

Energy supply planning in Iran by using fuzzy linear programming approach (regarding uncertainties of investment costs)

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Abstract

For many years, energy models have been used in developed or developing countries to satisfy different needs in energy planning. One of major problems against energy planning and consequently energy models is uncertainty, spread in different economic, political and legal dimensions of energy planning. Confronting uncertainty, energy planners have often used two well-known strategies. The first strategy is stochastic programming, in which energy system planners define different scenarios and apply an explicit probability of occurrence to each scenario. The second strategy is Minimax Regret strategy that minimizes regrets of different decisions made in energy planning. Although these strategies have been used extensively, they could not flexibly and effectively deal with the uncertainties caused by fuzziness. “Fuzzy Linear Programming (FLP)” is a strategy that can take fuzziness into account. This paper tries to demonstrate the method of application of FLP for optimization of supply energy system in Iran, as a case study. The used FLP model comprises fuzzy coefficients for investment costs. Following the mentioned purpose, it is realized that FLP is an easy and flexible approach that can be a serious competitor for other confronting uncertainties approaches, i.e. stochastic and Minimax Regret strategies.

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1. Introduction

Economics is the scientific study of decisions affecting the allocation of scarce resources between competing ends. In this issue, uncertainty arises whenever a decision can lead to more than one possible consequence.

In economy, nothing is more certain than existence of uncertainty. How many consumers demand commodities, how much prices increase or decrease, how much the interest rate will be and many questions like these are questions that economic decision-makers always encounter. Replying to these questions is not easy for decision-makers, because the future is not clear and obvious to them. They can just estimate the future and

so their estimation, undoubtedly, are full of guessing and judgments. Therefore, a decision maker cannot be sure that his current decision will lead to a certain consequence or not.

In Iran, decision and policy making, also, face with a vast domain of uncertainties. Inefficient economic institutions, governmental structure of the economy and numerous legal constraints are the simplest problems in this regard. These challenges make many uncertainties in economic planning, especially in energy planning in Iran.

Among the uncertainties in energy planning, the uncertainty of investment costs is of special importance. Energy sector is the most costly and capital-intensive sector of an economy. Therefore, all the countries intend to expand, develop or rehabilitate their energy sectors, and are trying to provide suitable economic, political, legal and even, cultural conditions for investments.

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Unfortunately, energy investment in Iran always face with a lot of challenges such as the lack of security in private ownership, occurring domestic crises, instability and lack of up-date of the law, various policy makers, etc. These challenges make the investment costs of energy sector uncertain. Therefore, energy planning in Iran cannot follow the goals without considering this kind of uncertainty.

Confronting uncertainties, energy planners often choose two different strategies. The first strategy is stochastic programming and the second is Minimax Regret strategy. Although these strategies have been used extensively, they could not flexibly and effectively deal with the uncertainties caused by fuzziness. Therefore, another strategy that takes fuzziness into account is introduced, i.e. “Fuzzy linear programming (FLP)”.

In three past decades, different contributions were published about fuzzy optimization and especially FLP. In despite of this large literature, literature of energy planning by using fuzzy optimization methods is so recent. One of the early published contribution in this field is Canz (1996). This paper summarized the results of the research conducted by the author during the Young Scientists Summer Program (YSSP) in IIASA’s¹ Methodology of Decision Analysis (MDA) Project. The basic purpose of the research was to evaluate how the methodology of FLP can support the decision-making process in energy system planning under uncertainty. The research reported in the paper provided an overview of the methods and tools used for supporting decision-making in energy system planning in Germany. It also tried to show how one can improve some elements of FLP applied to a real-world problem by learning from applications of MCMA² for decision support and by using software tools developed for MCMA. Also, different papers can be mentioned in this issue such as Gwo-Hshiung et al. (1996), Yang and Lee (1999), Mavrotas et al. (2003) and Borges and Antunes (2003).

Gwo-Hshiung studied Taipower, the official electricity authority of Taiwan, encountered several difficulties in planning annual coal purchase and allocation schedule. In this study, these concerns were formulated as a fuzzy bicriteria multi-index transportation problem. Furthermore, an effective and interactive algorithm was proposed which combined reducing index method and interactive fuzzy multi-objective linear programming technique to cope with a complicated problem which may be prevalent in other industries. Results obtained in this study clearly demonstrated that this model could not only satisfy more of the actual requirements of the integral system but also offered more information to the decision makers for reference in favor of exalting decision making quality.

The Yang study was concerned with the applications of linear goal programming and fuzzy theory to the analysis of management and operational problems in the radioactive processing system (RWPS). The developed model was validated and verified using actual data obtained from the RWPS at Kyoto University in Japan. The solution by goal programming and fuzzy theory would show the optimal operation point which was to maximize the total treatable radioactive waste volume and minimize the released radioactivity of liquid waste even under the restricted resources.

Mavrotas used a linear programming model, including both continuous and integer variables, which represented energy flows and discrete energy technologies in a large hotel unit as a case study nearby Athens. The model comprised fuzzy parameters in order to handle adequately the uncertainties regarding energy costs. The obtained FLP model was then translated into the equivalent multiple objective linear programming model, which provided a set of efficient solutions, each one characterized by quantification of the risk associated with the uncertain energy costs.

Finally, Borges used an interactive approach to deal with fuzzy multiple objective linear programming problems, which was based on the analysis of the decomposition of the parametric (weight) diagram into indifference regions corresponding to basic efficient solutions. The approach was illustrated to tackle uncertainty and imprecision associated with the coefficients of an input–output energy–economy planning model, aimed at providing decision support to decision makers in the study of the interactions between the energy system and the economy on a national level.

This paper is using a FLP model, including fuzzy objective coefficients of investment costs, that represents the supply energy system of Iran. In this paper, we try to demonstrate the method of application of FLP for optimization of supply energy system of Iran, as a case study. Following this purpose, we realize that FLP is an easy and flexible approach that can be a serious competitor for other confronting uncertainties approaches, i.e. stochastic and Minimax Regret strategies.

2. Current strategies for confronting uncertainty in energy planning

Faced with uncertainties, energy planners often use two well-known strategies. The first strategy is stochastic programming in which energy system planners define different scenarios and apply an explicit probability of occurrence to each scenario. The second strategy is Minimax Regret strategy that minimizes regrets of different decisions made in energy planning.

¹International Institute for Applied Systems Analysis.

²Multiple criteria model analysis.

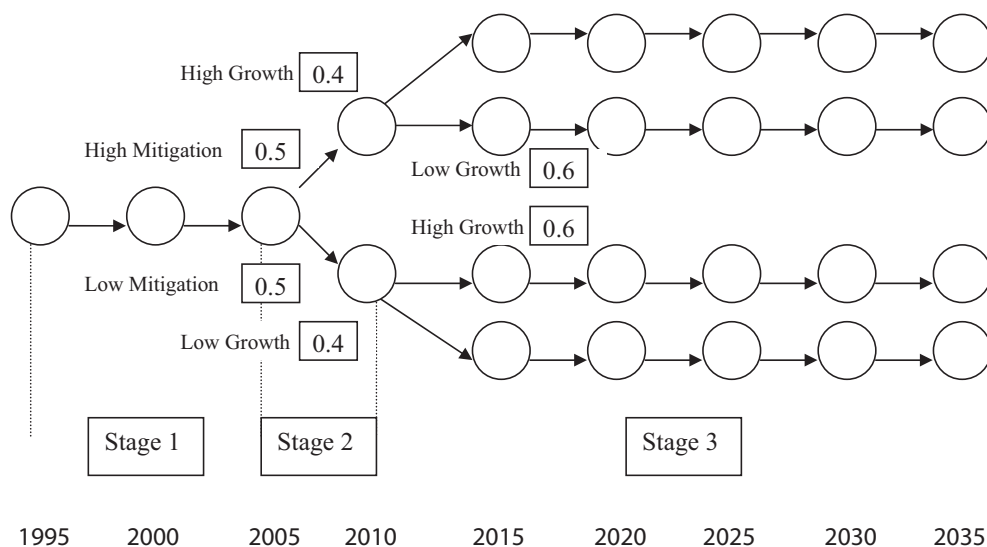


Fig. 1. Uncertainties in the event tree for carbon dioxide emission reduction in Quebec.

2.1. Stochastic programming strategy

Stochastic programming deals with different scenarios and an explicit probability of occurrence to each scenario, applicable until the uncertainty is resolved at an assumed future date when corrective action may be taken. Taking these assumptions into account, the model is then solved once and for all, selecting a single course of action that is optimal in the case of uncertainty. The model thus determines the hedging strategy: the singular optimal mix of technologies for the near term until the uncertainty is resolved. Thus, in one optimization run, a contingent policy that adapts to the possible evolution of the scenarios is determined. This adaptive policy may be much closer, in spirit, to the way decision makers have to deal in real life with uncertain futures.

The time path of uncertainties can be described as an event tree. A path from the “root” to a “leaf” of the event tree represents a scenario. A scenario in a MARKAL model³ is a specification of all the exogenous parameters of the database (socioeconomic parameters, useful demands, energy prices and availability, technico-economic, parameters of new technologies). Each scenario may have a given probability, or all scenarios can be considered as equally probable.

Stochastic programming has been used extensively by energy planners. For example, three of the participating ETSAP⁴ countries—Canada, the Netherlands and Switzerland—have used stochastic programming with the MARKAL model. Canada looked at the effect of two

major uncertainties—stringency of future carbon dioxide emission restrictions and rate of economic growth—on the energy future of the province of Quebec. The Netherlands examined the difference in the degree of carbon dioxide emission reductions, including sensitivity analysis on several key variables, and taking into account risk aversion. Switzerland evaluated uncertainty in future emission reduction requirements and the demand-side management potential in developing a local energy plan for Geneva.

For better acquaintance with stochastic programming and its application, we represent stochastic programming of Quebec for pollution mitigation (ETSAP, 1999).

2.1.1. Stochastic programming in Quebec

The event tree for the example of carbon dioxide emission reduction in Quebec is shown in Fig. 1. The two major uncertainties are (1) whether high or low mitigation of carbon dioxide emissions will be required, assumed to be decided in the year 2010, and (2) whether Quebec will experience high or low economic growth, assumed to be known by 2015. Thus, there are four alternative scenarios. The chances are assumed to be even so that mitigation requirements will be high or low (probability of 50 percent for each). With low mitigation, the chances are assumed to be even, so that there will be high or low economic growth. With high mitigation, the chances are assumed to be higher (probability of 60 percent) so that there will be low economic growth, and lower (probability of 40 percent) so that there will be high economic growth.

This strategy leads policy makers to a single optimal hedging strategy that contained contingent actions. In general, hedging strategy takes an intermediate path until the uncertainty is resolved, and the trajectory of carbon dioxide emissions falls between those calculated

³MARKAL is the abbreviation of MARKet ALlocation. This model has been developed by ETSAP since the end of 1970s.

⁴Energy technology system analysis programme.

for high and low mitigation (Kanudia and Loulou, 1996).

2.2. The minimax regret strategy

For countries with a MARKAL model of their energy system, stochastic programming can be used to identify the best interim hedging path to be followed until the uncertainty is resolved, as shown in the previous section, provided that a probability of occurrence can be assigned to various future scenarios. Although there may be grounds for assigning these probabilities, with today's uncertainty any such estimation would be subject to sharp criticism.

In decision theory, a distinction is sometimes made between decision making under risk (where specific probabilities can be associated with different possible outcomes) and decision making under uncertainty (where the probabilities of the possible outcomes are unknown or unknowable). Stochastic programming is thus decision making under risk since probabilities are assigned to alternative scenarios. So, what can be done in the case of pure uncertainty?

Among several criteria that have been proposed, one choice is that of the “bad loser”: the Minimax Regret criterion. The amount of “regret” is measured by the difference between the cost actually incurred and the cost that would have been incurred if the future had been known beforehand. Regret corresponds to the economists’ “opportunity cost”, the proper measure in a comparison of alternatives. Moreover, there is a powerful empirical argument in its favor; namely, it is a criterion that can make a hedging, as widely practiced in financial markets, an optimal strategy.

Earlier tests of this approach within ETSAP were taken by Per Anders Bergendahl and Tomas Larsson of Sweden. The application of the Minimax Regret criterion was illustrated by Loulou and Kanudia (1997) using the MARKAL model of the Quebec energy system for the 45-year time span between 1993 and 2037. Loulou and Kanudia compared the Minimax Regret results with those applying the Laplace criterion which are obtained using stochastic programming with equal probabilities assigned to each of the outcomes. The results in this case are almost the same. However, with different scenario specifications, the two strategies may diverge more (Loulou and Kanudia, 1997).

3. FLP

The complexity in the analysis of natural, social and human behaviors is ever rooted in the incompatible nature of subjectivity and objectivity, accuracy and inaccuracy, simplicity and complexity, certainty and uncertainty, etc. Trying to analyze the subjectivity, inaccuracy and uncertainty of natural, social and human

systems had never led to satisfactory conclusions. Although under certain and random circumstances, mathematical and stochastic methods have been used successfully in the simulation of natural and human behaviors, respectively, these methods could not describe reality perfectly.

Confronting the enormity and complexity of social and human systems, current methods react so simplistically, mechanically and in inflexible manners. The reason for this kind of manner is clear. Current mathematics cannot describe human behaviors perfectly. In other words, there are not any suitable practical models based on current mathematics for accurate approximation, imitation and finally, controlling of social and human systems. In fact, in confronting human systems, mathematical models are encountering with situations that are not accurate. In other words, these situations are fuzzy. Many terms like development, utility, optimization, etc. are fuzzy concepts. These concepts that are not accurate and crisp often, play important roles in human behaviors.

Nowadays, natural scientists and social scientists have gradually come to believe that social and human systems can be described effectively by a new mathematics. In other words, a new mathematics can consider “inaccuracy” and “fuzziness” in a logical manner. Because of this, a new mathematics—fuzzy mathematics—has been considered strongly (Zimmermann, 1996).

Fuzzy theory has been used extensively in different areas such as “fuzzy control”, “fuzzy logic”, “artificial intelligence”, etc. One of the most important and practical areas of fuzzy theory is fuzzy optimization. In recent years, fuzzy optimization and especially, FLP is utilized in many economic areas such as energy planning. In the next section, we will introduce different kinds of FLP models and particularly, describe the defuzzification methods of FLP models with fuzzy objective function coefficients.

3.1. Kinds of FLP

For understanding the different kinds of FLP, we consider a firm that produces different chemical substances. This firm intends to maximize its profit with regard to its constraints about the amount of raw substance (b_1) and working hours of laborers (b_2). Thus, this firm encounters an optimization problem

maximize (profit) $c_1x_1 + c_2x_2 + \dots + c_nx_n$,

subject to :

(raw substance

$$a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n \leq b_1,$$

constraint)

(time constraint)

$$a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n \leq b_2,$$

$$x_1, x_2, \dots, x_n \geq 0.$$

These amounts of raw substance (b_1) and working hours (b_2) are not exact completely. If the firm's manager decides to produce more (less), he needs more (less) amount of (b_1 and b_2). Therefore, the firm's planner should consider these tolerances in the firm's model. Thus, for entering these tolerances to the model, he should use fuzzy numbers for R.H.S.⁵ instead of crisp numbers. So, the first kind of fuzziness reveals in resources (b_i) in R.H.S.

The second kind of fuzziness may reveal in objective function coefficients. Because of uncertainties in goods markets, the planner cannot exactly determine the profit of each unit of products. The amount of $c_1, c_2, \dots, c_n$ in classical linear programming are just profits with greater possibilities. So, it is logical that the planner uses fuzzy numbers for objective function coefficients.

The third kind of fuzziness may reveal in L.H.S.⁶ coefficients. Because of technical improvements, carelessness of laborers, etc. the needed rate of raw substance ($a_{11}, a_{12}, \dots, a_{1n}$) and required hours ($a_{21}, a_{22}, \dots, a_{2n}$) for producing one unit of chemical substances may alter time after time. Therefore, it is better to use fuzzy numbers instead of crisp L.H.S. coefficients.

Due to this example, planners encounter with three kinds of FLP problems:

(i) FLP with fuzzy resources:

$$\begin{aligned} &\text{maximize} && cX, \\ &\text{subject to :} && AX \leq \tilde{b}, \\ &&& X \geq 0, \end{aligned}$$

where $\tilde{b} = (\tilde{b}_1, \tilde{b}_2, \dots, \tilde{b}_n)$ is a vector with fuzzy amount of resources.

(ii) FLP with fuzzy objective function coefficients:

$$\begin{aligned} &\text{maximize} && \tilde{c}X, \\ &\text{subject to :} && AX \leq b, \\ &&& X \geq 0, \end{aligned}$$

where $\tilde{c} = (\tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_n)$ is a vector with fuzzy objective function coefficients.

(iii) FLP with fuzzy L.H.S. coefficients:

$$\begin{aligned} &\text{maximize} && cX, \\ &\text{subject to :} && \tilde{A}X \leq b, \\ &&& X \geq 0, \end{aligned}$$

where $\tilde{A} = [\tilde{a}_{ij}]$ is a matrix with fuzzy L.H.S. coefficients (Wang, 1994).

By combination of these three different types, we lead to new kinds of FLP problems. In this paper, since our question is about uncertainties of investment costs, we will focus on the second type of FLP problems that is FLP with fuzzy objective function coefficients.

3.2. FLP with fuzzy objective function coefficients

Consider a FLP problem with fuzzy objective function coefficients:

$$\begin{aligned} &\text{maximize} && \tilde{c}X, \\ &\text{subject to :} && AX \leq b, \\ &&& X \geq 0. \end{aligned}$$

For simplicity and without missing the generality of problem, we assume that $\tilde{c}_i$ are triangular fuzzy numbers with the following membership functions, $\mu_{\tilde{c}_i}(x; c_i^*, c_i^-, c_i^+)$. We denote these fuzzy coefficients by $\tilde{c}_i = (c_i^*, c_i^-, c_i^+)$, where c_i^* is mean, c_i^- is left spread (tolerance) and c_i^+ is right spread (tolerance). We can rewrite the above FLP as follows:

$$\begin{aligned} &\text{maximize} && ((c^* - c^-)X, c^*X, (c^* + c^+)X), \\ &\text{subject to :} && AX \leq b, \\ &&& X \geq 0 \end{aligned}$$

which is equivalent to a goal programming problem (multi-objective problem). For solving this multi-objective problem, different methods have been proposed of which we just explain three well-known methods here.

The first method is a combination of these three objective functions to a single objective function. For example, $(c^* - c^-)X$, c^*X and $(c^* + c^+)X$ can be combined by "Strong Probability" factor. Strong probability factor is defined as

$$\frac{(4c^* + (c^* - c^-) + (c^* + c^+))}{6}.$$

Therefore, a FLP problem with fuzzy objective function coefficients could be converted to the following:

$$\begin{aligned} &\text{maximize} && \frac{(4c^* + (c^* - c^-) + (c^* + c^+))}{6}, \\ &\text{subject to :} && AX \leq b, \\ &&& X \geq 0. \end{aligned}$$

Weighted sum of fuzzy coefficients method also can be used. For example, we can use "Possibilistic Approach" that alters objective function in the following way:

$$Z = w_1(c^* - c^-)X + w_2(c^* + c^+)X$$

that

$$\begin{aligned} w_1 + w_2 &= 1, \\ w_1, w_2 &\in [0, 1]. \end{aligned}$$

Therefore, we can rewrite FLP with fuzzy objective function coefficients as

$$\begin{aligned} &\text{maximize} && Z = w_1(c^* - c^-)X + w_2(c^* + c^+)X, \\ &\text{subject to :} && AX \leq b, \\ &&& X \geq 0, \end{aligned}$$

⁵Right-hand side.

⁶Left-hand side.

where w_1 and w_2 are selective and planners dealing with problem condition and situation can freely choose it (Wang, 1994).

The third method considers this fact that our purpose in an optimization problem is maximizing these triangular fuzzy coefficients, $((c^\bullet - c^-)X, c^\bullet X, (c^\bullet + c^+)X)$. Thus, instead of simultaneous maximization of $(c^\bullet - c^-)X, c^\bullet X, (c^\bullet + c^+)X$, we can maximize mean $\bar{c}X$, minimize left spread c^-X and maximize right spread c^+X . By using this method in a maximization problem, the objective function shifts to right. Thus, our problem becomes as the following formulation

$$\begin{aligned} &\text{minimize} && z_1 = c^-x, \\ &\text{maximize} && z_2 = c^\bullet x, \\ &\text{maximize} && z_3 = c^+x, \\ &\text{subject to :} && AX \leq b, \\ &&& X \geq 0. \end{aligned}$$

One solving method of this multi-objective programming problem is determination of these objective functions by their membership functions and maximization of their alpha-cuts.⁷ For this purpose, we first calculate these objective functions in which $X = \{X | AX \leq b, X \geq 0\}$, z_i^p are optimal positive objective functions and z_i^n are optimal negative objective functions

$$\begin{aligned} z_1^p &= \text{maximize } c^-X, & z_1^n &= \text{minimize } c^-X, \\ X &\in x & X &\in x \\ z_2^p &= \text{maximize } c^\bullet X, & z_2^n &= \text{minimize } c^\bullet X, \\ X &\in x & X &\in x \\ z_3^p &= \text{minimize } c^+X, & z_3^n &= \text{minimize } c^+X, \\ X &\in x & X &\in x \end{aligned}$$

Afterwards, for determination of objective functions, we consider three following membership functions

$$\mu_{z_1}(X) = \begin{cases} 1 & c^-X < z_1^p, \\ \frac{z_1^n - c^-X}{z_1^n - z_1^p} & z_1^p \leq c^-X \leq z_1^n, \\ 0 & c^-X > z_1^n, \end{cases}$$

$$\mu_{z_2}(X) = \begin{cases} 1 & c^\bullet X > z_2^p, \\ \frac{c^\bullet X - z_2^n}{z_2^p - z_2^n} & z_2^n \leq c^\bullet X \leq z_2^p, \\ 0 & c^\bullet X < z_2^n, \end{cases}$$

⁷Alpha—cuts are slices through a fuzzy set producing regular (non-fuzzy) sets. If $\tilde{A}$ is a fuzzy subset of some set Ω , then an α -cut of $\tilde{A}$, written $\tilde{A}[\alpha]$ is defined as $\tilde{A}[\alpha] = \{x \in \Omega | \tilde{A}(x) \geq \alpha\}$, for all $\alpha, 0 < \alpha \leq 1$.

$$\mu_{z_3}(X) = \begin{cases} 1 & c^+X > z_3^p, \\ \frac{c^+X - z_3^n}{z_3^p - z_3^n} & z_3^n \leq c^+X \leq z_3^p, \\ 0 & c^+X < z_3^n. \end{cases}$$

Finally we should solve the following usual linear programming:

$$\begin{aligned} &\text{maximize} && \alpha, \\ &\text{subject to :} && \begin{cases} \mu_{z_i}(x) \geq \alpha & i = 1, 2, 3, \\ AX \leq b, \\ X \geq 0, \end{cases} \end{aligned}$$

where α is the minimum of membership functions (Delgado et al., 1987, 1990).

4. Energy supply planning in Iran

4.1. Uncertainties in investment costs

Energy sector generally is the most costly and capital-intensive sector. Energy sector costs are so high that every country that intends to expand, develop or rehabilitate its energy sector needs gigantic amounts of investments. Iran which possesses the second and fifth largest gas and oil reservoirs greatly needs extensive investments in energy sector. In investing in Iran, many weak and strong points can be enumerated that filled investment in Iran with a vast domain of uncertainties. In this part, we consider some of these weak and strong points.

4.1.1. Strong points of investing in Iran

(i) *Low-priced energy carriers*: Compared with other countries, energy carriers in Iran are cheap and convenient for production. For example, raw materials in oil and petrochemical industries are low-priced. This advantage can make Iran a convenient place for foreign investors.

(ii) *Youthful and inexpensive human capitals*: Human capitals in Iran are young and cheap relative to other developing or developed countries. Wages of white-collars, specialists and high-educators are very low. Thus, total cost of labor-intensive commodities, compared to other countries, is low and consequently, production of these commodities is profitable in Iran.

(iii) *Size of market*: Iran has approximately 70 million population. Regarding high purchasing power and good tastes, Iran has the best market among the Middle East countries. Therefore, Iran can be the best place for foreign and domestic investors.

(iv) *Other strong points*: Other strong points for investing in Iran are:

- Existence of essential economic infrastructure.

- Access to free waters and international seas through southern ports.
- Effective transportation networks.

4.1.2. Weak points of investing in Iran

(i) *Insecurity in the Middle East region*: Numerous bloody wars, quarrels between Arabs and Israel and disputes between India and Pakistan, non-democratic nations, etc., converted the Middle East to the most insecure region in the world.

(ii) *Afterwar crises*: Various internal crises not only ruin the inclination of foreign investors but also chases away domestic investors. Although going out of domestic capitals had declined after war, inflation and unemployment crises accelerated this process again.

(iii) *Development of government ownership*: Various legal and political obstacles make private ownership insecure in Iran. Seizure and confiscation of capital and assets are always an apprehension of capitalists in Iran.

(iv) *Instability of the law*: Instability of the law and lack of up-dating of it pose a huge obstacle against foreign and domestic investments. Nowadays, the issue of contradictory laws is a concern in economic investment.

(v) *Lack of transparency in Foreign Investment Act*: There is not any comprehensive Act about absorption, support and facilities for foreign investment. Now Foreign Investment is approved by the parliament.

All of these points in addition to governmental structure of economy, plurality of policy makers, lack of transparency in taxes and custom duties, etc. have made foreign and domestic investors uncertain about investing in Iran. While considering the importance and size of investment, ignoring these uncertainties will certainly bias planning. Thus, economic planning and especially energy planning of Iran should consider these uncertainties.

In the next section, we try to enter these uncertainties to investment costs and consequently to energy planning of Iran by using FLP.

4.2. Energy supply planning

4.2.1. Reference energy system of the model

In our model, the reference energy system is represented by an oriented network in which the energy, starting in the form of primary energy is flowing and is gradually transformed further down to useful energy so as to satisfy a given exogenous demand.

The network is a concatenation of links with upstream and downstream nodes. Fig. 2 shows reference energy system that is a simplified reference energy system of Iran.

The nodes of this network represent an energy form, while the links represent an energy supply, conversion or

consumption process. The boundary nodes of the system are represented as $\odot$ (these are supply, demand, export or import energy forms) while other nodes are represented as $\circ$ (intermediate energy form).

Generally, a process (network link) converts an energy form (upstream node) into another energy form (downstream node). Some other processes are fed by substitutable energy forms; their upstream node represents a mix of substitutable energy forms. Thus, a node represents an energy form or a mix of energy form.

Most links of the reference energy system represent processes converting an energy form (or a mix of energy form) into another energy form (or a mix). Other links of the network are allocation links, pseudo links, Psi-load links, import and export links.

Our reference energy system consists of four sub-sectors, they are gas, oil, coal and electricity subsectors. In the gas subsector, GTL,⁸ natural gas and LNG⁹ processes are considered. In the oil subsector, refinery is considered as a single node. In the coal subsector we considered two coke- and coal-subsectors. In the electricity subsector, seven power plants are considered they are coal, steam, gas turbine, combined cycle, hydro, wind and geothermal power plants.

4.2.2. Structure of the model

4.2.2.1. *Fuzzy objective function*. The parameters involved in the total discounted cost function are

(i) *Variable Cost (VC)*: The VC includes all costs proportional to the outflow (production level) except for the fuel operating cost of both the main and ancillary inputs. This cost includes the variable operating and maintenance cost.

(ii) *Fixed Cost (FC)*: The FC represents the yearly sum of all operating costs proportional to the capacity increment. It therefore does not include the capital cost of the investment.

(iii) *Investment Cost (IC)*: The IC represents the sum of all charges incurred to build one unit of capacity. This parameter must include the financial charges paid during the construction.

For fuzzification of investment costs, economic factors, Inflation and exchange rate were considered. Certainly, investment costs are strongly affected by these two economic factors. Thus, inflation and exchange rate fluctuations can show investment costs fluctuations. Due to Iran's inflation and exchange rate statistics, investment costs can spread 40% to right and 10% to left at the most. Thus, IC can be defined as ($\tilde{IC}$) that $\tilde{IC}_i = (IC_i, 10\%IC_i, 40\%IC_i)$. Therefore, we can write the total

⁸Gas to liquid.

⁹Liquid natural gas.

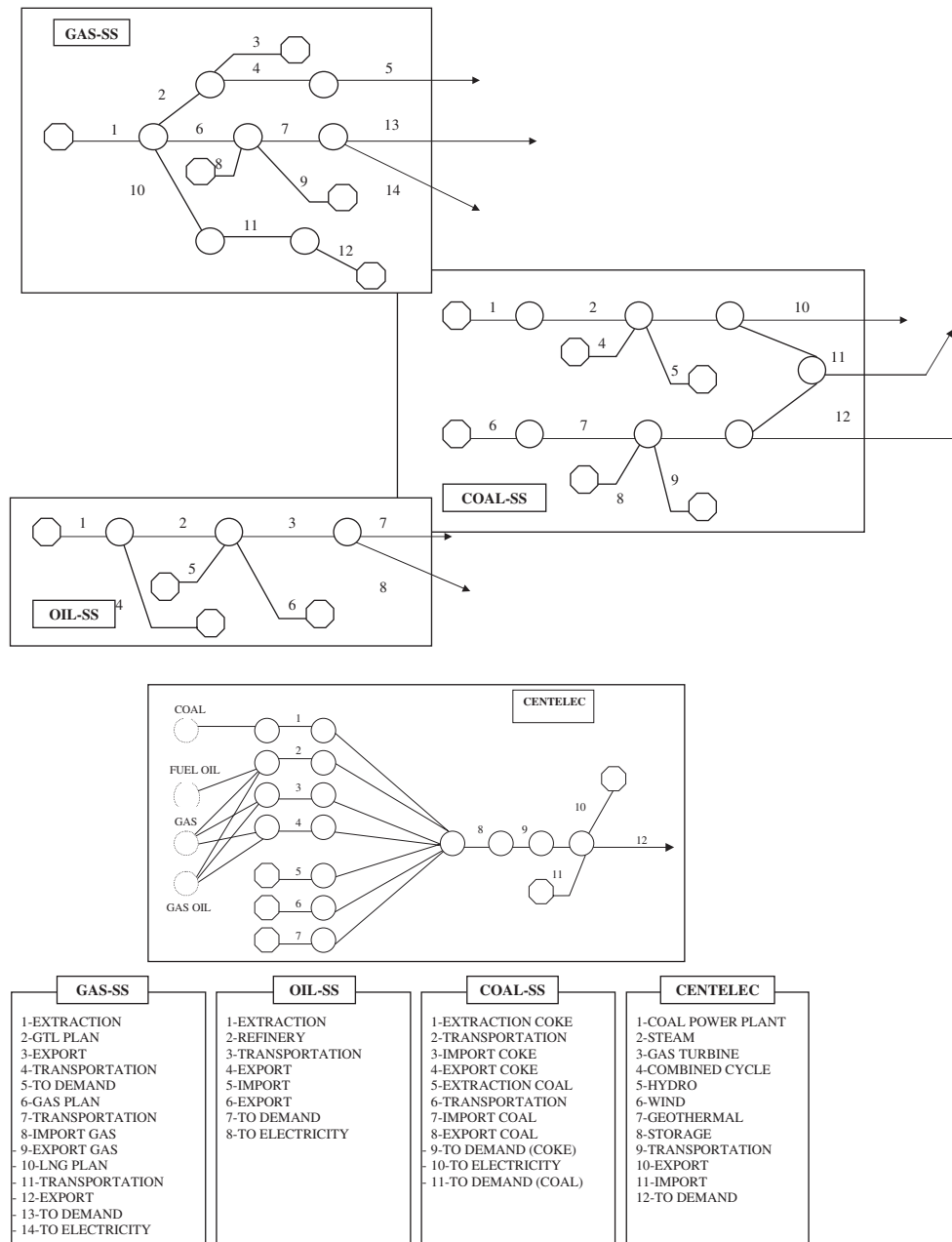


Fig. 2. Reference energy system.

cost as

$$\text{Total cost} = \sum_{t=T_o+1}^{T_p} \left[\frac{1}{(1+r)^{t-T_o+1}} \sum_{i=1}^N (VC_{it}E_{it} + FC_{it}X_{it} + I\tilde{C}_{it}X_{it}) \right].$$

P is the number of sub-periods, and in our study, where we have two five year sub-periods P equals to two. In the first sub-period, $T_o = 2004$ and $T_1 = 2009$, and in second one $T_o = 2009$ and $T_2 = 2014$. Total cost

is composed of variable costs (proportional to the flows), fixed costs (proportional to the new invested capacities) and investment costs (proportional to the new invested capacities).

4.2.2.2. Model Constraints. The constraints of the model consist of:

- (i) flow balance equations at network nodes,
- (ii) market allocation constraints at the nodal inputs with their fixed, or maximum and minimum value,
- (iii) product allocation constraints at the nodal outputs,

- (iv) capacity factor constraints, linking the flow and its related total capacity,
- (v) fixed value or upper and lower bounds on the flows,
- (vi) fixed value or upper and lower bounds on the total capacity,
- (vii) maximum market share of a given technology,
- (viii) limits on imports, exports, etc. (e.g. oil export limits that are based on OPEC¹⁰ quotas).

4.2.3. Model results

For solving the fuzzy model, we should firstly choose the best method among rival methods. For the best selection, we should consider these criteria:

(i) *Axiomatic strength*: Solving method should have enough logical explanations and justifications for their axioms.

(ii) *Empirical fit*: Methods should adapt themselves to real-system variations appropriately.

(iii) *Efficiency in calculation*: Methods should be efficient in different sizes of models.

Due to these criteria, the third method was chosen; because this method, in addition to axiomatic strength, obtains membership function numbers (α). Based on the methodology, optimal positive and negative results (z_i^p and z_i^n) were obtained firstly. Then, results were put in their membership functions and the membership function placed in the crisp model constraints. The fuzzy models were solved and their results were compared with the crisp model results.

In this research, two five-year durations have been considered. First duration started from 2004 to 2009 and second started from 2009 to 2014. By solving these models, membership numbers $\alpha_1 = 0.07251876$ and $\alpha_2 = 0.4999948$ were obtained. Whatever the membership numbers that were approximate to 1, the results of the fuzzy models were approximate to results of crisp ones. Thus, the results of the fuzzy model in the second duration were closer to crisp model results than in first duration.

4.2.3.1. Gas subsector. Uncertainty affects gas subsector more than other subsectors. In the first duration, entry of uncertainties to the model forces model to choose more production for gas subsector. Thus, the fuzzy model proposes to extract 44 MTOE¹¹ more than the crisp model. Allocation of extracted gas to natural gas plants and GTL plants also differs. The crisp model proposes to consume all extracted gas only in gas plants; but the fuzzy model prefers to consume close to 70% of extracted gas in GTL plants and the remainder in gas plants. None of the models proposes to produce LNG.

Both models also obtain equal results in gas export and import.

In the second duration, the results of two models do not differ much and just fuzzy model proposes to extract 52 thousand TOE¹² less. Although in the second sub-period crisp model does not propose to produce GTL, fuzzy model prefers to allocate 8% of extracted gas to GTL plants. The amount of gas import and export in both models are equal. Like the first duration, none of the models proposes to produce LNG.

4.2.3.2. Oil subsector. In the first duration, the amount of crude oil extraction, export, refinement and export and import of oil products are equal in both fuzzy and crisp models. The difference between two models is revealed in the second duration. Although in the second duration the fuzzy and the crisp models propose equal amount of crude oil extraction, because of uncertainty in investment costs, the fuzzy model prefers to allocate more amount of this allocation to domestic consumption instead of crude oil export. Therefore, the fuzzy model proposes to export 22 MTOE less crude oil and consequently refine 20 MTOE more. In the export and import of oil products, the crisp model proposes to import 2 MTOE of oil products in contrast to the fuzzy model that proposes to import nothing, and instead of it, exports 18 MTOE of oil products.

4.2.3.3. Coal subsector. In the coal subsector, both fuzzy and crisp models do not have any disagreement about coal extraction, transportation and coal import and export. The difference between two models is revealed in coke subsector. In both durations, the fuzzy model intends to extract more in the coke subsector.

In the first sub-period, the fuzzy model proposes to extract 700 KTOE¹³ more coke in contrast to the crisp model that intends to satisfy coke demand by 729 KTOE coke import. In the second sub-period, because of the coke extraction bound, the fuzzy model can just allow to extract 164 KTOE more coke. The rest of the coke should be provided by coke import. Both models do not allow exporting any coke.

4.2.3.4. Electricity subsector. Entering of uncertainties to investment costs affects steam power plants mostly. In the first duration, the crisp model does not allow use of fuel oil in steam power plants. Instead the model proposes to use gas and gas oil in steam power plants. At the same time, the fuzzy model obtains opposite results and prefers to use fuel oil instead of gas oil. Fuel gas remains unchanged in steam power plants. The amount and kind of fuels in other coal, gas turbine and combined cycle power plants are similar in both models.

¹⁰Organization of petroleum exporting countries.

¹¹Million ton oil equivalent.

¹²Ton oil equivalent.

¹³Kilo ton oil equivalent.

In the second duration also, fuzzy model prefers to use no gas oil in the steam power plants. The amount and kind of fuels in other power plants are similar in both models. In this manner, capacity of hydro, wind and geothermal power plants remain unchanged. The capacity of coal, steam, gas turbine and combined cycle are similar in both crisp and fuzzy models in the first duration. In the second one, the fuzzy model proposes to increase steam, gas turbine and combined cycle power plants capacities to about 10%. The capacity of coal power plants also remains unchanged in both crisp and fuzzy models.

Both fuzzy and crisp models do not propose to export electricity in both durations. In the first duration, electricity import is equal in both models but in the second one, although the crisp model proposes to import 272 800 KWh, the fuzzy model prefers to import nothing.

The minimized total cost in both crisp and fuzzy models differs. Because uncertainty imposed investment costs to spread more to the right (right spread is equal to 40% of the investment costs) than to the left (left spread is equal to 10% of the investment costs), the investment costs and consequently the total cost are greater in the fuzzy model than in the crisp model. Thus, the total cost in the fuzzy model is estimated to be about 3 billion, and 79 million dollars more than that in the crisp model in the first duration. In the second duration, this difference reaches to about 4 billion and 635 million dollars.

5. Conclusion

In this paper, we showed that the practice of entering uncertainties to objective function affects the results of the model fundamentally. In the fuzzy model, natural gas should be extracted more and despite the crisp model, GTL plants should be used more. In the oil subsector, the fuzzy model prefers to allocate more amount of oil to domestic consumption instead of crude oil export. Furthermore, the fuzzy model intends to extract more in coke subsector in both durations. Finally, in the electricity subsector, entering of uncertainties to investment costs affects steam power plants mostly.

In fact, in this paper, we did not mean to fuzzify the main energy model of Iran and optimize it for operational purposes. We just tried to design an energy model and show how uncertainties affect energy model results. Based on the analysis of the results of the fuzzy model, the following conclusions are drawn:

1. FLP is a simple and suitable tool for optimization problems.
2. Considering flexibility structure and unproblematic defuzzification methods, FLP strategy can be considered

a serious competitor for stochastic and Minimax Regret strategies.

3. Plurality of fuzzification and defuzzification methods can be considered as a perplexing feature of FLP approach. In fact, this feature arises from lacking of exhaustive and comprehensive studying of these methods.

4. Lack of an effective package for FLP is a serious problem for users of this approach.

5. Considering the above-mentioned conclusions, an exhaustive and comprehensive studying for evaluation and validation of FLP approach is essential as the next step. Designing an effective package is also necessary for this purpose.

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