Multicriteria analysis of power generation expansion planning

MULTICRITERIA ANALYSIS OF POWER GENERATION EXPANSION PLANNING

A Dissertation by

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MULTICRITERIA ANALYSIS OF POWER GENERATION EXPANSION PLANNING

I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy with a major in Industrial Engineering

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ABSTRACT

This thesis describes and evaluates a set of multiobjective generation expansion planning models that include four objectives and importance given to renewable generation technologies while considering location of generation units. Using multicriteria decision making theory, these models provide results which indicate the most recommendable amount of each type of generating technology to install at each location. A framework to solve and generate alternative solutions is provided for each model, and representative case studies from the Mexican Electric Power System are used to show the performance of the proposed models and solution methods.

The models include a single-period model, a multi-period model, single-period mixed-integer non-linear model, and a fuzzy multi-criteria model. Among the attributes considered are the investment and operation cost of the units, the environmental impact, the amount of imported fuel, and the portfolio investment risk. The approaches to solve the models are based on multiobjective linear programming, analytical hierarchy process, and evolutionary algorithms.

The incorporation of more than three criteria to generate the expansion alternatives, the importance given to renewable generation technologies, and the geographical location of the new generation units are some features of the proposed models which have not been considered simultaneously in the literature. A novel multiobjective evolutionary programming algorithm has been proposed in this thesis.

Although the solutions obtained in this thesis can be considered as approximations to the real generation expansion planning problem, they look reasonable given the considered data and scenario. In addition, the computational effort to obtain the expansion plans is not high. With more accurate input data, the results can be better. Nowadays, the expansion planning of electric power systems is usually done by using sophisticated and costly computational tools. However, with the methodology described in this thesis, good and fast results can be obtained for the problem.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
BOT	Build, Operate and Transfer Arrangements
CFE	Comision Federal de Electricidad
CP	Compromise Programming
DM	Decision Maker
DP	Dynamic Programming
DSM	Demand Side Management
EA	Evolutionary Algorithm
EC	Evolutionary Computation
EP	Evolutionary Programming
GA	Genetic algorithm
GBD	Generalized Bender's Decomposition
GDP	Gross Domestic Product
GENCO	Generation Company
GEP	Generation Expansion Planning
IAEA	International Atomic Energy Agency
IGA	Improved Genetic algorithm
IMOLP	Interactive Multiple Objective Linear Programming
IRP	Integrated resource planning
MODM	Multiobjective Decision Making Methods
MODM	Multi-attribute Decision Making Methods
MGEP	Multiobjective Generation Expansion Planning
MOEA	Multiobjective Evolutionary Algorithms
MOGA	Multiobjective Genetic Algorithms
MOLP	Multiple Objective Linear Programming

LIST OF ABBREVIATIONS (Continued)

MOP	Multiobjective Optimization Problems
PD	Power Distribution Company
PG	Power Generation Company
PSO	Particle Swarm Optimization
RE	Renewable Energy
WASP	Wien Automatic System Planning

CHAPTER 1
INTRODUCTION

1.1 Background

In the traditional electricity supply chain, there are three main processes to deliver electricity to consumers: generation (electricity production plants), transmission (high voltage network), and distribution (local lines). Electricity all over the world is commonly generated from hydro, gas, coal, nuclear and geothermal resources, with an increasing production from renewable sources. Electricity is produced at generation stations and then connected to high voltage national electricity transmission networks, called national grids. The electricity transmission system brings electricity from remote generation sites to customers. High voltage electricity is transmitted across the grid to the points of distribution (substations). At the substations, electricity is reduced to lower voltage for distribution on local networks to commercial and domestic consumers. Consumers are the end users of electricity. The goal is to perform each one of these processes (generation, transmission and distribution) in the best way, when different objectives are considered. The problem addressed in this thesis is centered in the Generation phase, more precisely in its expansion planning.

The Generation Expansion Planning (GEP) Problem is defined as the problem of determining WHAT, WHEN and WHERE new generation units should be installed over a long-range planning horizon, to satisfy the expected energy demand. This problem is a strategic planning problem for any country. Since the demand is expected to increase in most cases, a small error in choosing the correct mix of generating facilities at assumed costs could result in a loss of hundred of millions of dollars, not to mention the social costs of not

meeting the energy demand.

The GEP problem has been one of the most studied problems as an early application of Operations Research. Several methods have been proposed to solve the problem. Optimization methods used to solve GEP include traditional approaches such as linear, mixed-integer, non-linear, decomposition schemes, dynamic programming; metaheuristics approaches such as simulated annealing, tabu search, evolutionary algorithms, particle swarm optimization and a combination of both [36]. GEP keeps being a challenge for several reasons: first of all, there is uncertainty associated with the input data, such as forecasts of demand for electricity, economic and technical characteristics of new evolving generating technologies, construction lead times, and governmental regulations. A second difficulty arises as a result of considering several objectives (often conflicting) simultaneously. These objectives might include minimization of total cost, maximization of the system's reliability, and minimization of environmental effects. Usually, other costs and factors besides generation expansion costs are incorporated as constraints in the optimization problem, i.e., most GEP problems have been modelled as single-objective models which consider only minimization of the total cost. However, the least-cost expansion plan often may not be the preferred option if environmental effects are considered. With the aid of the multiobjective models, decision makers may grasp the conflicting nature and the trade-offs among the different objectives in order to select satisfactory compromise solutions for the GEP problem.

1.2 Motivation of the Research

According to the International Energy Agency (IEA) [76] in 2003 more than 50% of the electricity production in the world was generated from non-renewable sources (Figure 1.1). This means high levels of CO_2 emissions to the atmosphere, thus contributing to the adverse greenhouse effect. Power systems like in the USA have incorporated policies to reduce the

amount of non-renewable generated electricity [43].

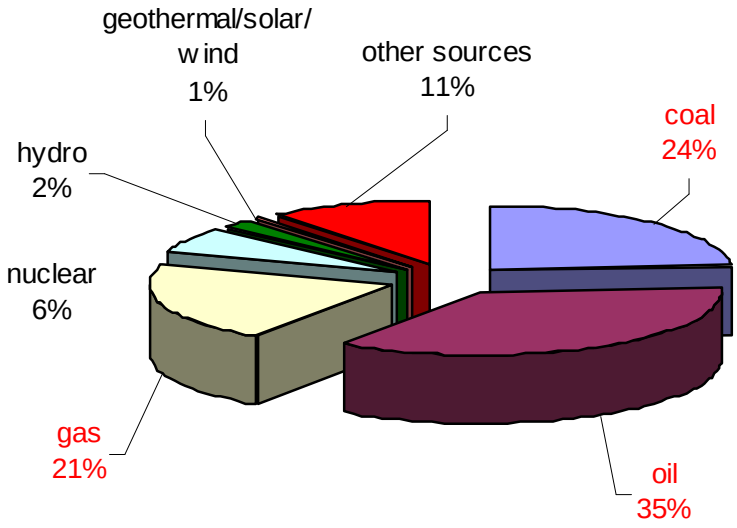

Figure 1.1: World energy production in 2003 [76]

Even with the intentions of reducing the amount of non-renewable generation units, the rapid change to renewable energy sources is unlikely because their high cost and their availability. Therefore, non-renewable units will continue to provide a large proportion of the world's commercial energy for the near future, making the world to think about carbon dioxide capture and storage (CCS) to control the CO_2 emissions from non-renewable units. The CCS process involves capture, transportation, injection and storage technologies. Capture of CO_2 is best carried out at large point sources of emissions, such as power stations as well as other large industrial production plants. After capture, CO_2 is usually compressed to form a supercritical or dense fluid and is generally transported by high pressure pipeline to the storage site [32].

Another issue more relevant to consider nowadays when planning the expansion of electric systems, is the high uncertainty in fuel prices and their increasing trend [76], as observed in Figure 1.2.

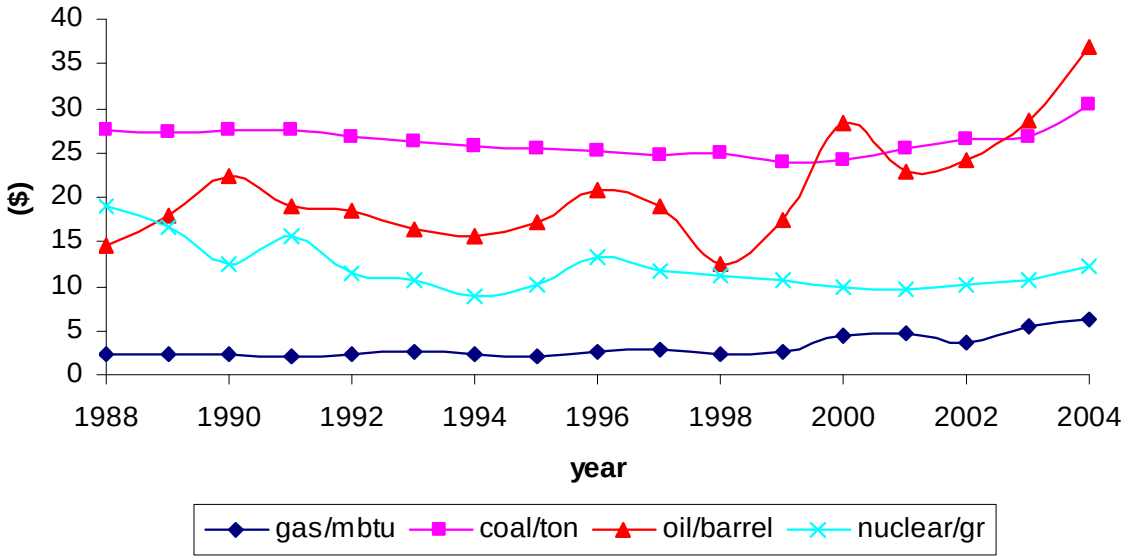

Figure 1.2: Fuel prices trend [76]

Generation units that use gas to produce electricity are usually cleaner and cheaper than other non-renewable technologies (oil and coal); however, the risk of high gas prices must be considered in the planning process. In addition, although it is known that renewable energy such as wind, hydro, solar, and geothermal are relatively expensive and limited in their availability, to mitigate the environmental impacts to the planet and the risk of depending only on few sources of energy, there is an increasing interest in renewable energy sources [3]. The alternative to produce more electricity from nuclear sources is also reconsidered by some decision makers [20].

The electricity demand in most countries of the world is increasing and more investments in generation are needed every year. For example, the expected electricity demand in Mexico [53] for the period (2005-2014) is shown in Figure 1.3.

In Mexico, Comision Federal de Electricidad (CFE) is the company that provides the services of generation, transmission and distribution of electrical power to 21.6 million customers, nearly 80 million Mexicans. Electric power generation by CFE is made possible through technologies available today: hydro power, thermal power, wind-driven power and nuclear power plants. Most of this electric power system is interconnected through all the

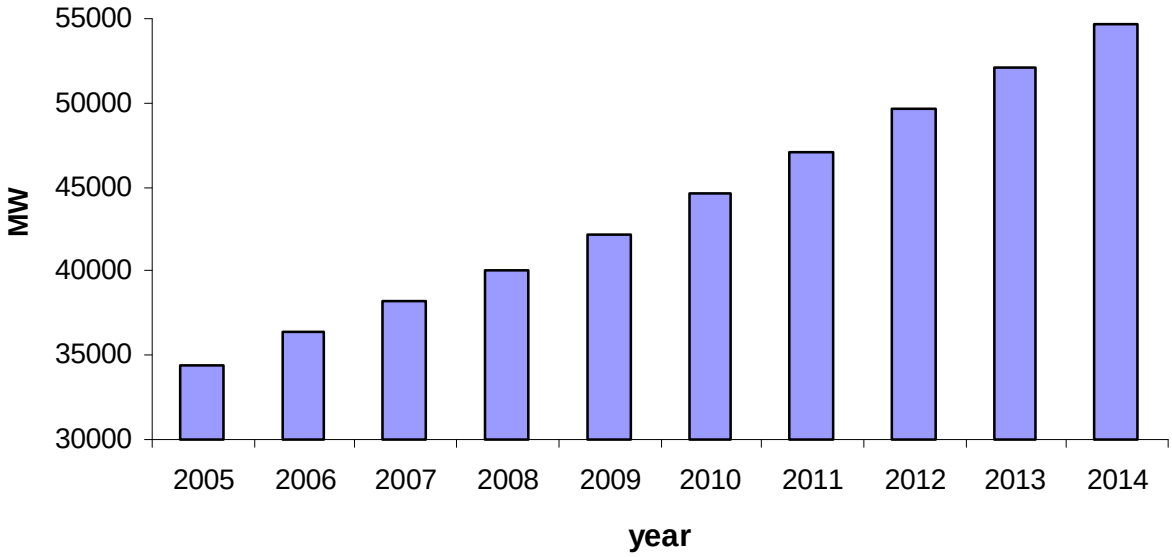

Figure 1.3: Projected electricity demand in Mexico [53]

territory. The condensed geographical regions that constitute the system are shown in Figure 1.4. The regions (nodes) in Figure 1.4 represent points where generation/demand exists in the system, and the arcs are the transmission lines that connect such electrical network. A computational tool used to decide the expansion of the system by CFE, is described in [56].

To consider all the aspects mentioned above is the desire of any decision maker in generation expansion planning, and that is the motivation for the work presented in this thesis.

1.3 Outline of the thesis

Literature on GEP applications is summarized in chapter 2. Some of these applications are single objective expansion models and multiobjective models. The most of the applications found are using single objective models. Even when some results have been presented for multiobjective models, there is a great opportunity to propose different models and solution approaches, as is described in this thesis.

In chapter 3, a single-period, multiobjective, linear model (MGEP1) is described. First, the problem is defined; then the proposed method to solve it is presented. A case study is

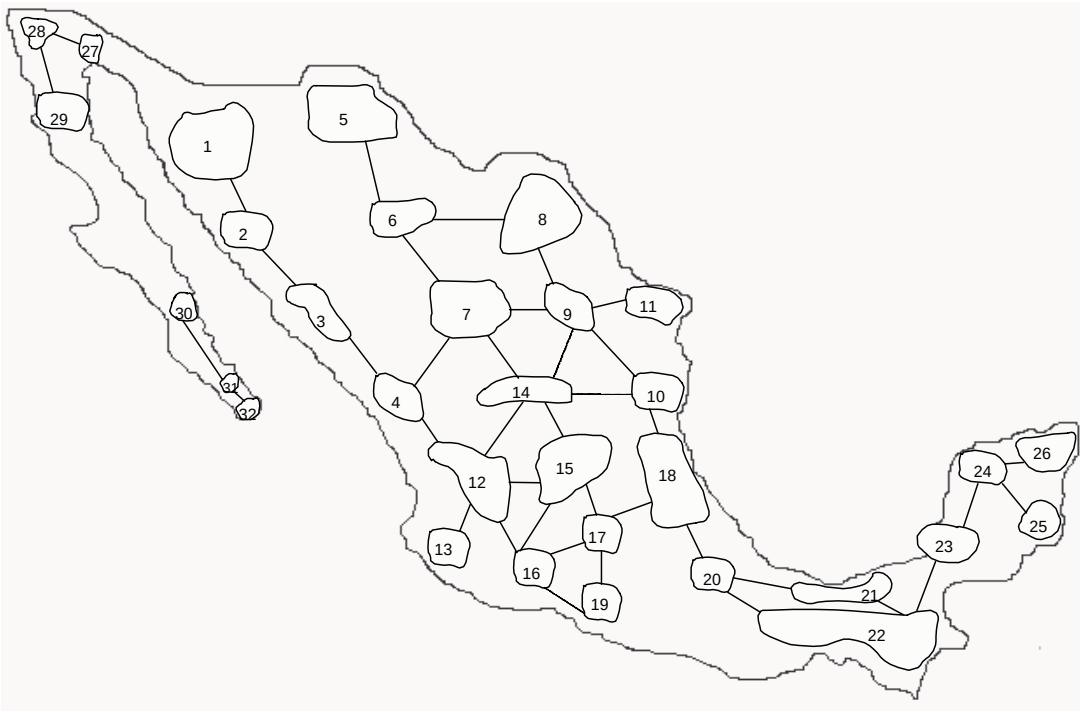

Figure 1.4: Mexican Interconnected Electric System [53]

included to illustrate the use of the model.

A multi-period, multiobjective, linear model (MGEP2) is described in chapter 4. The model is presented as well as the methodology of solution used, and a case study to illustrate them.

In chapter 5, a mixed-integer, multiobjective, non-linear model (MGEP3) is presented. The proposed model is for a single-period case and represents the most complex model among the proposed ones. The solution method proposed to solve it is based on evolutionary algorithms, which can provide a good approximation to the set of non-dominated solutions of complex multiobjective optimization problems. The performance of the algorithm is evaluated with a study case.

A simple fuzzy GEP model is presented in chapter 6. The fuzzy approach used is based on fuzzy linear programming which is first described in the chapter. The fuzzy model is

described and a case study is presented to show the results obtained from its evaluation.

Finally, chapter 7 contains some conclusions from the activities performed in the thesis, and presents possible future research directions to conduct.

1.4 Contributions

Taking as reference the previously discussed factors, the desire of this thesis is to propose novel multiobjective optimization models which can provide adequate results, in a reasonable amount of time, for the multi-criteria GEP. Besides of the modelling contribution, a methodology of solution is proposed for each presented model. The proposed methodologies are based on known multicriteria decision making methods and are tested with case studies from the Mexican Electric Power System. The summary of the contributions from the thesis are presented next.

1.4.1 Modelling

The main contributions from the proposed models is the inclusion of more than three objectives to generate a set of expansion alternatives, and the consideration of the transmission network to measure the geographical impact of the generation additions, obtaining better results in the electricity supply chain as shown in Figure 1.5.

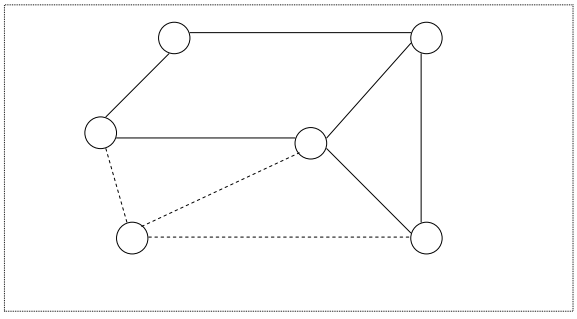

Figure 1.5: Power System Network

The nodes in Figure 1.5 represent the points of demand and/or supply of energy, and the arcs represent the transmission lines. The dashed lines are potential new links in the network. To solve separately the transmission expansion planning problem, different methodologies have been presented [9].

The uncertainty in the GEP problem is also considered in the presented models by using Fuzzy theory concepts. The demand and the goals can be represented as fuzzy numbers in the formulations.

1.4.2 Solution Methods

When solving multiobjective problems like the GEP, it is desirable to find many Pareto-optimal solutions. Depending on the complexity of the problem (real-life problems are more complicated to solve), the type of solution approach is selected to use. The first two proposed models (MGEP1 and MGEP2) were evaluated using traditional and existing solution methods; however, for solving the third model (MGEP3) an original multiobjective evolutionary algorithm was proposed. The good performance of the evolutionary approach indicates promising results. Both types of solution methods can provide fast and good approximations to the true Pareto fronts. In addition, a complete framework was proposed to find the expansion alternatives (non-dominated solutions), and select the most attractive among these.

1.5 Summary

In this chapter, the definition of the problem to solve, the motivation to work on this topic, as well as the main contributions from this research are described.

In addition, the content of the thesis in each chapter is described briefly. The material presented pretend to explain the objective of the thesis and the originality of the proposed models and methodologies of solution.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

According to Hobbs [29], until the 1970s the decision planner's task was to determine the best size, timing, and type of generation plant to meet growing electric power demands. The problem today is more complex. There are more options which include demand side management (DSM), cogeneration, greater uncertainty in load growth, fuel markets, technological developments, government regulations, small-scale and renewable power resources, and power transactions in a more increasingly deregulated market. Not only is there uncertainty in future demands for electricity within a given region, but competition with other Power Generation (PG) and Power Distribution Companies (PD) means that these companies cannot take their market share for granted. Also, PG/PD objectives have expanded beyond cost; other important objectives now include price minimization, customer satisfaction, promotion of economic development, and preservation of environmental quality. In many countries, the expansion of the PG/PD systems is a result of simultaneous increase in competitive pressures and the consideration of several factors. As a result, the decision makers need modelling tools which explicitly examine tradeoffs among objectives, recognize uncertainty, account for increasing competition, and include DSM on an equal footing with supply options.

Most generation expansion planning (GEP) problems have been modelled as single-objective programming problems which consider only the total cost (least-cost) [29]. Since the early 1980s studies have begun using multiobjective models to solve the GEP problem. Powerful and attractive multi-criteria decision making analysis approaches have been devel-

oped and applied to power systems planning. In some, the alternatives (expansion plans) are generated and in others these are known a priori for a comparison and selection among them. The assumptions (number of objectives, representation of the input data, etc.) also make different problems more complex, since more detail is considered in the models. The idea is to propose a model which can provide adequate results in a reasonable amount of time. In this chapter some of the reported applications of single and multiobjective models for the GEP problem are reviewed.

2.2 Single Objective Generation Expansion Planning

Applications of single objective models can be classified into two groups: applications in regulated systems (monopoly) and applications in competitive markets (competition). Kagiannas et al. [35] mention that during the last two decades, electric power generation industry in many countries and regions around the world has undergone a significant transformation from being a centrally coordinated monopoly to a deregulated liberalized market. In the majority of those countries, competition has been introduced through the adoption of a competitive wholesale electricity spot market. Short-term efficiency of power generators under competitive environment has attracted considerable effort from researchers, while long-term investment performance has received less attention.

Electricity generation no longer possesses the sub-additive cost properties of a natural monopoly due to technology driven decreases in efficient plant sizes. Diminishment of scale of economies in generation has made competition possible among power producers. This restructuring has broken the utility industry into generation firms who compete among each other to sell power, which is transmitted by a monopoly high-voltage transmission system to independent distribution firms and local consumers.

A number of studies concerned with the competitive performance of electricity spot markets exist in the literature; however less attention has been paid to the long-run efficiency of restructuring, specifically, the area of investment in generation. GEP models have a long tradition in both power sector and the operations research literature. They were one of the first applications of linear programming in the 1950s when the industry was operating under the regulated monopoly regime.

2.2.1 Generation Planning in Monopoly

As Kagiannas et al. [35] claim, the aim of a traditional electricity power company has been to provide an adequate supply of electric energy at minimum cost. Various models for generation planning were developed to fulfill this function through optimization algorithms and probabilistic production costing simulation. The purpose of generation planning models is to determine units to be constructed, the time to be constructed and the amount of power to be produced so that the total cost (fixed and production cost) to a company is minimized. Thus, solving an optimal GEP problem is equivalent to finding the optimal decision vector, which minimizes an objective function under several constraints.

Traditional methods

It is known that a long-term GEP problem is a constrained non-linear discrete dynamic optimization problem. The high non-linearity of a GEP problem originates from the production cost and the set of non-linear constraints. The dynamic programming (DP) approach has been one of the most used algorithms in GEP. However, in the generation expansion problem, the so-called 'curse of dimensionality' troubles the method of DP. As a result, commercial packages like WASP [37] use heuristic tunnel-based techniques in the DP routine, where users pre-specify state configurations and successively modify tunnels to arrive at local optimum. The Wien Automatic System Planning (WASP) package was originally developed in the United States for the needs of the International Atomic Energy Agency (IAEA). It is

the most frequently used and best proven program for electric capacity expansion analysis in the public sector. It is used for long-term expansion planning for a period up to 30 years. He and David [27] propose an expert system in the dynamic programming algorithm to incorporate a number of rule based procedures in the decision making part of the algorithm. David and Zahao [16] integrate expert systems with dynamic programming to reduce the state space size through an intelligent tunnel that allows to model large dimension problems. David and Zahao [17] present an expert system with Fuzzy Sets for optimal expansion planning, this is an extension of their previously presented work [16].

Another successful method has been the generalized Bender's decomposition (GBD) algorithm. GBD subdivides the master GEP problem into a set of sub-problems that are solved in an iterative way until the optimum cost is found. The master problem is solved using integer programming, and the sub-problems are solved using linear and non-linear programming methods.

Integrated resource planning (IRP) [28] is defined as a process that attempts to find an optimal combination of supply-side and demand-side measures to meet energy service needs within an electric utility's service territory. Supply-side options can range from new generation plant construction to bulk power purchases and transmissions efficiency improvements. Demand-side management (DSM) alternatives include utility programs that encourage more efficient energy use, trim or shift peak loads, and encourage demand during off-peak periods.

A number of comprehensive IRP models for optimizing supply and demand-side options have been applied by electric utilities [28]. There are at least two major classes of optimization-based IRP models. Mathematical programming-based IRP models define decision variables for the capacity of new supply sources and the amount of DSM. In IRP models an "optimal" plan is most typically defined as one that is "least cost": the combination of resources that minimizes the cost to utility or society of meeting demands for

energy services. Another related concept to IRP is electric utility resource planning which is the selection of power generation and energy efficiency (conservation) resources to meet customer demands for electricity over a multi-decade time horizon. Hobbs [29] examines how the needs of electric power companies' planners for optimization models have changed in response to environmental concerns, increased competition, and growing uncertainty.

Heuristics methods

Because of the complexity of GEP (non-linearity, non-convexity, and large scale) some modern heuristics methods (simulated annealing, tabu search, evolutive algorithms, particle swarm optimization) have been explored to solve GEP [36]. For example, genetic algorithms (GA) is a search algorithm based on the mechanism of natural selection and genetics and uses the concept of "Survival of the fittest" to find the optimal solution. Improved genetic algorithm (IGA) with stochastic crossover technique and elitism are applied to solve the GEP problem. Evolutionary programming (EP), one of the Evolutionary Computation (EC) techniques, is emerging as an efficient approach for various search, classification, and optimization problems [9]. GA and EP use genetic operators. EP does not perform crossover operation as GA, but obtains the solution by selection, mutation and competition.

An improved genetic algorithm (IGA) for the GEP problem is presented by Park et al. [51]. The IGA algorithm is based on an artificial creation scheme for the initial population and a stochastic crossover strategy in order to overcome some difficulties of the conventional GA. The results of the IGA are compared with those of the conventional simple genetic algorithm, the full DP, and the tunnel-constrained DP employed in WASP.

Park et al. [52] propose an advanced EP algorithm using domain mapping procedure and quadratic approximation technique for solving the GEP problem. Though for small and medium large scale systems the EP computational time is longer than the DP method,

for large scale systems EP takes shorter time than DP. Furthermore, using DP for those large scale systems it might be impossible to find the global optimal. The results presented in [52] show that EP can be a promising optimization method for a practical large scale systems. Firmo and Legey [69] propose a decomposition scheme based on GBD and GA to solve the GEP problem. The approach proposed consists of an iterative procedure that computes a lower bound to the GEP, by solving a relaxed investment subproblem. The solution to this problem is then used as an input to the operation subproblem, whose solution constitutes an upper bound to the GEP and provides sensitivity vectors to conform a new investment subproblem. The investment problem is solved via an iterative genetic algorithm.

Since in EC a population is in fact a set of alternative solutions, it is possible to use them as alternatives for the final decision. This is an important source of flexibility in real world solutions. In the case of the power systems expansion planning problem, this flexibility is very welcome, as it means the possibility of taking into account other aspects of the problem, besides cost minimization. For instance, in competitive electricity markets where technical, economic and political uncertainties exist, the planners have to choose among similar cost alternative solutions.

Recently, swarm intelligence techniques, particle swarm optimization (PSO) and ant colony optimization techniques are gaining more attention. These techniques use swarm behavior to solve the problem; they use the concept of group intelligence along with individual intelligence. PSO technique is used to solve continuous combinatorial optimization problems. PSO is similar to EAs techniques in which, a population of potential solutions to the problem under consideration is used to probe the search space. The major difference is that, the EC techniques use genetic operators whereas SI techniques use the physical movements of the individuals in the swarm. Coello et al. [14] present five variants of PSO to solve the GEP problem. The test results are compared with DP and their performances are evaluated. The PSO techniques produced the best result in much less time compared to DP.

2.2.2 Generation Planning in Perfectly Competitive Markets

As indicated by Kagiannas et al. [35], scale economies are changing in electricity production: small generation units are no longer necessarily much more expensive per MW than large facilities. Consequently, the planner has more flexibility in choosing generation sites. Until the 1970s, the resource planner's task was just to determine the best size, timing, and type of large central station generation plants to meet the future electric loads. The way that GEP has been approached and solved has been totally redirected through the introduction of competition and deregulation of electricity markets. The problem of power GEP has been reformulated from being cost minimization to profit maximization. The privatized approach evaluates a resource alternative's benefits according to its own revenue stream. This private revenue stream will depend on a number of factors (how privatization is carried out and the type of market or contract). Uncertainties in load growth, fuel markets and government regulations have made the problem even more complex. Not only are future demands for electricity within a given region uncertain, but competition with other power generators also means that many utilities cannot take their market share for granted.

Each firm must look to maximize its production surplus (market revenues minus operation costs) in an uncertain context where its perception of risk, the behavior of the competitors, the ownerships structures, the technology mix, as well as multitude of other external, technical, economical and managerial factors heavily condition the market. The system behavior will therefore be characterized by the economic market equilibrium as a result of the interaction of all these factors. Market equilibrium [35] defines a point of convergence of the market, provided that each participant behaves to maximizing its own profits. The case of the California power crisis during the summer months of 2000 and the winter months of 2000-2001 showed that the most important factor was the shortage of power supply relative to demand. Events such as the California case have made the power generation expansion planning activity even more important for power generators. In addition, the critical as-

sumption was that intense competition among rival generators would force prices down and keep them low. This would obviate the need for price regulations. This utopian dream of a self-regulating wholesale market blurred the policy markers' vision and became the fundamental assumption that drove everything else [65].

Bresesti et al. [5] describe some factors affecting both generation and transmission market-based expansions: price-forecasting, inter-area congestions, grid phenomena, transmission capacity increase, transmission technologies and system planning design. According to this paper, expected energy price is the main driver in all market-based expansion projects. In both generation and transmission, the market players plan their investments on the basis of the expectations of the future energy prices. In competitive electricity markets the price of energy is affected by several exogenous and endogenous factors such as:

- power planning technologies and efficiencies
- costs and the availability of the primary energy resources
- ratio of installed capacity/load demand
- availability and reliability of both generation and transmission facilities
- demand elasticity with respect to the price
- constraints on the transmission system
- energy exchanges with bordering systems
- market arrangements
- strategic behavior of the market players and, in particular, of the generation companies

David et al. [18] mention that in the traditional least cost strategy, power plant installation and operation follow the most economic itinerary, regardless of plant ownership. However, to obtain access to investment funds from international or local private investors,

deviations from the plan may be required. For example, investor owned projects may have to be built as early as possible, because of investor pressure or the host company's lack of finance. The traditional least cost strategy may reject certain projects entirely from the expansion plan because of higher capacity and/or energy costs. However, a private investor may show preference for such a project and a deviation is made from the optimal strategy in order to attract the investor. The authors describe the impact of changes in project sequence, and insertion of projects not normally included within the optimal strategy.

Solution methods

In modelling market equilibrium, some approaches have been proposed, such as microeconomics theory (Cournot and Bertrand model among others), game theory (non-cooperative games), mixed complementary problems and mathematical programming with equilibrium constraints [10].

Park et al. [51] mention that the new generation expansion planning in a competitive market is a complex problem due to conflicts among generation companies (GENCOs). The objective function of each GENCO for investment decision-making is to maximize its profit. The objectives of individual GENCOs are correlated, interlinked, and in conflict with each other. One of the objectives of a market regulatory body is market stabilization through coordination between GENCOs by providing long-term market information to GENCOs, which can prevent extreme over/under investments in the electricity market. One alternative to tackle this problem has been the application of game theory [51]. Although there are many inherent advantages in the application of game theories to a competitive electricity market, the problem of dimensionality for N-player application still exists. Therefore, they decompose the problem into two problems. The main problem for the regulatory body is to evaluate the market prices and capacity stability in a long-term sense based on the investment strategies of individual GENCOs. The subproblems correspond to individual GENCOs

where each GENCO tries to maximize its profits using a genetic algorithm with the information supplied by the main problem. An iterative process between the main problem and the subproblems is applied to find an equilibrium investment solution.

Ryuya et al. [57] describe how a linear programming generation planning program has been extended to model price and demand interactions, and how the result is mutually consistent demand projections and generation expansions.

Build, operate and transfer (BOT) arrangements have been considered as an attractive model and have gained popularity in competitive markets. BOT arrangement is one where a private power development consortium, usually foreign, build a power plant whose output is purchased by an electric power company in the host nation. At the end of the franchise period, typically between 10 and 25 years, ownership of the plant is transferred to the host company or government. Xing and Wu [78] propose an approach of calculating the breakeven cost (price for an electric company willing to pay for BOT's electricity) to the company of a BOT power plant. The proposed approach requires the computation of production costs from the long-term GEP under future uncertainties. To facilitate the inclusion of constraints introduced by BOT plants in GEP and uncertainties, a genetic algorithm method is utilized.

2.3 Multiobjective Generation Expansion Planning

Since early 1980s several papers have been published using multiobjective models for the GEP problem. With the aid of multiobjective models, decision makers may grasp the conflicting nature and the trade-offs among different objectives to select satisfactory compromise solutions.

2.3.1 Definitions

In multiobjective models, the concept of optimal solution in single objective problems gives place to the concept of the non-dominated solutions i.e., feasible solutions for which no improvement in any objective function is possible without sacrificing at least one of the other objective functions. The concept of non-dominated solution is also known as Pareto optimum, non-inferior solution, and efficient solution [15]. In 1950, Kuhn and Tucker extended the theory of nonlinear programming for one objective function to a vector minimization problem and introduced necessary and sufficient conditions for 'proper' solution [79].

A multiobjective mathematical model is defined as [79]:

$$\begin{array}{lll} \min_x & \{f_1(x), f_2(x) \dots f_n(x)\} & \\ \text{subject to} & g_k(x) \leq 0 & k = 1, 2, ..., m \end{array} \tag{2.1}$$

where x is an N-dimensional vector of decision variables; $f_i(x)$, $i = 1, 2 \dots n$ are n objective functions; and $g_k(x), k = 1, 2 \dots m$ are m constraint functions.

A decision x^* is said to be a non-dominated solution to the system (2.1) if and only if there does not exist another $\bar{x}$ such that

$$f_i(\bar{x}) \leq f_i(x^*), i = 1, 2 \dots n,$$

and strict inequality holding for at least one i. Consequently, for any non-dominated point no one of the objective functions $f_i(x)$ can be improved without causing degradation in any other $f_j(x), i \neq j$.

2.3.2 Multi-Criteria Decision Making Methods

Multi-criteria decision making (MCDM) methods can be classified into two groups [48]: multiobjective decision making (MODM) and multi-attribute decision making (MADM) methods. These two decision methodologies have the common characteristics of MCDM problems, such as conflicting criteria, and difference of units. In MODM, the decision space is continuous and alternatives are not pre-determined. The decision problem is solved using multiobjective linear or nonlinear mathematical programming models in which several objective functions are integrated and optimized subject to a set of constraints. For the MADM approach, the decision space is discrete and each candidate alternative can be evaluated using a combination of analytical tools [30].

Multiobjective decision making (MODM) methods

Mainly, MODM problems can be defined and solved by several alternative optimization models: compromising programming, ϵ-constraint method, goal programming, and fuzzy multi-objective programming [48].

Compromising Programming methods may be classified into weighted sum method and composite distance method [40]. In the first method, the multiobjective programming problems are converted into a single-objective optimization formulation by assigning a set of weights to individual objectives and summing them up. The second method is based on the concept of ideal solution and measures the composite distance from an ideal point on the direction preferred by the DM. In either case, the optimization problem can be solved by existing optimization software for various combinations of weights to create a set of non-dominated solutions. From this set of non-dominated solutions, the best compromise solution can be found or a set of desired compromise solutions can be identified.

In ϵ-Constraint Method [47], the most essential objective is taken as the objective function while others are treated as constraints by providing a proper tolerance level to each of them. Similar to the compromising method, a set of non-dominated solutions can be identified by varying the tolerance levels.

Goal Programming [66] method employs a minimum distance concept, which is defined with respect to goals specified by the DM for each objective. Additional unknown variables are defined which represent positive and negative deviations from goals. In real-world decision problems, objectives and constraints can be vague in the degree of attainment.

Fuzzy Mathematical Programming has been developed significantly in recent years to solve a class of multiobjective optimization problems with fuzzy objectives and constraints [82]. It is an effective method of making coordination among conflicting objectives. The coordination can be done through the shape of membership functions assigned to objectives and also to constraints. Future demand and other primary parameters are considered as fuzzy numbers such that the influences of uncertainties can be included in the optimization process.

Multi-attribute decision making (MADM) methods

The most commonly used MADM methods in electric utility planning studies include utility function method, tradeoff analysis method, TOPSIS, ELECTRE, PROMETHEE and analytical hierarchy process method (AHP). Utility Function method selects an optimal planning or design strategy based on a formulated function known as multi-attribute utility function. This utility function is comprised of the preference functions for individual attributes and the weights that reflect the relative importance of these attributes [38]. If a condition of additive utility independence of attributes holds, then the linear additive utility model can be used. Thus, the contributions of an individual attribute to the composite

utility are independent of other attribute values. By this method, the alternatives to be evaluated are ranked according to their expected utility values, which are computed as a probability-weighted mean of all possible future conditions [75].

Tradeoff Analysis method has been developed to support the identification of robust plans under uncertainty [7]. In tradeoff analysis, tolerance levels or significant parameters are specified by the DM for each individual attribute which define the relative importance of attributes or indicate how far the DM is willing to tradeoff one attribute with respect to another. The process is then repeated for all futures and the global decision set is finally determined by the conditional decision sets. The ranking of alternatives are based on the measure of robustness, i.e., the number of futures supporting the plan.

TOPSIS (technique for preference by similarity to the ideal solution) was initially presented in [31]. In TOPSIS, the only subjective input needed from decision makers is weights in order to minimize the distance to the ideal alternative while maximizing the distance from the anti-ideal one. The method uses an index, which combines the closeness of an alternative to the ideal solution with its remoteness from the anti-ideal solution. The alternative that maximizes this index value is the preferred alternative.

ELECTRE method uses the concept of an outranking relationship. This method consists of a pair-wise comparison of alternatives based on the degree to which evaluations of the alternatives and the preference weights confirm or contradict the pair-wise dominance relationship between alternatives. It examines both the degree to which the preference weights are in agreement with pair-wise dominance relationships and the degree to which weighted evaluations differ from each other. These stages are based on a concordance and discordance matrices.

The Preference Ranking Organization Method of Enrichment Evaluations (PROMETHEE) method has been developed in [4]. The PROMETHEE Method is based on the determination of preference and indifference. Every alternative is compared pair-wise to each of the other alternatives. Preference values determined from the pair-wise comparisons are then analyzed to develop an overall rating value for each alternative.

Analytical Hierarchy Process (AHP) method has been used as a structured approach for dealing with multi-attribute decision problems, especially when the decision process are defined hierarchically [59]. The AHP technique may be described as three-step procedure. First, create judgment matrix by pair wisely comparing all the factors at one level of the hierarchy with respect to each factor in the immediately proceeding level. Then, compute the eigenvector of judgment matrix corresponding to the largest eigen-value. Finally, calculate the composite priority vector from the local priorities associated with each judgment matrix.

2.3.3 Applications

The work presented by Yacov and Warres [79] presents the development of the surrogate worth trade off method for the multiobjectives in water resource systems analysis. This analysis was further extended by Vira et al. [72] to integrate in an interactive way two methodologies: dynamic programming method for capacity expansion and the surrogate worth tradeoff method for optimizing multiple objectives. The multiobjective mathematical programming problem is converted to singles objective dynamic programming problems. This research is a good start in this kind of applications but just small test cases are reported. For example it just considered two criteria (total cost and pollution index).

Evans et al. [21] illustrate how the conflicting criteria in the long-range generation planning process can be considered by using multiattribute utility theory for measuring electric company's objectives, and dynamic programming to optimize the choice of an expansion pol-

icy. The preference structure of the electric company over uncertainty of multiple objectives is represented in a multiattribute utility function. Here the uncertainty is considered in the demand and four scenarios are considered in such case. Yang and Chen [80] present a detailed multiobjective optimization approach to generation expansion planning. Four attributes and 14 subattributes are considered in the paper. The approach is designed by adding a new multicriteria decision procedure to the conventional algorithm that combines dynamic programming with production simulation method. The proposed procedure combines a specially designed questionnaire and the Saaty's intensity scale, the Eigenvector method to determine the weights, and the TOPSIS method. Five cases studied are presented in the paper. Because the weights calculated have a significant impact on the results obtained for each case, their calculation must be done carefully.

Two methods are presented by Climaco et al [11] to deal with the multicriteria problem: an interactive tricriteria linear programming tool (TRIMAP), and an outranking method (ELECTRE IV). The objectives considered in the first method are the total system cost, the environment impact and a reliability function. In the second, a set of economical and welfare attributes are used for evaluating several alternatives which may be obtained with the aid of a screening process of the output of the first method. The TRIMAP method is based on a progressive and selective learning of the set of Pareto solutions, combining three main procedures: weighting space decomposition, introduction of constraints on the objective functions space and/or the weighting space.

Ryuya et al. [58] propose a methodology using dynamic programming for evaluating the flexibility of a generation mix considering uncertainties. Fixed and variable cost of generation technologies are selected as uncertain variables and the robust generation mix problem is formulated as a multiobjective optimization problem. The multiobjective optimization problem is transformed into a single objective optimization problem using the weighting method. The single objective problem is then solved by dynamic programming. According

to the authors, a flexible generation mix, from the planner's point of view, is one that has an appropriate allowance for uncertainty; i.e., the production cost of the flexible generation mix shows minimum fluctuations due to changes in the assumptions. Something important to point out is that obtaining Pareto optimal solution using the weighting method requires the convexity of all objective functions.

Kim and Byong [39] describe a preference-order dynamic programming approach. Three decision attributes: cost, CO_2 emissions, and nuclear hazards are considered. Major decision variables are annual capacity additions by plant types that minimize the three attributes in a vector sense while meeting reliability and other conventional technical constraints. In their methodology they have incorporated the multiattribute objective into a dynamic-programming framework by replacing the conventional real-valued return functions by preference-order ranking. The preferred solutions are determined in terms of approximations of the ideal and anti-ideal solutions, and the Euclidian distance to the ideal solution.

A multiple objective linear programming model (TRIMAP) is presented by Climaco et al. [12] that considers three objective functions: total system cost, environmental impact (both to be minimized), and the reliability of the supply system (to be maximized). Three types of constraints were considered: satisfaction of demand, operational capacity and budget restrictions. The TRIMAP method had already been presented by Climaco et al. [11] and is based on a progressive and selective learning of the set of non-dominated solutions.

Kalika and Frant [73] describe a not very detailed methodology (dynamic tree and TOPSIS) for power generation system planning, which is used to select a predetermined number of best ("reasonable") alternatives from an initial set according to the given criterions. Vladimir et al. [74] present a methodology for incorporating environmental issues into electric system expansion planning. The authors combine a conventional least-cost optimization tool, an environmental model, and a multicriteria interval decision analysis system. The least-cost

electric system expansions plans are passed to a module (IMPACTS) to determine the resulting level of environmental residuals (air emissions, water effluents, water use, solid waste generation, and land use), along with resource requirements and statistics on occupational health and safety. The information on the least-cost expansion plan for each of the alternatives considered in the study, along with the associated environmental impacts, is then transferred to the model MCITOS (Multiple-Criteria Interval Trade-Offs System), a general-purpose decision support system, to determine the most desirable alternatives.

The MOPCA model (Model of Power system planning and Comprehensive Assessment) presented by Xiangjun et al. [77] is applied to a comprehensive assessment of different expansion options for regional power generation systems, and provides decisions makers a comparative ranking of several options. Because all the criteria have different concepts, their relative importance in assessment is different and need to be judged qualitatively by experts and decision makers, considering the detailed conditions of the regions. The Analytic Hierarchy Process (AHP) is adopted as a basic approach in MOPCA. Each criterion has more than one subcriterion, the Saaty's scale is used to formulate the judgment matrices, and the eigen-vector procedure is used to determine the weights.

Voropai and Ivanova [75] present an approach based on the fundamental concepts of the utility theory and hierarchical analysis technique. Finally, Antunes et al. [2] propose a multi-objective mixed integer linear programming model for power generation expansion planning. Their approach is based on a weighting sum of multiple objective functions that relaxes the integer problem using linear programming to look for the non-dominated solutions. This procedure requires the participation of the decision maker (DM); like any other interactive method.

2.4 Summary

In this chapter, the state of art in Generation Expansion Planning models has been reviewed. Applications in both single and multiobjective models were considered. Also, the vertical integrated (monopoly) type of generation company versus the horizontal (competence) one was described in the chapter.

As seen from the applications described in the multiobjective section, there is no reported application in the literature of multiobjective evolutionary algorithms, for solving the generation expansion planning problem.

CHAPTER 3
A MULTIOBJECTIVE LINEAR EXPANSION MODEL

3.1 Introduction

In this chapter, we propose a new multi-criteria, single-period generation expansion planning model (MGEP1). The purpose of the MGEP1 model is to determine the location, type and capacity of new generation units to achieve the best compromise between different objectives, and yet meet all the operating and economic restrictions that are placed on the system. In this multiobjective model, minimization of the investment, operation and transmission costs, environmental impact, the total fuel imports and risks related to fuel price fluctuations are considered. In the last two objectives we consider determining the expansion alternatives with the use of multiobjective optimization methods that minimize the dependency on foreign energy sources (such as gas, petroleum, coal, etc.) and obtain a solution which potentially minimizes the volatility in fuel prices. The proposed MGEP1 model is a deterministic linear model which considers the current flow conservation according to Kirchoff's laws. The importance of considering the transmission network is basically to find a generation expansion plan which can optimize more globally the electricity supply chain.

The next sections of this chapter describe the model in mathematical terms, definitions used, the methodology proposed, and one case study to test the performance of the proposed method.

3.2 Mathematical Formulation

In this section the MGEP1 model is described mathematically. The decision variables, constraints and objective functions are presented, as well as some constants and terms used in the formulation.

3.2.1 Definitions

Some terms that are utilized in this formulation are described first.

Node: a point at which load, generation capacity and one or more arcs have a common connection. It can be a supply, demand, transhipment or a combination node.

Arc (i, j)**:** a transmission path, which connects node i to any other node j. An arc may contain one or more electric circuits.

Circuit: a single electric transmission element on an arc.

Power flow: electric power flow in a circuit or arc.

Generation: electric power generation.

Load: electric power demand.

3.2.2 Indices

$i \in \mathcal{N}$	nodes
$q \in \Theta$	types of generation units
$k \in \mathcal{F}$	types of fuel
$(i, j) \in \mathcal{A}$	arcs from node i to node j

3.2.3 Parameters of the model

The following data are input to the MGEP1:

D_i Expected load (MW) at node i.

I_{iq} Investment cost ($/MW) of a unit of type q at node i.

G_{iq} Generation cost ($/MW) of a unit of type q at node i (operation & maintenance).

C_{ij} Cost ($/MW) for new transmission capacity in arc (i, j).

$\bar{X}_{ij}$ Existing (MW) capacity of transmission in arc (i, j).

$\bar{G}_{iq}$ Maximum (MW) generation capacity of units of type q at node i.

$\bar{GE}_{iq}$ Maximum (MW) generation capacity for an existing unit of type q at node i.

V_k Cost ($/units) of imported fuel of type k.

E_q Tons of carbon dioxide emission (CO_2) per MW generated by a unit of type q.

U_k National available amount (corresponding units) of fuel type k.

W_q Fuel needed (units/MW) to operate a unit of type q.

S_k Historical coefficient of variation in prices of fuel type k.

J_k Index of units of fuel type k.

3.2.4 Decision Variables

Six groups of decision variables in the model are:

ge_{iq} Generation (MW) from the existing units of type q at node i.

gn_{iq} Generation (MW) from new units of type q at node i.

x_{ij} Flow (MW) through arc (i, j).

Δx_{ij} Additional transmission capacity (MW) in arc (i, j).

u_k Imported fuel (units) of type k.

3.2.5 Objective Functions

In this multiobjective model the minimization of the investment and operation costs, environmental impact, imports of fuel and fuel prices risks of the whole system are considered. The last two objectives have not been explicitly considered in the literature when determining the expansion alternatives with the use of multiobjective optimization methods.

- Investment & Operational Cost. This objective function is defined as the sum of the investment cost for new units, the generation costs, and the cost for additional capacity of transmission. It is,

$$f_1 = \sum_{i \in \mathcal{N}} \sum_{q \in \Theta} I_{iq} g n_{iq} + \sum_{i \in \mathcal{N}} \sum_{q \in \Theta} G_{iq} \left[g e_{iq} + g n_{iq} \right] + \sum_{(i,j) \in \mathcal{A}} C_{ij} \Delta x_{ij} \tag{3.1}$$

  Here, the first part is the investment cost associated to new generation capacity; the second part is the operational cost of the system, and the third one is the cost for new transmission capacity.

- Environmental impact. The aggregate Carbon Dioxide Emissions (CO_2) from fossil-fuel plants is minimized. Fossil-fuel units produce CO_2 which is the main greenhouse gas. Emissions of this gas into the atmosphere are responsible for enhancing the greenhouse effect, leading to global warming, a rise in sea level and changes in rainfall. This may have a substantial detrimental impact on the ecosystem, people and economies.

$$f_2 = \sum_{i \in \mathcal{N}} \sum_{q \in \Theta} E_q \left[g e_{iq} + g n_{iq} \right] \tag{3.2}$$

- Imported Fuel. The minimization of possible import of fuel by the system is considered by this objective.

$$f_3 = \sum_{k \in \mathcal{F}} V_k u_k \tag{3.3}$$

- Energy Price Risks. This objective seeks to minimize the exposure to fuel price volatility in the expansion decisions.

$$f_4 = \sum_{k \in \mathcal{F}} S_k \sum_{q \in J_k} \sum_{i \in \mathcal{N}} \left[g e_{iq} + g n_{iq} \right] \tag{3.4}$$

Here, S_k is the expected coefficient of variation in prices of fuel type k, utilized to minimize such exposure. This way to measure the risk in prices is simple but original in multiobjective models; other ideas could be obtained from [3].

3.2.6 Constraints

In MGEP1 model, five types of constraints are imposed: flow balance constraints in the network, transmission limits on arcs, generation capacity, amount of available local fuel, and non-negativity of the decision variables.

- Node Balance Equations in each node i: The inflow in each node (generation + flow from other nodes) is equal to the outflow (demand + flow to other nodes).

$$\sum_{(j,i)\in\mathcal{A}} x_{ji} - \sum_{(i,j)\in\mathcal{A}} x_{ij} + \sum_{q\in\Theta} [ge_{iq} + gn_{iq}] = D_i; \quad i \in \mathcal{N} \tag{3.5}$$

- Transmission Capacity on each arc (i, j): There are physical limits on the amount of power flow that can be transmitted through the arcs of the network.

$$x_{ij} \leq \bar{X}_{ij} + \Delta x_{ij}; \;\; (i,j) \in \mathcal{A} \tag{3.6}$$

- Generation Capacity for each unit type q in node i: Operating limits are imposed by the generation units.

$$\begin{aligned} ge_{iq} &\leq \bar{GE}_{iq} \\ gn_{iq} &\leq \bar{G}_{iq}; \;\; i \in \mathcal{N}, q \in \Theta \end{aligned} \tag{3.7}$$

- Fuel demand for each fuel type k: Fuel used will be either from local markets (U_k), or if necessary imported.

$$\sum_{i\in\mathcal{N}} \sum_{q\in J_k} W_q \, [ge_{iq} + gn_{iq}] \leq U_k + u_k \;\; k \in \mathcal{F} \tag{3.8}$$

- Non-negativity: No negative values are permitted for the decision variables.

$$ge_{iq}, gn_{iq}, \Delta x_{ij}, x_{ij}, u_k \geq 0, \quad \forall i, q, (i,j) \tag{3.9}$$

The model is a multiobjective linear programming problem with $2*|\mathcal{N}|*|\Theta|+2*|\mathcal{A}|+|\mathcal{F}|$ variables, and $|\mathcal{N}|+|\mathcal{A}|+|\mathcal{F}|+2*|\mathcal{N}|*|\Theta|$ constraints.

Let

$$\begin{aligned} f_l(y) &= l^{th} \text{ objective function, } l = 1, 2, ..., 4 \\ y &= (ge, gn, x, \Delta x, u) \text{ decision or solution vector} \\ y \in Y &= \text{feasible solution space} \end{aligned}$$

The general MGEP model can be written as:

$$\begin{aligned} Min \quad & [f_1(y), f_2(x), f_3(y), f_4(y)] \\ s.t. \quad & y \in Y \end{aligned} \tag{3.10}$$

3.3 Framework to solve MGEP1

The proposed solution approach of this model consists of two phases. In the first phase a set of non-dominated solutions (expansion plans) are found using four multicriteria programming methods: max-min, min-max, compromise programming, and weighting approach [15]. These methods do not require any preference information from the decision maker (DM). For the second phase, the non-dominated solutions are rank-ordered by using the Analytical Hierarchy Process (AHP) [59].

Max-Min

This method is based on the assumption that DM is very pessimistic in the outlook and wants to maximize over the decision alternatives the achievement in the weakest criterion for each individual alternative (solution). An alternative is characterized by the minimum achievement amongst all of its criterion values. The method, thus, uses only a portion of

the available information by ignoring all other criterion values.

Mathematically, this method works as follows (assuming linear normalization):

$$\begin{array}{ll} \text{Max} & \left[\text{Min}\left\{\frac{f_l(y)-L_{l*}}{H_l^*-L_{l*}}\right\},\ l=1,2,...,4\right] \\ s.t. & y \in Y \end{array} \tag{3.11}$$

where, H_l^* is the Ideal Solution value for the l^{th} criterion, and L_{l*} is the Anti-Ideal Solution value for the l^{th} criterion.

Let $\alpha = \text{Min}\left\{\frac{f_l(x)-L_{l*}}{H_l^*-L_{l*}}\right\}$, then the previous problem can be written as,

$$\begin{array}{lll} \text{Max} & \alpha & \\ s.t. & \frac{f_l(y)-L_{l*}}{H_l^*-L_{l*}} \geq \alpha, & l=1,2,...,4,\ \ 0 \leq \alpha \leq 1 \\ & y \in Y & \end{array} \tag{3.12}$$

Solving this linear programming problem the first A_1 alternative (preferred solution) is found for the problem.

Min-Max

The purpose in this method, also known as Regret method, is to minimize the maximum opportunity loss. Opportunity loss is defined as the difference between the Ideal Solution value of a criterion, and the achieved value of that criterion in an alternative. Thus, Min-Max method tries to identify a solution that is close to the Ideal Solution.

Mathematically, this method is represented by the following problem,

$$\begin{aligned} \text{Min} \quad & \left[\text{Max}\left\{\frac{H_l^*-f_l(y)}{H_l^*-L_{l*}}\right\},\ l=1,2,...,4\right] \\ s.t. \quad & y \in Y \end{aligned} \tag{3.13}$$

Let $\alpha = \text{Max}\left\{\frac{H_l^*-f_l(y)}{H_l^*-L_{l*}}\right\}$, then the previous problem can be written as,

$$\begin{aligned} \text{Min} \quad & \alpha \\ s.t. \quad & \frac{H_l^*-f_l(y)}{H_l^*-L_{l*}} \leq \alpha,\ \ l=1,2,...,4,\ \ 0 \leq \alpha \leq 1 \\ & y \in Y \end{aligned} \tag{3.14}$$

After solving this linear programming problem the next A_2 alternative is found for the problem. It could be that this solution is equal to the previous one.

Compromise Programming

Compromise Programming (CP) identifies the preferred solution (alternative) that is as close to the Ideal Solution as possible. That is, it identifies the solution whose distance from the Ideal Solution is minimum. Distance is measured with different metrics p. In this chapter the metric $p = 1$ (City-Block) is used. CP is also known as the Global Criterion Method. Mathematically, Compromise Programming with $p = 1$ involves solving the following problem:

$$\begin{aligned} \text{Min} \quad & \sum_{l=1}^{4} \frac{H_l^* - f_l(y)}{H_l^* - L_{l*}} \\ s.t. \quad & y \in Y \end{aligned} \tag{3.15}$$

The solution of this linear programming problem provides the next A_3 alternative for the problem. It could be that this solution is equal to some of the previous ones.

Weighting Approach

In this method, the non-dominated solutions are obtained by solving a single-objective optimization problem in which the objective function is a weighted sum of the objective functions [15]. Solving the following single-objective problem we can obtain a non-dominated solution for the multiobjective one [66].

$$\text{Min} \quad \sum_{l=1}^{4} w_l \; f_l(y) \tag{3.16}$$

$$s.t. \;\; y \in Y$$

where $w_l \geq 0$ for all l and is strictly positive for at least one objective. The sum of all the weights must be equal to one. Thus, the weighting coefficients locate points on the Pareto front, but they do not reflect the relative importance of the objectives. The units in which the objectives are expressed must be considered, and a normalization of their coefficients is suggested.

Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) [59] is a multi-attribute decision making (MADM) method where the preference of the DM is represented in terms of levels of a hierarchy (Figure 3.1). 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.

In Figure 3.1, A_i is the i^{th} alternative expansion plan found in the phase one. There are four criteria, S_i, in the first level. The first criterion S_1 is cost (\$) which consist of three subcriteria: investment S_{11}, operation S_{12} and transmission S_{13}. The second criterion S_2, is environmental impact (tons of CO_2). The third criterion S_3, is imported fuel (\$). Finally, the fourth criterion S_4 is risk, which includes risk of fuel price fluctuations S_{41} (\$) and nuclear risk S_{41} (MW).

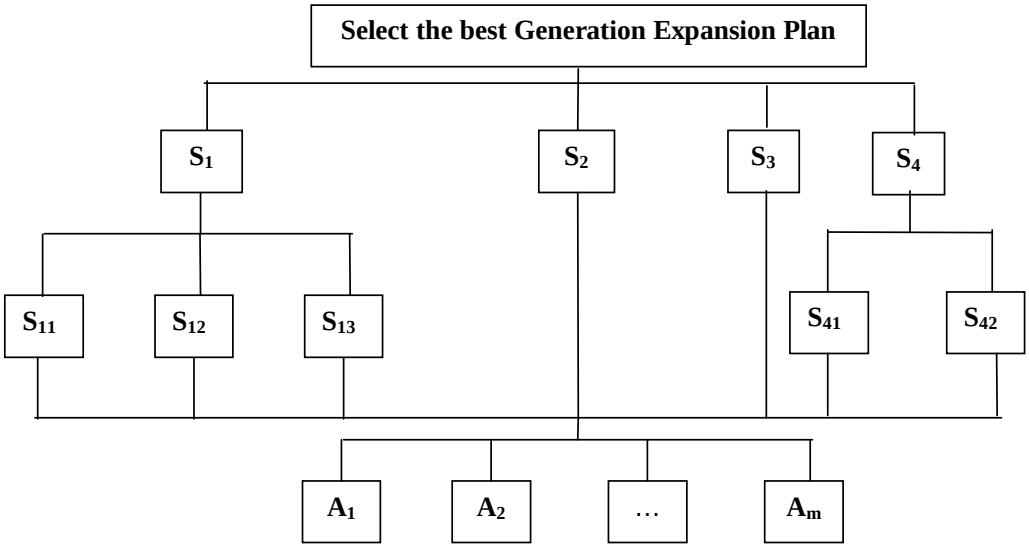

Figure 3.1: AHP Hierarchy

After the problem has been structured in the form of a hierarchy, the next step is to seek value judgments concerning the alternatives with respect to the next higher-level subcriteria. The pairwise comparison (preference judgment) θ_{ij} is established for any two alternatives (or sub-criteria) A_i and A_j, with respect to a given criterion from a set of criteria. Such that $\theta_{ji} = 1/\theta_{ij}$ for all i and j. Thus, θ_{ij} indicates how strongly alternative A_i is preferred to (or better than) alternative A_j. These value judgments may be obtained from available measurements or, if measurements are not available, from pairwise comparison or preference judgments. For this thesis, the scale showed in Table 3.1 is used to provide the preference judgment [59].

Using the defined pairwise judgments θ_{ij}, the next activities of the AHP approach are described in the following steps.

Table 3.1: Preference Judgment Scale [59]

Scale value	Explanation
1	Equally preferred
3	Slightly more preferred
5	Strongly more preferred
7	Very strongly more preferred
9	Extremely more preferred
2,4,6,8	Used to reflect compromise between scale values

- Step 1: Compute Normalized Geometric Mean Vector, g.

$$g = \begin{bmatrix} g_1 \\ g_2 \\ ... \\ g_n \end{bmatrix} = \begin{bmatrix} g'_1/\sum g'_i \\ g'_2/\sum g'_i \\ ... \\ g'_n/\sum g'_i \end{bmatrix}$$

where,

$$\begin{bmatrix} g'_1 \\ g'_2 \\ ... \\ g'_n \end{bmatrix} = \begin{bmatrix} \sqrt[n]{\theta_{11}\theta_{12}...\theta_{1n}} \\ \sqrt[n]{\theta_{21}\theta_{22}...\theta_{2n}} \\ ... \\ \sqrt[n]{\theta_{n1}\theta_{n2}...\theta_{nn}} \end{bmatrix}$$

- Step 2: Normalize each pairwise comparison matrix to a matrix R. A simple normalization scheme is to divide each θ_{ij} by the sum of the corresponding column values,

$$i.e. \quad r_{ij} = \theta_{ij}/\sum_{i=1}^{n} \theta_{ij}$$

- Step 3: Compute G as follows,

$$G = \left(\sum_{i=1}^{n} \sum_{j=1}^{n} |r_{ij} - g_i| \right) /n$$

- Step 4: Inconsistency is too high, or unacceptable (review the pairwise comparisons) if G is greater than the N_s values in Table 3.2 [26] for the matrix of size n (4 and M in this case):

Table 3.2: Acceptable Level of Consistency [26]

n	3	4	5	6	7	8	9	10	11
N_s	0.1204	0.2032	0.2586	0.2991	0.3218	0.3442	0.3596	0.3729	0.3833

Thus, G is the measure of inconsistency and g is the vector of relative evaluation. After computing g for all the levels in the hierarchy presented in Figure 3.1, the overall (or, composite) relative values of the alternatives is computed. If consistency is acceptable, a ranking of alternatives can be identified from the overall values. Details of this procedure are illustrated in the next sections.

3.3.1 Phase One

1. After finding the ideal and anti-ideal solutions for the MGEP1 problem, three non-dominated solutions (A_1, A_2, A_3) are found using the min-max, max-min, and compromise programming methods, respectively. The ideal solution is found by solving the problem for each objective separately; the obtained solutions are evaluated in each objective and the minimum values at them are taken as the ideal values. The anti-ideal solution is obtained in the same way as the ideal solution; except that the maximum values are found instead of the minimum ones.

2. By generating a large number (N) of random sets of weights for each criterion, N normalized single-objective GEP problems are solved. The large number of cases gives the opportunity to explore widely the feasible region of non-dominated solutions for the problem.

3. The K-means cluster algorithm is used to obtain K clusters (K additional non-dominated solutions) based on the cost criteria $f_1(y)$. The reason to do the clustering only for $f_1(y)$ (investment, operation and transmission costs) is because this is the most significant and representative criteria in the GEP problem. Furthermore, different configurations of the network (generation and/or transmission) do produce different costs but in some cases it might not give differences in the other criteria.

   K-means algorithm is one of the simplest unsupervised learning algorithms that solve the clustering problem [81]. The procedure follows a simple and easy way to classify a given data set through a certain number of clusters fixed a priori. It is based on minimizing the Euclidian distance J for every point $f_1(y)^t$ in each cluster S_j to the representative point μ_j (centroid) of the cluster, as shown in the following equation.

$$J = \sum_{j=1}^{K} \sum_{t \in S_j} \left(f_1(y)^t - \mu_j \right)^2 \tag{3.17}$$

   where,

$$\mu_j = \sum_{t \in S_j} \frac{f_1(y)^t}{|S_j|} \tag{3.18}$$

   is iteratively determined. Initially, the data points are assigned at random to the sets (clusters). Then, the centroid is computed for each set. Every point is assigned to the cluster whose centroid is closest to that point. These two last steps are alternated until no further change in the assignment of the data points exists.

   The results that can be obtained from the K-means algorithm depend on the initial values for the centroid, and it frequently happens that suboptimal partitions (clusters) are found [45]. The solution might be to try a number of different starting points.

In this thesis, the SPSS 9.0 for Windows software was utilized to obtain the K-means clustering.

4. A total of $K + 3 = m$ possible non-dominated solutions or expansion alternatives are obtained from this phase (Table 3.3). These alternatives are the inputs for completing the second phase.

Table 3.3: Pay-off table

	Criteria			
Alternatives	S_1	S_2	S_3	S_4
$A_1 = y^1$	θ_{11}	θ_{12}	θ_{13}	θ_{14}
$A_2 = y^2$	θ_{21}	θ_{22}	θ_{23}	θ_{24}
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
$A_m = y^m$	θ_{m1}	θ_{m2}	θ_{m3}	θ_{m4}

S_1 : Investment, Operation and Transmission Cost ($)

S_2 : Environmental Impact (Tons of CO_2)

S_3 : Imported Fuel ($)

S_4 : Risk of fuel prices fluctuation ($)

Each θ_{ij} of the Table 3.3 is the outcome of the alternative i with respect to the criterion j.

3.3.2 Phase Two

1. Use AHP to rank-order the alternatives generated in phase one. The criteria hierarchy is presented in Figure 3.1.

2. The pairwise judgments comparisons between criteria and subcriteria are given by the DM.

3. Obtain the priority for each one of the alternatives considered.

4. The alternatives are ranked and the best is identified from the ranking.

The two levels of hierarchy in Figure 3.1 contain criteria that can be quantitatively expressed; however it is possible to incorporate criteria which might be only subjectively assessed, like societal criteria (health, community impacts, employment, etc.). The number of hierarchical levels and the criteria included can be expanded according to the decision maker interests. The lower levels in the hierarchy usually contain criteria to measure or evaluate more explicitly the alternatives considered [44].

3.4 Illustrative Example

The proposed methodology will be illustrated using the Interconnected Grid Mexican Power System (IRMES) at the level of regions (see Figure 3.2). In Mexico, as in many developing countries, the energy demand grows faster than its total GDP. Given the importance of energy as crucial input for the rest of the economy, it is clear that the sector will require large amounts of investment in the near future. Also, the energy sectors of many countries are going through profound processes of structural reform aimed at introducing a greater degree of private participation and competition. Since 1992 private investments in generation expansion has been allowed by the Mexican government, and since then different proposals and studies have been presented in order to assure a reliable and efficient way to provide of electricity in the country for the future years [42].

In IRMES, there are 26 nodes (regions), 37 arcs, 8 types of generation units, and four types of fuel. Generation technology options for capacity additions include: conventional steam units, coal units, combined cycle modules (CC), nuclear, gas turbines (TG), wind farms, geothermal and hydro units. The types of non-renewable fuel are: coal, gas, oil and

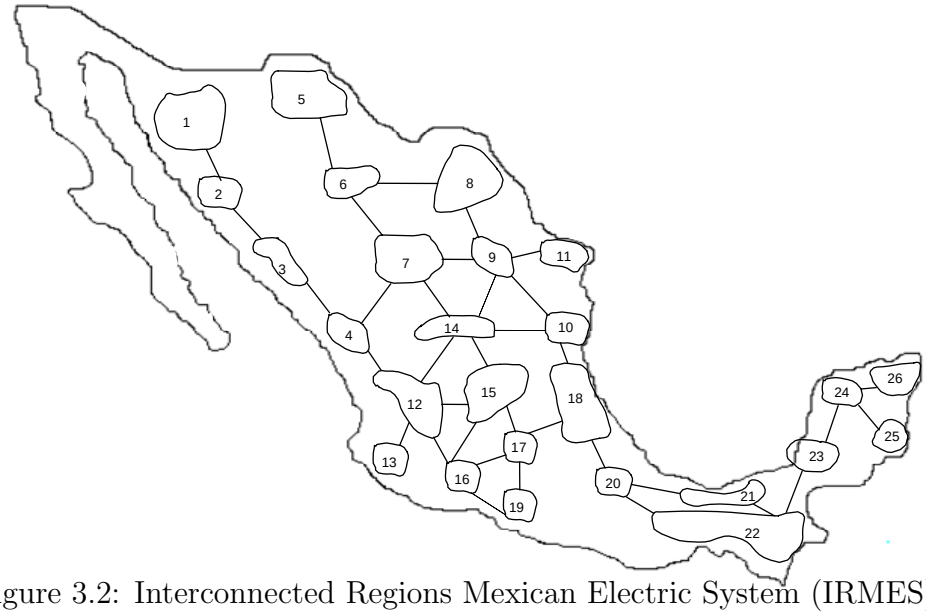

Figure 3.2: Interconnected Regions Mexican Electric System (IRMES)

uranium. Some of the needed input data was taken from [53], and the rest was estimated using different sources [34]. The base year is 2004, and the planning horizon consists of 10 years; the existing capacity in the system is 41443 MW and the expected demand in 2015 is 54670 MW. For this system, the resulting MGEP1 model has 2*26*8 + 2*37 + 4 = 494 variables, and 26 + 37 + 4 = 67 constraints.

A GAMS [8] code was used to generate the expansion alternatives in the first phase of the proposed methodology. GAMS (General Algebraic Modelling System) is a high level language for developing mathematical models through algebraic statements, which reduces the programming work in order to solve an optimization problem. A total of 2000 normalized single-objective problems were solved using randomly generated set of weights for each criteria. The normalization is done by dividing the coefficients of each objective function by the difference between its corresponding anti-ideal and ideal solutions. Those 2000 non-dominated solutions were filtered to 8 alternatives (clusters) using the K-means algorithm, respect with the cost objective.

The obtained alternatives besides the min-max and compromise non-dominated solutions represent a total of 10 non-dominated solutions (see Table 3.4) which are be the base for

the second phase of the proposed methodology (select the most attractive expansion plan). The max-min solution coincided with the min-max solution, therefore only one of them is reported.

As shown in Table 3.4, each alternative (non-dominated solution) is between the ideal and anti-ideal values, and diversity exists among them. The new capacity for each alternative is presented in Table 3.5.

In Table 3.5, *Government* means the reported expansion Plan from the Mexican Entities for the same planning horizon (2005-2014) [53]. Such is a partial expansion plan since it does not show the technology to use for 6000 MW that it plans to add. All of the alternatives shown in Table 3.5 present diversity in the types of technologies proposed to install, and in some cases such diversity is similar to the Mexican government's expansion plan. Since the Mexican government's plan was obtained using different methodologies and input data, a comparison with it is not possible. We cannot tell if this plan is a non-dominated solution in MGEP1, but it does give a reference to analyze the expansion plans obtained with our model.

With respect to the second phase of the proposed methodology, the payoff table for the second level (subcriteria) in the AHP hierarchy is presented in Table 3.6.

According to Table 3.6, the highest cost is the investment component, followed by the operation and transmission components. The nuclear risk (new MW installed using such technology) is almost the same in all of the alternatives, which is because of the restrictions placed on the system (only a few of nuclear units can be installed). Continuing with the second phase of the methodology, we as DM define the following pairwise judgment matrix for the first level of the AHP hierarchy (Table 3.7). Also, the pairwise judgment matrices for the second level of the hierarchy are presented in Table 3.8 and Table 3.9. It is important to mention that these matrices can be different for another DM, thus obtaining different conclusions.

Based on the scale proposed in [59], and according to Table 3.7, cost, environment and risk prices criteria are equally preferred. Also, the environment is slightly more preferred to

Table 3.4: Resulting Pay-off table

	weights				S_1	S_2	S_3	S_4
Alternative	w_1	w_2	w_3	w_4	**COST**	**ENVIRON**	**FUEL**	**Risk Prices**
A_1	min-max				1.75E+10	21929.89	155.65	81544.64
A_2	compromise programming				2.35E+10	19294.00	2786.18	66646.91
A_3	0.45	0.06	0.45	0.04	1.20E+10	26452.15	74382.87	111101.58
A_4	0.28	0.08	0.51	0.12	1.57E+10	22945.43	0.00	87411.45
A_5	0.37	0.08	0.15	0.40	1.82E+10	21715.90	2786.18	79150.48
A_6	0.41	0.29	0.11	0.19	1.92E+10	21118.27	155.65	77736.23
A_7	0.34	0.13	0.22	0.31	1.70E+10	22214.30	155.65	82504.83
A_8	0.08	0.43	0.40	0.09	2.39E+10	19214.49	2786.18	66773.36
A_9	0.07	0.06	0.40	0.47	2.37E+10	19644.25	10500.00	64819.59
A_{10}	0.04	0.16	0.40	0.40	2.39E+10	19591.92	2786.18	64804.21
ideal					1.20E+10	19214.49	0.00	63891.40
anti-ideal					3.37E+10	29844.50	8089772.89	140232.86

Table 3.5: Technologies added

	Capacity (MW) added by technology (2014)								
Alternative	**STEAM**	**CC**	**TG**	**COAL**	**NUCLEAR**	**GEO**	**WIND**	**HYDRO**	**Total**
A_1	918.40	10513.50	1987.20	414.20	2394.00	837.20	400.00	1330.72	18795.22
A_2	918.40	10513.50	1987.20	414.20	2861.40	837.20	400.00	3885.20	21817.10
A_3	3583.60	9182.20	1987.20	1628.80	0.00	0.00	160.00	191.20	16733.00
A_4	1364.86	10513.50	1987.20	414.20	2366.34	837.20	160.00	421.00	18064.30
A_5	918.40	10496.00	2004.70	414.20	2861.40	837.20	400.00	1235.80	19167.70
A_6	918.40	10513.50	1987.20	414.20	2394.00	837.20	400.00	2178.80	19643.30
A_7	918.40	10513.50	1987.20	414.20	2394.00	837.20	400.00	1073.00	18537.50
A_8	1086.20	10759.70	1987.20	414.20	2861.40	837.20	400.00	3916.00	22261.90
A_9	688.60	10513.50	1987.20	644.00	2861.40	837.20	400.00	3885.20	21817.10
A_{10}	688.60	10759.70	1987.20	644.00	2861.40	837.20	400.00	3916.00	22094.10
Government	0.00	11683.00	1119.00	700.00	0.00	125.00	592.00	2254.00	16473.00

Table 3.6: Resulting Pay-off table for subcriteria

	S_{11}	S_{12}	S_{13}	S_{42}
Alternative	**Investment**	**Operation**	**Transmission**	**Nuclear Risk**
A_1	1.64E+10	1.15E+09	179234.30	5550.40
A_2	2.24E+10	1.19E+09	211348.76	6413.80
A_3	1.10E+10	1.05E+09	183047.07	3367.80
A_4	1.46E+10	1.14E+09	233941.48	5522.74
A_5	1.71E+10	1.17E+09	221646.00	6413.80
A_6	1.81E+10	1.16E+09	218986.30	5550.40
A_7	1.58E+10	1.15E+09	194729.94	5550.40
A_8	2.27E+10	1.19E+09	203926.62	6413.80
A_9	2.25E+10	1.21E+09	220061.61	6413.80
A_{10}	2.27E+10	1.21E+09	361184.03	6413.80

Table 3.7: Judgment Criteria Matrix

	S_1	S_2	S_3	S_4
S_1	1	1/3	1	1
S_2	3	1	2	1
S_3	1	1/2	1	1/3
S_4	1	1	3	1

cost criterion, less than slightly more preferred to imported fuel criterion and equal preferred to risk prices criterion. Finally, risk prices criterion is slightly more preferred to imported fuel criterion. Observing Table 3.8, investment and transmission costs are equally preferred; investment is slightly more preferred to operation cost, and operation and transmission are equally preferred. As noticed in Table 3.9, risk in prices is less than slightly more preferred to nuclear risk.

The value judgments for the alternatives respect to each criteria and subcriteria are obtained from the results shown in payoff Tables 3.4 and 3.6. Based on the defined judgments and following the AHP calculations procedure, the priorities obtained for each alternative are presented in Table 3.10.

Table 3.8: Judgment cost criteria matrix

	S_{11}	S_{12}	S_{13}
S_{11}	1	3	1
S_{12}	1/3	1	1
S_{13}	1	1	1

Table 3.9: Judgment risk criteria matrix

	S_{41}	S_{42}
S_{41}	1	2
S_{42}	1/2	1

According to Table 3.10, the alternatives are ranked in the following way:

$$A_4 > A_3 > A_1 > A_7 > A_6 > A_8 > A_9 > A_2 > A_5 > A_{10}$$

The best expansion alternative is A_4, followed by A_3 and A_1 (min-max). Alternative A_4 is better by a significant amount since this is the only alternative that do not require import of fuel. Also, A_3 is the one who has the minimum total cost (see Table 3.4). These alternatives are like outliers for the set of the examined alternatives, and therefore removing them or changing the judgment pairwise values can produce a different ranking. For example, the lowest ranked alternative A_{10} might be the best for different pair-wise comparisons. Thus, A_1 is an attractive option for expansion that do not require any weights definition; and A_7 is also another interesting alternative to analyze. The comparison between the first four ranked alternatives and the Mexican government's alternative is presented in Figure 3.3.

From Figure 3.3, it is important to mention that nuclear additions are proposed by most of the alternatives considered, contrary to the Mexican government's option. The explosions in Chernobyl in 1996 made the International Atomic Energy Agency (IAEA) to have as one of its more important activities to build a strong and effective global nuclear safety regime, which requires effective international cooperation (sharing information, setting clear safety

Table 3.10: Alternative Priorities

Alternative	**PRIORITY**
A_1	0.0881
A_2	0.0846
A_3	0.0931
A_4	0.2248
A_5	0.0829
A_6	0.0868
A_7	0.0876
A_8	0.0847
A_9	0.0847
A_{10}	0.0827

standards, reviewing operational performance). Specially, nowadays when more additions of nuclear power are considered to meet increasing energy demands in many parts of the world.

However, nuclear power should not be viewed as being in competition with renewable sources of energy, such as wind, solar and geothermal plants. With the aim to reduce carbon emissions, both nuclear and these renewable sources could have much larger roles to play. But, the fact is that renewable sources do not have the capacity to provide the amount of power needed to replace large non-renewable plants. Wind power, for example, may be an excellent choice for sparsely populated rural economies, particularly if they lack modern electrical infrastructure; on the other hand, it seems unlikely that wind power will be able to support the electricity needs of tomorrow's mega-cities [34].

The composition of technologies installed by alternative A_4 can be observed in Figure 3.4.

According to Figure 3.4, the given importance for each one of the criteria and subcriteria, and the limited availability of renewable sources turns out in a high percentage of combined cycle (CC) technologies, which is one of the cheapest and cleanest (less CO_2 emissions) non-renewable type of units. Most renewable technologies are installed at their maximum permissible levels.

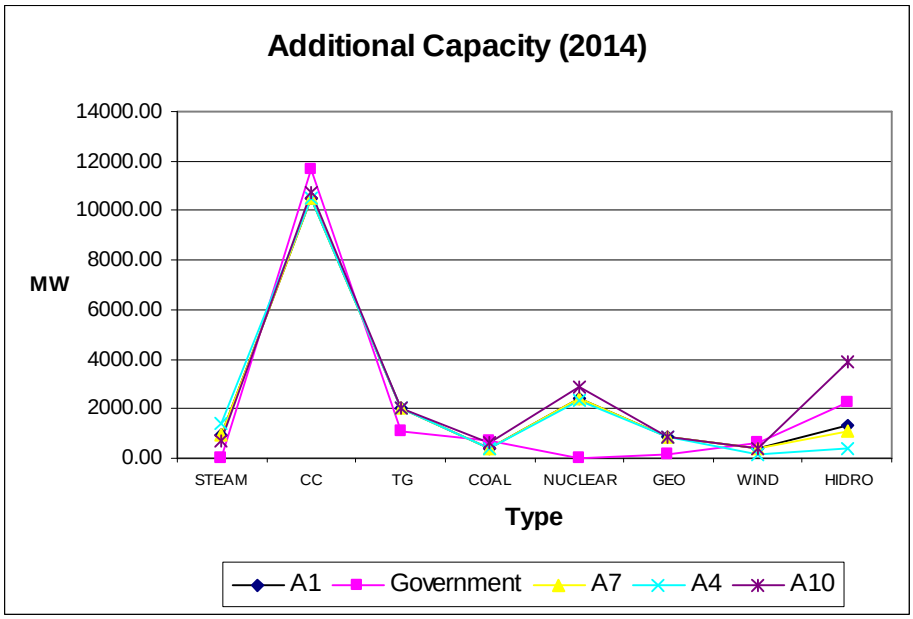

Figure 3.3: Comparison of expansion plans

3.5 Summary

A single-period multiobjective model (MGEP1) has been proposed in this chapter which considers aspects that previous models have not included. The incorporation of more than three criteria to generate the expansion alternatives, the importance given to renewable generation technologies, and the geographical location of the new generation units are some features of the MGEP1 which have not been considered simultaneously in the literature.

Although the solutions obtained with MGEP1 can be considered as approximations to the real generation expansion planning problem (integer investment variables, multi-period model, and with the two Kirchoff's laws), they look reasonable (see the Mexican government's expansion plan). In addition, the computational effort to obtain them is low; with more accurate input data, the results can be better. Nowadays, the expansion planning of electric power systems is usually done by using sophisticated and costly computational tools [33], [37]. However, with MGEP1 good and very fast mix additions results can be obtained for the problem.

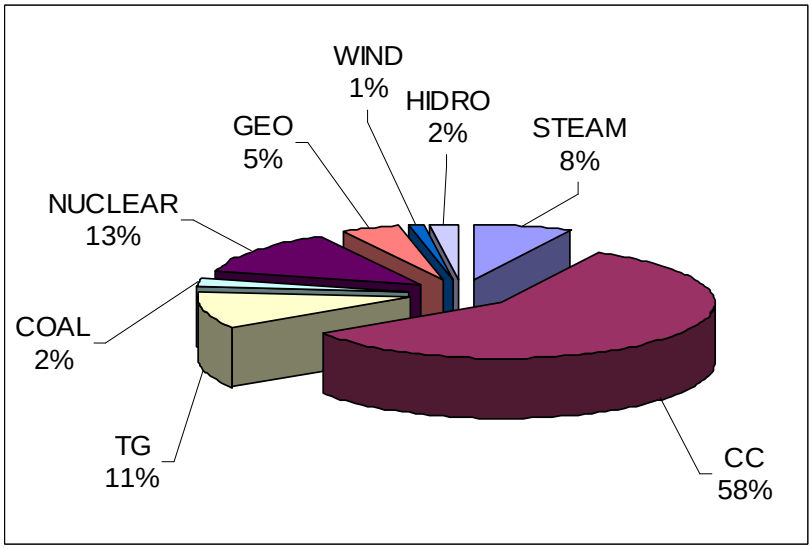

Figure 3.4: Expansion plan by A_4

CHAPTER 4

A MULTI-PERIOD MULTIOBJECTIVE LINEAR MODEL

4.1 Introduction

In a multi-period model the decision variables are the number of generating units of each type that will be constructed at each period. The resulting model is a multi-period, mixed-integer one for which Bender's decomposition method has been commonly used for single-objective models [6]. In this chapter, a multi-period, multiobjective, linear programming model (MGEP2) is presented and tested for the generation expansion problem. The MGEP2 models considers only one (current conservation) of the two Kirchoff's laws, has continuous decision variables, and is deterministic. The importance of considering the transmission network is basically to find a generation expansion plan which can optimize more globally the electricity supply chain. MGEP2 is still a very large-scale, linear mathematical programming problem with different conflicting objectives that must be considered simultaneously.

4.2 Mathematical Formulation

The input data for MGEP2 includes the existing network configuration and its transmission capacity limits; technology costs for new equipment; investment constraints; the generating capacity and investment/production costs of generating units; as well as the expected electric load, and economical factors. In this section, MGEP2 is described mathematically. The parameters, constants, decision variables, constraints and objective functions used in the formulation are presented.

4.2.1 Indices

$i \in \mathcal{N}$	nodes
$q \in \Theta$	types of generation units
$k \in \mathcal{F}$	types of fuel
$(i,j) \in \mathcal{A}$	arcs from node i to node j
$t \in \mathcal{T}$	time periods

4.2.2 Parameters of the model

The following data are input to MGEP2:

$\mathcal{T}$	Set of periods in the planning horizon.
r	Discount factor (opportunity cost).
D_{it}	Load (MW) at node i in period t.
$\bar{X}_{ij}$	Existing (MW) capacity of transmission in arc (i,j).
$\bar{GE}_{iq}$	Existing (MW) generation capacity for a unit of type q at node i.
$\bar{IG}_{iqt}$	Maximum investment (MW) of capacity for new units of type q at node i in period t.
W_q	Consumption of fuel (units/MW) for a unit of type q.
I_{iqt}	Investment cost (\$/MW) of a unit of type q at node i in period t.
G_{iqt}	Generation cost (\$/MW) of a unit of type q at node i (operation & maintenance) in period t.
C_{ijt}	Cost (\$/MW) for new transmission capacity in arc (i,j) in period t.
V_{kt}	Cost (\$/unit) of imported fuel of type k in period t.
E_q	Tons of carbon dioxide emission (CO_2) per MW generated by a unit of type q.
U_{kt}	National available amount (corresponding units) of fuel type k in period t.
S_{kt}	Expected coefficient of variation in prices of fuel type k in period t.
J_k	Index of units of fuel type k.

4.2.3 Decision Variables

Seven groups of decision variables in the model are described next.

g_{iqt}	Generation amount (MW) of unit type q at node i in period t.
$\mathcal{U}_{iqt}$	Capacity addition (MW) of unit type q at node i in period t.
$\mathcal{Y}_{iqt}$	Cumulative capacity (MW) of unit type q at node i in period t.
x_{ijt}	Flow (MW) through arc (i, j) in period t.
Δx_{ijt}	Additional transmission capacity (MW) in arc (i, j) in period t.
$C\Delta x_{ijt}$	Cumulative capacity (MW) in arc (i, j) in period t.
u_{kt}	Imported fuel (units) of type k in period t.

4.2.4 Objective Functions

In this multiobjective, model the minimization of the investment, operation and transmission costs, environmental impact, imports of fuel and fuel prices risks of the whole system are considered. The last two objectives have not been explicitly considered in the literature when determining the expansion alternatives with the use of multiobjective optimization methods.

- Investment, Operational & Transmission Costs. This objective function is defined as the total present value sum of the investment cost for new units, the generation costs, and the cost for additional capacity of transmission.

$$f_1 = \sum_{t\in\mathcal{T}} (1+r)^{-t} \left[\sum_{i\in\mathcal{N}} \sum_{q\in\Theta} I_{iqt}\mathcal{U}_{iqt} + \sum_{i\in\mathcal{N}} \sum_{q\in\Theta} G_{iqt}\, g_{iqt} + \sum_{(i,j)\in\mathcal{A}} C_{ijt}\Delta x_{ijt} \right] \tag{4.1}$$

  Here, the first part is the investment cost associated to new generation units; the second part is the operational cost of the system, and the third one is the cost for new transmission capacity.

- Environmental impact. Only the aggregate Carbon Dioxide Emissions (CO_2) from fossil-fuel plants is minimized, since there are not enough ways (flora) to absorb such

emissions, making them the most hazardous for the global warming (greenhouse) in the planet [43].

$$f_2 = \sum_{t \in \mathcal{T}} \left[\sum_{i \in \mathcal{N}} \sum_{q \in \Theta} E_q \; g_{iqt} \right] \tag{4.2}$$

- Imported Fuel. The minimization of possible import of fuel by the system is considered by this objective.

$$f_3 = \sum_{t \in \mathcal{T}} (1+r)^{-t} \left[\sum_{k \in \mathcal{F}} V_{kt} u_{kt} \right] \tag{4.3}$$

- Energy Price Risks. This objective seeks to minimize the exposure to fuel price volatility in the expansion decisions.

$$f_4 = \sum_{t \in \mathcal{T}} \left[\sum_{k \in \mathcal{F}} S_{kt} \sum_{q \in J_k} \sum_{i \in \mathcal{N}} g_{iqt} \right] \tag{4.4}$$

  Here, S_{k_t} is the expected coefficient of variation in prices of fuel type k in period t, utilized to minimize such exposure. This way to measure the risk in prices is simple but original in multiobjective models; other ideas could be obtained from [3].

4.2.5 Constraints

In MGEP2, eight types of constraints are imposed: flow balance constraints in the network, transmission limits on arcs, generation capacity, investment capacity, amount of available local fuel, cumulative generation capacity, cumulative transmission capacity, and non-negativity of the decision variables. Such constraints are described below in details.

- Node Balance Equations in each node i in period t: The inflow in each node (generation + flow from other nodes) is equal to the outflow (demand + flow to other nodes).

$$\sum_{(j,i)\in\mathcal{A}} x_{jit} - \sum_{(i,j)\in\mathcal{A}} x_{ijt} + \sum_{q\in\Theta} g_{iqt} = D_{it}; \quad i \in \mathcal{N}, t \in \mathcal{T} \tag{4.5}$$

- Transmission Capacity on each arc (i, j) in period t: There are physical limits on the amount of power flow that can be transmitted through the arcs of the network.

$$x_{ijt} \leq C\Delta x_{ij(t-1)} + \Delta x_{ijt}; \quad (i,j) \in \mathcal{A}, t \in \mathcal{T} \tag{4.6}$$

- Generation Capacity for each unit type q in node i during period t: Operating limits are imposed to the generation units.

$$g_{iqt} \leq \mathcal{U}_{iqt} + \mathcal{Y}_{iq(t-1)}; \quad i \in \mathcal{N}, q \in \Theta, t \in \mathcal{T} \tag{4.7}$$

- Maximum investment for each unit type q in node i during period t: Because of natural reasons (space, resources, etc.), there is a maximum of investments in generation units.

$$\mathcal{U}_{iqt} \leq \bar{IG}_{iqt} \quad i \in \mathcal{N}, q \in \Theta, t \in \mathcal{T} \tag{4.8}$$

- Fuel demand for each fuel type k in period t: Fuel used will be either from local markets (U_k), or if necessary imported.

$$\sum_{i\in\mathcal{N}} \sum_{q\in J_k} W_q \; g_{iqt} \leq u_{kt} + U_{kt}; \quad k \in \mathcal{F}, t \in \mathcal{T} \tag{4.9}$$

- Cumulative generation capacity for each unit type q in node i during period t: The new generation capacity is accumulated through the horizon.

$$\mathcal{Y}_{iqt} = \mathcal{Y}_{iq(t-1)} + \mathcal{U}_{iqt}; \quad i \in \mathcal{N}, q \in \Theta, t \in \mathcal{T} \tag{4.10}$$

- Cumulative transmission capacity on each arc (i, j) in period t: The new transmission capacity is accumulated through the horizon.

$$C\Delta x_{ijt} = C\Delta x_{ij(t-1)} + \Delta x_{ijt}; \quad (i,j) \in \mathcal{A}, t \in \mathcal{T} \tag{4.11}$$

- Non-negativity: No negative values are permitted for the decision variables.

$$\mathcal{Y}_{iqt}, \mathcal{U}_{iqt}, g_{iqt}, \Delta x_{ijt}, x_{ijt}, u_{kt} \geq 0; \quad i \in \mathcal{N},\ q \in \Theta,\ (i,j) \in \mathcal{A};\ k \in \mathcal{F}, t \in \mathcal{T} \tag{4.12}$$

- Initial values.

$$\mathcal{Y}_{iq0} = \bar{GE}_{iq}; \quad i \in \mathcal{N}, q \in \Theta \tag{4.13}$$

The generation capacity in period 0 is equal to the existing capacity.

$$C\Delta x_{ij0} = \bar{X}_{ij}; \quad (i,j) \in \mathcal{A} \tag{4.14}$$

The transmission capacity in period 0 is equal to its existing capacity.

The model is a multiobjective linear programming problem with $3 * |\mathcal{N}| * |\Theta| * |\mathcal{T}| + 3 * |\mathcal{A}| * |\mathcal{T}| + |\mathcal{F}| * |\mathcal{T}|$ variables, and $|\mathcal{T}| * [\ |\mathcal{N}| + 2 * |\mathcal{A}| + 3 * |\mathcal{N}| * |\Theta| + |\mathcal{F}|\ ]$ constraints.

Since this multi-period MGEP2 model is linear, it will be solved using the methodology proposed in section 3.3. In this case, a larger multiobjective linear programming (MOLP) problem is solved to find the expansion alternatives (non-dominated solutions).

4.3 Tests and Results

The proposed methodology will be illustrated using the Interconnected Grid Mexican Power System (see Figure 4.1), at the level of areas. The planning horizon (2005-2014)

consists of five biannual periods within the time horizon. The base year is 2004, and the existing capacity in the system is 41443 MW. This system is formed by 7 nodes (areas), 7 arcs, 8 types of generation units, and four types of fuel. Generation technology options for capacity additions include: conventional steam units, coal units, combined cycle modules (CC), nuclear, gas turbines (TG), wind farms, geothermal and hydro units. The types of non-renewable fuel are: coal, gas, oil, and uranium. Some of the input data was taken from [53], and the rest was estimated using different sources. For this system, the resulting MGEP2 model has 5*(3*7*8 + 3*7 + 4) = 965 variables, and 5*(7 + 2*7 + 3*7*8 + 4) = 965 constraints.

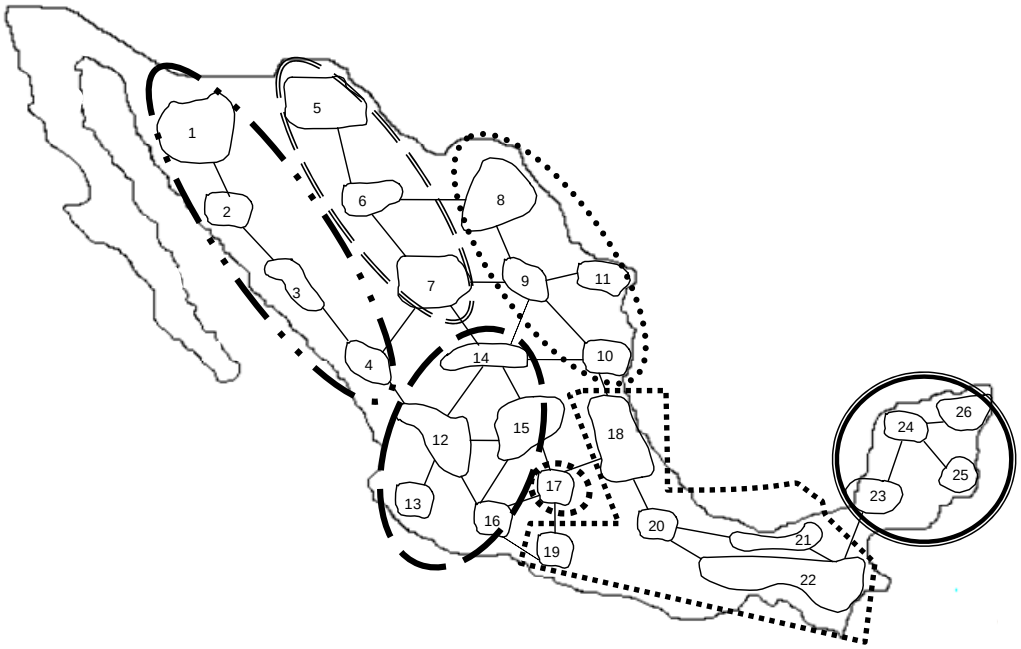

Figure 4.1: Interconnected Areas Mexican Electric System (AIMES)

A GAMS [8] code which uses ILOG Cplex 9.0 Solver for linear programming problems is used to obtain the expansion alternatives in the first phase of the proposed methodology. A total of 2000 scaled single-objective problems were solved using randomly generated set of weights for each criteria. The scaling is done by dividing the coefficients of each objective function by the difference between its corresponding anti-ideal and ideal solutions. Those 2000 non-dominated solutions were filtered to 8 alternatives (clusters) using the K-means

algorithm.

The obtained alternatives besides the min-max (the max-min solution coincided with the min-max one) and compromise programming solutions represent a total of 10 non-dominated solutions (see Table 4.1) which are the input for the second phase (select the most attractive expansion plan) of the framework.

As shown in Table 4.1, each alternative is between the ideal and anti-ideal values. The sets of randomly generated weights give different importance to each criteria, allowing to get a group of diverse non-dominated solutions (alternatives) to the problem. The new capacity for each alternative is presented in Table 4.2.

In Table 4.2, *Government* denotes the Current Reported Expansion Plan from the Mexican Entities for the same planning horizon (2005-2014) [53]. In such expansion plan, the type of generation unit needs to be decided for the remaining 6000 MW of the expected electricity demand. All of the alternatives shown in Table 4.2 present diversity in the types of technologies proposed to install, and in some cases such diversity is similar to the Mexican government's expansion plan. Since the Mexican government's expansion plan was obtained using different methodologies and input data, a comparison with it is not possible. We cannot tell if such plan is a non-dominated solution in MGEP2, but it does give a reference for the expansion plans obtained with our model.

The payoff table for the second level (subcriteria) in the AHP hierarchy is presented in Table 4.3.

According to Table 4.3, the highest cost is the investment component, followed by the operation and transmission components. The nuclear risk (new MW installed using such technology) is almost the same in all of the alternatives, which is because of the restrictions placed on the system (a few of nuclear units can be installed). Continuing with the second phase of the methodology, we as DM define the following pairwise judgment matrix for the first level of the AHP hierarchy (Table 4.4). Also, the pairwise judgment matrices for the

Table 4.1: Resulting Pay-off table MGEP2

	weights				S_1	S_2	S_3	S_4
Alternative	w_1	w_2	w_3	w_4	**COST**	**ENVIRON**	**FUEL**	**Risk Prices**
A_1	min-max				1.53E+10	76280.84	5502476.65	251415.31
A_2	compromise programming				2.16E+10	69864.77	4084270.96	204186.75
A_3	0.56	0.17	0.20	0.07	2.34E+10	68899.72	3988645.83	198670.88
A_4	0.16	0.49	0.18	0.18	2.51E+10	65863.91	4381110.10	213806.30
A_5	0.17	0.30	0.35	0.18	2.70E+10	69068.97	3893440.22	195672.89
A_6	0.06	0.50	0.17	0.27	2.88E+10	67393.81	4163545.97	205681.64
A_7	0.07	0.38	0.48	0.07	3.07E+10	71407.86	3869756.38	239669.94
A_8	0.15	0.20	0.25	0.40	3.26E+10	67776.87	4082156.40	203009.87
A_9	0.06	0.25	0.42	0.27	3.46E+10	69188.96	3877276.91	195046.87
A_{10}	0.04	0.31	0.36	0.30	3.69E+10	68772.80	3949733.84	197703.74
ideal					8.54E+09	65520.17	3119242.14	195046.87
anti-ideal					5.64E+10	141790.72	34058574.04	594580.60

Table 4.2: Technologies added MGEP2

	Capacity (MW) added by technology (2014)								
Alternative	**STEAM**	**CC**	**TG**	**COAL**	**NUCLEAR**	**GEO**	**WIND**	**HYDRO**	**Total**
A_1	0.00	11686.80	2318.40	0.00	760.00	627.90	640.00	1584.00	17617.10
A_2	0.00	11686.80	1854.72	0.00	2366.34	732.55	720.00	3476.59	20837.00
A_3	0.00	11271.58	1622.88	0.00	2366.34	941.85	800.00	4554.00	21556.65
A_4	907.32	12376.48	2202.48	0.00	2366.34	1046.50	800.00	4950.00	24649.12
A_5	1260.00	11963.80	2318.40	1330.35	2366.34	1046.50	800.00	4950.00	26035.39
A_6	3150.00	11707.80	2318.40	1932.00	2366.34	1046.50	800.00	4950.00	28271.04
A_7	3249.41	11963.80	2202.48	3392.16	2366.34	1046.50	800.00	4950.00	29970.69
A_8	353.76	12030.48	2318.40	1288.00	6658.44	1046.50	800.00	4950.00	29445.58
A_9	4061.44	12030.48	2318.40	6440.00	2366.34	1046.50	800.00	4950.00	34013.16
A_{10}	2797.32	12395.04	2666.16	9016.00	2366.34	1046.50	800.00	4950.00	36037.36
Government	0.00	11683.00	1119.00	700.00	0.00	125.00	592.00	2254.00	16473.00

Table 4.3: Resulting Pay-off table for subcriteria MGEP2

	S_{11}	S_{12}	S_{13}	S_{42}
Alternative	**Investment**	**Operation**	**Transmission**	**Nuclear Risk**
A_1	1.13E+10	4.01E+09	1.72E+06	10625.00
A_2	1.72E+10	4.40E+09	8.12E+06	17721.07
A_3	1.89E+10	4.43E+09	6.81E+07	17721.07
A_4	2.08E+10	4.27E+09	2.13E+07	17721.07
A_5	2.25E+10	4.47E+09	5.55E+06	17721.07
A_6	2.43E+10	4.36E+09	1.16E+08	17721.07
A_7	2.61E+10	4.46E+09	1.16E+08	17721.07
A_8	2.82E+10	4.39E+09	3.81E+06	17721.07
A_9	3.00E+10	4.48E+09	1.16E+08	17721.07
A_{10}	3.23E+10	4.45E+09	1.16E+08	17721.07

second level of the hierarchy are presented in Table 4.5 and Table 4.6. Note that the pairwise judgement matrices might be different for another decision maker.

Table 4.4: Judgment Criteria Matrix MGEP2

	S_1	S_2	S_3	S_4
S_1	1	1/3	1	1
S_2	3	1	2	1
S_3	1	1/2	1	1/3
S_4	1	1	3	1

Based on the scale proposed by [59], and observing Table 4.4, cost, environment and risk prices criteria are equally preferred. Also, the environment is slightly more preferred to cost criterion, less than slightly more preferred to imported fuel criterion and equal preferred to risk prices criterion. Finally, risk prices criterion is slightly more preferred to imported fuel criterion. Observing Table 4.5, investment and transmission costs are equally preferred; investment is slightly more preferred to operation cost, and operation and transmission are equally preferred. As noticed in Table 4.6, risk in prices is less than slightly more preferred to nuclear risk.

Table 4.5: Judgment cost criteria matrix MGEP2

	S_{11}	S_{12}	S_{13}
S_{11}	1	3	1
S_{12}	1/3	1	1
S_{13}	1	1	1

Table 4.6: Judgment risk criteria matrix MGEP2

	S_{41}	S_{42}
S_{41}	1	2
S_{42}	1/2	1

The value judgments for the alternatives respect to each criteria and subcriteria are obtained from the results shown in payoff Tables 4.1 and 4.3. Based on the defined judgments and following the steps of the second phase, the priorities obtained for each alternative are presented in Table 4.7.

Table 4.7: Alternative Priorities MGEP2

Alternative	**PRIORITY**
A_1	0.1281
A_2	0.1017
A_3	0.0967
A_4	0.0947
A_5	0.1035
A_6	0.0932
A_7	0.0910
A_8	0.1043
A_9	0.0939
A_{10}	0.0929

According to Table 4.7, the alternatives are ranked in the following way:

$$A_1 > A_8 > A_5 > A_2 > A_3 > A_4 > A_9 > A_6 > A_{10} > A_7$$

The A_1 (min-max) alternative turns out in the best expansion plan, followed by A_8 and A_5. The comparison between the first four ranked alternatives and the Mexican government's alternative is presented in Figure 4.2.

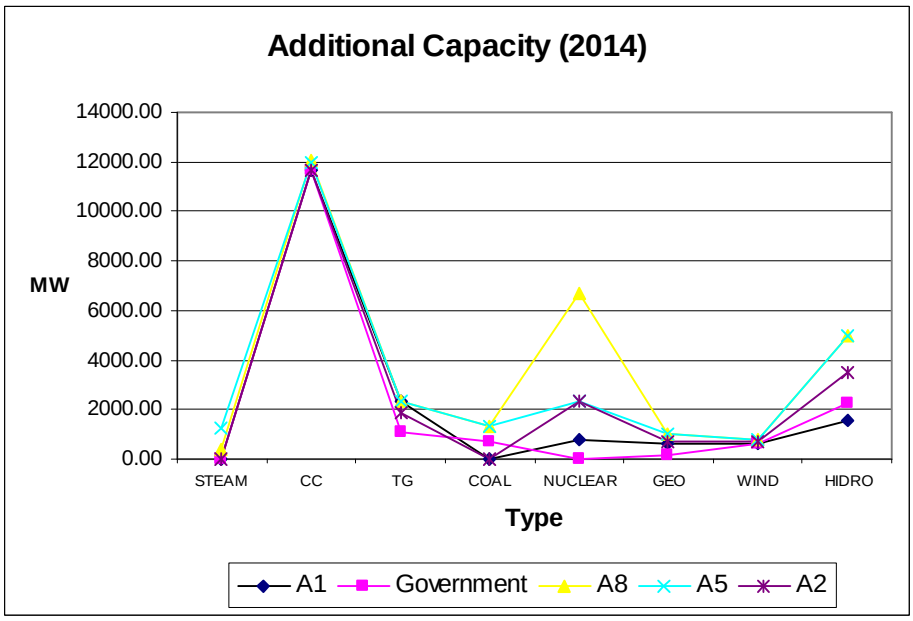

Figure 4.2: Comparison of expansion plans MGEP2

As observed in Figure 4.2, most of the new capacity comes from CC units, even for the Mexican government's option. The most significant difference between these alternatives is observed in the nuclear capacity, which gives a wide and rich range for the final decision to make. The composition of technologies installed by alternative A_1 is presented in Figure 4.3.

As shown in Figure 4.3, the given importance for each one of the criteria and subcriteria, the attractiveness of using gas units, and the limited availability of renewable sources turns out in a high percentage of combined cycle (CC) technologies. Note an undesirable dependence on natural gas fuel sources can make A_8 or A_5 as better alternatives for the DM.

The added capacity (MW) by area for alternative A_1 is shown in Table 4.8.

As it is observed in Table 4.8, the area with major additional capacity is the Oriental, followed by the Occidental and Northeast. The area with minor additions is the Peninsular.

Table 4.8: Expansion by area (A_1) MGEP2

ALTERNATIVE 1							
Area	**Northwest**	**North**	**Northeast**	**Occidental**	**Central**	**Oriental**	**Peninsular**
STEAM	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CC	1822.80	1822.80	1822.80	1822.80	1822.80	1822.80	750.00
TG	0.00	0.00	579.60	579.60	579.60	579.60	0.00
COAL	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NUCLEAR	0.00	0.00	0.00	0.00	0.00	760.00	0.00
GEO	0.00	0.00	0.00	313.95	0.00	313.95	0.00
WIND	320.00	0.00	0.00	0.00	0.00	320.00	0.00
HYDRO	396.00	0.00	396.00	396.00	198.00	198.00	0.00
Total	**2538.80**	**1822.80**	**2798.40**	**3112.35**	**2600.40**	**3994.35**	**750.00**

Table 4.9: New capacity (MW) by period (A_1)

Node	**Type**	**2006**	**2008**	**2010**	**2012**	**2014**
1	cc	364.56	364.56	364.56	364.56	364.56
	wind	80.00	80.00	80.00	80.00	
	hydro	198.00	198.00			
2	cc	364.56	364.56	364.56	364.56	364.56
3	cc	364.56	364.56	364.56	364.56	364.56
	tg	115.92	115.92	115.92	115.92	115.92
	hydro	198.00	198.00			
4	cc	364.56	364.56	364.56	364.56	364.56
	tg	115.92	115.92	115.92	115.92	115.92
	geo	104.65	104.65	104.65		
	hydro	198.00	198.00			
5	cc	364.56	364.56	364.56	364.56	364.56
	tg	115.92	115.92	115.92	115.92	115.92
	hydro	198.00				
6	cc	364.56	364.56	364.56	364.56	364.56
	tg	115.92	115.92	115.92	115.92	115.92
	nuclear	760.00				
	geo	104.65	104.65	104.65		
	wind	80.00	80.00	80.00	80.00	
	hydro	198.00				
7	cc	184.00	164.64	213.00	191.00	

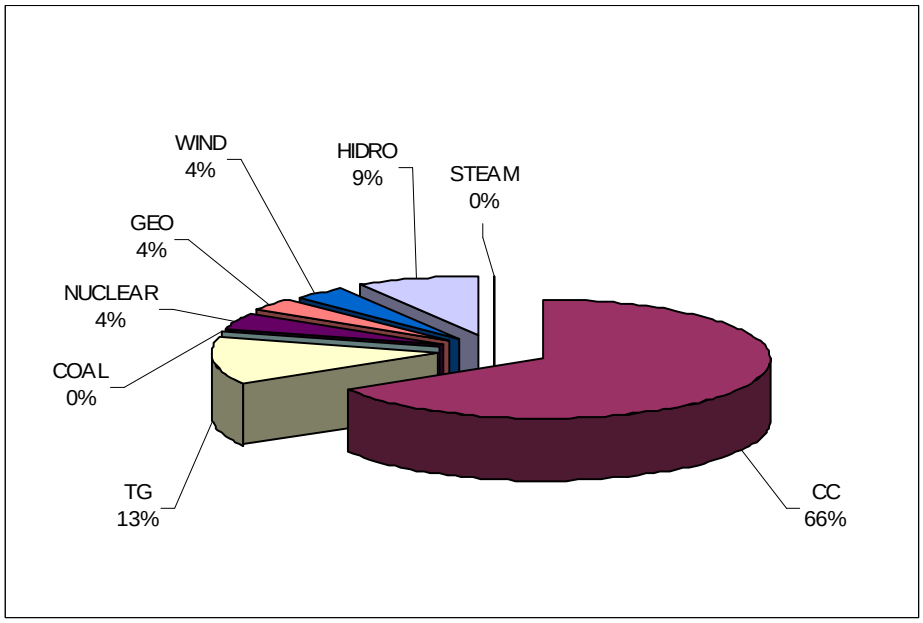

Figure 4.3: Expansion plan by A_1 MGEP2

All these results and the previous ones, indicate reasonable solutions to the case presented, using the model and the methodology described in this paper chapter. The new capacity per period of time proposed by alternative A_1 is shown in Table 4.9. Finally, the new capacity per period proposed by each alternative is presented in Table 4.10, which shows a reduction in additions through the time.

The pairwise judgments given for this illustrative example tried to represent a case where environmental impact is the most critical issue, followed by the equally important other criteria. It produced alternatives where renewable sources, some grade of nuclear power and natural gas are used preferably, which seems to be reasonable. Other judgments can produce different ranking of the alternatives, and that is one of the advantages of this proposed framework.

4.4 Summary

The model long-term multiobjective generation expansion planning problem (MGEP2) described in this chapter represents an extension to the single-period model (MGEP1) pre-

Table 4.10: New capacity (MW) by period

Alternative	**2006**	**2008**	**2010**	**2012**	**2014**
A_1	4954.34	3776.34	3233.34	3002.04	2651.04
A_2	5393.20	4876.14	4135.93	3700.69	2731.04
A_3	5230.20	5078.70	3972.94	3778.50	3496.31
A_4	5689.68	5824.62	4524.42	4580.30	4030.10
A_5	6073.76	6186.99	5161.85	4834.29	3778.50
A_6	5985.28	7112.62	5168.42	5854.30	4150.42
A_7	8340.45	7471.44	5031.93	5348.37	3778.50
A_8	7062.50	6127.94	6439.17	5477.16	4338.81
A_9	7585.63	8640.70	6696.50	7008.38	4081.95
A_{10}	8303.39	8699.51	7408.82	6134.82	5490.82

sented in chapter 3. The same methodology of solution for MGEP1 was used for solving MGEP2. The obtained results are reasonable. Since the size of the MGEP2 model is larger than the single-period one, the performance of the proposed methodology was verified with a smaller case study. although a larger system is also possible to test.

CHAPTER 5

A MULTIOBJECTIVE MIXED-INTEGER NON-LINEAR MODEL

5.1 Introduction

This chapter describes and evaluates a single-period multiobjective mixed-integer non-linear programming model (MGEP3), which is an extension of the model (MGEP1) presented in chapter 3. The incorporation of more than three criteria to generate the expansion alternatives, the importance given to renewable generation technologies, and the decisions related to determining the location of the new generation units are also features of the MGEP3 model. Since the MGEP1 model represents an electricity transhipment network to which only one of Kirchoff's laws applies (conservation of current), the voltages are ignored. Thus, transmission losses are assumed to be a constant fraction of the power flows, and the non-linear nature of active and reactive power flows is disregarded [9]. For these reasons, MGEP1 is an approximation for the inclusion of transmission costs. Considering the second Kirchoff's law (voltage conservation) permits the representation of the transmission network more realistically, but at the same time, it increases the complexity of the problem since the equations associated with the node balance constraints and transmission capacity constraints are now non-linear, and a new integer variable (number of circuits to add in the arcs) is necessary.

The main characteristic and contribution of MGEP3 is that it considers the integrality of the investment decisions (generation and transmission), includes the second Kirchoff's law, and it is still a multiobjective model. A model with such characteristics is considered highly difficult to solve. In this chapter, an original multiobjective evolutionary programming algorithm is proposed and evaluated to solve the problem.

The following sections describe the model considered, the solution approach and the results obtained from its application.

5.2 Mathematical Formulation

The input data for MGEP3 includes the existing network configuration and its transmission capacity limits; technology costs for new equipment; investment constraints; the generating capacity and investment/production costs of generating units; as well as the expected electric load. However, more information about the transmission network is required than in the previously presented models. For example, a transmission line will be represented by its susceptance, which is associated with the ability of a electric circuit to permit current flow.

In this section, MGEP3 is described mathematically. The parameters, decision variables, constraints and objective functions are defined.

5.2.1 Indices

i nodes

q types of generation units

k types of fuel

ij arcs from node i to node j

5.2.2 Input Data

The following data should be provided to the model:

$\mathcal{G}$ Configuration of the electric network; where $\mathcal{G} = \{\mathcal{N}, \mathcal{A}\}$, $\mathcal{N}$ is the set of nodes, and $\mathcal{A}$ is the set of arcs.

Θ Set of types of generation units.

$\mathcal{F}$ Set of fuel types.

D_i Expected load (MW) at node i.

I_{iq} Investment cost (\$/MW) of a unit of type q at node i.

G_{iq} Generation cost (\$/MW) of a unit of type q at node i (operation & maintenance).

$\bar{GE}_{iq}$ Existing capacity (MW) of existing units of type q at node i.

Q_q Maximum capacity (MW) of generation of a unit of type q.

γ_{ij} Susceptance (pu) of a circuit on arc (i, j).

l_{ij}^0 Number of existing circuits on arc (i, j).

C_{ij} Cost of adding a circuit on arc (i, j).

$\bar{f}_{ij}$ Flow capacity of a circuit on arc (i, j).

$\bar{n}_q$ Maximum number of new generation units of type q.

$\bar{l}_{ij}$ Maximum number of new circuits on the arc (i, j).

V_k Cost (\$/unit) of imported fuel of type k.

E_q Tons of carbon dioxide emission (CO_2) per MW generated by a unit of type q.

U_k National available amount (corresponding units) of fuel type k.

W_q Fuel needed (units/MW) to operate a unit of type q.

r Percentage of operating reserve in the system.

S_k Historical coefficient of variation in prices of fuel type k.

J_k Index of units of fuel type k.

5.2.3 Decision Variables

Five groups of decision variables in the model are described next. The purpose is to find the best possible value for each one of those variables.

n_{iq} Number of new units of type q at node i.

g_{iq} Generation (MW) from units of type q at node i.

l_{ij} Number of new circuits on the arc (i, j).

θ_i Voltage phase angle at node i.

u_k Imported fuel (units) of type k.

5.2.4 Objective Functions

In this multiobjective model, the minimization of the investment and operation costs, environmental impact, imports of fuel, and fuel prices risks of the whole system are considered.

- Investment & Operational Cost. This objective function is defined as the sum of the investment cost of new units, the generation costs, and the cost for additional capacity of transmission. It is to be minimized,

$$f_1 = \sum_{i \in \mathcal{N}} \sum_{q \in \Theta} I_{iq} n_{iq} + \sum_{i \in \mathcal{N}} \sum_{q \in \Theta} G_{iq} g_{iq} + \sum_{(i,j) \in \mathcal{A}} C_{ij} l_{ij} \tag{5.1}$$

- Environmental impact. The aggregate Carbon Dioxide Emissions (CO_2) from non-renewable plants is minimized.

$$f_2 = \sum_{i \in \mathcal{N}} \sum_{q \in \Theta} E_q g_{iq} \tag{5.2}$$

- Imported Fuel. The minimization of possible imports of fuel to the system is considered by this objective.

$$f_3 = \sum_{k \in \mathcal{F}} V_k u_k \tag{5.3}$$

- Energy Price Risks. This objective seeks to minimize the exposure to fuel price volatility in the expansion decisions.

$$f_4 = \sum_{k \in \mathcal{F}} S_k \sum_{q \in J_k} \sum_{i \in \mathcal{N}} g_{iq} \tag{5.4}$$

Here, S_k is the historical coefficient of variation in prices of fuel type k, utilized to minimize such exposure.

5.2.5 Constraints

In MGEP3 model, nine types of constraints are imposed: flow balance constraints in the network, transmission limits on arcs, generation capacity, amount of available local fuel, investment in generation, investment in transmission, operating reserve, non-negativity and integrity of the decision variables. Such constraints are described below in details. Let,

f_{ij} Flow through a circuit of arc (i, j). It is positive if power flows from node i to node j

$f_{arc_{ij}}$ Flow through arc (i, j)

The power flow through a circuit in arc (i, j) is expressed in terms of both the voltage phase angles at nodes i and j and the circuit susceptance:

$$f_{ij} = \gamma_{ij} \ (\theta_j - \theta_i) \tag{5.5}$$

Finally, the power flow through arc (i, j) is expressed in terms of the number of circuits in the arc:

$$f_{arc_{ij}} = \left(l_{ij} + l_{ij}^0\right) \gamma_{ij} \ (\theta_j - \theta_i) \tag{5.6}$$

Thus, we have the following constraints in MGEP3.

- Node Balance Equations in each node i: The flow that enters each node is equal to the one that leaves it.

$$\sum_{(j,i)\in\mathcal{A}} f_{arc_{ji}} - \sum_{(i,j)\in\mathcal{A}} f_{arc_{ij}} + \sum_{q\in\Theta} g_{iq} = D_i \tag{5.7}$$

- Transmission Capacity on each arc (i, j): There are limits on the amount of power flow that can be transmitted in arcs of the network.

$$\left(l_{ij} + l_{ij}^0\right) \gamma_{ij} \ |(\theta_j - \theta_i)| \leq \left(l_{ij} + l_{ij}^0\right) \ \bar{f}_{ij} \tag{5.8}$$

  In this group of constraints the multiplication of integer l_{ij} and continuous θ_{ij} variables, makes the problem a mixed-integer bilinear large-scale one [9]. Bilinear problems are global optimization problems which are NP hard.

- Generation Capacity for each unit type q in node i: Physical limits are imposed by the generation units.

$$g_{iq} \leq \bar{GE}_{iq} + Q_q \ n_{iq} \tag{5.9}$$

- Fuel demand for each fuel type k: Fuel used will be either from local markets (U_k), or if necessary imported.

$$\sum_{i\in\mathcal{N}} \sum_{q\in J_k} W_q \ g_{iq} \leq U_k + u_k \tag{5.10}$$

- Maximum investment in generation for each type q of technology: Because of various reasons (space, resources, etc.), there is an upper limit on the investments in generation units.

$$\sum_{i \in \mathcal{N}} n_{iq} \leq \bar{n}_q \tag{5.11}$$

- Maximum investment in transmission on each arc (i, j) of the network: Also, because of various reasons (space, resources, etc.), there is an upper limit on the investments in transmission lines.

$$l_{ij} \leq \bar{l}_{ij} \tag{5.12}$$

- Operating reserve in the system: The total capacity (existing and new) in the system must exceed the total demand.

$$\sum_{i \in \mathcal{N}} \sum_{q \in \Theta} \left[\bar{GE}_{iq} + Q_q \; n_{iq} \right] \geq \sum_{i \in \mathcal{N}} d_i \; (1 + r) \tag{5.13}$$

- Non-negativity: No negative values are permitted for the decision variables.

$$g_{iq}, u_k \geq 0, \quad \forall \;\; i, q, k \tag{5.14}$$

- Integrality: Investment decision variables are integers.

$$n_{iq}, l_{ij} \;\; integers \quad \forall \;\; i, q, (i, j) \tag{5.15}$$

In summary, the MGEP3 model is:

Min $[f_1(y), f_2(x), f_3(y), f_4(y)]$

s.t.

$$\sum_{(j,i)\in\mathcal{A}} f_{arc_{ji}} - \sum_{(i,j)\in\mathcal{A}} f_{arc_{ij}} + \sum_{q\in\Theta} g_{iq} = D_i; \quad i \in \mathcal{N}$$

$$\left(l_{ij} + l_{ij}^0\right)\gamma_{ij} \ |(\theta_j - \theta_i)| \leq \left(l_{ij} + l_{ij}^0\right) \ \bar{f}_{ij}; \ \ (i,j) \in \mathcal{A}$$

$$g_{iq} \leq \bar{GE}_{iq} + Q_q \ n_{iq}; \ \ i \in \mathcal{N}, q \in \Theta$$

$$\sum_{i\in\mathcal{N}} \sum_{q\in J_k} W_q \ g_{iq} \leq U_k + u_k; \ \ k \in \mathcal{F}$$

$$\sum_{i\in\mathcal{N}} n_{iq} \leq \bar{n}_q; \ \ q \in \Theta$$

$$l_{ij} \leq \bar{l}_{ij}; \ \ (i,j) \in \mathcal{A}$$

$$\sum_{i\in\mathcal{N}} \sum_{q\in\Theta} \left[\bar{GE}_{iq} + Q_q \ n_{iq}\right] \geq \sum_{i\in\mathcal{N}} d_i \ (1+r)$$

$$g_{iq}, u_k \geq 0; \quad i \in \mathcal{N}, \ q \in \Theta, \ k \in \mathcal{F}$$

$$n_{iq}, l_{ij}, \ \ integers; \quad i \in \mathcal{N}, \ q \in \Theta, \ (i,j) \in \mathcal{A}$$

The model is a multiobjective mixed-integer non-linear programming problem with $2 * |\mathcal{N}| * |\Theta| + |\mathcal{A}| + |\mathcal{N}| + |\mathcal{F}|$ variables of which $|\mathcal{N}| * |\Theta| + |\mathcal{A}|$ are integers, and $|\mathcal{N}| + 2 * |\mathcal{A}| + |\mathcal{N}| * |\Theta| + |\mathcal{F}| + |\Theta| + 1$ constraints of which $|\mathcal{N}| + |\mathcal{A}|$ are non-linear.

5.3 The Proposed Solution Method

The proposed approach to solve the above problem is based on evolutionary computation concepts. These kind of algorithms are extensively used to solve complex, most of the time combinatorial, problems. With the aid of evolutionary algorithms (EA) it is possible to obtain an approximation to the true Pareto front of non-dominated solutions for multiobjective optimization problems. In EA, there are no assumptions of convexity of the objective functions like in other traditional methods, and in one iteration of the algorithm it is possible to

get more than one non-dominated solution.

The main steps of the proposed method are:

1. Use the proposed multiobjective evolutionary programming algorithm (MEPA) to identify a set of non-dominated solutions for MGEP3.

2. Use k-means algorithm to reduce the number of alternatives (non-dominated solutions), such that a representative set of them is retained.

3. Use AHP, as in the previous chapters, to identify a ranking of the alternatives found.

In the following sections, the basic ideas about multiobjective evolutionary computation algorithms, and the proposed MEPA are described.

5.3.1 Evolutionary Multiobjective Optimization

Evolutionary algorithms (EA) are stochastic optimization techniques that are 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 to find good approximations of complex optimization problems. Among the most representative EA are evolutionary programming (EP) and genetic algorithms (GA) [23]. In contrast to genetic algorithms, EP does not require crossover to achieve good global convergence [24].

Several methods for adapting evolutionary algorithms to cope with multiobjective optimization problems have been proposed during the last few years [13]. In a multiobjective optimization problem, an improvement of one objective of a non-dominated solution requires a decrease in one or more of the other objectives. Relation among the objectives can be indicated by the hyper-surface (Pareto front) which consists of many Pareto-optimal (non-dominated) solutions. It is desirable to find many Pareto-optimal solutions quickly.

Therefore, it is attractive to use a multiobjective evolutionary algorithm (MOEA) since it can search for and evaluate many solutions simultaneously. An appropriately modified evolutionary algorithm approach can generate a large number of non-dominated solutions that represent the Pareto set for a multiobjective problem with nearly the same computational effort required to solve a single objective problem [1].

There exists numerous MOEAs in the literature [15]. Fonseca and Fleming [25] proposed in 1993 a quite popular method called Multiobjective Genetic Algorithm (MOGA), in which the rank of a certain individual corresponds to the number of solutions in the current population by which it is dominated. The main operations of MOGA are shown next [25]:

- Initialize population
- Evaluate objective values
- Assign rank based on Pareto dominance
- Compute Niche count
- Assign linearly scaled fitness
- Assign shared fitness
- For a number of generations
  - Selection via stochastic universal sampling
  - Single point crossover
  - Mutation
  - Evaluate objective values
  - Assign rank based on Pareto dominance
  - Compute Niche count

- Assign linearly scaled fitness
- Assign shared fitness

- End loop

The proposed approach in this chapter is based on MOGA. To describe MOGA, let us consider an individual x_i at generation t, which is dominated by ${p_i}^t$ individuals in the current generation. Here, $rank(x_i, t) = 1 + {p_i}^t$. All non-dominated individuals are assigned rank 1, while dominated ones are penalized according to the population density of the corresponding region of the trade-off surface.

Individuals in the population receive a rank value based upon their degree of non-inferiority or non-dominance. Here, inferiority is evaluated only with respect to the current population, so it is not necessary for an individual to be in the actual Pareto set to be considered non-inferior. For a given population, the individuals that are non-inferior are assigned the lowest (best) rank and individuals that are highly dominated (dominated by many individuals) are assigned the highest (worst) rank. A fitness value based on this rank is then assigned to each individual.

$$fitness(x_i, t) = \frac{1}{rank(x_i, t)} = \frac{1}{1 + {p_i}^t} \tag{5.16}$$

Some fitness assignments are likely to produce premature convergence to a particular region of the Pareto front. To avoid that, the niche count was introduced over the Pareto-optimal region. The idea of niches [25] is used to preserve the diversity of the population along the approximated Pareto front. A normalized distance between two solutions i and j in the same rank is defined as follows:

$$d_{ij} = \left[\sum_{k=1}^{M} \frac{\left(f_k^i - f_k^j \right)^2}{f_k^{max} - f_k^{min}} \right]^{1/2} \tag{5.17}$$

Where ${f_k}^{max}$ and ${f_k}^{min}$ are, respectively, the maximum and minimum objective function values of the $k-th$ objective, in the current iteration. Also, f_k^i and f_k^j are the objective function values of i and j. For every solution i, d_{ij} is computed for each solution j having the same rank. The sharing function value is computed as follows:

$$sh(d_{ij}) = \begin{cases} 1 - \left(\frac{d_{ij}}{\sigma_{share}}\right)^a & if \;\; d_{ij} \leq \sigma_{share} \\ 0 & \text{otherwise} \end{cases} \tag{5.18}$$

σ_{share} is a maximum distance allowed between any two individuals to become a member of a niche, and a is a positive scaling factor typically less than 1. The niche count of i is calculated by summing the sharing function:

$$nc_i = \sum_{j=1}^{N} sh(d_{ij}) \tag{5.19}$$

Finally, the fitness for solution i is adjusted by:

$$fitness_i = fitness_i / nc_i \tag{5.20}$$

According to [25], this added feature in MOGA algorithms allows obtaining a better distribution of the found non-dominated solutions over the Pareto front, since the fitness for very close solutions is reduced.

The approximation to the Pareto optimal is particularly difficult because the true Pareto optimal is unknown. The traditional way is to experiment and decide either by using prior knowledge or by comparing with the results of other methods if the current Pareto front is improving towards the Pareto optimal. In general, caution must be taken when using evolutionary algorithms. Even if a good choice of parameters is found for a particular application; this set will be sub-optimal for many other problems. Making the wrong choice of parameters can produce exceedingly poor results [22]. Solutions of real-world MOPs often offer only a finite number of points that may or may not be truly Pareto optimal. Therefore,

for such complex MOPs for which it is not easy to find an analytical determination of the true Pareto front, any good approximation is the goal.

5.3.2 Multiobjective Evolutionary Programming Algorithm

The proposed algorithm is illustrated with a flow diagram presented in Figure 5.1. The processes contained in Figure 5.1 are described in more details next.

Representation of the individual

The individual is represented by two arrays n and l whose dimensions are $|\mathcal{N}| * |\Theta|$ and $|\mathcal{A}|$ respectively, see Figure 5.2.

The first component in Figure 5.2, n, contains the number of new generation units in the system; and the second one contains the number of new circuits in the system.

Initial population

The initial population of solutions to the problem can be formed randomly and/or with solutions of previous relaxations of the problem (chapter 3). A total of N solutions are maintained in the population.

Evaluate population

Since this a multiobjective problem, the evaluation of solutions must be done for each objective considered. For a particular objective, once the integer variables n and l are fixed ($n^{'}$ and $l^{'}$ for example), the resulting single-objective problem turns into the following linear programming problem.

Min $f_i\left(n^{'}, l^{'}\right)$

s.t.

$$\sum_{(j,i)\in\mathcal{A}} f_{arc_{ji}} - \sum_{(i,j)\in\mathcal{A}} f_{arc_{ij}} + \sum_{q\in\Theta} g_{iq} = D_i; \quad i \in \mathcal{N}$$

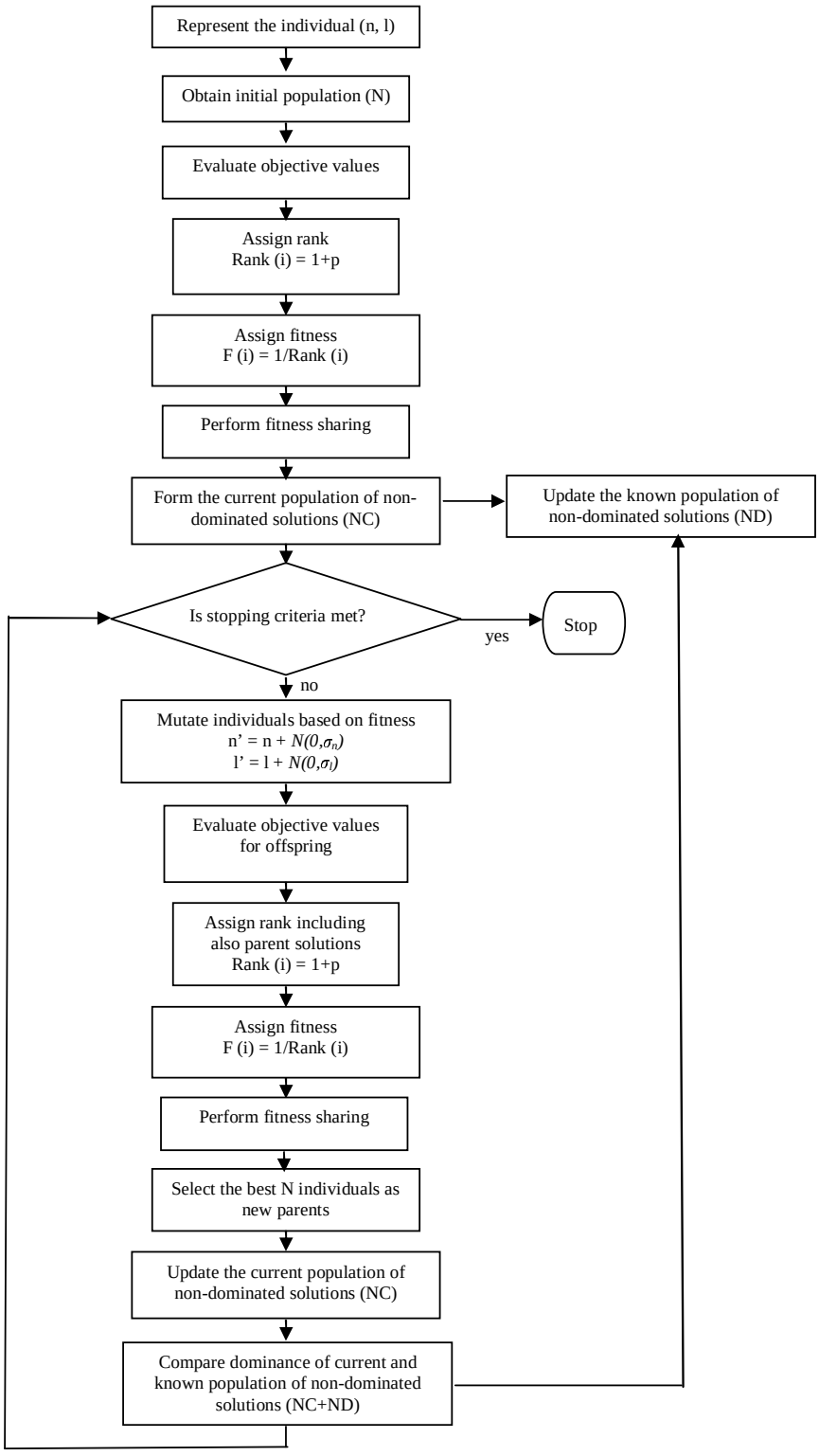

Figure 5.1: MEPA algorithm

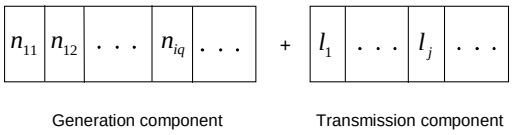

Figure 5.2: Representation of the individual

$$\left(l'_{ij} + l^0_{ij}\right) \gamma_{ij} \ |(\theta_j - \theta_i)| \leq \left(l'_{ij} + l^0_{ij}\right) \ \bar{f}_{ij}; \ \ (i,j) \in \mathcal{A}$$

$$g_{iq} \leq \bar{GE}_{iq} + Q_q \ n'_{iq}; \ \ i \in \mathcal{N}, q \in \Theta$$

$$\sum_{i \in \mathcal{N}} \sum_{q \in J_k} W_q \ g_{iq} \leq U_k + u_k; \ \ k \in \mathcal{F}$$

$$\sum_{i \in \mathcal{N}} \sum_{q \in \Theta} \left[\bar{GE}_{iq} + Q_q \ n'_{iq}\right] \geq \sum_{i \in \mathcal{N}} d_i \ (1+r)$$

$$g_{iq}, u_k \geq 0; \quad i \in \mathcal{N}, \ q \in \Theta, \ k \in \mathcal{F}$$

Thus, the objective values are obtained for each individual in the population. Infeasible solutions are penalized with a high cost in order to eliminate them from the population.

Assign rank

The non-dominance among the individuals in the population is determined by comparing against all of them. The rank for each individual s is defined as $Rank(s) = 1 + p$, where p is the number of solutions that dominate the solution s. Thus, the non-dominated solutions in the population will have a rank equal to 1.

Assign fitness

The fitness (F) for each individual is assigned according to the equation $F(s) = \frac{1}{Rank(s)}$. According to this definition, the non-dominated solutions will have the highest fitness (1),

while the fitness is reduced for the dominated solutions in terms of the number of solutions that dominate them.

Fitness sharing

The fitness (F) for each individual is modified as explained before (see equation 5.20), according to its niche count.

Stopping criteria

The process stops till it reaches a given number of generations or meets other conditions such as no more improvements in the number of non-dominated solutions found.

Reproduction

The new individuals (solutions) are obtained via mutations of the parent solutions. In this case, no-crossover is performed since some reported applications of genetic algorithms (GA) [9] indicate slow and maybe no convergence when it is used. The performed mutation is based on the normal distribution and in the fitness of the parent solution s [9], as it is illustrated next.

$$n'_{iq_s} = n_{iq_s} + N\left(0, \sigma_{g_s}\right) \tag{5.21}$$

where $N\left(0, \sigma_{g_s}\right)$ is the value of a normal distributed random number with mean zero and standard deviation $\sigma_{g_s} = \beta_1 * \left(\frac{1}{F(s)}\right) * \bar{n}_q$.

And,

$$l'_{ij_s} = l_{ij_s} + N\left(0, \sigma_{t_s}\right) \tag{5.22}$$

where $N(0, \sigma_{t_s})$ is the value of a normal distributed random number with mean zero and standard deviation $\sigma_{t_s} = \beta_2 * \left(\frac{1}{F(s)}\right) * \bar{l}_{ij}$.

In equations 5.21 and 5.22, β_1 and β_2 are positive scaling factors not larger than 1. When the calculated values for the number of units and circuits in the arc exceed either the lower or upper limits, then the number is truncated at the corresponding limit value.

The new solutions will tend to be close to the parent solution if it is a non-dominated solution and far away from the parent if it is dominated solution, helping to visit other regions in the feasible space.

Selection

The $2N$ solutions are ordered with respect to their fitness and the first N are selected to form the next generation of parents.

Current and known non-dominated solutions population

The non-dominated solutions in the current population are compared for dominance with known non-dominated population from earlier iteration. The non-dominated solutions found so far will be included in the known population which is updated in each iteration. Any previous solution that is found to be dominated by any current solution, is deleted from the known population.

5.4 Tests and Results

The proposed MEPA will be illustrated using the same Interconnected Grid Mexican Power System used in chapter 4 (see Figure 4.1). The planning horizon consists of a period of ten years (2005-2014), with base year 2004, and current capacity of 41,443 MW. This system is formed by 7 nodes (areas), 7 arcs, 8 types of generation units, and four types of

fuel. Generation technology options for capacity additions include: conventional steam units, coal units, combined cycle modules (cc), nuclear, gas turbines (tg), wind farms, geothermal and hydro units. The types of fuel are: coal, gas, oil, and uranium. Some of the input data was taken from [53], and the rest was estimated using different sources. For this system, the resulting MGEP3 model has 2*7*8 + 7 + 7 + 4 = 130 variables, and 7 + 2*7 + 7*8 + 4 + 7 + 1 = 89 constraints.

5.4.1 A two-objectives case

The results of a two-objective case is next presented in order to have a better understanding of the performance of the proposed MEPA. The objectives considered were the cost and the environmental impact. The presented idea in chapter 3 and 4 about generating a set of non-dominated solutions via random set of weights was used for this model too. Thus, 2000 sets of random weights were generated, and a single-objective mixed-integer non-linear problem was solved for each set. The solution for those problems was found using GAMS with the BARON (Branch-And-Reduce Optimization Navigator) solver [68]. BARON is a computational system for solving non convex optimization problems to find global optimality. Pure continuous non-linear programs, pure integer, and mixed-integer non-linear programs can be solved with the software. The software derives its name from its combining duality with branch and bound concepts. The elapsed time to solve all the problems was 21 minutes using the same PC; however, no warranty of global optimality was reported for 1944 sets of weights. Figure 5.3 presents the solutions for the randomly generated weights.

Some of the 2000 solutions are dominated solutions, which may mean that the global optimum was not reached for those solutions. Only the non-dominated are shown in Figure 5.3, and the whole set of solutions can be found in Appendix C.

A C program was written to obtain non-dominated solutions via the proposed MEPA. Different set of parameters for the evolutionary algorithm were tested. The most represen-

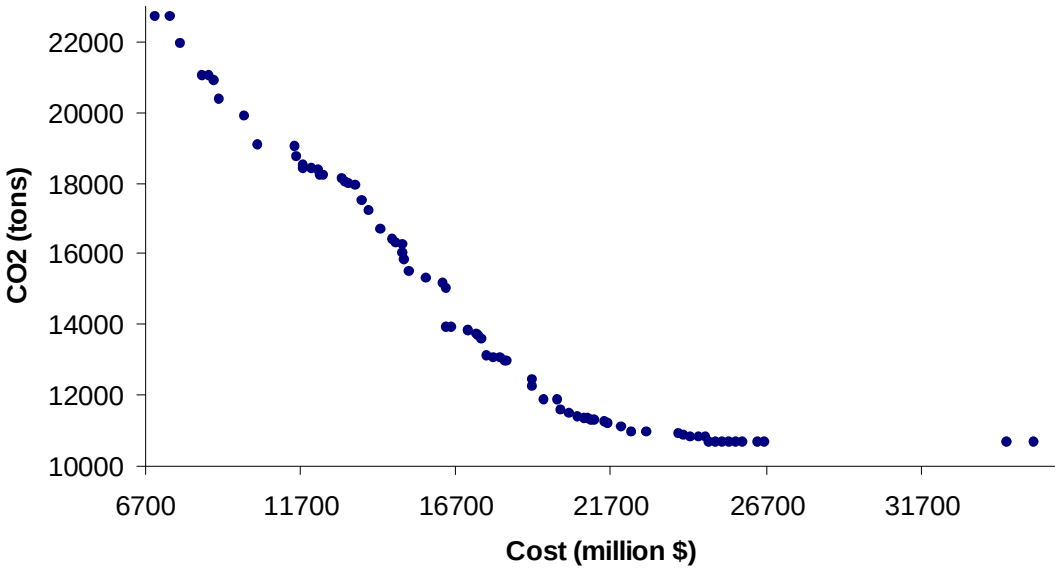

Figure 5.3: Non-dominated solutions using BARON

tative results (Pareto front approximation) were obtained for the parameters shown in Table 5.1.

Table 5.1: Parameters of MEPA

Parameter	**Value**
population size	50
scaling factor1	0.35
scaling factor2	0.25
σ_{share}	0.0038
a	1
iterations	4000

Different types of initial populations were examined for the algorithm, these are summarized in Table 5.2. In this table, the column **Initial population** represents the type of initial population in the MEPA algorithm; it can be random, non-random and a combination of these two types. The random solutions are found by assigning an uniformly distributed value to the number of new generation units of each type at each node, and to the number of new circuits on each arc; rounding them up and satisfying the minimum and maximum capacity limits. As shown in Table 5.2, more non-dominated solutions were found with a combined (random, non-random) initial population. Since the MGEP1 model presented in

chapter 3 is a relaxation of MGEP3, the initial non-random solutions for MGEP3 are obtained by solving MGEP1. These non-random solutions (parents) are not feasible solutions for MGEP3; however, after one iteration of MEPA they become feasible offspring solutions. The relaxation made in MGEP3 is in the integrality of the investment variables and in the representation of the transmission network (consider only the first Kirchoff's law). The random component of the population increase the chances for searching in different regions of the Pareto front.

Table 5.2: Types of initial population - 2 objectives

Initial population	**Population size**	**Non-dominated solutions found**
Random	50	35
Non-random	25	23
Random and Non-ran	25 and 25	44

The set of obtained non-dominated solutions is presented and compared with BARON non-dominated solutions in Figure 5.4. If we consider the BARON non-dominated solutions as the true Pareto front, the non-dominated solutions obtained with MEPA are close to the desired trade-off (BARON).

5.4.2 Four-objectives case

All the parameters shown in Table 5.1 were used for this case. Different types of initial populations were examined for the algorithm, these are summarized in Table 5.3.

Table 5.3: Types of initial population - 4 objectives

Initial population	**Population size**	**Non-dominated solutions found**
Random	50	174
Non-random	25	151
Random and Non-ran	25 and 25	211

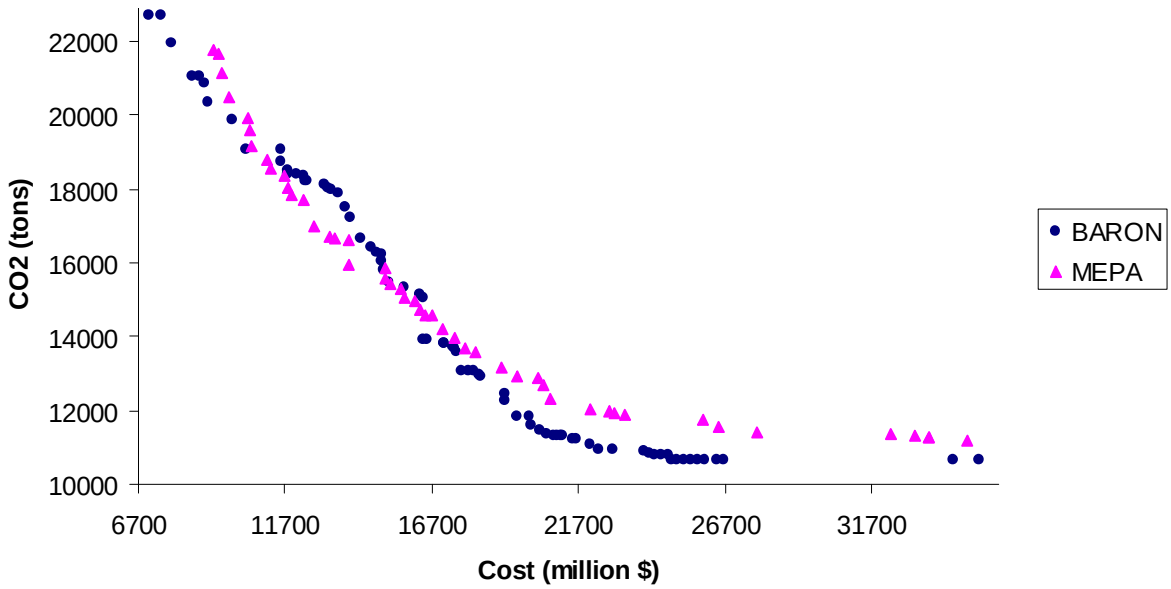

Figure 5.4: Non-dominated solutions: two objectives

The execution time for obtaining the 211 non-dominated solutions in a PC Pentium 4 CPU 3.00GHz was 29 minutes. With more individuals and iterations, more non-dominated solutions can be identified; however, the computational load becomes heavier too.

The convergence of MEPA can be observed in Figures 5.5, 5.6, and 5.7. Those figures show the comparison of the cost objective (investment, operation, and transmission), against the other three objectives (environmental impact, import of fuel, and risk in fuel prices).

As seen in 5.5, usually the higher the cost in generation investment, the lower in environmental impact. The reason is mainly because with more investments in renewables (usually expensive) and cc units, it is possible to satisfy the expected demand with minimum amount of CO_2 emissions.

Observing 5.6, it can be conclude that usually the higher the cost, the lower in risk in prices. The reason is because of investing as much as possible in renewable technologies (more expensive) can mean the less dependence on non-renewable technologies which have the problem of volatility in their fuel prices.

Since the possible addition of renewable capacity to the system is limited, there is always the need to invest in other type of technologies to satisfy the expected demand. From those other technologies, gas is the most attractive (low investment, operation and CO_2 emissions);

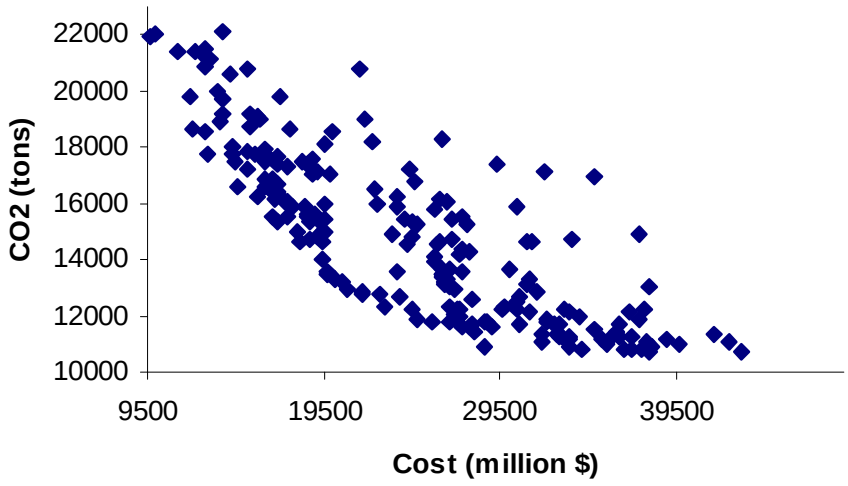

Figure 5.5: Non-dominated solutions: cost vs environment impact

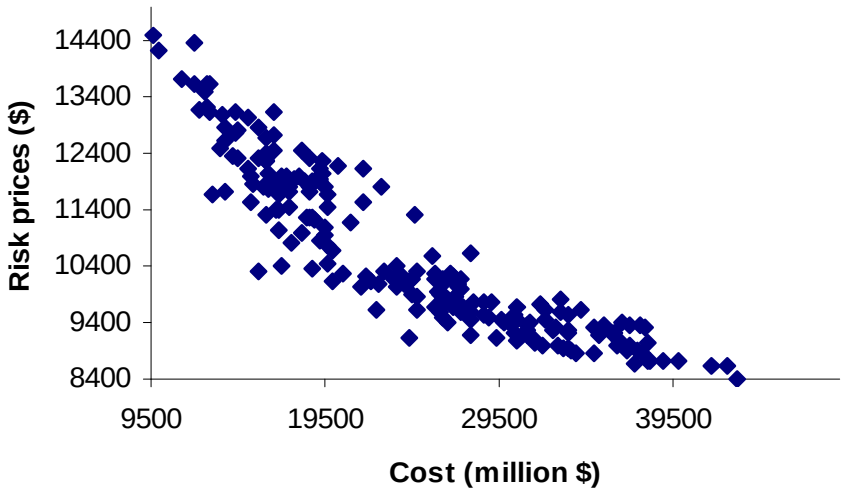

Figure 5.6: Non-dominated solutions: cost vs risk prices

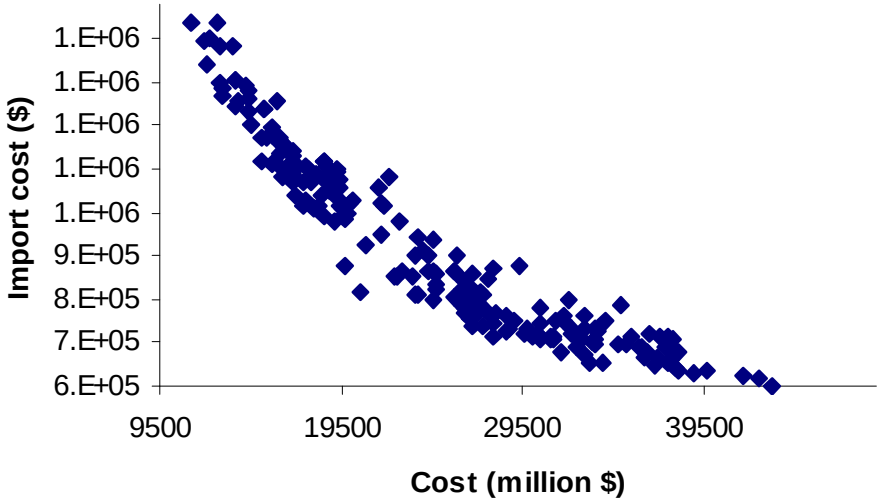

Figure 5.7: Non-dominated solutions: cost vs import of fuel

however, the available amount of gas to produce electricity is also limited. Therefore, usually low cost alternatives will have high import of fuel cost, as presented in Figure 5.7.

The question that arises at this point is how do we know if the obtained Pareto front is a good approximation to the true Pareto front for this problem. It was a good approximation for the two-objectives case. To have an idea about the characteristics of the obtained non-dominated solutions using MEPA for the four-objectives, the Table 5.4 presents some statistics of them.

Table 5.4: Statistics of non-dominated solutions

Statistics	**COST**	CO_2	**IMPORT**	**RISK**
minimum	9626.35	10708.18	621572.63	8408.63
maximum	43198.95	22078.75	1588848.69	14521.36
range	33572.61	11370.57	967276.06	6112.73
mean	24250.76	14888.41	948934.31	10627.21
median	24516.12	14723.60	883560.02	10160.08
standard deviation	7788.72	2949.07	219114.89	1422.03
coefficient of variation	0.32	0.20	0.23	0.13
ideal	7189.71	10661.35	614720.68	8344.63
anti-ideal	72573.94	27618.02	4245237.04	17583.24

Table 5.5: Cluster of non-dominated solutions

	S_1	S_2	S_3	S_4
Alternative	**Cost**	CO_2	**Fuel import**	**Risk prices**
A_1	9626.35	21901.54	1588848.69	14521.36
A_2	11257.23	21360.57	1457968.30	13716.38
A_3	14562.63	16621.00	1219970.43	12325.88
A_4	17036.79	19757.86	1058285.21	10396.24
A_5	20169.61	13306.46	1048072.42	12200.32
A_6	22926.19	12328.66	885103.86	10332.26
A_7	24776.28	11839.22	840146.31	10306.50
A_8	38085.76	10865.42	654119.30	8696.53
A_9	39692.78	10975.96	653515.48	8706.99
A_{10}	43198.95	10708.18	621572.63	8408.63
ideal	7189.71	10661.35	614720.68	8344.63
anti-ideal	72573.94	27618.02	4245237.04	17583.24

As Table 5.4 indicates, the set of non-dominated solutions is inside of the range formed with the ideal and anti-ideal solutions for each objective. Also, the low coefficients of variation, and the proximity of the mean to the median values, indicate that the non-dominated solutions may have a good distribution along the approximated Pareto front.

Once a set of non-dominated solutions has been identified, the next step is to cluster them in order to reduce the number of alternatives for the selection of the most attractive one (second phase). The K-means clustering algorithm is used, obtaining the non-dominated solutions presented in Table 5.5.

As observed in Table 5.5, each alternative is between the ideal and anti-ideal values. The set of alternatives represent a group of very different non-dominated solutions (alternatives) to the problem. The proposed new capacity for each alternative is presented in Table 5.6.

In Table 5.6, the alternatives shown present great diversity in the types of technologies proposed to install; such is a characteristic of non-dominated solutions in a multiobjective optimization problem. We can see for example that alternatives A_9 and A_{10} include excess capacity compared to alternative A_2, which means a very high cost for those two alternatives

Table 5.6: Technologies added (MW) by MEPA

Technology	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
STEAM	1050	1750	2800	700	2100	2100	3850	4900	7350	5600
CC	11760	11760	13440	3920	25760	20160	21840	28560	26320	36400
TG	5520	2760	5704	3864	2024	3128	2760	4968	4784	5520
COAL	0	350	0	3500	0	1750	1050	4900	5250	5250
NUCLEAR	0	0	0	0	0	0	0	1506	1506	1506
GEO	1150	920	920	1380	1610	1150	1840	1840	1150	1840
WIND	1100	1000	0	1000	700	0	0	1000	1800	1600
HYDRO	0	2000	6200	7400	5600	9600	9600	9800	9800	10000
TOTAL	20580	20540	29064	21764	37794	37888	40940	57474	57960	67716

(see Table 5.5). However, some of the alternatives with minimum values for environmental impact, imported fuel and risk in fuel prices are precisely alternatives A_9 and A_{10}. Such results show the trade-off that exists in multiobjective optimization problems. Extra new capacity may also mean that some of the existing capacity will be retired.

Following the second phase of the methodology described in previous chapters (selection of the most attractive alternative), the payoff table for the second level (subcriteria) in the AHP hierarchy is presented in Table 5.7. The cost components (investment, operation, and transmission) are expressed in million of dollars.

Table 5.7: Pay-off table for subcriteria

	S_{11}	S_{12}	S_{13}	S_{42}
Alternative	**Investment**	**Operation**	**Transmission**	**Nuclear risk (MW)**
A_1	9550.50	44.26	31.58	0.00
A_2	11214.70	42.53	0.00	0.00
A_3	14513.90	39.26	9.47	1506.00
A_4	16981.00	38.90	16.89	0.00
A_5	20100.80	35.71	33.09	0.00
A_6	22879.40	35.27	11.51	0.00
A_7	24714.90	34.14	27.24	1506.00
A_8	38028.38	32.47	24.91	1506.00
A_9	39634.28	32.60	25.90	0.00
A_{10}	43145.98	32.27	20.70	0.00

According to Table 5.7, the highest cost is the investment component, followed by the operation and transmission components. The nuclear risk (new MW installed using such technology) is almost the same in all of the alternatives, because of the restrictions placed on the system (a few of nuclear units can be installed). Continuing with the selection of the most attractive alternative, we as DM use the same pairwise judgment matrices defined in chapter 3 (Tables 3.7, 3.8, and 3.9). In those, cost, environment and risk prices criteria are equally preferred. Environment is slightly more preferred to cost criterion, less than slightly more preferred to imported fuel criterion and equal preferred to risk prices criterion. Risk

prices criterion is slightly more preferred to imported fuel criterion. Also, investment and transmission costs are equally preferred; investment is slightly more preferred to operation cost, and operation and transmission are equally preferred. Finally, risk in prices is less than slightly more preferred to nuclear risk. As before, these pairwise judgement matrices can be different for another decision maker. The value judgments for the alternatives respect to each criteria and subcriteria are obtained from the results shown in payoff Tables 5.5 and 5.7.

Based on the defined judgments and following the steps of the second phase, the priorities calculated for each alternative are presented in Table 5.8.

Table 5.8: Priority of alternatives

Alternative	**PRIORITY**
A_1	0.0952
A_2	0.1508
A_3	0.0782
A_4	0.0983
A_5	0.0945
A_6	0.0990
A_7	0.0825
A_8	0.0887
A_9	0.1055
A_{10}	0.1071

According to Table 5.8, the alternatives are ranked in the following way:

$$A_2 > A_{10} > A_9 > A_6 > A_4 > A_1 > A_5 > A_8 > A_7 > A_3$$

The A_2 alternative has the highest priority, followed by A_{10} and A_9. The comparison between the first three ranked alternatives and the Mexican government's planned expansion [53] is presented in Figure 5.8.

As observed in Figure 5.8, most of the new capacity comes from cc units. According to alternatives A_{10} and A_9 and for the given input data, the environmental impact, import of

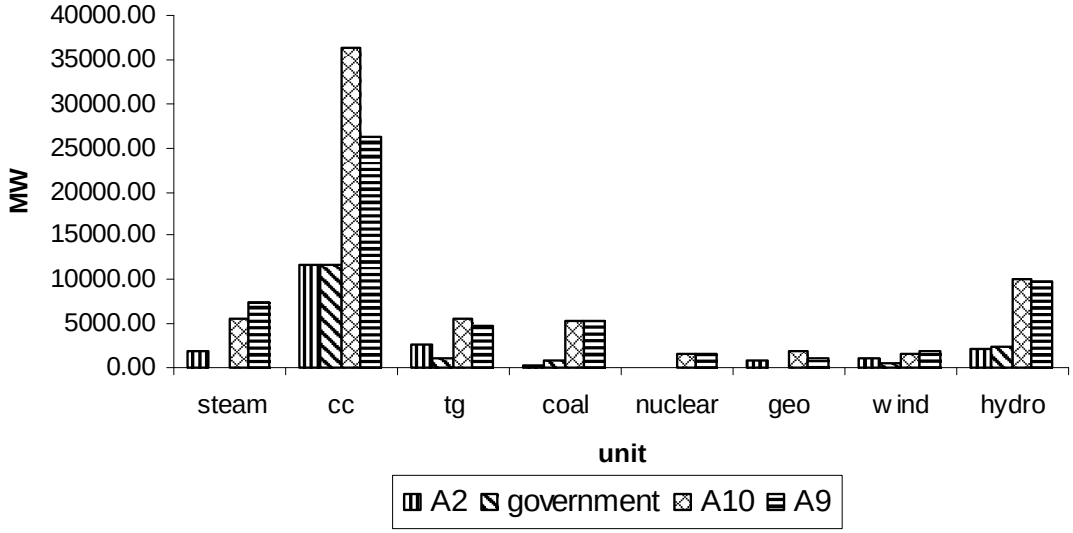

Figure 5.8: Comparison of expansion plans for new capacity by 2014

fuel and risk in fuel prices can be minimized in a long term if new clean units (renewable and gas) are installed. The existing units operate basically with oil, hydro, coal and gas (see Figure 5.9).

The composition of technologies installed by alternative A_2 is presented in Figure 5.10.

As shown in Figure 5.10, the given importance for each one of the criteria and subcriteria, the attractiveness of using gas units, and the limited availability of renewable sources turns out in a high percentage of combined cycle (cc) technologies. Note an undesirable dependence on natural gas fuel sources can make A_4 or A_1 as better alternatives for the DM.

The added capacity (MW) by area for alternative A_2 is shown in Table 5.9.

As it is observed in Table 5.9, the area with major additional capacity is the Central, followed by the Occidental and Northeast. Those nodes are the ones with the highest demand. The area with minor additions is the Peninsular. The pairwise judgments given for this illustrative example tried to represent a case where environmental impact is the most critical issue, followed by the equally important other criteria. It produced alternatives where renewable sources, some grade of nuclear power and natural gas are used preferably, which seems to be reasonable. Other judgments can produce different ranking of the alternatives, and that is one of the advantages of this proposed framework.

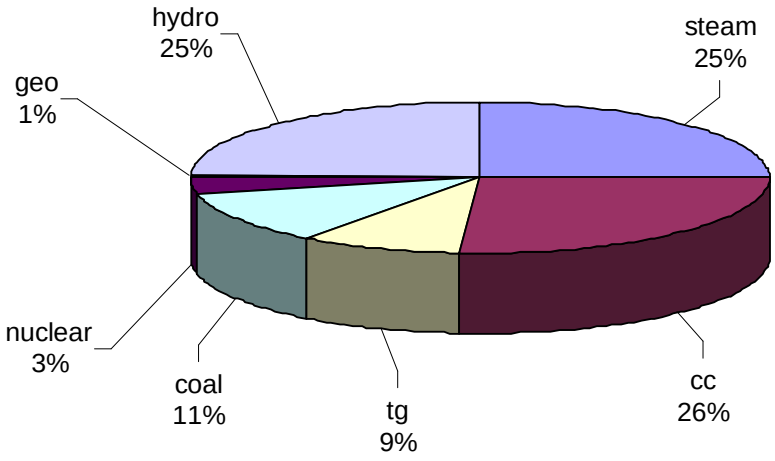

Figure 5.9: Existing capacity in 2004 [53]

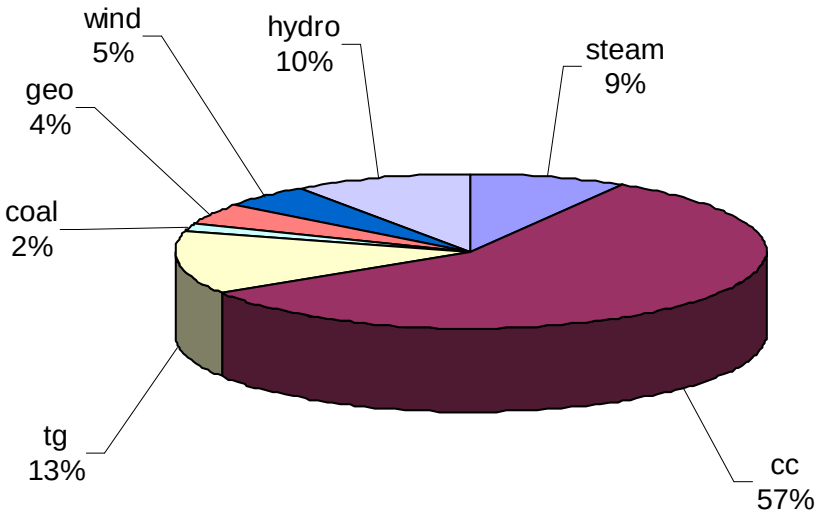

Figure 5.10: Expansion plan by A_2

Table 5.9: Expansion by area (A_2)

ALTERNATIVE 2							
Area	**Northwest**	**North**	**Northeast**	**Occidental**	**Central**	**Oriental**	**Peninsular**
STEAM	0.00	1400.00	0.00	0.00	0.00	0.00	350.00
CC	3360.00	1680.00	1680.00	2800.00	2240.00	0.00	0.00
TG	0.00	0.00	0.00	0.00	2760.00	0.00	0.00
COAL	0.00	0.00	350.00	0.00	0.00	0.00	0.00
NUCLEAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GEO	0.00	0.00	0.00	0.00	0.00	920.00	0.00
WIND	0.00	0.00	0.00	0.00	0.00	1000.00	0.00
HYDRO	0.00	0.00	0.00	2000.00	0.00	0.00	0.00
Total	**3360.00**	**3080.00**	**2030.00**	**4800.00**	**5000.00**	**1920.00**	**350.00**

5.5 Sensitivity Analysis

The purpose of this section is to show how the obtained results can change if different scenarios are considered. Three fuel price scenarios are used to show such changes. Table 5.10 presents the fuel prices [46] considered for this sensitivity analysis exercise. **Low** and **High** scenarios mean extreme conditions of fuel prices, and **Expected** is a similar scenario to the one considered in previous chapters.

Table 5.10: Fuel Price Scenarios in 2015 [46]

Fuel	**Low**	**Expected**	**High**
Oil ($/barrel)	20.99	26.75	40.67
Natural gas ($/Mbtu)	4.23	4.70	7.00
Coal ($/ton)	26.43	33.00	42.00
Uranium ($/gr)	2.10	2.10	2.10

As observed in Table 5.10, the biggest change in prices is when a High scenario is considered; prices in uranium are expected to remain constant. Following the methodology proposed in this chapter, the results obtained for the highest ranked alternatives in each scenario are presented in Table 5.11.

Table 5.11: Objective values for scenario

Criteria	**Low**	**Expected**	**High**
cost (million $)	22,356.70	22,583.60	25,050.90
environment (CO_2 tons)	16,407.58	16,337.46	16,099.86
fuel import (thousands $)	477.31	526.33	749.64
risk in fuel prices ($)	9,811.03	9,821.44	9,679.07

We can observe in Table 5.11 that the cost (investment, operation, and transmission) increases through each scenario, as well as the cost for fuel imports. However, the environmental impact and the risk in fuel prices are kept almost at the same level. The mix of additions for each scenario of prices is presented in Table 5.12.

Table 5.12: Capacity additions (MW) for scenario

Option	Low	Expected	High
steam	0	0	0
cc	14,560	15,120	14,000
tg	0	0	0
coal	3,500	3,500	3,500
nuclear	0	0	1,506
geo	1,840	1,840	1,840
wind	1,000	1,000	1,000
hydro	10,000	10,000	10,000

According to Table 5.12, in the expected scenario, as the one considered in the previous section, the natural gas units are very attractive to install, since they are clean and cheap; and there is no attractiveness to add nuclear units. However, the consideration of a High scenario in fuel prices produces a reduction in the addition of units that use natural gas (cc), and some additions of nuclear units are incorporated. The geothermal (geo), wind, and hydro renewable units are added at their maximum limits in all scenarios. We can observe that the addition results between the Low and Expected scenarios are not very different.

5.6 Summary

The model presented in this chapter (MGEP3) is a multiobjective mixed-integer non-linear programming model for the generation expansion planning problem that considers the transmission network as well. The resulting MGEP3 model is not easy to solve.

A novel multiobjective evolutionary programming algorithm (MEPA) has been proposed in this chapter in order to obtain an approximation of the Pareto front for MGEP3. The performance of MEPA has been validated for a representative Mexican power system. A set of non-dominated solutions has been found for the problem, and the most attractive alternative has been identified using the AHP approach. The results show coherent decisions given the objectives and scenarios considered. Some sensitivity analysis has been presented when considering different fuel price scenarios.

CHAPTER 6

A FUZZY MULTI-CRITERIA EXPANSION PLANNING MODEL

6.1 Introduction

In the real world, most decisions must be made on the basis of uncertain data or information. Fuzzy mathematical programming represents the uncertainty or ambiguity in decision making by the use of fuzzy concepts [41]. Fuzzy multiobjective linear programming was proposed by Zimmermann [83], and since then many advances and applications have reported in the literature ([17], [60], [61], and [62]). In fuzzy approaches, the uncertainty is represented as membership functions or probabilistic distribution functions. The membership information may not be known but is easy to determine [55]. The use of fuzzy linear programming has been considered successfully [63]. Other kind of approaches to deal with the uncertainty have been proposed using interval numbers or grey numbers ([55], [70], and [71]). With the use of interval numbers there is no need to define a membership function but a range of possible values for the uncertain variables.

In this chapter we present a simple fuzzy multiobjective model for the generation expansion planning (FMGEP) problem, which considers the uncertainty in both objectives and constraints of the problem. Thus, the objectives and constraints need not be fulfilled rigorously but some violation is tolerated by the DM. The way to solve this problem is based on the fuzzy linear programming technique, which will be explained briefly in the following section. The model will be tested for the expansion planning of the Mexican Electric Power System, where the demand of electricity will be considered uncertain and represented as a fuzzy number. Actually, FMGEP can be seen as an extension of the model MGEP1 pre-

sented in chapter 3, where the four objectives considered in MGEP1 are now considered as fuzzy goals by the DM.

6.2 Fuzzy Linear Programming Technique

As it was said in chapter 2, fuzzy mathematical programming methods have been developed in the last few years to solve a class of multiobjective optimization problems [82], which have fuzzy objectives and constraints. Future demand and other primary parameters are considered as fuzzy numbers such that the uncertainties are considered in the problem. The following description of the Fuzzy Linear Programming technique was taken from [64]. A fuzzy constraint for the decision variable vector y is expressed in the following form:

$$g(y) \preceq b \tag{6.1}$$

The feasible solution set for (6.1) is characterized by a triangular membership function:

$$\mu_g\left(g(y)\right) = \begin{cases} 1 & (g(y) \leq b) \\ [0,1] & (b \leq g(y) \leq b+d) \\ 0 & (g(y) \geq b+d) \end{cases} \tag{6.2}$$

where d is a tolerance width of violation specified by the DM. A triangular (trapezoidal) membership function usually makes easier the mathematical tractability of the problem [41], and that is the main reason to use it in this formulation. It should be noted that this triangular membership functions shows a lower level and a upper level at their membership values 0 and 1 respectively. This membership function is presented in Figure 6.1:

To deal with fuzzy objectives nearly at certain aspiration levels defined by a DM, the objectives can be called fuzzy goals which are expressed as:

$$f(y) \preceq z \tag{6.3}$$

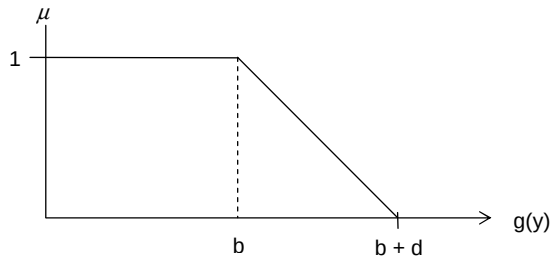

Figure 6.1: Triangular Membership function

where z is an aspiration level. The fuzzy equation (6.3) can be characterized by a membership function $\mu_f(f(y))$, as in (6.2). Therefore, a fuzzy goal and fuzzy constraint are considered mathematically identical concepts.

Let us consider l fuzzy goal sets $(G_1, ..., G_l)$ and m fuzzy constraint sets $(C_1, ..., C_m)$. The decision-making for this kind of problems is achieved first by finding the decision set D, second by selecting the DM's most preferable solution (x^*) among alternatives in D, which is defined as:

$$D = \left(\bigcap_{i=1}^{l} G_i\right) \bigcap \left(\bigcap_{j=1}^{m} C_i\right) \tag{6.4}$$

$$\mu_D(y) = \min\left(\min_i \mu_{G_i}, \min_j \mu_{C_j}\right) \tag{6.5}$$

In this case, the min-operator can be used to find the intersection of fuzzy constraints and fuzzy objective functions (goals) [64]. Thus, the most preferable (highest degree of membership) solution (y^*) among alternatives in D, can be found by:

$$\mu_D(y^*) = \max_y \mu_D(y) \tag{6.6}$$

This solution can be represented by Figure 6.2.

As seen in Figure 6.2, the solution (y^*) lies in the intersection of both fuzzy membership functions.

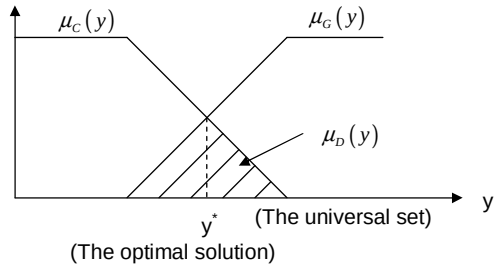

Figure 6.2: Concept of Fuzzy Decision-Making [64]

A Fuzzy Linear Problem (FLP), where the goals and constraints are linear functions, is generally expressed as follows [64]:

$$\begin{array}{lllll} \text{Determine} & y & & & \\ \text{s.t.} & Cy & \preceq & z; & \text{fuzzy goals} \\ & Ay & \preceq & b; & \text{fuzzy constraints} \\ & y & \geq & 0 & \end{array} \tag{6.7}$$

where z, b, y are l, m, n dimensional vectors and C, A are (l, m) and (m, n) coefficient matrices respectively. According to the equations (6.4), (6.5) and (6.6) the problem (6.7) is equivalent to the following conventional $\max - \min$ problem:

$$\begin{array}{ll} \max & \left[\min_y \left[\mu_i \left((By)_i\right)\right]\right] \quad (i = 1, ..., l + m) \\ \text{s.t.} & y \geq 0 \end{array} \tag{6.8}$$

where B is a $(l + m, n)$ matrix composed of the matrices C and A, $\mu_i \left((Bx)_i\right)$ is a membership function of the $i - th$ fuzzy equation, and for $Bx \preceq b'$, b' is a $(l + m)$ dimensional vector composed of the vectors z, b. Assuming that μ_i has the monotony with $(By)_i$ and introducing and additional variable λ, the $\max - \min$ problem (6.8) is reduced to the following mathematical programming model:

$$\begin{array}{lllll} \max & \lambda & & & \\ \text{s.t.} & \lambda \leq & \mu_i \left((By)_i\right) & & (i = 1, ..., l + m) \\ & y \geq 0 & \lambda \geq 0 & & \end{array}$$

Let d_i be a tolerance width of the violation of the $i-th$ fuzzy equation on $By \preceq b'$. Assuming a triangular membership function $\mu_i\left((By)_i\right)$, as in Figure 6.1, of the form:

$$\mu_i\left((By)_i\right) = \begin{cases} 1 & \left((By)_i\right) \leq b_i' \\ 1 - \left((By)_i - b_i'\right)/d_i & \left(b_i' \leq (By)_i \leq b_i' + d_i\right) \\ 0 & \left((By)_i \geq b_i' + d_i\right) \end{cases} \tag{6.9}$$

The problem (6.9) is equivalent to the following conventional linear programming problem [64]:

$$\begin{array}{lll} \max & \lambda & \\ \text{s.t.} & \lambda \leq & 1 - \left((By)_i - b_i'\right)/d_i \qquad (i = 1, ..., l+m) \\ & y \geq 0 & \lambda \geq 0 \end{array} \tag{6.10}$$

For fuzzy equalities such as:

$$h(y) \simeq e \tag{6.11}$$

where $h(y)$ is equal to about e or $h(y)$ is roughly equal to e, we can define two fuzzy inequalities as [41]:

$$h(y) \preceq e \;\; and \;\; h(y) \succeq e \tag{6.12}$$

Given a tolerance width d by the DM, the linearized membership function of the fuzzy equality (6.12) is illustrated in Figure 6.3.

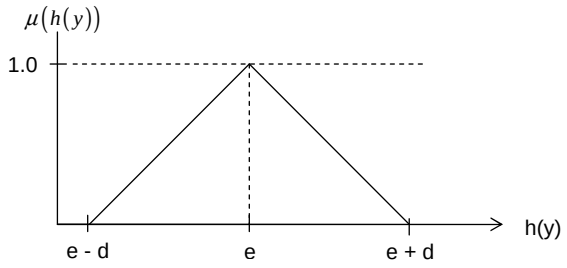

Figure 6.3: Triangular membership function of fuzzy equalities [64]

According to [64], the optimal value of λ has an interpretation. It represents the level of coordination between the planning objectives (goals) and constraints; it also shows severe trade-off relationship of the planning objectives and constraints. If $1-\left((By^*)_i - b_i^{'}\right)/d_i \neq \lambda^*$ then the $i-th$ equation is not a decisive factor. To obtain higher coordination levels, the tolerance widths must be wider in order to allow larger deviations from the planning objectives and constraints.

6.3 Fuzzy Multiobjective GEP

The previously described technique is applied to the model presented in chapter 3. The next presented model (FMGEP) is a fuzzy model where the demand of electricity is not deterministic, and deviations from a defined goal for each objective function are considered. The proposed FMGEP model is:

max λ

s.t.

$$\left(\sum_{i\in\mathcal{N}}\sum_{q\in\Theta} I_{iq}gn_{iq} + \sum_{i\in\mathcal{N}}\sum_{q\in\Theta} G_{iq}\left[ge_{iq}+gn_{iq}\right] + \sum_{(i,j)\in\mathcal{A}} C_{ij}\Delta x_{ij} + \lambda d1\right)/\left(L_1 - H_1\right) \leq \left(d1+b1\right)/\left(L_1-H_1\right)$$

$$\left(\sum_{i\in\mathcal{N}}\sum_{q\in\Theta} E_q\left[ge_{iq}+gn_{iq}\right] + \lambda d2\right)/\left(L_2 - H_2\right) \leq \left(d2+b2\right)/\left(L_2-H_2\right)$$

$$\left(\sum_{k\in\mathcal{F}} V_k u_k + \lambda d3\right)/\left(L_3 - H_3\right) \leq \left(d3+b3\right)/\left(L_3-H_3\right)$$

$$\left(\sum_{k\in\mathcal{F}} S_k \sum_{q\in J_k}\sum_{i\in\mathcal{N}}\left[ge_{iq}+gn_{iq}\right] + \lambda d4\right)/\left(L_4 - H_4\right) \leq \left(d4+b4\right)/\left(L_4-H_4\right)$$

$$\sum_{(j,i)\in\mathcal{A}} x_{ji} - \sum_{(i,j)\in\mathcal{A}} x_{ij} + \sum_{q\in\Theta}\left[ge_{iq}+gn_{iq}\right] + \lambda d_i \leq D_i + d_i; \quad i\in\mathcal{N}$$

$$\sum_{(j,i)\in\mathcal{A}} x_{ji} - \sum_{(i,j)\in\mathcal{A}} x_{ij} + \sum_{q\in\Theta}\left[ge_{iq}+gn_{iq}\right] - \lambda d_i \geq D_i - d_i; \quad i\in\mathcal{N}$$

$$x_{ij} \leq \bar{X}_{ij} + \Delta x_{ij}; \;\; (i,j)\in\mathcal{A}$$

$$ge_{iq} \leq \bar{GE}_{iq}; \;\; i\in\mathcal{N}, q\in\Theta$$

$$gn_{iq} \leq \bar{G}_{iq}; \quad i \in \mathcal{N}, q \in \Theta$$

$$\sum_{i \in \mathcal{N}} \sum_{q \in J_k} W_q \left[ge_{iq} + gn_{iq}\right] \leq U_k + u_k; \quad k \in \mathcal{F}$$

$$ge_{iq}, gn_{iq}, \Delta x_{ij}, x_{ij}, u_k \geq 0; \quad i \in \mathcal{N},\ q \in \Theta,\ (i,j) \in \mathcal{A};\ k \in \mathcal{F}, \lambda \geq 0$$

Here, bl is the goal for the $l-th$ objective, dl and d_i are the tolerance widths of the violation in the $l-th$ objective, and in the $i-th$ node-balance equation (see chapter 3). Each $l-th$ objective constraint is scaled by dividing it by the difference between its anti-ideal (L_l) and ideal (H_l) solutions.

To show results using FMGEP, let us consider the case study presented in chapter 3. We will set bl as the ideal solution, and dl as a percentage of the distance from the ideal to the anti-ideal solution for the $l-th$ objective. The deviation (d_i) from the demand, for each node, is presented in Table 6.1.

Table 6.1: Tolerance widths for the demand

Node	Deviation (%)
1	7
2	4
3	5
4	8
5	1
6	8
7	7

The deviations presented in Table 6.1 are hypothetical cases where the demand in each node is assumed to increase/decrease in the shown percentage. A GAMS [8] code was developed to evaluate FMGEP, given the defined deviations. The obtained results are presented in Table 6.2.

In Table 6.2, Fuzzy-demand represents a case where only deviations are allowed from the expected demand, and the objective constraints have their ideal values as righthand sides. Fuzzy-objectives is a case where no deviations are allowed from the expected demand, and

Table 6.2: Fuzzy models results

Case	λ	**Cost (million \$)**	**Tons CO_2**	**Fuel Imports (\$)**	**Risk Prices (\$)**
Fuzzy-demand	0.737	10548.70	20565.93	1291859.86	12941.92
Fuzzy-objectives	0.776	12535.60	20757.08	1296806.76	13064.70
10% deviation	0.808	10736.20	20582.24	1332159.74	12991.63
20% deviation	0.835	10871.80	20602.04	1321309.06	12996.56
25% deviation	0.842	10929.90	20599.10	1373810.04	12984.67
50% deviation	0.878	11145.60	20417.87	1349329.38	13006.52
100% deviation	0.914	11387.00	20638.86	1348605.63	13015.29
Ideal		10548.70	20565.93	1291859.86	12984.81
Anti-ideal		20337.93	21417.64	3396189.63	13340.80

Table 6.3: Fuzzy models additions (MW)

Case	**10%**	**20%**	**25%**	**50%**
steam	-	-	-	-
cc	10,080	10,080	10,080	10,080
tg	2,760	2,760	2,720	2,561
coal	1,490	1,252	1,258	1,305
nuclear	64	295	327	431
geo	920	920	920	920
wind	1,000	1,000	1,000	1,000
hydro	2,000	2,000	2,000	2,000

the objective constraints have their anti-ideal values as righthand sides. The following five cases (10%, 20%, 25%, 50% and 100% of deviation) represent cases where deviation in the expected demand is allowed in the percentages shown in Table 6.1, and percentages (10, 20, 25, 50, and 100) of deviation are allowed from the ideal solution in each objective constraint.

The coordination level λ is lower for the two first cases since no deviations for the demand and objectives are allowed in the model. This level of coordination λ gradually increases since more deviation is also gradually permitted. Observe that the cases 10, 20, 25 and 50 percentage of deviation provide a set of non-dominated solutions for the multiobjective GEP problem. The capacity addition for those four cases in presented in Table 6.3.

Observe in Table 6.3 that all the solutions are very similar, except that the nuclear additions increase as the allowance for deviations also increases. It can mean that nuclear technologies become more attractive for uncertain conditions in demand and goals.

In Figure 6.4, the mix of additions for the case 25% is presented. As it can be seen, there is diversity in the additions of capacity, as in the deterministic case (MGEP1); it does not include additions of steam units but a high percentage of gas units (cc) is included. Further sensitivity analysis can be done for other deviations in demand, and for other value goals in the objectives. A set of non-dominated solutions from FMGEP can be found for the multiobjective generation expansion planning problem if for example random deviations

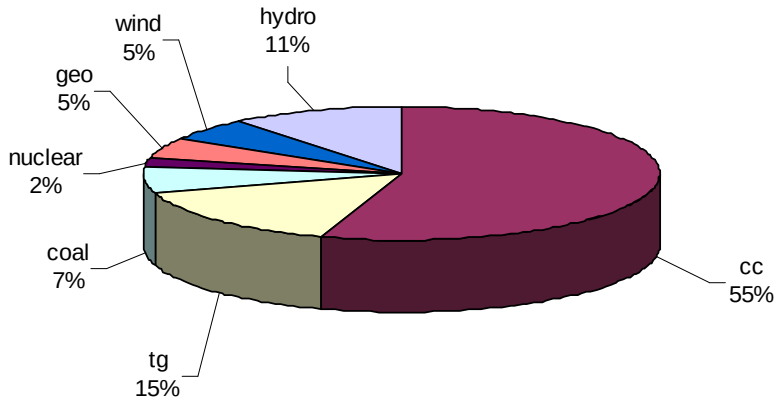

Figure 6.4: Mix of additional capacity - Fuzzy model

from the goals are generated. Solving the FMGEP for each random deviation between (0, 100%) can provide a non-dominated solution for the multiobjective GEP.

6.4 Summary

In this chapter, a fuzzy multiobjective model for the generation expansion planning problem has been presented. The proposed model can be easily used for situations where the demand is not deterministic, and there are more than one conflicting objective in a generation expansion planning problem, like the one presented in chapter 3.

CHAPTER 7
CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

In this thesis, a set of different multiobjective models have been proposed for the generation expansion planning problem. In addition, a solution method has been developed and tested using the representative Mexican power systems. Two different optimization techniques (weighting approach and evolutionary programming) were explored for solving a complex expansion problem (MGEP3). Based on the current research in multiobjective evolutionary algorithms [15], the proposed algorithm (MEPA) in this thesis takes some of the existing ideas to become an original multiobjective evolutionary algorithm.

A comparison of the expansion plans obtained from each presented model and the Mexican government's expansion plan [53], is presented in Figure 7.1. The mixes obtained from the proposed models give the same conclusion: more renewable and gas technologies. Although, the Mexican government's expansion plan was obtained with other kinds of assumptions (costs, operating conditions, computational tools, etc.), and it does not identify the type of generation unit for 6000 MW that will be needed to satisfy the demand, all of the mixes obtained with the proposed models seem reasonable compared to such government's expansion plan.

MGEP3 is the closest to the real problem (integer variables and better transmission modelling). Therefore, its mix can serve as a reference for the DM in the expansion planning of the system. In addition, non-dominated solutions from each proposed model can be also considered to make the final decision.

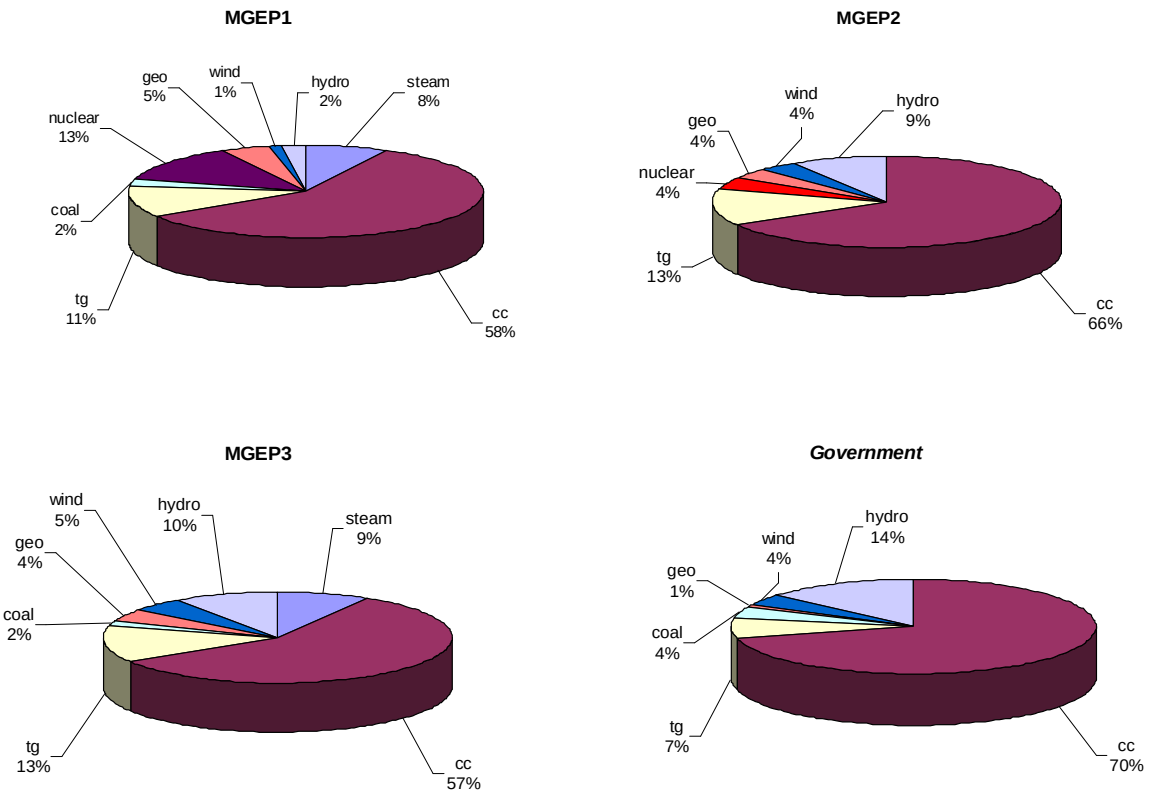

Figure 7.1: Comparison of mix generation additions

The models presented in this thesis consider aspects that previous works have not included. The contributions from this research can be summarized in the following points.

1. Incorporation of more than three criteria to generate the expansion alternatives.

2. Importance given to renewable generation technologies. Inclusion of the transmission network in the multiobjective generation expansion planning problem.

3. A framework for solving each one of proposed models.

4. An original multiobjective evolutionary programming algorithm (MEPA) for solving complex (mixed-integer and non-linear) multiobjectives problems.

However, there are limitations and drawbacks in such models which will serve to define research directions.

7.2 Future work

Some of the further research directions to be pursued are:

1. Extensions of the MGEP3 model by including fuzzy concepts proposed in chapter 6 to include: uncertainty, more objectives, and a multi-period model.

2. Use of different solution methods.

Below, a detailed description of the proposed future research direction is presented.

7.2.1 New MGEP Models

Including more objectives, considering uncertainty, and solving a multi-period problem are possible extensions to the MGEP3 model. These extensions are further explored in this section.

Uncertainty

Scenarios for different growths of demand, capacity, and fuel prices can overcome such uncertainty but at the same time increase the complexity of the model. A fuzzy approach was described in chapter 6 to consider the uncertainty in the demand and objectives.

Uncertainty in multiobjective problems, as was presented in chapter 6, has usually been modelled with fuzzy logic approaches ([17], [60], [61], [62], and [63]); where uncertainties are presented as membership functions or probabilistic distribution functions. However, in many practical situations, the membership information may not be known and most of the algorithms for fuzzy MOP might often lead to complicated intermediate submodels which are hard (not practical) to solve [55]. Alternatives for handling the uncertainty have been proposed ([55], [70], and [71]) through the use of interval numbers or grey numbers. The use of interval numbers can overcome the shortcoming of fuzzy numbers (unknown membership functions or probabilistic distribution functions). What was described in chapter 6 can be extended for the MGEP3 model.

Modification and/or inclusion of more criteria

The inclusion of more objectives in the MGEP3 model will be always of interest for a DM. For example, additional objectives could be to maximize reliability of the system, and to obtain better social impacts. However, the more objectives in a multicriteria problem, implies a more complex problem to be solved. The additional objectives require more computational effort to generate the expansion alternatives (non-dominated solutions).

In particular, the reliability in the transmission network can be incorporated as an additional objective or as a constraint. Most often, this is solved by adding an additional constraint to the problem [51].

A multi-period MGEP3

In a multi-period MGEP3, there would be separate periods (years) in the planning horizon. The decision variables would be the number of generating units and circuits to install at each period. Thus, the MGEP3 is converted to a multi-period mixed-integer non-linear problem, for which the proposed MEPA may be used. In this case, the MGEP3 model presented in chapter 5 would be extended in the following way.

$$\text{Min}\,[f_1, f_2, f_3, f_4]$$

s.t.

$$\sum_{(j,i)\in\mathcal{A}} sc_{jit}\ (\theta_{it} - \theta_{jt}) - \sum_{(i,j)\in\mathcal{A}} sc_{ijt}\ (\theta_{jt} - \theta_{it}) + \sum_{q\in\Theta} g_{iqt} = D_{it}; \quad i \in \mathcal{N}, t \in \mathcal{T}$$

$$|sc_{ijt}\,(\theta_{it} - \theta_{jt})| \leq F_{ijt}; \ \ (i,j) \in \mathcal{A}, t \in \mathcal{T}$$

$$sc_{ijt-1} + \gamma_{ij} l_{ijt} = sc_{ijt}; \ \ (i,j) \in \mathcal{A}, t \in \mathcal{T}$$

$$F_{ijt-1} + \bar{f}_{ij} l_{ijt} = F_{ijt}; \ \ (i,j) \in \mathcal{A}, t \in \mathcal{T}$$

$$g_{iqt} \leq CG_{iqt-1} + Q_q\ n_{iqt}; \ \ i \in \mathcal{N}, q \in \Theta, t \in \mathcal{T}$$

$$CG_{iqt-1} + + Q_q \; n_{iqt} = CG_{iqt}; \;\; i \in \mathcal{N}, q \in \Theta, t \in \mathcal{T}$$

$$\sum_{i \in \mathcal{N}} \sum_{q \in J_k} W_q \; g_{iqt} \leq U_k + u_k t; \;\; k \in \mathcal{F}, t \in \mathcal{T}$$

$$\sum_{i \in \mathcal{N}} n_{iqt} \leq \bar{n}_{qt}; \;\; q \in \Theta, t \in \mathcal{T}$$

$$l_{ijt} \leq \bar{l}_{ijt}; \;\; (i,j) \in \mathcal{A}, t \in \mathcal{T}$$

$$\sum_{i \in \mathcal{N}} \sum_{q \in \Theta} CG_{iqt} \geq \sum_{i \in \mathcal{N}} d_i t \; (1+r); \;\; t \in \mathcal{T}$$

$$n_{iqt}, l_{ijt} \;\; integers; \quad i \in \mathcal{N}, \; q \in \Theta, \; (i,j) \in \mathcal{A}$$

$$CG_{iqt}, sc_{ijt}, g_{iqt}, F_{ijt}, u_{kt} \geq 0; \quad i \in \mathcal{N}, \; q \in \Theta, \; (i,j) \in \mathcal{A}; \; k \in \mathcal{F}, t \in \mathcal{T}$$

where,

$\mathcal{T}$	Set of periods in the planning horizon.
D_{it}	Load (MW) at node i in period t.
F_{ij0}	Existing (MW) capacity of transmission in arc (i,j).
CG_{iq0}	Existing (MW) capacity of generation for a unit of type q at node i.
U_{kt}	National available amount (corresponding units) of fuel type k in period t.
W_q	Consumption of fuel (units/MW) for a unit of type q.
n_{iqt}	Number of new units of type q at node i in period t.
CG_{iqt}	Cumulative capacity (MW) of units type q at node i in period t.
Q_q	Capacity (MW) of a unit type q.
g_{iqt}	Generation (MW) from new units of type q at node i in period t.
F_{ijt}	Transmission capacity (MW) through arc (i,j) in period t.
l_{ijt}	Number of additional transmission lines in arc (i,j) in period t.
θ_{it}	Voltage angle at node i in period t.
γ_{ij}	Susceptance of a circuit in arc (i,j).
$\bar{f}_{ij}$	Maximum flow (MW) of a circuit in arc (i,j).
u_{k_t}	Imported fuel (units) of type k in period t.

The model is a multiobjective mixed-integer non-linear programming problem with $|\mathcal{T}| * [3 * |\mathcal{N}| * |\Theta| + 3 * |\mathcal{A}| + |\mathcal{F}|]$ variables of which $|\mathcal{T}| * [|\mathcal{N}| * |\Theta| + |\mathcal{A}|]$ are integers, and $|\mathcal{T}| * [|\mathcal{N}| + 4 * |\mathcal{A}| + 2 * |\mathcal{N}| * |\Theta| + |\mathcal{F}| + |\Theta| + 1]$ constraints of which $|\mathcal{T}| * [|\mathcal{N}| + |\mathcal{A}|]$ are non-linear.

We consider four objective functions:

$$f_1 = \sum_{t \in \mathcal{T}} (1+z)^{-t} \left[\sum_{i \in \mathcal{N}} \sum_{q \in \Theta} I_{iqt} n_{iqt} + \sum_{i \in \mathcal{N}} \sum_{q \in \Theta} G_{iqt}\ g_{iqt} + \sum_{(i,j) \in \mathcal{A}} C_{ijt} \Delta l_{ijt} \right] \tag{7.1}$$

$$f_2 = \sum_{t \in \mathcal{T}} \left[\sum_{i \in \mathcal{N}} \sum_{q \in \Theta} E_q\ g_{iqt} \right] \tag{7.2}$$

$$f_3 = \sum_{t \in \mathcal{T}} (1+z)^{-t} \left[\sum_{k \in \mathcal{F}} V_{kt} u_{kt} \right] \tag{7.3}$$

and

$$f_4 = \sum_{t \in \mathcal{T}} \left[\sum_{k \in \mathcal{F}} S_{kt} \sum_{q \in J_k} \sum_{i \in \mathcal{N}} g_{iqt} \right] \tag{7.4}$$

where,

z Discount factor (opportunity cost).

I_{iqt} Annual investment cost (\$/MW) of a unit of type q at node i in period t.

G_{iqt} Annual generation cost (\$/MW) of a unit of type q at node i (operation & maintenance) in period t.

C_{ijt} Annual cost (\$/MW) for new transmission capacity in arc (i, j) in period t.

V_{kt} Annual cost (\$/unit)of imported fuel of type k in period t.

E_q Tons of carbon dioxide emission (CO_2) per MW generated by a unit of type q.

U_{kt} National available amount (corresponding units) of fuel type k in period t.

S_{kt} Expected coefficient of variation in prices of fuel type k in period t.

J_k Index of units of fuel type k.

The first objective is to minimize the investment & operational cost; the second objective is to minimize the environmental impact in the system; the third objective is to minimize the imported amount of fuel; and the last objective is to minimize the risks due to the volatility of fuel prices.

7.2.2 Solving the MGEP Models

Use of interactive methods

The methodologies described in chapters 3,4 and 5 are based on 'A Priori' Preference Methods. These approaches rely on receiving some relative preference judgment from the DM prior to actually solving the decision problem. By comparing the preferences chosen and the resulting ranks of alternatives, potential areas of consensus areas are identified, as well as points of disagreement requiring further discussion.

The main difficulty with prior preference methods is that most people will be unsure of their priorities when a decision involves a unique problem along with conflicting values. As a result different methods may yield different decisions. Interactive methods have an advantage in this situation. Instead of determining prior preferences, the alternatives are evaluated and new information can be used to identify additional plans. Therefore, the DM is asked to provide some preference or trade-off information in each iteration of the solution process which increase the chance to accept the final decision. The iterative request for information also provides learning for DM about the nature of the solution space.

There have been few applications of interactive methods to GEP problems. A major obstacle is time: access to key decision makers is limited and it could be costly. A second obstacle is that there is relatively little experience with such methods in a group setting, where group members have very different priorities. Applications investigating these issues are needed.

It becomes attractive to explore the use of interactive multiobjective linear programming (IMOLP), which involves interactively the decision maker (DM). A typical IMOLP system can be viewed as consisting of the following stages [19]:

- Input the problems parameters into the system.
- Generate a candidate solution (non-dominated) or a small set of solutions.
- Interact with the user. The DM is questioned by the analyst during this interactive stage, and a decision is made whether the candidate solution is adequate or whether to generate new solution(s), and if so, what should influence the computation of the new solution(s).
- Generate new improved solution(s) from the present solution(s) after the interaction with the DM.

7.3 Summary

A set of possible future extensions for the developed research work has been described in this chapter. The extensions include the modelling aspect as well as the methodologies of solution.

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APPENDICES

APPENDIX A

INPUT DATA

A.1 MGEP1 experimentation on IRMES

The first information read is about the nodes in the network (Table A.1).

	Node	Number of Units	D_i (MW) Demand
1	SONORTE	3	1923
2	SONSUR	2	707
3	MOCHIS	6	1195
4	MAZATLAN	1	310
5	JUAREZ	3	1425
6	CHIHUAHUA	2	1561
7	LAGUNA	2	1846
8	RIOESCOND	3	1640
9	MONTERREY	4	6359
10	REYNOSA	3	1398
11	HUASTECA	3	1114
12	GUADALAJA	4	2862
13	MANZANILL	2	471
14	SANLUISPO	1	2368
15	BAJIO	7	4551
16	LCARDENAS	3	1241
17	CENTRAL	4	12069
18	ORIENTAL	10	4406
19	ACAPULCO	1	832
20	TEMASCAL	1	1147
21	MINATITLA	0	1262
22	GRIJALVA	4	1912
23	LERMA	2	404
24	MERIDA	3	1113
25	CANCUN	1	375
26	CHETUMAL	0	180

Table A.1: Nodes

Next, information about arcs is as in Table A.2.

Information about the types of fuel considered is presented in Table A.3. The type of generation units to consider is shown in Table A.4. Finally, the information about existing generation units is presented in Table A.5.

Origin	Destine	X_{ij} (MW) Capacity	Fixed C C_{ij}(\$/KW)	Var C C_{ij}(\$/KW)	Length (Miles)
1	2	500	3.903	0.208	150
2	3	220	3.903	0.208	141
4	3	750	3.903	0.208	247
4	7	300	3.903	0.208	176
4	12	320	3.903	0.208	252
5	1	380	3.903	0.208	176
6	5	500	3.903	0.208	193
7	6	350	3.903	0.208	329
7	9	260	3.903	0.208	215
7	14	250	3.903	0.208	263
8	6	225	3.903	0.208	600
8	9	2100	3.903	0.208	203
9	11	1000	3.903	0.208	251
9	14	1000	3.903	0.208	410
9	10	1150	3.903	0.208	448
10	18	1000	3.903	0.208	231
10	14	1500	3.903	0.208	351
12	14	650	3.903	0.208	194
12	15	750	3.903	0.208	225
13	12	1700	3.903	0.208	211
15	14	850	3.903	0.208	99
15	17	1000	3.903	0.208	232
16	12	400	3.903	0.208	254
16	15	460	3.903	0.208	366
16	17	1900	3.903	0.208	254
16	19	200	3.903	0.208	215
18	17	3400	3.903	0.208	280
18	20	1300	3.903	0.208	229
19	17	400	3.903	0.208	142
20	17	2800	3.903	0.208	231
20	21	1550	3.903	0.208	231
20	22	2200	3.903	0.208	392
21	22	2200	3.903	0.208	147
22	23	435	3.903	0.208	296
23	24	435	3.903	0.208	281
24	26	435	3.903	0.208	170
24	25	150	3.903	0.208	291

Table A.2: Arcs

Fuel	Units	U_k (Units) Capacity	V_k (\$/Units) Import Cost	S_k (\$) Prices CF
oil	Barril/day	1742.27460	26.75	0.29
gas	Mbtu/day	42630.45704	4.70	0.40
coal	Ton/year	16800.000000	33.00	0.05
nuclear	GR	1000.00000	2.10	0.025

Table A.3: Fuel Types

A.2 MGEP2 experimentation on AIMES

Input data for the multi-period model MGEP2 is presented in this section. First, the nodes in the network (Table A.6) represent areas in the system.

The arcs are inter-area links as shown in Table A.7.

The demand by period is shown in Table A.8.

	TYPE	G_t (MW) Capacity	Factor Avail	Fuel	W_t Consume	Units	E_t CO2 E	I_{it} ($/KW) Invest	O&M G_{it}($/MW)
1	STEAM	350	0.90	oil	1.54000	Barrel	0.795	830000	930
2	CC	560	0.93	gas	7.00893	Mbtu	0.359	400000	780
3	TG	184	0.90	gas	10.43537	Mbtu	0.508	300000	1320
4	COAL	350	0.92	coal	0.46587	TON	0.957	1300000	330
5	NUCLEAR	1506	0.95	nuclear	2.68000	GR	0.000	1930000	950
6	GEO	230	0.91	steam	0.00000	TON	0.000	1060000	430
7	WIND	100	0.40	wind	0.00000	no	0.000	1000000	1230
8	HYDRO	200	0.99	water	0.00000	no	0.000	900000	510

Table A.4: Type of Units

The existing capacity by technology and node is presented in Table A.9.

Information about generation unit types and fuel types is the same as the one described in the previous section. Additional information regarding to economical components in the model to calculate costs, is presented in Table A.10.

Unit	Node	$\bar{GE}_{it}$ (MW) Capacity	Type of unit
Puerto Libertad	SONORTE	632	1
Hermosillo (PIE)	SONORTE	238	2
Naco Nogales (PIE)	SONORTE	258	2
Pdte. Elas C. (El Novillo)	SONSUR	135	8
C. Rodrguez R. (Guaymas II)	SONSUR	484	1
Prof. R. J. Marsal (Comedero)	MOCHIS	100	8
Bacurato	MOCHIS	92	8
L. Donaldo Colosio (Huites)	MOCHIS	422	8
J. Dios Btiz (Topolobampo II)	MOCHIS	360	1
27 de septiembre	MOCHIS	59	8
Humaya	MOCHIS	90	8
J. Aceves P. (Mazatln II)	MAZATLAN	616	1
Samalayuca	JUAREZ	316	1
Samalayuca II	JUAREZ	522	2
Chihuahua III (PIE)	JUAREZ	259	2
Francisco Villa	CHIHUAHUA	399	1
Chihuahua II (El Encino)	CHIHUAHUA	554	2
Guadalupe Victoria	LAGUNA	320	1
Gmez Palacio	LAGUNA	200	2
Ro Escondido	RIO ESCONDIDO	1200	4
Carbn II	RIO ESCONDIDO	1400	4
La Amistad	RIO ESCONDIDO	66	8
Monterrey	MONTERREY	465	1
Huinal I y II	MONTERREY	968	3
Saltillo (PIE)	MONTERREY	248	2
Monterrey III (PIE)	MONTERREY	449	2
E. Portes G. (RoBravo)	REYNOSA	520	3
Ro Bravo II (PIE)	REYNOSA	495	2
Ro Bravo III (PIE)	REYNOSA	495	2
Altamira	HUASTECA	800	1
Altamira II (PIE)	HUASTECA	495	2
Altamira III y IV (PIE)	HUASTECA	1036	2
Aguamilpa	GUADALAJARA	960	8
Agua Prieta	GUADALAJARA	240	8
M. M. Dieguez (Sta. Rosa)	GUADALAJARA	61	8
Colimilla	GUADALAJARA	51	8
Manzanillo II	MANZANILLO	700	1
M. lvarez M. (Manzanillo)	MANZANILLO	1200	1
Villa de Reyes	SANLUISPO	700	1
Salamanca	BAJIO	866	1
El Sauz	BAJIO	597	3
Azufres	BAJIO	190	6
Cupatitzio	BAJIO	72	8
Cbano	BAJIO	52	8
Lerma (Tepuxtepec, LFC)	BAJIO	67	8
El Sauz (Bajo, PIE)	BAJIO	577	2
J. Ma. Morelos (Villita)	LAZARO CARDENAS	280	8
Infiernillo	LAZARO CARDENAS	1000	8
Pte. P. Elas C. (Petacalco)	LAZARO CARDENAS	2100	4
Fernando Hiriart B. (Zimapn)	CENTRAL	292	8
Fco. Prez R. (Tula)	CENTRAL	1989	2
Valle de Mxico	CENTRAL	1087	3
Jorge Luque (LFC)	CENTRAL	362	3
Necaxa (LFC)	ORIENTAL	109	8
Mazatepec	ORIENTAL	220	8
Humeros	ORIENTAL	40	6
Patla (LFC)	ORIENTAL	37	8
A. Lpez M. (Tuxpan)	ORIENTAL	2263	1
Laguna Verde	ORIENTAL	1365	5
Dos Bocas	ORIENTAL	452	2
Poza Rica	ORIENTAL	117	1
Tuxpan II (PIE)	ORIENTAL	495	2
Tuxpan III y IV (PIE)	ORIENTAL	983	2
C. Ramrez U. (Caracol)	ACAPULCO	600	8
Temascal	TEMASCAL	354	8
B.Domnguez (Angostura)	GRIJALVA	900	8
M. Moreno T	GRIJALVA	2400	8
Malpaso	GRIJALVA	1080	8
Peitas	GRIJALVA	420	8
Lerma	LERMA	150	1
Campeche (PIE)	LERMA	252	2
Mrida II	MERIDA	198	3
Nachi-Cocom II	MERIDA	79	3
Mrida III (PIE)	MERIDA	498	2
F. Carrillo Puerto	CANCUN	295	2

Table A.5: Existing Units

	Node	Number of Units
1	Northwest	3
2	North	2
3	Northeast	5
4	Occidental	6
5	Central	3
6	Oriental	5
7	Peninsular	3

Table A.6: Areas

Origin	Destine	X_{ij} (MW) Capacity	Fixed C C_{ij_t}(\$/KW)	Var C C_{ij_t}(\$/KW)	Length (Miles)
1	2	300	3.903	0.208	176
1	4	320	3.903	0.208	252
2	3	260	3.903	0.208	215
3	6	1000	3.903	0.208	231
4	5	2900	3.903	0.208	232
6	5	3800	3.903	0.208	280
6	7	435	3.903	0.208	296

Table A.7: Inter-area links

Node	2006	2008	2010	2012	2014
1	2873	3140	3473	3821	4135
2	3216	3542	3941	4382	4832
3	6673	7363	8293	9352	10511
4	7412	8302	9344	10423	11493
5	8762	9453	10298	11196	12069
6	6187	6890	7743	8617	9558
7	1229	1391	1604	1816	2072

Table A.8: Demand by period (MW)

Node	steam	cc	tg	coal	nuclear	geo	wind	hydro
1	2092	496						898
2	1035	1535						
3	1265	3218	1488	2600				66
4	3466	577	597	2100		190		2783
5		1989	1449					292
6	2380		1930		1365	40		6120
7	150	1045	277					

Table A.9: Existing capacity by technology (MW)

Parameter	Rate (%)
Opportunity cost	10
Investment inflation	3
Operation inflation	5
Fuel inflation	4
Transmission inflation	3

Table A.10: Economical components

APPENDIX B

RESULTS

B.1 BARON solutions

Table B.1: BARON 2-objective solutions

COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
25309.54	10661.35	17945.55	13064.90	17219.65	13956.84	23926.01	10889.83
20317.22	11679.66	22067.37	11108.03	34017.45	10697.17	14166.13	17320.68
18481.58	12305.28	18966.68	12874.09	20549.51	11563.70	20846.70	11295.06
24306.52	10794.34	19570.98	12031.97	21067.48	11423.03	16554.35	13924.86
34017.43	10692.01	34017.43	10690.95	34021.69	10650.74	20845.01	11587.16
18489.82	13113.41	18966.65	12836.16	19189.93	12770.89	20317.43	11799.05
21069.07	11413.54	20844.12	11370.79	18299.30	13266.13	25303.16	10650.74
25303.33	10750.49	25304.61	10650.74	20853.48	11367.79	20845.22	11313.22
21844.36	11136.61	21068.26	11259.33	34029.03	10711.05	21067.34	11293.53
19565.70	12040.32	25304.55	10788.97	21070.03	11262.24	34019.20	10650.74
20845.46	11557.08	25302.34	10667.53	34021.82	10650.74	14872.23	16710.60
21070.91	11361.14	20541.37	11668.88	18074.62	13219.98	21846.02	11108.03
21846.66	11167.81	25078.56	10727.13	22621.62	11051.73	25304.29	10701.47
23756.86	10948.55	11029.19	19228.17	34019.20	10650.74	21623.91	11108.03
17391.15	13715.36	21073.62	11318.33	21067.21	11313.11	18966.85	12898.04
24304.46	10811.66	21291.38	11360.25	21070.48	11251.63	21067.48	11421.17
33795.13	10676.31	22630.94	10996.13	34250.33	10708.73	22628.23	11031.90
21067.57	11474.26	20541.26	11613.67	22400.09	10964.43	21292.27	11462.23
21292.14	11312.31	24537.14	10794.34	20319.88	11554.63	20317.27	11707.03
20014.41	11852.74	17181.04	13948.50	21069.12	11252.73	17133.82	13986.86
18965.88	12768.52	14975.18	16244.94	21069.01	11338.16	21068.23	11345.12
20096.05	12045.46	21852.66	11108.03	34018.32	10743.50	19874.01	11867.77
20542.93	11552.19	15919.90	15344.88	34018.06	10666.66	21068.80	11251.63
21067.42	11383.52	20542.42	11681.10	20843.40	11363.98	25078.35	10668.85
18214.97	13056.83	24751.20	10835.61	21069.07	11367.54	21067.49	11424.70
20846.04	11276.34	12003.46	18781.50	20398.87	11561.35	15063.26	16244.76
18970.49	12756.28	24307.37	10794.34	34017.31	10668.06	25200.92	10794.34
21072.46	11324.36	25302.51	10712.83	21067.92	11262.26	20320.06	11552.19
20850.79	11251.63	15295.15	16578.25	15062.38	15830.84	33799.57	10710.17
34019.28	10684.67	24305.80	10820.26	13943.16	17409.13	18746.87	12794.17
24304.70	10804.95	20319.22	11682.70	21621.70	11349.90	17770.46	13272.73
21845.03	11135.86	8553.72	21047.39	19724.22	12741.02	17659.89	13909.05
19414.24	13125.80	20541.26	11699.45	18299.04	13101.29	19565.67	12023.01
21067.93	11297.33	19872.05	12045.46	25303.17	10653.03	21845.31	11206.63
21076.49	11257.50	12811.21	18336.57	25080.72	10794.29	17220.69	13956.84
22070.02	11108.03	25528.39	10702.63	25304.12	10700.10	24751.01	10811.66

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COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
34245.30	10650.74	20845.84	11251.63	21069.22	11262.24	18304.70	13157.11
25082.82	10650.74	34018.17	10675.30	21068.90	11271.96	34244.59	10667.25
19649.64	11788.32	24306.37	10927.59	16885.95	13962.39	19792.36	12122.15
11561.02	18730.09	21068.40	11350.16	14397.85	17289.07	16427.43	13927.82
18063.44	13467.10	24302.25	10834.41	19640.35	12263.01	21068.19	11337.98
24530.53	10825.38	19566.42	12042.22	25305.84	10668.06	18299.23	13099.50
21069.15	11272.19	20541.17	11552.19	21069.41	11522.21	24528.74	10794.34
21068.80	11251.63	24527.71	10794.34	33802.06	10753.13	15419.48	15842.76
25081.66	10650.74	18965.96	13025.09	9072.97	20351.92	18300.98	13101.29
18219.68	12811.85	19190.74	13031.61	18298.57	13186.73	35369.31	10650.74
24529.73	10804.95	16822.20	14034.56	9167.08	21057.62	34020.87	10650.74
24750.10	10794.34	21068.56	11341.24	21291.95	11262.20	20318.93	11552.19
33795.10	10682.53	18076.01	13095.68	21070.79	11251.63	21849.55	11161.24
34017.36	10671.32	21846.02	11108.03	18300.50	13192.64	24303.89	10846.85
14619.52	17328.67	21292.13	11283.81	22067.80	11225.96	25082.82	10650.74
25305.08	10706.63	33797.04	10655.63	18075.12	13243.60	21072.70	11261.01
24750.98	10794.34	21843.41	11203.71	15513.50	15844.99	25081.36	10668.06
21075.58	11251.63	18298.50	13148.64	18268.27	13048.97	34017.34	10667.72
21844.55	11234.64	18077.08	13108.82	18439.67	13251.94	17449.02	13703.28
21843.65	11184.68	21845.56	11226.80	25303.36	10704.05	20542.23	11564.89
24754.27	10794.34	20845.88	11273.36	25082.82	10650.74	21068.23	11344.91
20318.37	11605.90	25526.28	10650.74	21070.75	11357.94	17221.55	14349.05
34019.26	10666.03	21067.37	11356.30	24306.64	10794.34	21624.68	11134.39
21067.35	11351.68	18075.45	13098.88	13041.16	17653.04	19416.20	12267.62
24079.83	10850.49	19418.25	12263.01	24302.21	10824.52	24526.30	10913.98
21067.45	11405.71	34252.63	10678.93	18299.41	13163.89	25985.05	10650.74
24150.84	10944.47	24764.96	10794.34	18514.16	13141.75	18966.91	12756.28
24411.55	10964.43	20844.09	11343.66	13269.13	17999.89	22070.02	11108.03
21067.40	11376.18	20844.31	11483.11	18300.96	13101.29	21292.87	11251.63
21845.05	11322.13	21068.91	11278.43	19421.56	12492.64	21847.91	11108.03
21293.84	11251.63	24082.65	10799.76	25304.43	10785.45	21067.49	11428.77
17097.94	13830.34	21067.35	11467.51	18479.12	13097.04	15194.53	15965.01
21067.29	11331.32	20846.77	11279.65	24305.02	10811.66	21069.84	11251.63
24527.68	10832.07	33799.25	10798.94	21293.77	11264.92	20095.90	11567.08
34019.37	10698.45	34018.30	10686.94	18298.61	13627.56	33794.36	10767.95
34023.55	10674.69	34018.31	10735.46	18079.17	13099.49	33571.97	10675.67
24527.09	10857.01	20852.48	11326.73	24760.19	10794.34	34018.22	10680.16
21068.10	11313.11	18968.04	12867.41	21621.34	11228.89	25308.93	10690.97
25304.84	10658.28	24751.49	10897.50	18968.58	12756.28	24527.01	10811.66
18076.28	13189.41	20098.82	11816.99	25528.04	10650.74	25528.26	10667.92
24528.02	10794.34	21847.13	11108.03	18077.00	13334.92	20767.88	11552.19
25079.89	10650.74	25305.31	10747.94	22629.87	10964.43	25528.20	10650.74
33797.19	10849.59	22070.97	11108.03	33798.55	10650.74	25081.24	10650.74
20318.23	11654.00	25082.82	10650.74	21845.54	11176.02	21082.49	11311.63
20844.85	11400.93	20540.40	11660.79	21628.94	11108.03	15208.17	15499.03
20853.58	11297.31	20540.55	11706.36	24750.23	10828.95	21292.08	11251.63
21848.00	11160.58	21620.32	11126.07	18074.31	13138.22	21072.68	11251.63
25528.20	10650.74	18299.21	13101.29	20541.23	11664.28	21624.64	11108.03
18213.45	13085.46	20846.35	11314.09	20544.12	11636.80	21619.75	11212.92
25079.22	10709.52	24150.20	10937.64	24528.76	10797.35	21845.19	11166.63

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COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
20541.40	11601.37	24150.77	10895.89	18966.87	12925.03	16997.35	14025.68
7029.21	22721.07	25089.77	10772.78	34017.32	10661.35	21626.25	11133.94
9320.62	21502.56	33796.44	10817.37	21629.51	11123.12	10066.17	20803.63
21582.73	11835.08	10574.73	19484.98	20544.60	11552.19	20318.93	11552.19
34018.22	10700.79	34018.26	10707.97	34242.04	10661.35	21068.87	11461.48
21071.73	11251.63	21069.21	11401.82	33797.82	10650.74	20847.82	11301.63
21068.92	11438.99	15292.50	16578.25	11648.92	18791.56	13721.93	17510.78
12675.71	18495.56	18298.27	13432.14	25303.74	10810.43	8779.64	21047.39
7820.70	21920.96	21067.39	11367.95	24758.36	10794.34	14169.94	17343.36
21068.18	11315.65	10910.54	19398.85	24478.66	10887.11	19567.69	11934.41
19874.48	11873.11	20324.05	11692.79	20619.40	11374.89	25081.44	10726.79
24306.60	10794.34	34018.17	10737.05	11866.34	18945.22	24303.01	10811.66
18255.10	13030.83	21843.45	11128.61	20323.41	11619.55	25526.60	10739.69
22620.85	11079.96	11689.49	19563.22	34243.96	10661.35	20318.97	11562.80
20543.88	11552.19	19413.80	12320.89	16644.94	15251.20	20846.79	11251.63
18299.41	13284.51	18075.33	13319.25	19649.72	12045.46	18299.46	13557.74
34249.49	10692.01	18787.04	13111.21	21843.41	11128.66	21068.41	11325.75
20847.76	11268.66	18298.56	13326.09	14389.27	17244.71	19873.79	11690.65
20846.89	11304.26	20543.88	11552.19	18967.64	12756.28	21845.02	11130.77
20851.65	11266.50	17175.93	14046.50	19413.24	12513.36	12138.25	19299.74
24857.21	10847.35	21845.35	11142.02	21069.30	11303.13	19195.27	12419.78
21073.14	11251.63	34018.18	10654.15	25082.19	10650.74	20846.34	11353.45
10065.57	20923.07	21068.10	11313.11	19875.62	12045.46	16995.73	14207.73
20542.34	11728.84	18298.41	13095.36	25302.43	10690.95	21069.84	11251.63
24527.94	10836.94	26651.71	10650.74	21292.38	11394.30	24527.74	10812.62
21293.11	11251.63	21844.50	11174.66	17221.41	13956.84	21068.92	11441.98
19190.72	12826.72	18522.49	13139.92	34019.93	10650.74	21067.55	11462.89
25304.61	10650.74	20321.61	11705.64	21068.30	11296.75	33796.87	10650.74
17000.36	14086.06	20846.79	11251.63	24751.32	10834.72	21628.01	11340.59
17133.01	14083.66	34018.42	10766.21	24303.98	10859.06	21073.08	11267.22
22852.91	10964.43	20847.27	11693.28	21852.80	11133.86	9563.59	20838.71
18965.72	12766.26	19189.94	12773.79	24751.71	10863.89	7817.16	21946.96
21067.45	11402.04	19415.46	12263.01	21294.52	11417.61	34020.21	10781.78
18965.02	13273.29	17221.67	14261.00	18298.33	13120.17	25540.18	10650.74
21068.16	11393.72	17131.06	13912.22	33798.73	10650.74	24752.20	10812.10
21622.97	11108.03	19791.12	12074.69	24305.06	10794.34	20956.42	11346.42
21620.39	11184.42	21068.41	11325.75	20844.10	11315.05	23751.54	11036.88
20845.92	11275.48	24527.10	10863.62	34019.49	10661.35	21067.45	11403.44
18031.67	13530.27	10067.05	20361.68	8554.05	21744.89	12814.84	18386.28
22077.39	11108.03	13487.22	18010.92	24527.71	10797.50	19875.75	11768.09
20322.64	11653.14	33801.41	10693.46	20852.32	11584.34	24536.36	10895.85
18965.84	12930.96	8554.13	21809.11	21072.46	11251.63	18299.92	13101.29
25307.06	10650.74	33798.00	10650.74	25541.50	10688.79	20846.05	11282.78
21168.19	11302.41	20847.82	11300.28	20846.07	11293.93	18076.93	13061.14
20846.81	11264.99	25087.57	10650.74	21845.41	11139.93	19869.45	12244.41
21068.00	11299.18	21295.12	11395.73	21068.89	11303.64	25526.60	10739.69
20319.89	11558.78	24528.28	10833.12	26429.68	10650.74	25304.29	10702.56
24528.90	10794.34	21847.91	11108.03	34019.28	10759.10	24528.31	10815.15
34018.90	10658.81	20852.52	11271.76	21843.46	11131.41	18966.69	12905.97
19789.46	11963.72	33797.82	10650.74	20850.42	11251.63	34018.26	10707.72

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COST	CO_2	COST	CO_2	COST	CO_2	COST	CO_2
21068.29	11348.55	20541.17	11640.58	24530.88	10811.11	25081.53	10874.55
18074.75	13292.98	18298.39	13181.18	22858.79	11006.18	20316.46	11656.76
25078.65	10866.29	21068.10	11313.11	18034.15	13085.46	21067.94	11296.72
24529.81	10811.66	24526.13	10811.66	22069.86	11108.03	33795.11	10650.74
24527.01	10811.66	34019.92	10650.74	34020.81	10650.74	21068.12	11388.51
24303.75	10817.16	24530.67	10811.66	21624.10	11214.43	19736.15	12185.29
21067.45	11405.19	33797.82	10650.74	14168.87	17338.59	20543.88	11552.19
18522.33	13101.29	21291.53	11395.90	21845.56	11267.20	24526.82	10794.34
21068.17	11309.10	19791.44	12025.08	21067.25	11323.72	22070.02	11108.03
19417.30	12263.01	34019.17	10685.18	21845.15	11111.07	20843.40	11372.28
18305.57	13099.10	18521.16	12996.55	21622.90	11108.03	20847.69	11358.87
12137.14	18496.03	21292.23	11270.59	34242.99	10661.35	21848.64	11108.03
25082.82	10650.74	21072.46	11251.63	25083.23	10650.74	13495.29	17594.34
18299.20	13101.29	20844.87	11350.33	25079.92	10668.06	21068.10	11267.13
18298.56	13184.51	22067.63	11180.00	21847.93	11117.37	20844.16	11299.22
24527.71	10794.34	21845.42	11180.96	21067.44	11388.19	21292.96	11251.63
24303.10	10864.48	17721.64	13332.12	20847.43	11251.63	20846.95	11251.63
24527.67	10866.60	21844.41	11149.61	17944.52	13064.90	18714.54	13093.16
25526.43	10692.01	24528.86	10794.34	21077.01	11251.63	21068.36	11421.25
21069.84	11256.64	18489.82	13111.05	25304.25	10708.81	21843.42	11120.67
21852.66	11108.03	24531.19	10829.42	17993.03	13514.22	24274.86	10904.01
24526.10	10802.68	21845.44	11192.65	25528.20	10650.74	18074.71	13269.52
17928.69	13430.97	16997.54	14078.04	34025.38	10663.39	25304.92	10650.74
12855.91	18317.96	22069.86	11108.03	21292.15	11251.63	21067.69	11546.46
11662.81	19361.06	21067.92	11251.63	21627.71	11150.17	34019.32	10728.57
21843.65	11273.32	21078.42	11348.27	34244.81	10650.74	25304.07	10668.06
21068.08	11251.63	21300.22	11319.15	18076.30	13171.73	15782.82	15874.40
15736.35	15322.54	18743.66	12791.49	34243.20	10650.74	18298.53	13166.39
21068.25	11353.80	21846.97	11108.03	22291.41	11117.51	15293.70	16666.00
21068.48	11321.16	16055.66	15566.79	21069.43	11436.65	25306.82	10650.74
24530.29	11005.34	34018.31	10694.33	21068.87	11370.62	18298.37	13098.30
16997.54	14075.22	17219.66	13959.58	18976.65	12202.39	19190.60	12756.28
7487.66	22705.64	18075.26	13214.68	34021.82	10650.74	24302.98	10794.34
24529.16	10794.34	25304.92	10650.74	20326.85	11641.14	21624.86	11108.03
21627.69	11145.27	21073.58	11307.63	25302.43	10692.01	33794.06	10822.46
20093.46	11595.25	25078.46	10756.50	15295.64	16578.25	20845.98	11326.07
21843.43	11262.35	20623.53	11547.18	9058.26	21469.26	22628.96	10983.45
18965.08	12878.26	25080.38	10755.20	24302.53	11044.89	20096.20	11641.14
22068.29	11118.64	10119.06	20566.61	18081.39	13219.52	18967.63	12756.28
16995.55	13992.64	25081.87	10650.74	9169.68	21120.96	20844.28	11356.19
17218.90	14359.74	24308.29	10794.34	21068.27	11310.80	21069.75	11251.63
18299.28	13096.19	24527.75	10804.95	11881.89	18889.71	18742.18	12970.48
33795.21	10751.64	21069.87	11268.00	21067.42	11383.82	21623.20	11149.31
11078.07	19163.99	22068.27	11141.04	24528.59	10837.20	20543.91	11569.51
24303.15	10984.68	20317.30	11722.00	15015.45	16038.23	20856.49	11306.79
25080.93	10650.74	20845.84	11251.63	20844.89	11307.45	25306.82	10650.74
25080.27	10787.84	23950.71	10927.45	12855.02	18306.08	25304.32	10650.74
12226.27	18638.82	18966.72	12955.94	17218.77	13956.84	25304.30	10677.17
21845.45	11253.84	24303.87	10794.34	25078.44	10744.53	22068.29	11118.64
12097.57	18900.97	24084.64	10949.40	18713.68	13101.29	21293.14	11338.03

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COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
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24751.74	10811.66	20094.97	11722.49	19790.99	11852.74	9903.39	19898.46
18076.24	13244.25	18080.82	13228.29	21852.66	11108.03	24528.46	10811.66
24527.02	10847.86	19790.41	12033.22	18966.83	13024.98	21067.92	11251.63
10904.23	19781.76	25082.82	10650.74	20851.06	11264.27	22067.47	11134.40
13941.50	17230.37	18301.22	13101.29	24527.71	10794.34	25303.16	10650.74
18746.86	12786.29	33797.82	10650.74	8109.82	21943.50	21071.73	11251.63
24305.41	10811.66	18439.80	13270.45	19637.01	12377.16	20319.88	11552.19
34020.25	10670.25	20541.23	11722.31	21069.47	11307.88	10060.74	20230.55
20095.04	11617.22	18831.03	12948.18	21295.69	11251.63	21069.98	11290.26
24526.98	10794.34	33794.53	10864.27	24751.76	10808.46	18965.04	13259.76
20850.51	11289.09	12675.71	18495.56	20093.46	11635.23	24750.25	10835.61
24307.40	10794.34	24543.97	10794.34	21184.66	11334.54	21292.95	11251.63
21623.91	11108.03	21068.21	11648.67	24306.67	10811.66	34017.35	10670.12
24527.05	10812.05	21847.62	11132.32	16649.51	14528.53	24750.15	10807.85
17177.50	13899.74	21292.79	11293.46	34018.97	10822.81	20845.36	11491.16
24305.69	10794.34	33797.82	10650.74	33797.82	10650.74	18968.69	13123.56
18076.76	13347.68	13486.60	17916.68	20843.95	11268.95	20619.40	11369.89
21847.10	11144.76	22400.10	10966.22	20541.37	11659.43	15293.54	16578.25
21293.30	11514.90	24080.00	10986.02	20541.67	11961.36	12594.05	18287.46
21627.04	11108.03	21072.68	11251.63	21291.96	11264.27	19638.50	12305.45
25306.86	10668.06	23974.71	10956.14	18302.31	13101.29	10573.59	20340.99
25304.32	10652.68	18966.96	12970.18	34017.56	10728.46	24302.96	10831.23
18746.31	12789.86	33800.88	10838.19	18077.17	13098.15	21073.14	11251.63
22624.09	10964.43	21067.30	11313.67	20847.73	11251.63	21292.11	11262.24
21071.71	11472.92	21846.38	11189.75	21847.70	11113.35	20845.22	11407.52
21068.20	11359.80	34019.92	10650.74	21067.96	11275.42	8951.12	20876.67
25087.18	10661.67	15065.97	16122.22	18299.05	13101.29	18966.85	12906.91
21068.10	11313.11	24528.77	10811.66	12677.08	18497.47	21068.08	11251.63
21071.73	11251.63	21070.79	11251.63	24752.25	10932.62	17175.74	14105.63
24304.05	10811.66	25079.14	10728.26	24302.12	10826.77	21844.56	11118.64
18965.94	12852.52	34025.88	10650.74	22068.26	11108.03	33802.57	10650.74
34241.60	10739.69	24759.57	10835.41	20542.02	11755.00	22069.18	11143.25
24528.30	10798.99	21068.11	11364.10	17537.44	13584.40	24527.12	10849.05
19118.30	12284.15	34018.37	10773.24	19192.48	12302.00	21516.30	11272.57
21067.41	11381.22	21075.79	11251.63	15959.64	15341.07	20847.80	11292.75
19190.48	12766.89	24526.93	10856.76	18079.87	13364.78	20848.46	11252.50
21070.91	11272.26	21070.09	11355.69	20318.04	11734.82	15638.72	15703.80
25303.31	10692.01	25304.05	10716.33	24303.03	10832.09	25081.21	10737.07
20843.46	11410.93	19790.31	11988.81	22069.34	11164.53	24527.06	10836.67
21846.09	11205.07	24306.66	10874.88	25080.25	10682.75	21072.46	11251.63
20319.82	11559.08	18298.52	13300.69	14655.45	16519.72	21070.86	11293.30
18075.36	13371.15	24751.33	10798.70	24527.21	10927.29	22068.98	11108.03
21069.15	11461.14	18745.41	12806.16	19190.03	12756.28	13758.45	17672.27
21068.20	11342.39	24757.57	10794.34	34018.89	10650.74	21845.01	11192.58
34481.09	10650.74	14390.15	16978.61	21845.13	11108.03	24306.40	10804.95
21068.80	11251.63	19649.41	11785.41	24527.11	10868.94	18968.58	12774.55
25303.89	10652.91	8669.46	21716.44	18967.63	12756.28	18966.92	12989.01
9607.73	20857.37	18965.90	13019.49	21070.47	11251.63	18074.54	13169.81
21067.40	11374.04	14620.42	16320.84	24302.53	10939.69	21292.34	11319.28

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COST	CO_2	COST	CO_2	COST	CO_2	COST	CO_2
20844.45	11385.19	20844.33	11360.56	24858.05	10807.04	17132.00	13853.34
24530.49	10813.59	12723.93	18620.95	24303.23	10937.52	21844.38	11179.32
19790.47	11932.47	33799.79	10661.35	24530.32	10794.34	17976.40	13425.29
14657.14	16411.22	16994.90	14077.04	34018.20	10671.66	24528.02	10794.34
25303.26	10705.49	20843.95	11272.26	21068.80	11251.99	20319.96	11552.19
21067.35	11351.88	24527.90	10811.66	18490.54	13090.87	34020.07	10687.82
20324.90	11696.72	20016.02	11852.74	21067.32	11328.74	20319.88	11552.19
24302.89	10831.36	22070.02	11108.03	17220.58	14078.12	16995.57	14100.07
33799.67	10650.74	18266.62	13096.85	34018.20	10661.35	22067.63	11259.53
25762.27	10650.74	21853.64	11215.94	21067.40	11373.80	20845.03	11613.12
16017.17	15852.20	10061.35	20171.14	20848.46	11251.63	24526.13	10811.66
20319.89	11560.56	18075.32	13109.85	9386.99	20784.30	20317.36	11660.32
24302.30	10911.36	20318.87	11566.10	21845.24	11136.61	18965.81	12890.96
20847.77	11350.86	18743.63	12756.28	22068.28	11159.86	21070.79	11251.63
13122.98	18495.56	21293.13	11356.56	25079.47	10745.78	21844.36	11176.31
21068.25	11351.13	24754.18	10846.36	18496.04	13130.73	18299.04	13101.29
34018.95	10689.13	34018.26	10676.59	19650.56	11768.09	13758.41	17691.95
21296.68	11251.63	21069.82	11251.63	25085.27	10650.74	18075.94	13144.07
19657.23	12046.56	21071.59	11332.89	25303.28	10716.55	25303.16	10650.74
20316.35	11571.02	24856.10	10679.20	21069.25	11333.20	21072.46	11251.63
17175.33	14337.56	19189.87	12756.28	19638.69	12418.97	21630.80	11151.45
24526.26	10888.21	25086.20	10792.03	25079.47	10745.78	24526.13	10802.09
21067.39	11368.19	12815.51	18150.96	21068.15	11327.69	22854.90	10986.86
21068.16	11330.33	21068.13	11378.22	21067.45	11404.39	21071.66	11287.94
24528.09	10814.12	21067.41	11381.61	13710.63	17971.21	21068.92	11266.15
33795.90	10800.84	21069.13	11278.17	25303.17	10656.78	18030.51	13088.59
21069.79	11262.24	24866.93	10749.58	9833.81	20812.29	17177.72	14196.48
21067.48	11420.76	34018.16	10650.74	33802.05	10670.89	21068.00	11298.77
24526.90	10836.54	34022.73	10661.35	18976.31	12756.28	21843.52	11201.70
19647.74	11785.41	34018.93	10661.35	34020.01	10749.46	10729.99	20036.29
21067.42	11388.71	24751.71	10794.34	10584.10	19443.85	24303.13	10863.55
18651.06	12952.40	17018.84	14426.65	21848.64	11108.03	21067.37	11355.20
20851.58	11251.63	21627.04	11108.03	18965.04	12832.19	21069.84	11254.53
21070.06	11286.76	20844.14	11325.91	21068.21	11329.00	25303.69	10960.86
21067.42	11388.37	25651.53	10794.34	21852.65	11146.05	25309.19	10650.74
34021.82	10650.74	18075.39	13248.46	18965.87	12756.28	21631.74	11148.81
21846.97	11108.03	24303.90	10811.66	15295.94	16620.23	24304.69	10811.66
25304.34	10733.60	22070.02	11108.03	21068.10	11316.25	21074.79	11251.63
18295.40	12977.99	16278.09	15141.46	21844.26	11108.03	21068.25	11354.38
21068.13	11467.66	17208.34	14316.09	34020.90	10814.14	22069.31	11157.84
18873.33	13148.16	21846.97	11108.03	25303.89	10651.05	21068.27	11284.86
21846.97	11108.03	20320.11	11559.25	21292.87	11251.63	21069.38	11367.91
25081.04	10660.80	19870.92	11911.45	20317.35	11684.21	20542.21	11552.19
21068.84	11320.87	13486.65	18027.21	21068.10	11313.11	21293.84	11251.63
34019.05	10650.74	18968.58	12756.28	33794.30	10729.74	19579.53	11852.74
20326.48	11570.09	21291.92	11251.63	21068.15	11382.11	21067.87	11437.31
18650.19	13092.15	21068.10	11313.11	18965.76	12768.09	18074.33	13117.04
21852.66	11108.03	21068.34	11319.82	21070.79	11251.63	21067.35	11347.80
25090.03	10650.74	18743.13	13178.84	18097.87	13075.87	21072.46	11251.63
24304.94	10805.30	19189.88	12446.08	21844.51	11158.90	18304.54	13230.24

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COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
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21067.37	11356.90	21067.52	11446.65	21399.75	11323.94	20542.12	11552.19
21068.87	11251.63	19568.28	11962.05	21068.01	11309.84	24080.35	10971.09
24753.01	10915.35	20846.19	11367.22	18030.49	13060.55	20549.58	11552.19
11464.19	19325.02	21844.36	11166.56	12723.66	18463.66	25080.97	10679.92
24526.82	10794.34	17133.84	13858.22	21069.42	11433.22	20844.42	11303.85
21068.78	11335.02	25306.10	10650.74	24303.96	10847.63	21067.45	11324.09
15058.62	16566.64	20542.29	11563.01	18074.42	13102.38	21067.46	11379.92
20319.20	11562.80	21846.93	11118.64	12455.64	18206.26	24526.55	10918.22
17901.51	13187.70	24305.62	10794.34	20847.77	11275.16	25303.31	10735.72
18966.60	12763.01	20850.19	11351.69	24528.08	10811.23	34019.77	10650.74
23977.84	11240.39	17250.78	14063.92	24526.37	10868.35	21852.71	11162.89
9613.88	20597.87	24079.82	11109.78	19414.49	12442.26	19872.76	11828.66
20843.80	11507.62	14393.06	17289.07	25303.60	10816.35	24304.85	10823.05
21294.82	11260.71	34248.62	10650.74	25093.00	10841.07	12500.49	18394.34
19789.53	11943.66	18075.51	13135.61	25653.41	10878.12	18076.12	13157.08
20846.17	11365.27	25311.65	10811.00	21291.44	11375.28	14880.41	16411.22
18075.26	13168.54	21071.78	11354.31	18489.92	13171.23	14616.00	17422.39
24750.25	10836.52	21068.81	11287.59	34020.21	10661.35	21068.17	11313.11
21843.78	11219.84	9665.08	20826.65	20546.49	11591.80	12313.42	18381.60
10272.00	20283.15	21516.70	11267.25	25082.82	10650.74	12901.63	18497.47
24526.26	10886.83	18299.27	13096.75	20317.93	11576.69	18745.40	12993.73
21296.02	11338.95	18501.06	13078.80	21292.95	11292.91	34020.09	10653.00
18743.01	12999.52	20319.17	11559.36	20101.60	11566.43	34020.60	10661.35
18970.96	12761.30	21845.06	11342.05	20845.52	11251.63	20399.48	11467.54
22070.05	11141.48	16821.97	13851.95	21847.13	11108.03	25087.05	10865.02
20944.23	11315.12	21515.92	11251.63	19414.05	12380.05	12674.99	18498.88
20846.79	11251.63	33795.96	10661.35	21068.12	11369.78	20099.68	11552.19
18966.72	12790.55	21620.69	11186.28	20846.13	11290.17	20845.15	11276.72
20848.58	11323.68	24857.21	10847.35	25303.35	10759.13	20845.95	11319.99
16821.05	14015.77	21071.73	11251.63	21846.97	11108.03	25082.82	10650.74
25304.84	10650.74	20541.19	11567.14	18382.04	12943.73	21847.91	11108.03
20765.38	11590.38	17176.07	14250.94	18266.68	13282.49	34019.20	10650.74
18965.96	12957.08	20320.60	11552.19	25303.51	10745.36	18077.12	13136.64
13035.78	18116.59	18266.61	13128.96	21067.47	11415.42	20843.25	11323.25
19875.28	11768.09	20846.79	11251.63	24302.45	10889.46	25762.50	10650.74
21292.57	11370.09	24526.35	10864.14	24305.92	10811.66	17996.35	12796.78
15702.10	16151.76	21845.34	11126.09	24305.00	10811.66	12451.92	18528.14
18298.31	12972.18	21068.13	11400.34	33796.13	10768.62	20319.17	11694.55
21067.48	11424.46	20540.46	11657.14	21292.08	11252.75	25079.65	10741.86
16771.57	14033.61	21843.46	11184.79	12814.62	18380.07	34017.35	10670.27
22623.15	10964.43	24302.14	10818.79	20849.09	11610.72	21069.84	11251.63
24750.16	10810.17	14394.15	17307.60	24537.33	10907.37	25303.00	10650.74
24529.38	10794.34	20849.55	11356.16	21067.66	11379.41	26654.40	10650.74
21070.14	11315.78	21069.77	11399.35	18299.21	13101.29	12002.74	18966.95
21846.97	11108.03	25303.21	10783.15	25303.26	10707.94	24526.92	10849.75
19415.47	12264.53	14391.07	17293.81	21294.17	11363.11	19204.63	12261.36
21067.92	11265.72	21068.10	11315.05	21852.66	11108.03	9280.35	20431.28
25304.32	10650.74	21845.54	11108.03	21626.58	11118.64	25526.35	10669.36
14390.64	17289.07	11805.25	18408.26	24526.25	10835.61	18299.24	13099.05

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COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
34021.38	10653.56	21858.58	11143.74	19640.19	12263.01	34021.61	10670.90
20317.46	11726.77	18075.35	13125.14	18967.63	12756.28	20014.51	11998.33
25536.37	10650.74	24080.09	10924.31	20324.57	11603.90	21070.79	11251.63
20316.43	11658.56	16996.53	14213.17	17177.66	13899.74	20543.88	11552.19
25302.42	10731.77	19568.02	11852.74	20846.79	11251.63	21291.92	11251.63
34017.66	10874.78	18075.20	13236.49	21845.01	11192.00	21067.25	11324.49
25303.38	10775.71	19648.54	11925.85	20316.49	11675.90	21067.36	11353.43
18075.96	13138.65	15016.37	16081.28	21628.87	11154.18	9783.31	20380.59
21068.41	11325.75	25303.48	10839.72	20844.32	11305.03	21852.66	11108.03
21068.86	11285.35	21846.02	11108.03	20318.27	11638.85	24759.24	10794.34
18744.58	12772.60	24752.02	10794.34	20843.53	11396.85	21069.19	11485.77
20844.97	11260.97	25526.32	10661.35	15736.46	15734.42	21847.01	11119.73
34244.16	10721.31	21072.99	11274.88	21076.67	11251.63	18154.92	13269.89
34242.03	10668.06	24304.05	10867.35	18970.49	12756.28	20851.49	11441.12
20318.72	11659.77	20845.15	11272.26	24307.83	10866.36	18965.85	12941.37
33794.38	10753.66	21293.84	11251.63	20317.35	11755.07	24302.25	10886.64
25079.19	10668.06	18743.67	12790.99	18299.28	13179.19	21291.21	11313.11
16913.31	13947.33	8824.73	21811.88	24855.10	10677.67	20845.41	11386.60
34243.12	10758.40	19191.46	12795.28	20844.95	11251.63	33797.82	10650.74
21620.56	11128.66	21845.21	11128.50	12677.08	18564.68	20318.07	11613.67
19413.72	12324.49	21068.14	11269.40	21843.42	11248.35	21067.98	11290.97
18554.33	13106.39	21623.91	11108.03	34242.16	10650.74	11543.82	19056.43
18305.70	13101.29	25082.91	10650.74	25303.34	10755.91	20095.36	11628.04
25303.17	10661.50	22629.74	10991.79	25082.82	10650.74	21846.21	11140.43
20094.55	11754.43	18492.51	13471.29	34018.89	10650.74	26430.40	10650.74
25310.77	10650.74	21843.50	11144.18	25304.84	10650.74	34018.29	10686.05
25303.19	10668.06	34020.98	10696.10	20316.45	11646.99	20843.22	11329.62
21067.40	11372.35	20544.06	11657.10	24752.26	10810.06	21069.84	11251.63
18742.75	12756.36	19789.54	11945.41	18966.80	13079.10	21847.05	11190.29
34243.16	10680.30	23750.76	10968.67	25084.72	10650.74	18966.60	12756.28
20319.16	11556.38	19648.07	12078.16	21068.96	11257.65	21294.79	11251.63
22852.84	10964.43	21628.77	11123.28	20623.16	11371.30	21068.34	11305.83
19639.46	12263.01	24304.11	10832.81	21292.33	11312.90	18741.97	13105.24
25305.76	10661.35	25080.93	10650.74	12899.31	18691.57	19412.90	12373.60
24527.04	10825.76	21293.41	11427.70	22853.79	11006.14	21843.41	11118.64
20844.82	11359.14	21292.80	11251.63	24527.01	10811.66	24305.62	10820.43
20846.06	11379.29	21069.84	11251.63	21624.64	11108.03	22070.08	11122.24
21068.93	11423.47	24303.70	10835.61	24534.24	10796.08	18258.21	13094.21
23750.82	11169.26	18298.47	13173.25	21075.55	11251.63	25303.25	10704.09
21067.54	11455.75	15511.24	15734.27	17883.49	13835.88	10287.66	20591.30
24304.34	10984.89	25303.16	10650.74	19416.34	12773.16	24526.13	10811.66
21668.79	11176.08	21068.93	11424.75	24526.97	10877.72	34020.79	10650.74
21069.43	11438.94	20846.94	11374.85	21076.05	11424.98	24528.14	10800.88
19638.58	12506.95	21621.34	11227.78	21071.73	11251.63	12226.17	18630.40
25079.29	10843.16	34018.89	10650.74	23750.99	10955.26	20541.98	11799.38
21067.43	11393.27	20318.96	11613.67	21068.22	11683.81	24304.06	10913.37
21845.01	11128.66	24302.25	10835.61	20319.32	11679.21	34018.21	10706.37
21069.32	11313.11	24527.53	10902.05	21067.49	11428.79	19415.46	12263.01
24528.05	10996.53	20542.72	11659.23	14300.09	16684.19	25084.48	10820.37
18304.36	13096.99	18743.11	12867.85	24528.41	10850.62	11602.11	19299.76

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COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
20849.09	11610.72	20398.62	11471.31	33797.99	10663.96	34243.10	10686.33
25082.82	10650.74	21067.45	11406.48	18742.79	13024.07	21846.02	11108.03
20540.31	11610.63	13947.02	17504.97	33796.03	10661.64	20541.32	11602.82
21292.32	11395.08	20319.81	11552.19	24307.28	10859.12	20318.49	11719.98
21070.67	11313.11	24528.02	10794.34	21624.64	11108.03	18077.12	13135.38
21067.44	11395.50	9944.19	20574.06	25303.31	10735.36	13080.63	18306.08
22067.42	11121.81	20845.88	11326.62	21292.01	11309.18	24526.88	10825.66
18298.40	13169.21	24304.82	10794.34	16911.32	13927.69	10352.63	19078.16
19414.69	12372.48	21070.86	11343.13	25761.55	10650.74	21069.10	11369.11
21068.10	11313.11	21845.34	11136.45	17899.85	13086.25	21845.37	11342.17
21845.77	11240.68	21628.78	11121.32	21067.27	11328.47	21067.51	11441.84
25305.15	10650.74	33795.89	10663.83	20323.48	11568.10	33797.82	10650.74
18749.01	12756.28	21292.21	11333.40	14790.61	16309.00	18978.73	12267.92
20848.46	11251.63	25303.16	10650.74	17131.78	13816.54	20398.64	11473.35
19639.06	12450.41	21844.35	11179.53	14392.52	16565.48	21628.67	11152.90
21295.74	11251.63	25303.25	10703.38	24526.27	10894.11	21069.35	11390.57
24303.07	11028.47	25080.26	10686.92	25527.38	10692.01	18966.69	12903.46
21845.29	11197.35	21068.15	11271.56	22067.37	11108.03	24529.69	10794.34
18300.37	13351.82	24529.69	10794.34	24751.74	10811.66	33809.05	10790.22
21068.10	11317.95	18304.76	13188.64	22623.90	11072.67	21844.10	11108.03
25536.56	10650.74	20855.50	11292.30	21069.59	11455.58	18745.40	12756.28
24752.59	10794.34	18967.63	12756.28	21068.04	11286.15	18299.05	13101.29
18523.13	13095.51	21847.07	11140.39	25304.15	10668.06	21847.91	11108.03
24976.04	10794.34	21068.16	11380.43	25080.25	10767.75	21292.08	11251.63
21853.65	11161.89	17218.87	14116.94	20846.96	11298.83	19415.46	12263.01
25303.06	10683.48	34020.09	10839.38	20848.77	11251.63	34242.43	10650.74
19654.36	11768.09	20843.40	11376.76	25081.74	11014.05	20542.93	11552.19
21067.35	11468.36	20848.51	11404.04	20543.92	11562.80	25082.61	10650.74
25304.06	10653.00	21067.48	11386.19	18969.56	12879.73	24750.13	10811.66
21291.38	11367.85	18299.30	13224.58	21628.66	11108.03	34018.19	10731.94
18074.54	13222.40	21068.59	11554.52	9157.64	21339.26	21073.84	11251.63
34256.36	10650.74	34019.87	10668.06	34019.93	10650.74	21846.02	11108.03
21843.43	11264.37	25305.47	10650.74	25080.05	10650.74	18077.04	13213.31
20321.20	11580.10	17718.47	13082.87	20846.10	11315.99	21069.40	11262.24
21845.38	11345.12	15238.56	16233.30	25303.90	10779.45	24527.10	10959.46
11783.46	18501.23	21300.11	11290.11	20853.58	11281.85	19415.06	12452.50
33795.20	10652.47	23194.47	11108.03	16415.94	15040.35	18965.10	12903.06
33800.60	10710.98	25087.20	10667.48	21846.03	11116.12	19198.28	12756.28
25307.90	10706.68	20542.15	11571.01	20541.64	11659.03	19790.35	11996.42
21292.95	11251.63	12062.49	18131.89	21621.71	11131.82	25080.32	10816.00
21070.32	11296.86	17988.65	13079.30	21067.50	11430.88	21069.98	11251.63
24527.71	10794.34	20847.60	11272.26	21293.78	11265.92	22624.09	10964.43
17139.02	14202.67	25303.33	10745.49	24527.14	10981.89	22067.42	11136.88
18266.77	13187.74	24304.75	10825.38	20846.02	11356.09	23760.31	10937.94
21069.43	11264.74	18490.71	13101.29	25539.23	10650.74	20318.93	11552.19
20543.88	11552.19	35369.40	10650.74	24089.32	10794.34	20858.54	11272.26
18034.11	13118.27	25306.92	10724.62	20846.80	11350.19	22068.44	11157.88
24306.27	10841.94	15295.24	16635.03	21849.86	11137.97	25305.20	10717.64
24306.64	10794.34	25080.92	10650.74	18742.68	12836.63	25305.32	10723.60
21846.97	11108.03	11784.08	18603.42	18296.43	13018.24	25083.26	10650.74

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COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
21621.31	11208.56	18032.55	13085.46	34018.16	10650.74	18075.30	13192.62
24308.59	10933.75	34019.65	10661.35	25527.43	10650.74	26651.71	10650.74
24752.39	10847.33	21844.56	11148.99	18745.85	12780.48	20317.70	11867.01
20325.58	11552.19	25303.26	10708.79	25089.08	10719.34	33794.25	10884.87
21067.35	11351.63	25080.26	10687.38	24303.81	10811.66	21621.46	11136.09
34242.16	10650.74	21844.32	11108.03	24529.67	10813.17	12002.48	18785.65
18965.93	12829.77	34019.28	10785.92	25078.52	10716.41	18744.44	12778.63
18298.54	13168.97	20317.95	11643.78	20541.17	11552.19	20543.70	11627.59
18966.33	13029.73	20319.15	11552.19	25081.35	10821.17	20541.89	11552.19
24310.24	10794.34	21844.47	11210.91	20401.55	11576.89	24302.99	10796.07
20845.29	11451.54	21071.74	11251.63	19565.21	12319.54	21068.86	11285.11
16826.33	13866.07	24304.89	10930.09	21075.47	11385.89	24309.01	10794.34
25531.00	10650.74	18965.91	12803.27	21067.92	11251.63	18299.06	13102.60
13263.75	18115.32	21067.50	11433.64	24526.84	10798.71	34018.19	10668.06
25528.38	10765.27	21068.23	11340.36	20316.52	11688.64	21068.46	11359.71
21069.56	11272.26	21068.95	11251.63	18075.55	13463.60	19414.01	12352.28
19192.36	12756.28	8718.34	21872.11	21067.33	11331.73	21620.54	11167.85
15463.45	16032.24	34017.50	10710.50	17218.77	13960.58	24050.89	10998.19
12675.89	18508.56	21293.11	11251.63	21067.48	11422.14	21846.82	11114.54
18298.47	13177.94	25309.29	10706.22	20319.88	11552.19	20858.50	11312.28
21844.71	11283.44	18211.00	13400.18	18967.73	12782.91	18304.27	13101.29
18967.63	12756.28	21068.10	11326.33	20318.65	11801.82	20404.34	11560.52
20845.12	11256.98	34023.17	10705.46	24527.20	10835.61	21853.88	11108.03
34018.55	10766.29	18744.97	12478.91	33796.92	10661.35	20848.53	11272.97
34018.12	10683.90	33797.82	10650.74	25306.70	10650.74	20845.84	11251.63
25303.26	10709.26	25085.38	10763.04	20849.57	11363.76	25080.23	10670.52
34242.93	10661.35	33797.82	10650.74	18513.88	13490.57	21068.31	11353.94
20846.00	11295.75	17219.62	14079.50	14392.79	17289.07	24302.98	10794.34
25304.45	10796.20	25308.47	10651.82	21069.11	11340.65	20843.40	11374.89
14520.52	16790.19	20316.56	11896.65	18479.15	13196.24	21068.35	11506.50
22070.97	11108.03	18332.11	13100.29	21067.47	11414.23	18743.03	12919.95
34025.42	10650.74	15611.02	16319.63	24304.49	11068.76	21069.42	11436.42
21067.27	11329.00	34020.18	10699.66	23753.08	11015.93	20095.15	11552.19
34018.08	10670.32	21067.92	11251.63	21851.83	11162.05	19651.78	12024.76
34018.26	10708.44	24303.58	10811.66	20849.63	11251.63	34243.92	10650.74
33799.52	10678.90	18966.86	12911.09	20844.28	11401.18	10568.98	19651.60
18299.05	13071.75	21291.24	11319.55	24526.14	10816.99	25302.56	10813.40
18300.14	13213.72	21292.08	11251.63	22069.21	11108.03	18074.59	13199.03
18078.23	13171.06	19415.46	12263.01	21620.33	11172.88	21070.79	11251.63
16996.80	14456.49	25303.29	10684.09	33797.89	10661.35	12368.88	18216.63
25304.33	10724.93	21844.48	11168.95	18967.63	12756.28	33795.84	10650.74
20320.60	11552.19	17220.79	14038.11	34017.50	10710.84	34022.57	10737.01
20844.43	11372.94	24863.60	10669.27	18075.38	13239.27	21068.23	11340.32
21080.51	11337.34	22627.93	10964.43	22071.91	11108.03	21069.99	11276.08
21067.37	11355.01	18968.52	12756.28	22629.87	10964.43	25082.82	10650.74
18743.63	12756.28	21068.24	11346.59	12227.20	18628.36	25082.51	10650.74
13178.21	18017.96	20540.57	11719.65	24752.90	10835.61	24306.64	10794.34
10799.82	19169.19	33797.84	10654.24	34019.06	10656.46	25527.67	10790.20
20320.68	11552.19	21848.64	11108.03	21069.42	11344.47	21071.96	11280.69
20542.81	11585.82	18966.89	12929.59	12182.57	18563.65	20317.37	11869.07

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COST	CO_2	**COST**	CO_2	**COST**	CO_2	**COST**	CO_2
19189.76	12375.10	21068.94	11473.26	21080.47	11251.63	20319.88	11552.19
20319.11	11661.53	17839.21	13575.21	18743.75	12789.96	18716.49	13216.10
24303.95	10825.38	20862.92	12119.41	21068.20	11322.70	21845.98	11253.41
10795.07	20439.20	21069.08	11320.35	17227.99	14465.32	20850.14	11272.26
25304.92	10650.74	21068.10	11322.12	18492.40	13095.55	21068.30	11313.83
13043.32	18459.16	25088.33	11101.86	20844.40	11355.30	24303.33	10910.25
21624.74	11169.84	25304.27	10714.04	12060.97	18404.94	34021.85	10665.69
21292.14	11288.17	33795.30	10722.23	21291.42	11384.77	18299.21	13101.29
21067.45	11403.48	25304.12	10650.74	24304.98	10821.51	21292.13	11343.79
25529.15	10650.74	24303.40	10950.00	18478.59	13095.54	13945.05	17375.84
19637.74	12286.55	12456.70	18449.98	33798.00	10650.74	14878.61	16790.70
34018.31	10692.01	20317.01	11552.19	18123.79	13062.88	10806.75	19383.18
20318.62	11552.98	20845.87	11270.42	25303.25	10701.58	21292.83	11272.05
20544.04	11648.52	34018.68	10751.37	13267.39	18234.95	24303.00	10801.08