Modeling for Environmental-Economic Management Systems under Uncertainty

Y.F. Li\textsuperscript{a}, Y.P. Li\textsuperscript{a*}, G.H. Huang\textsuperscript{a}, M. Zhou\textsuperscript{b}, Y.L. Xie\textsuperscript{a}

\textsuperscript{a}S-C Research Academy of Energy and Environmental Studies, North China Electric Power University, Beijing 102206, China
\textsuperscript{b}College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

Abstract

In this study, an interval-fuzzy multiobjective programming (IFMOP) model is developed for supporting planning of environmental and economic management activities of chemical industry district in Tianjin, China. In the IFMOP model, both interval-parameter programming (IPP) and fuzzy programming (FP) methods are introduced into a multiobjective programming framework. The modeling approach inherits advantages of IPP and FP, and allows uncertainties and decision-makers’ aspirations to be directly communicated into the optimization process and resulting solutions. The developed model can help tackle dynamic, uncertain and multiobjective characteristics of the water environmental and economic management system in the chemical industry district, and can address issues concerning plans for cost-effective industrial production.

Keywords: environmental and economic management; interval; fuzzy; multiobjective; uncertainty

1. Introduction

For many decades, the constantly increasing demand for water in terms of both sufficient quantity and satisfied quality has forced planners to contemplate and propose ever more comprehensive, complex and ambitious plans for water resources systems [1, 2]. However, multiple conflicting objectives generally characterize the current water resources systems. The goals of environmental quality protection and the needs of economic planning for environmental and economic management activities are not easy to be reconciled in decision making [3]. Moreover, such planning efforts are complicated with a variety of uncertain parameters as well as their interactions [2]. It is thus deemed necessary to develop effective optimization methods for supporting water resources management under such complexities.

Previously, stochastic MOP (SMOP) and fuzzy MOP (FMOP) methods were proposed to address such uncertain system features, especially the uncertainty of system parameters [3-5]. However, indispensable possibilistic or
probabilistic information is usually unavailable for practical problems using SMOP and FMOP methods; for many system factors, only intervals can be identified. Thus, these methods have not been widely used and better ways for tackling uncertainties are required [5-7]. Interval-fuzzy multiobjective programming (IFMOP), a hybrid of interval-fuzzy linear programming (IFLP; [8]) and multiobjective optimization, is superior to the former MOP methods in its data requirements, solution algorithms, computational requirements, and results interpretation [7]. IFMOP allows uncertainties presented as intervals to be directly communicated into planning processes through an interval linear programming algorithm [7, 9]. The interactive approach of this method helps account for the indispensable involvement of stakeholders. IFMOP has been successfully used in municipal solid waste management [10, 11], regional new-zone development planning [12], and optimal tourism management [13]. IFMOP also incorporates some practices effective for environmental and economic management. However, the weight coefficients of stakeholders’ aspiration levels were set to be equal in previous studies. As the scenarios of weight coefficients considered in previous works have been relatively simple, a more comprehensive IFMOP model is required for optimal water resources management.

Therefore, as an extension of the previous efforts, an interval-fuzzy multiobjective programming (IFMOP) model is developed for supporting planning of environmental and economic management activities of chemical industry district in Tianjin, China. The study area is one of the areas with the most dynamic economy in China, which utilize the most international capital and yield the highest rate of investment returns. However, with the rapid population increase and speedy economic development, conflict-laden water-allocation and water-quality management issues have become major obstacles to social and economic sustainable development for the region. The developed model can help tackle dynamic, uncertain and multiobjective characteristics of the water environmental and economic management system in the chemical industry district, and can address issues concerning plans for cost-effective industrial production. Three scenarios are considered based on different preferences of stakeholders, and consequently promote feasibility and robustness of decision.

2. Methodology

2.1. Definitions

Let \( x \) denote a closed and bounded set of real numbers. An interval-parameter number \( x^r \) is defined as an interval with known upper and lower bounds but unknown distribution information for \( x \) [8]:

\[
x^r = [x^-, x^+] = \{ t \in R | x^- \leq t \leq x^+ \}
\]

where \( x^- \) and \( x^+ \) are the lower and upper bounds of \( x^r \), respectively. When \( x^- = x^+ \), \( x^r \) becomes a deterministic number.

For \( x^r \), we define \( \text{Sign}(x^r) \) as follows:

\[
\text{Sign}(x^r) = \begin{cases} 
1, & \text{if } x^r \geq 0 \\
-1, & \text{if } x^r < 0 
\end{cases}
\]

(2)

Its absolute value \( |x^r| \) is defined as follows:

\[
|x^r| = \begin{cases} 
x^+, & \text{if } x^r \geq 0 \\
-x^-, & \text{if } x^r < 0 
\end{cases}
\]

(3a)

Thus we have

\[
|x^r| = \begin{cases} 
x^-, & \text{if } x^r \geq 0 \\
-x^+, & \text{if } x^r < 0 
\end{cases}
\]

(3b)

and

\[
|x^r| = \begin{cases} 
x^+, & \text{if } x^r \geq 0 \\
-x^-, & \text{if } x^r < 0 
\end{cases}
\]

(3c)
2.2. Interval-fuzzy multiobjective programming

An interval multiobjective programming (IMOP) problem with discrete interval parameters can be formulated as follows [7]:

\[ \text{Min } f_i^+ = C_i^+ X^+, \quad k = 1, 2, ..., p \]  \hspace{1cm} (4a)

\[ \text{Max } f_i^- = C_i^- X^-, \quad l = p + 1, p + 2, ..., q \]  \hspace{1cm} (4b)

subject to

\[ A_i^+ X^+ \leq b_i^+, \quad i = 1, 2, ..., m \]  \hspace{1cm} (4c)

\[ A_i^- X^- \geq b_i^-, \quad j = m + 1, m + 2, ..., n \]  \hspace{1cm} (4d)

\[ X^+ \geq 0 \]  \hspace{1cm} (4e)

where \( X^+ \in \{\mathbb{R}^+\}^{n_r}, \quad C_i^+ \in \{\mathbb{R}^+\}^{n_r}, \quad C_i^- \in \{\mathbb{R}^-\}^{n_r}, \quad A_i^+ \in \{\mathbb{R}^+\}^{n_r}, \quad A_i^- \in \{\mathbb{R}^-\}^{n_r} \), and \( \mathbb{R} \) denote a set of interval numbers. When some of the parameters are assigned with membership functions, the model becomes a hybrid interval-fuzzy multiobjective programming (IFMOP) problem. A fuzzy goal can be established by specifying ‘aspiration level’ and ‘inferior limit’ for each objective function or constraint. With ‘min’ operator \( \lambda^- \), model (4) can be transformed to:

\[ \text{Max } \lambda^- \]  \hspace{1cm} (5a)

subject to

\[ f_i^+(X^+) \leq \lambda^- (f_i^+ - f_i^-), \quad k = 1, 2, ..., p \]  \hspace{1cm} (5b)

\[ f_i^-(X^-) \geq f_i^+ - \lambda^- (f_i^+ - f_i^-), \quad l = p + 1, p + 2, ..., q \]  \hspace{1cm} (5c)

\[ A_i^+ X^+ \leq b_i^+ - \lambda^- (b_i^+ - b_i^-), \quad i = 1, 2, ..., m \]  \hspace{1cm} (5d)

\[ A_i^- X^- \geq b_i^- + \lambda^- (b_i^- - b_i^+), \quad i = m + 1, m + 2, ..., n \]  \hspace{1cm} (5e)

\[ X^+ \geq 0 \]  \hspace{1cm} (5f)

\[ 0 \leq \lambda^- \leq 1 \]  \hspace{1cm} (5g)

Given a specific bound of \( \lambda^- \) in model (5), it may not function consistently for all objective functions and constraints. For example, \( \lambda^- \) corresponds to both \( f_i^+(X^+) \) in (2b) and \( f_i^-(X^-) \) in (2c), while \( f_i^+(X^+) \) and \( f_i^-(X^-) \) correspond to different constraint structures (Wu and Huang, 2007). An approach to tackling this problem is to introduce two separate operators \( \lambda_1^- \) and \( \lambda_2^- \), where \( \lambda_1^- \) is for (2b) and (2d) with ‘\( \leq \)’ constraints, while \( \lambda_2^- \) for (2c) and (2e) with ‘\( \geq \)’ constraints. Thus, we have general format of IFMLP model:

\[ \text{Max } \omega_1 \lambda_1^- + \omega_2 \lambda_2^- \]  \hspace{1cm} (6a)

subject to

\[ f_i^+(X^+) \leq f_i^+ - \lambda_1^- (f_i^+ - f_i^-), \quad k = 1, 2, ..., p \]  \hspace{1cm} (6b)

\[ f_i^-(X^-) \geq f_i^+ - \lambda_2^- (f_i^+ - f_i^-), \quad l = p + 1, p + 2, ..., q \]  \hspace{1cm} (6c)

\[ A_i^+ X^+ \leq b_i^+ - \lambda_1^- (b_i^+ - b_i^-), \quad i = 1, 2, ..., m \]  \hspace{1cm} (6d)

\[ A_i^- X^- \geq b_i^- + \lambda_2^- (b_i^- - b_i^+), \quad i = m + 1, m + 2, ..., n \]  \hspace{1cm} (6e)

\[ X^+ \geq 0 \]  \hspace{1cm} (6f)

\[ 0 \leq \lambda_1^- \leq 1 \]  \hspace{1cm} (6g)

\[ 0 \leq \lambda_2^- \leq 1 \]  \hspace{1cm} (6h)

where \( \omega_1 \) and \( \omega_2 \) are weight coefficients. In this study, the interval-fuzzy linear programming (IFLP) algorithm [8] is used for converting an uncertain multiobjective problem into its deterministic form. Thus, coefficients in the objective functions and the constraints’ left-hand sides are handled as discrete intervals, while linear membership functions are assigned fuzzy goals of the system objectives and fuzzy constraints of the right-hand sides.

3. Case study

3.1. Overview of the study system

In the study area, there are a number of chemical industries, which emit a large quantity of sewage water. Because of the low level of centralized sewage treatment (e.g. the centralized disposal rate of wastewater was less than 60% at the end of 2007), all of the rivers are subject to different levels of pollution, and the main pollutant was chemical oxygen demand (COD). All rivers attain grade V of national water quality standard or worse than grade V accounted for 98% in 2006; the total wastewater discharged from the Binhai New Area was \( 167.36 \times 10^6 \) m\(^3\), and
the amount of COD discharged was $5.87 \times 10^3$ tonnes, which was beyond the carrying capacity of river water bodies; the majority of COD comes from the industrial sector, especially from the chemical industry. For example, the total wastewater discharged from the industrial sector was $122.20 \times 10^6$ m$^3$, and COD discharged from industry was $28.20 \times 10^3$ tonnes; and COD discharged from chemical industry account for more than 55% of the total discharge COD from the industrial sectors. In the recent years, many measures, such as formulation of environmental regulations/laws, restriction of fertilizer application, and practices of soil/water conservation, have been implemented. However, the river water quality has not been significantly improved (Tianjin Environmental Protection Agency, 2007; Tianjin Municipal Bureau of Water Conservancy, 2007). At the same time, due to continuous industry development in Binhai New Area, especially chemical industry (e.g. one million tonne ethylene project, 30 million tonne refinery project), water consumption and pollutants output have increased and lead to more difficult in water supply and pollution reduction.

3.2. Data collection

Basic hydrologic data in the study area is based on hydrological almanac of the Haihe River basin (1991 to 2009). Due to the lack of a systematic and comprehensive measurement and research on degradation coefficient, the general river water quality degradation factors are selected as a reference of the pollutants integrated degradation coefficient. The parameters of the model are from field surveys, statistical yearbooks, and related research; and the products price are shown in Table 1. According to the allowable discharge of COD simulation results, the allowable industrial COD discharge can be calculated. From 2003 to 2009, the fixed asset investment growth rate was 59.58%, 49.12%, 34.08, 10.89%, 45.98%, 43.20%, and 47.50%. Based on the portfolio investment of industrial development in several years and the fixed asset investment growth rate, the amount of available funds can be obtained.

4. Results analysis

Scenario analysis was introduced into the interactive solution process to ensure the practicality and operability of the planning alternatives [5]. In this study, three different cases are considered in order to make in-depth analysis of interactions among weight coefficients, economic benefit, and environmental requirement. Three different scenarios, though different, but represent the practical and scientific. Through interpretation and comparison of the three scenarios, scientific basis for decision-making could be obtained. These scenarios can be described as follow:

- Scenario 1 (S1): Without regard to policymakers’ preference, the natural equilibrium of the water environmental protection and economic development would be the target. According to the values of different weight coefficients, this scenario is divided into nine sub scenarios. Abbreviations and sub scenarios are given in Table 1.

| Scenario abbreviation | S1-1 | S1-2 | S1-3 | S1-4 | S1-5 | S1-6 | S1-7 | S1-8 | S1-9 |
|-----------------------|------|------|------|------|------|------|------|------|------|
| Weight value          | $\phi_1$ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|                       | $\phi_2$ | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 |

- Scenario 2 (S2): Considering the preference of local decision makers and relevant experts on the industrial structure and economic objectives, the value of $\phi_1$ and $\phi_2$ would be set to 1.0 and 0, respectively.
- Scenario 3 (S3): Considering the preference of local decision makers and relevant experts on the water environmental objectives, the value of $\phi_1$ and $\phi_2$ would be set to 0 and 1.0, respectively.

4.1. Chemical industry structure optimization

Under S1-1 (as shown in figure 1), due to the preference in the environment and resources protection and economic development, the circular economy industry chain was increased in the planning horizon. For the petroleum chemical industry, large refining of high quality (including petrol, kerosene and diesel) is the key
development projects. The output would reach the proportion of chemical industry of petroleum 50% above. Fine chemical project development ratio what also not only acrylic esters and balanced, vinyl acetate, and obtained a certain degree of development. For the energy utilization industry, LNG project scale would increase gradually. Under S1-9, the total industrial output would be the highest and the development of industrial scale would be more balanced. Among them, the petroleum chemical industry, plastic processing projects of production is small, but very high value in advocating energy-saving and environmental protection under the trend of showed a strong competitive advantage.

Figure 1. Industrial output under Scenario 1-1 and Scenario 1-9

4.2. Allocation of COD emissions target

Under S1-1 (as shown in Figure 2), petroleum chemical industry would allow large oil refining and ethylene oxide/styrene monomer projects emission relative higher COD in the first period. In the second period, epoxy propane/styrene monomer project of COD emissions would increase 2.5 times, while large oil refining projects would have no significant change. Fine chemical industry in the first period would allow acrylic ester, and reactive dyes, liquid high-grade, and EVA resin project discharge relative higher COD. Under S1-9, for the petroleum chemical industry, refining, diethyl ether and the density polyethylene project's share of increased. For the fine chemical industry, COD emissions of the diethanolamine and polyacrylamide project in the first period would greatly be changed.

Figure 2. COD emission under Scenario 1-1and Scenario 1-9

4.3. Wastewater emission
Under S1-1, for the petroleum chemical industry, methanol and propylene oxide/styrene monomer project for the entire oil wastewater to 90% of the chemical industry. While marine chemical engineering projects, silicone oil, polystyrene, polystyrene and polyvinyl alcohol (pva) project would be the largest and wastewater increasing trend. Fine chemical, aspartic acid/cluster aspartic and polyvinyl alcohol wastewater projects will account for large proportion. Comprehensive utilization of energy in the industry, LNG project also sewage emitters. Under S1-9, for the petroleum chemical industry, plastic processing projects would be great sewage emitter. Marine chemical industry, sewage emitters would be reduced to polycarbonate, polystyrene and vinyl/PVC projects.

4.4. Water resources allocation optimization

Under S1-1, during the planning period, water consumption of the marine chemical industrial would be the highest among the four industries. For the marine chemical industry, large water consumers would be acetate, polycarbonate, polystyrene, polystyrene, polycarbonate projects. Comparison of industry in the second period can be seen, water demand of all the water projects would be increased. Due to the industrial structure of the fine chemical industry development inevitably leads to the relatively small size, low water, but aspartic acid/cluster aspartic acid projects in the second period and water demand would increase obviously. Under S1-9, for the fine chemical industry project will become large ammonia water. Water consumption of energy utilization project would increase progressively in planning period.

5. Conclusions

In this study, an interval-fuzzy multiobjective programming (IFMOP) model is developed for supporting planning of environmental and economic management activities of chemical industry district in Tianjin, China. The
study area is one of the areas with the most dynamic economy in China, which utilize the most international capital and yield the highest rate of investment returns. However, with the rapid population increase and speedy economic development, conflict-laden water-allocation and water-quality management issues have become major obstacles to social and economic sustainable development for the region. The developed model can help tackle dynamic, uncertain and multiobjective characteristics of the water environmental and economic management system in the chemical industry district, and can address issues concerning plans for cost-effective industrial production. Three scenarios are considered based on different preferences of stakeholders, and consequently promote feasibility and robustness of decisions. The results indicate that reasonable solutions have been generated. They are helpful for supporting (a) mitigation of water pollutant discharges, (b) adjustment of local policies regarding chemical industrial structure, and (c) coordination of the conflict between environmental and economic objectives.

Acknowledgements

This research was supported by the Special Water Project of China (2008ZX07314-001 and 2009ZX07104-004), the Major State Basic Research Development Program of MOST (2005CB724200).

References

[1] Loucks DP, Stedinger JR, Haith DA. Water resource systems planning and analysis. Englewood Cliffs, NJ: Prentice-Hall; 1981.

[2] Li YP, Huang GH, Yang ZF and Nie SL. Interval-fuzzy multistage programming for water resources management under uncertainty. Resources, Conservation and Recycling 2008; 52: 800-812.

[3] Chang NB, Chen YL, Wang SF. A fuzzy interval multiobjective mixed integer programming approach for the optimal planning of solid waste management systems. Fuzzy Sets and Systems 1997; 89: 35-60.

[4] Zimmermann H-J. Fuzzy Set Theory and its Applications. Kluwer–Nijhoff Publishing 1985.

[5] Wang LJ, Meng W, Guo HC, Zhang ZX, Liu Y, Fan YY. An interval fuzzy multiobjective watershed management model for the Lake Qionghai watershed, China. Water Resources Management 2006; 20: 701-721.

[6] Huang GH, Baetz BW, Patry GG. A grey fuzzy linear programming approach for municipal solid waste management planning under uncertainty. Civil Engineering Systems 1993; 10: 123-146.

[7] Wu S, Huang GH. An Interval-Parameter Fuzzy Approach for Multiobjective Linear Programming Under Uncertainty. Journal of Mathematical Modelling and Algorithms 2007; 6: 195-212.

[8] Huang GH, Baetz W, Patry GG. A grey fuzzy linear programming approach for waste management and planning under uncertainty. Civil Engineering Systems 1993, 10: 123-146.

[9] Huang GH. IPWM: An interval-parameter water quality management model. Engineering Optimization 1996; 26: 79-103.

[10] Huang YF, Baetz BW, Huang G H, Liu L. Violation analysis for solid wastewater management systems: An interval fuzzy programming approach. Journal of Environmental Management 2002; 65: 431-446.

[11] Cheng S, Chan CW, Huang GH. An integrated multi-criteria decision analysis and inexact mixed integer linear programming approach for solid waste management. Engineering Applications of Artificial Intelligence 2003, 16: 543-554.

[12] Zou R, Guo H C, Chen B. A multiobjective approach for integrated environmental economic planning under uncertainty. Civil Engineering and Environmental Systems 2000; 17: 267-291.

[13] Chen B, Guo HC, Huang GH, Yin YY, Zhang BY. IFMEP: an interval fuzzy multiobjective environmental planning model for urban systems. Civil Engineering and Environmental Systems 2008, 25: 99-125.