as a measure of quality. The best values of the parameters were as follows: size of population N = 300, number of generations per year G =150 and probability of mutation P_m = 0. On average, the algorithm takes 30 min to plan a year.

The resulting Pareto front has on average 53 non-dominated solutions and each of these being mathematically equivalent and representing the best solutions that optimize the three objectives simultaneously. Table 2 shows the best solution of each objective per year of planning. The results are shown in Fig. 2, where the blue dot represents the non-dominated solution with the best value in the objective cost function. Similarly, the green and red points represent the non-dominated solution with the best value in the objective functions of environmental impact and social benefits, respectively.

Figs. 3–5 show the best solutions found for the total cost, the total environmental impact, and the amount of employees generated for the 21 year planning. The color scale in the regions indicates the generation level with a dark color representing increased generation. The icons on the node represent the technologies installed in each region. A continuous line between two nodes indicates that only the existing transport line was used. A dashed line indicates that more capacity was installed in the transport line.

In the minimum total cost solution (Fig. 3), the fossil fuel technologies are preferred, representing 89.6% of the total installed capacity. There is equitable generation between the regions, thus reducing the transport of energy and the losses. Solar units are the most installed type of unit, with a total of 105. The total installed capacity is 76,920 MW.

Figure 4 shows the case of the solution with the minimum environmental impact. The generation is concentrated in the regions of Veracruz, Acapulco, and Grijalva. There is an increase in the use of renewable energy, highlighting the use of nuclear energy, which doubled the installed capacity in 2016. The total installed capacity is 75,980 MW, which is less than that installed in the minimum cost solution, but the total energy transported was increased.

The solution with the maximum social benefits is also the one that has the highest total cost of investment, with the difference between the other two solutions being more than 2000 billion. Figure 5 shows the solution with the maximum number of jobs generated. The solar and wind units are the most installed type of units with a total of 113 for each type of unit. The installed capacity of renewable energy units is greater than that installed in the solution with the least environmental impact. The total installed capacity increased by 17% throughout the network.

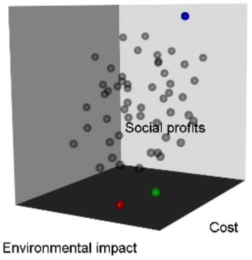

Fig. 2. The Pareto front of the non-dominated solutions.

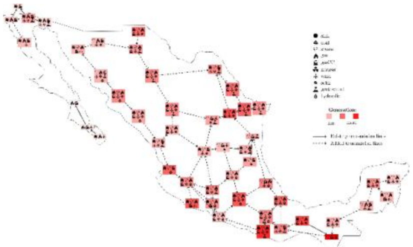

Fig. 3. The best solution for minimizing the cost.

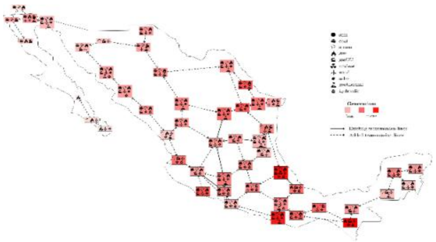

Fig. 4. The best solution for minimizing the environmental impact.

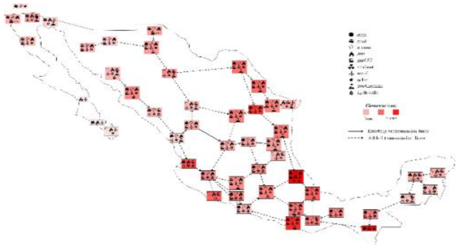

Fig. 5. The best solution for maximizing the social profits.

Table 2. The values of the best solutions for each of the objectives. For the three objective functions and each year.

	Best solution for minimizing the cost			**Best solution for minimizing the environmental impact**			**Best solution for maximizing the social profits**		
Year	**Cost (E+10)**	**EnvImp**	**SocPro**	**Cost (E+10)**	**EnvImp**	**SocPro**	**Cost (E+11)**	**EnvImp**	**SocPro**
2017	7.2293	119,884	430,927	7.2471	104,580	433,252	7.9522	208,493	876,533
2018	7.2298	119,884	441,549	7.2563	104,580	442,534	7.9638	215,424	881,301
2019	7.3216	123,869	455,121	7.4632	108,353	454,165	8.1638	208,215	883,096
2020	7.4273	129,894	469,867	7.7085	112,961	469,506	8.4671	215,424	885,584
2021	7.5672	133,826	488,144	8.1872	116,180	498,430	8.6518	225,903	888,766
2022	7.6973	139,251	507,617	8.3612	119,124	511,249	8.9219	224,384	892,467
2023	7.7274	143,976	525,996	8.5863	123,368	529,981	9.1601	223,497	894,764
2024	7.8653	150,329	543,945	8.7992	127,675	550,870	9.4727	229,673	895,480
2025	7.9124	152,553	559,488	8.9918	131,568	568,644	9.5730	221,088	896,928
2026	8.0024	161,674	584,869	9.2472	136,250	584,902	10.0160	210,721	897,040
2027	8.1108	168,210	612,561	9.6275	143,397	607,790	10.3580	232,655	898,836
2028	8.1972	173,387	630,704	10.0032	150,824	629,695	10.6185	207,747	899,844
2029	8.3274	181,305	652,954	10.1934	153,697	641,291	11.0215	212,952	902,530
2030	8.4034	187,022	671,302	10.5627	160,611	672,402	11.3033	220,074	904,152
2031	8.6342	191,535	689,739	10.8281	165,731	696,230	11.5369	242,175	905,958
2032	8.6895	199,291	717,485	11.2638	174,172	726,322	11.8924	232,740	907,999
2033	8.7027	206,571	733,784	11.5683	179,857	740,664	12.2591	233,280	908,926
2034	8.8682	218,093	762,299	11.8934	185,227	773,691	12.8137	235,227	909,800
2035	9.1055	229,593	796,085	12.4249	195,395	803,658	13.3755	231,672	910,765
2036	9.3164	237,254	821,663	12.7859	201,999	827,157	13.7731	237,943	912,346
2037	9.3672	249,384	850,513	13.2756	210,968	861,589	14.3787	238,834	912,850
Total	**171.7025**	**3,616,783**	**12,946,610**	**206.2748**	**3,106,517**	**13,024,020**	**221.6731**	**4,708,121**	**18,865,965**

6. Conclusions and Future Work

A multi-step multi-objective generation expansion planning model has been presented in this paper. The integration of three opposite criteria, namely economic, environmental, and social along with the details of the geographical location of the new lines and generation units, the efficiency of the equipment, and the allowed capacity per technology and region are some of the characteristics of this model, which have not been considered simultaneously in previous studies.

The test results using an extensive size real power system and in its biggest expansion stage (the power system of Mexico for 2017–2037) demonstrate that it is feasible to solve the MMGEP. Providing the decision maker with a broad set of high-quality solutions as a compromise between the three established objectives.

The development of this model will continue to appropriately represent the complex reality of the problem and to appropriately represent the volatility of renewable sources. Further, another direction of our future work is the inclusion of policies and the interaction between private agents and users. Finally, we intend to develop an application that facilitates the decision maker to work with this methodology.

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