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Integrated Planning for Regional Development Planning with Low Carbon Development Constraint under Uncertainty: A Case Study of Qingpu District, Shanghai

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Abstract: Regional development planning systems contain multiple uncertainties which come from economic restructuring, resource management, carbon peak action, environmental protection, and other factors, it is difficulty to handle all of these uncertainties in one method. In order to solve this problem, a new model developed in this study combines an interval fuzzy program with an environmental quality model for regional development planning in order to provide optimal solutions. The interval fuzzy program is put forward based on interval parameter programming (IPP) and fuzzy programing (FP). The environmental quality model is used to calculate water environmental capacity and atmospheric capacity, which are set as constraint conditions in the model. In order to meet the requirements of carbon peak action, a low carbon development constraint is added to the model. In this model, decision makers can choose the satisfaction level of constraints based on their preferences. The results suggest that the methodology is applicable for the regional development planning system within the planning period. The developed model can be used to generate a series of optimization schema under multiple credibility levels, ensuring that the regional development planning system can meet both societal demands and environmental quality requirements, considering a proper balance between the expected system benefits and risks of violating the resource constraint and low carbon development constraint.

Keywords: fuzzy programming; environmental quality model; regional development planning; uncertainty

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1. Introduction

Climate change has become a hot topic in the world; extreme weather caused by climate change has led to a series of disasters, and greenhouse gas emissions, represented by carbon dioxide, have a major impact on climate change [1]. At the general debate of the 75th Session of the United Nations General Assembly, China announced that it would increase its nationally determined contribution and take more effective measures to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060. At the Climate Ambition Conference, China announced some further commitments for 2030, including that China will lower its carbon dioxide emissions per unit of GDP by over 65 percent from the 2005 level, among others. For achieving the CO_2 emissions peak commitments, it is important for China to plan its regional development system under the constraint of carbon dioxide emissions. In this case, identification of solutions for industrial systems planning is desirable in order to achieve multiple targets, such as the maximizing the economic benefits while meeting the carbon peak target and satisfying China's requirements of regional environmental quality. Some areas whose local consumption of fossil resources has reached peak should improve their energy efficiency, lower carbon dioxide emissions per unit of GDP, and increase the proportion of renewable energy in the input grid to achieve a regional real CO_2 emissions peak. The areas need to combine regional development planning with the path of low-carbon development. However, it is hard to find such solutions because many factors, such as energy structure, environmental capacity, industrial benefit, resource availability, and so forth make the system complex and uncertain. Therefore, it is necessary to develop a systematic approach to solving these problems and calculating solutions in the context of regional development planning.

With high-speed social development the coincidence between urbanization and economic development is continuously increasing at an alarming pace, and this will definitely result in a series of negative effects, such as unprecedented environmental pressure. Meanwhile, the increasing energy demand and environmental protection pressure have aggravated the crisis of resources management. Nowadays, under the background of carbon emission reduction, there is almost no doubt that sectoral structural optimization and adjustment are the appropriate solutions to achieve sustainable development.

Therefore, it is desirable to develop a comprehensive and effective research framework with an optimization model as a core for regional development planning under multiple uncertainties. Previously, for sake of ensuring that the regional development planning system could meet both societal demands and environmental quality requirements, a number of models were proposed worldwide for tackling the aforementioned uncertainties and complexities at different temporal and spatial scales [2–5]. For example, Mi et al. developed an optimization model based on Input-Output analysis to assess the impacts of industrial structure on energy consumption and carbon emissions [6]. Cheng et al. proposed an optimization framework by using dynamic spatial panel models to explore the effects of industrial structure and technical progress on carbon intensity [7]. Stoyan and Dessouky advanced a stochastic mixed-integer programming model to minimize cost and emission levels associated with energy generation while meeting the energy demands of a given region [8]. Santos and Legey proposed an optimization formula for long-term electricity system expansion planning, taking environmental and operational costs into consideration [9]. Zhang et al. incorporated carbon emission-driving factors, decomposition, and interval parameter multiple-objective programming into a framework to support regional energy system administration under multiple uncertainties [10]. Lu et al. put forward an interval-fuzzy possibilistic programming (IFPP) method to optimize China's energy management system with CO_2 emission constraints [11]. Moreover, a number of economic research models have been used to study the relationship between upgrading the industrial structural and carbon dioxide emissions, such as the decomposition method [12], carbon entropy model [13], and total factor industrial carbon emission efficiency evaluation model [14]. When it comes to the prediction of industrial optimization, to predict the carbon intensity trends in Hangzhou city, Lu et al. conducted the component data prediction, scenario prediction, GMI (1, 1) model and other multidisciplinary approaches [15]. Han et al. developed a System Dynamics Model named "E&I-SD" to investigate the advancement of the energy structure and industrial structure in China as well as predicted average annual growth rates through 2030 [16]. Although many methods have been used to solve uncertainty problems, researchers should choose their methods based on the system characteristics.

In many systems, data often cannot be represented as an exact value or as the distribution or membership functions, we can represent this uncertainty as an interval number, which has only a lower and an upper bound. An interval parameter programming (IPP) model is an alternative for handling optimization problems in a system with interval numbers in objective function coefficients and constraint parameters [17]. Fuzzy programing (FP) can handle uncertainties using fuzzy sets, which are effective at reflecting ambiguity and vagueness in resource availabilities [18]. Thus, incorporating IPP within a FP framework is a potential method for better representing the uncertainties when the uncertain inputs conclude interval numbers. Fuzzy programing and interval-parameter programming can be used to handle uncertainty in the context of regional development planning, however environmental capacity and CO_2 emission constraints or low carbon development constraints must also be considered.

Environmental quality models have been used to evaluate environmental capacity, which represents the ability to supply resources and accept pollution. Zero-dimensional water quality models are used to calculate the concentration of biochemical oxygen demand, ammonia nitrogen, and dissolved oxygen for Steady state and evenly mixed river systems [19]. The atmospheric environmental quality model is used to calculate the environmental capacity of pollutants such as sulfur dioxide and nitrogen oxide. The atmospheric models commonly used are the Community Multiscale Air Quality (CMAQ), CALPUFF and others [20]. Therefore, how to blend environmental quality models into optimization model has significance for regional planning.

In order to overcome the aforementioned complexities, uncertainties and limitations, this study developed an interval fuzzy programming combined with environmental quality model (IFP-WQ) for regional development planning. The model solves the uncertainties through integrating the interval parameter programming and fuzzy programming into the optimization framework. The uncertainties can be presented in terms of crisp intervals in both the objective function and the constraints. The environmental quality models help the optimization framework express environmental quality requirements. Decision-makers can choose the different satisfaction levels of constraints based on their preferences, which can be applied as different scenarios. The model was used to optimize regional development plans for Qingpu district, Shanghai, and revealed the tradeoffs among economic, resource, population and environmental targets faced by governmental decision-makers. The effective industrial structure, resource utilization patterns, population planning, costs and violation risks of fuzzy credibility constraints under different satisfaction levels were investigated and analyzed.

2. Modeling Development

2.1. Zero-Dimensional Water Quality Model

The Qingpu district belongs to the plains river network area, with a high density of river systems significantly regulated by pump-sluice projects, so the regional water environmental capacity was calculated with the water district as the basic unit. The river self-purification capacity and dilution capacity in each water district were each calculated; the self-purification capacity refers to the self-purification of the channel storage, and the dilution capacity mainly denotes the dilution capacity of input water in the region and upstream water. The specific calculation equation is as follows:

$$W_L = Q_0(C_S - C_0) + qC_S + KVC_S \tag{1}$$

where W_L is the river environment capacity, C_S is the water quality target, Q_0 is the upstream inflow quantity, C_0 is the upstream inflow quality, q is the input quantity in this section, K is the river pollutant degradation coefficient, and V is the river storage and flood control capacity.

2.2. Air Quality Model

The Community Multiscale Air Quality (CMAQ, Ver 5.2) model driven by the Weather Research and Forecasting (WRF, Ver 3.9.1) model was utilized in this study to simulate air quality and calculate the air capacity.

CMAQ was established under the concept of the "One Atmosphere Approach" for compound unified simulation engineering by integrating various pollution issues, including ozone, particulate matter (PM), acid deposition and toxic substances. The CMAQ simulation system can be applied for simulating 284 different chemical and physical processes important for the transformation and distribution of atmospheric trace gases [20].

The centre of the CMAQ was set at coordinate 31_N, 122_E and a bidirectional nested technology was employed, producing three layers of grids with a horizontal resolution of 36, 12 and 3 km, respectively. The first layer of grids, with a 36 km resolution and 196 × 136 cells, covered most areas in East Asia (including China, Japan, North Korea, South Korea and other countries). The second layer of grids, with a 12 km resolution and 159 × 204 cells, covered eastern China (including North China, South China, and eastern coastal area of China). The third layer of grids, with a 3 km resolution and 120 × 120 cells, covered Shanghai and its surrounding cities. The vertical layer was divided into 14 layers.

The boundary conditions for the first domain were derived from the MOZART model, and the simulations from the outer domain were used as the boundary conditions for the inner domains. The CB05 gas phase chemistry mechanism, RADM water phase chemistry mechanism, ISORROPIA inorganic salt chemistry mechanism and SOAP secondary organic aerosol chemistry mechanism were used in this model.

WRF is a nonhydrostatic, compressible model with a mass coordinate system [21]. It was designed as a numerical weather prediction model, but can also be applied as a regional climate model. WRF was used to simulate the meteorological field. The setting of the centre and the nest for WRF and CMAQ was similar. The vertical dimensions were 32 levels with a 100 hPa model top. The meteorological background field and boundary information with an FNL (final) resolution of 1° × 1° and temporal resolution of 6 h were acquired from NCAR (National Center for Atmospheric Research) and NCEP (National Centers for Environmental Prediction), respectively. An estimation model for terrestrial ecosystems, MEGAN (version 2.1), was employed to process the natural emissions. MEIC 0.5° × 0.5° and the Shanghai emission inventory provided anthropogenic emission data. The processed natural and anthropogenic emission data generated comprehensive emission source files via the SMOKE model.

In this study, we defined air capacity as the pollutant emissions when air quality satisfies the targets of different periods. The targets were put forward by the study of Shanghai's "Three lines and one permit" based on the government policies of China and Shanghai. Based on the emission reduction scenarios for Shanghai and the surrounding cities, the concentration of each pollutant was calculated iteratively until the established target was reached. Then, the pollutant emission quantity is the environmental capacity. The emission reduction scenarios and simulation results were supported by the study of Shanghai's "Three Lines and One Order".

2.3. Interval Linear Programming

The interval-parameter programming model is as follows.

Objective function:

$$\text{Maximize } f^{\pm} = C^{\pm}X^{\pm} \tag{2}$$

Constraint condition:

$A^{\pm}X^{\pm} \leq B^{\pm}$

$X^{\pm} \geq 0$

where $X^{\pm} \in \{\Re^{\pm}\}^{n\times 1}$, $A^{\pm} \in \{\Re^{\pm}\}^{m\times n}$, $B^{\pm} \in \{\Re^{\pm}\}^{m\times 1}$, $C^{\pm} \in \{\Re^{\pm}\}^{1\times n}$, $\Re^{\pm}$ represents a set of uncertain numbers. f^{+} denotes a linear objective function. $x^{\pm}$ denotes an interval number, while x^{+} and x^{-} refer to the upper and lower bounds of $x^{\pm}$ (Prékopa, 1995).

2.4. Interval Fuzzy Programming

The specific forms of interval fuzzy linear programming are shown as follows. First of all, we consider the following interval fuzzy linear programming problem:

$$\min f^{\pm} = C^{\pm}X^{\pm} \tag{3}$$

Constraint condition:

$A^{\pm}X^{\pm} \leq B^{\pm}$

$X^{\pm} \geq 0$

where $X^{\pm} \in \{\Re^{\pm}\}^{n\times 1}$, $A^{\pm} \in \{\Re^{\pm}\}^{m\times n}$, $B^{\pm} \in \{\Re^{\pm}\}^{m\times 1}$, $C^{\pm} \in \{\Re^{\pm}\}^{1\times n}$, $\Re^{\pm}$ represents a set of uncertain numbers. We let $x^{\pm}$ refers to an interval number, x^{+} and x^{-} the upper and lower bounds of $x^{\pm}$; $=$ and $\leq$ denote fuzzy equality and fuzzy inequality, respectively.

On the basis of the principle of fuzzy flexible programming we connect the value of $\lambda^{\pm}$ and the membership function of a fuzzy decision. Specifically, the flexibility of constraint conditions and the fuzziness of system objectives would be denoted by a fuzzy number set, which was separately named "fuzzy constraint" or "fuzzy object", represented by $[\lambda^{\pm}]$ as the degree of membership associated with constraint or objective satisfaction. $\lambda = \min\{\mu_G, \mu_{C_1}, \mu_{C_2}, \hat{}\mu_{C_m}\}$ represents the membership level. Consequently, according to Huang et al., the interval fuzzy programming model would be converted as follows:

Constraint condition:

$C^{\pm}X^{\pm} \leq \lambda f^{+} + (1-\lambda^{\pm})f^{-}$

$A^{\pm}X^{\pm} \geq B^{-} + (1-\lambda^{\pm})(B^{+} - B^{-})$

$X^{\pm} \geq 0$

$0 \leq \lambda^{\pm} \leq 1$

$\lambda^{\pm}$ represents the control variable associated with the fuzzy objective or membership degree of fuzzy constraint satisfaction. f^{+} and f^{-} was set as the upper and lower bounds of the objective of expectation value by decisionmakers. The interactive two-step algorithm can solve the above model by analyzing the relationship between objective functions and constraints, as well as the relationship between parameters and variables.

2.5. Data Acquisition

In this study, the involved technical–economic–environmental data were obtained based on the Statistical Yearbook of Qingpu District (https://www.shqp.gov.cn/stat/, accessed on 20 August 2021), Shanghai Statistical Information Net (http://sheitc.sh.gov.cn/, accessed on 20 August 2021), and local government planning reports, including the National Economic Bulletin (http://tjj.sh.gov.cn/tjgb/, accessed on 20 August 2021), the Environment Quality Communique (https://sthj.sh.gov.cn/, accessed on 20 August 2021), and the 14th five-year plan of Shanghai(http://fgw.sh.gov.cn/shssswghgy/, accessed on 20 August 2021). The parameters in this study are presented as intervals, which could reflect their superiority in addressing modeling uncertainties and complexities in this manner.

The model considers key industries such as agriculture, manufacturing, construction, wholesale and retail, transportation, accommodation and catering, communications, finance, real estate, and other service industries. The relevant research can be calculated according to the specific research direction and the constraints of the data selection model. Table 1 shows the critical technical and economic parameters, including energy intensity and water intensity in different planning periods.

Table 1. Key technical and economic parameters related to energy systems in this study.

Key Parameters	Planning Period (t)		
	Period 1	Period 2	Period 3
Energy intensity (tce/10^4 yuan)			
Agriculture	[0.1232, 0.1355]	[0.0991, 0.1091]	[0.0798, 0.0878]
Manufacturing	[0.0548, 0.0602]	[0.0441, 0.0485]	[0.0355, 0.0390]
Construction	[0.1232, 0.1355]	[0.0992, 0.1091]	[0.0798, 0.0878]
Transportation	[0.1232, 0.1355]	[0.0992, 0.1091]	[0.0798, 0.0878]
Accommodation and catering	[0.1232, 0.1355]	[0.0992, 0.1091]	[0.0798, 0.0878]
Communications	[0.1232, 0.1355]	[0.0992, 0.1091]	[0.0798, 0.0878]
Financial	[0.1232, 0.1355]	[0.0992, 0.1091]	[0.0798, 0.0878]
Real estate	[0.1232, 0.1355]	[0.0992, 0.1091]	[0.0798, 0.0878]
Other service	[0.1232, 0.1355]	[0.0992, 0.1091]	[0.0798, 0.0878]
Water intensity (m^3/10^4 yuan)			
Agriculture	[162.8196, 179.1016]	[154.6787, 170.1465]	[146.9447, 161.6392]
Manufacturing	[7.7197, 8.4917]	[7.3337, 8.0671]	[6.9670, 7.6637]
Construction	[9.1527, 10.0679]	[8.6950, 9.5646]	[8.2603, 9.0863]
Transportation	[1.7696, 1.9465]	[1.6811, 1.8492]	[1.5970, 1.7567]
Accommodation and catering	[2.1924, 2.4116]	[2.0828, 2.2911]	[1.9786, 2.1765]
Communications	[12.6231, 13.8854]	[11.9919, 13.1911]	[11.3923, 12.5316]
Financial	[5.4510, 5.9961]	[5.1785, 5.6963]	[4.9195, 5.4115]
Real estate	[4.9071, 5.3979]	[4.6618, 5.1280]	[4.4287, 4.8716]
Other service	[4.0048, 4.4053]	[3.8046, 4.1850]	[3.6144, 3.9758]

3. Case Study

3.1. Overview of the Case Study

Qingpu District, which belongs to Shanghai Municipal District, is located in the west of Shanghai, as shown in Figure 1. Qingpu District has jurisdiction over three streets and eight towns with a total area of 668.54 square kilometers. Based on the 7th census data, the permanent resident population of Qingpu District is 1,271,424. In 2020, the gross domestic product (GDP) of Qingpu District reached 119.401 billion RMB, an increase of 3.8% over the previous year at comparable prices, ranking third in the city. Of this total, the added value of primary industry was 797 million RMB, up by 5.6%; the added value of secondary industry was 42.162 billion RMB, down 1.5%; and the added value of tertiary industry was 76.442 billion RMB, up by 7.1%. The proportion of the added value of the three industries in the region's GDP is 0.7%, 35.3%, and 64.0%, respectively. Qingpu district is rich in industrial carrier resources and industrial regional agglomeration. In the four areas of Qingpu Industrial Park, Zhangjiang Qingpu Park, Export Processing Zone, and Zhujiajiao Town, the output value of emerging industries in the whole region is as high as 70%. An innovation cluster, with industrial supporting equipment, outstanding innovation advantages, obvious regional characteristics and remarkable economies of scale, is under construction.

Figure 1. Geographical position (**a**) and districts (**b**) of Qingpu District.

According to "the 14th Five-Year Plan for Shanghai's National Economic and Social Development and the Outline of Long-term Goals for 2035", Shanghai plans to formulate a citywide action plan for peaking carbon emissions. In addition, the city will focus on promoting energy conservation and carbon reduction in key energy-using units and key areas such as electric power, steel, and chemical industry, so as to achieve peak carbon emissions by 2025. During the 13th Five-Year Plan period, Shanghai adhered to the dual control of total and intensity of carbon emissions. Proportion of coal consumption has declined and that of natural gas consumption has increased. Renewable and clean energy such as solar photovoltaic (PV) and wind power sustained their development. All these above lay a good foundation for the realization of peaking carbon emission in the next step. Hence, Shanghai will continue to implement the total coal consumption control system of key enterprises according to the plan. By 2025, the total coal consumption in Shanghai will be controlled at about 43 million tons, the proportion of coal consumption in primary energy consumption will be reduced to about 30%, the proportion of natural gas in primary energy consumption will be raised to about 15%, and the proportion of local renewable energy in total electricity consumption will be raised to about 8%. In 2020, total energy consumption in Shanghai will be 0.31 tons of coal equivalent (tce) per ten thousand RMB of GDP, 64.77% lower than that in 2005 (0.88 tce/10,000 RMB), which is close to the national target of reducing carbon dioxide (CO_2) emissions per unit of GDP by more than 65% in 2030 as compared with 2005. The total energy consumption in Qingpu District is 0.14 tce/10,000 RMB; along with that in Shanghai both are lower than the national value of 0.50 tce/10,000 RMB. According to "Shanghai's Key Work Arrangements for Energy Conservation, Emission Reduction and Climate Change Response in 2021", the comprehensive energy consumption per unit of GDP of Shanghai in 2021 will be reduced by about 1.5% compared with the previous year. In addition, energy consumption per unit of GDP of Qingpu District will be reduced by 2.5%. The energy consumption increment of the city is controlled at around 4.5 million tce; The increase in CO2 emissions should be controlled at around 9 million tons. Total emissions of major pollutants NO_x, VOCs, COD, and NH_3-N will be reduced by 2%, 1%, 3%, and 2%, respectively. The concentration of fine particulate matter ($PM_{2.5}$) will be consolidated and mended, and the good and moderate rate of air quality index (AQI) will be the same as that of the previous year and strive to improve. The local consumption of fossil resources of Qingpu has reached peak, but total energy consumption continues to rise, and the majority of new energy consumption comes from the power grid. So, increasing the proportion of renewable energy in the input grid is important to achieve a regional real CO_2 emissions peak. At the same time, Qingpu needs to engage in regional development planning along the path of low-carbon development and improving energy efficiency.

The following regional planning and management system is used to demonstrate the applicability of the IFP-WQ model, as shown in Figure 2. Due to the temporal variation of regional planning and management systems, the forecast of regional management is not only obscure and dynamic itself, but also influenced by several factors. Industry, environmental quality and energy consumption interact with each other within the system. Domestic pollution and industrial pollution have a direct impact on environmental quality, while industrial development is also affected by human resources and land resources. COD, NH_3-N, TP, SO_2, NO_x and PM, as the major pollutants, are considered under environmental capacity. Industry can be further subdivided into a series of industries. Energy efficiency is set as a low carbon development constraint; different satisfaction levels are set as different scenarios. Three planning periods were considered in this study and each planning period lasts five years.

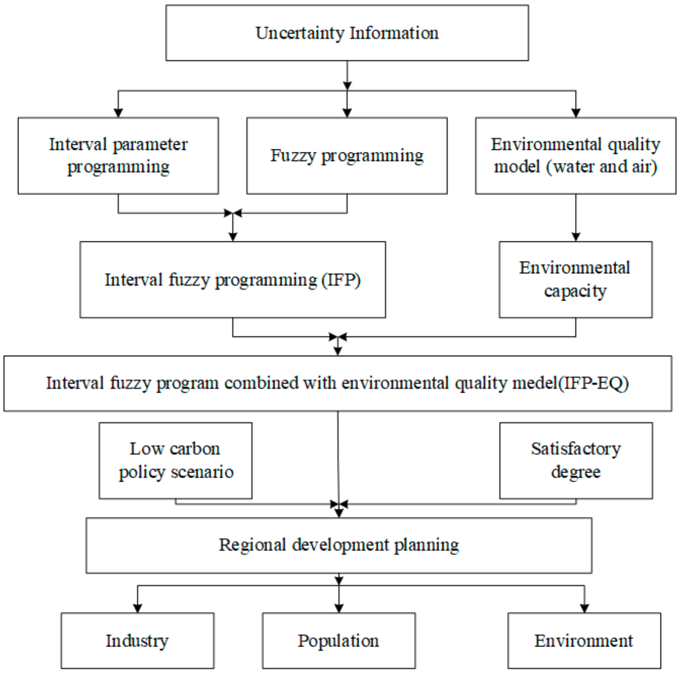


Figure 2. General framework of IFP-EQ model.

3.2. Model Development

The model was set with every five years as a planning period, a total of three planning periods, and the research time range as 15 years. The first planning period was 2021–2025, the second planning period 2026–2030, and the third planning period 2031–2035.

The model designs the objective function to take into account the resource costs brought by production and life in the process of economic development, the treatment costs of pollutants in different industries, the treatment costs of domestic sewage, etc. Meanwhile, the model contains several constraints, including water environment carrying capacity constraints, atmospheric environmental capacity constraints, satisfactory degree constraints on water resources consumption per unit output value, satisfactory degree constraints on energy consumption per unit output value, working population constraints, industrial development will constraints, land use constraints, etc. The satisfactory degree constraints are expressed as credibility levels. The higher credibility levels are, the lower the violation risk of credibility constraints is and the lower the economic growth is. The model provides the direction of industrial structure adjustment with the maximum economic benefits of different credibility levels in the future; resource and energy consumptions and pollutant emissions can also be obtained in the model. The results are expressed in the form of interval numbers, which can provide a certain fluctuation space for economic regulation. The decisionmakers can determine the direction of industrial structure adjustment according to the violation risks of credibility constraints and economic development benefits.

Objective function:

Maximize the object of economic growth and set it as the maximum cumulative value of GDP during the planning period, that is,

$$max \quad f^{\pm} = \sum_{i=1}^{I}\sum_{t=1}^{T} W_{it}^{\pm} - \sum_{i=1}^{I}\sum_{t=1}^{T} W_{it}^{\pm}\cdot WC_{it}^{\pm}\cdot WP_{it}^{\pm} - \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{k=1}^{K} W_{it}^{\pm}\cdot PE_{itk}^{\pm}\cdot PC_{itk}^{\pm}$$
$$-\sum_{t=1}^{T}\sum_{k=1}^{K}\left(UTP_{t}^{\pm}\cdot UPE_{tk}^{\pm}\cdot PUP_{tk}^{\pm}\right) - \sum_{i=1}^{I}\sum_{t=1}^{T} W_{it}^{\pm}\cdot WN_{it}^{\pm}\cdot NP_{it}^{\pm} - \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{j=1}^{J} W_{it}^{\pm}\cdot PN_{itj}^{\pm}\cdot NC_{itj}^{\pm}$$

Constraint condition:

(1) water environment carrying capacity.

The constraints on water environment carrying capacity are mainly composed of two parts: the restrictions on the available amount of water resources and the constraints on water environmental capacity. Consulting the calculation results on the available amount of water resources and water environmental capacity in the reference area, this constraint minimizes the occurrence of pollution while limiting the total amount of available water resources in the region and the maximum available amount of water resources for agriculture, industry, residential life and ecology.

$$\sum_{i=1}^{I} W_{it}^{\pm} \cdot WC_{it}^{\pm} + PWT_t^{\pm} + EWT_t^{\pm} \leq TTW_t^{\pm} + OW_t^{\pm}$$

$$\sum_{i=1}^{I} W_{it}^{\pm} \cdot PE_{itk}^{\pm} \cdot (1 - RP_{itk}^{\pm}) + UTP_t^{\pm} \cdot UPE_{tk}^{\pm} \cdot (1 - UPR_{tk}^{\pm}) \leq TP_{tk}^{\pm}$$

(2) Atmospheric capacity constraints.

These constraints refer to the local atmospheric environmental capacity limit so that the total emission of atmospheric pollutants shall not exceed the environmental capacity, determined by ensuring that the energy consumption of each industry is within the total control index.

$$\sum_{i=1}^{I} W_{it}^{\pm} \cdot WN_{it}^{\pm} \leq TNW_t^{\pm}$$

$$\sum_{i=1}^{I} W_{it}^{\pm} \cdot PN_{itj}^{\pm} \cdot \left(1 - RN_{itj}^{\pm}\right) \leq TN_{tj}^{\pm}$$

(3) Satisfactory degree constraints on water resources and energy consumption per unit output value.

The satisfaction values of water resources and energy consumption with different output values are obtained through the construction of membership functions, and the satisfaction constraints of regional energy and environment support are constructed as well. Improving energy efficiency is an important path for low-carbon development in Qingpu District, and the energy efficiency constraint is also the constraint of low-carbon development in Qingpu District.

$$f\left(\alpha_t^{\pm}\right) = \begin{cases} 1 & \text{if } x \leq m \\ l(x) & \text{if } m < x \leq n \\ 0 & \text{if } n < x \end{cases}$$

$$\alpha_t^{\pm} = \frac{\sum_{i=1}^{I}\sum_{t=1}^{T} W_{it}^{\pm} \cdot WC_{it}^{\pm}}{\sum_{i=1}^{I}\sum_{t=1}^{T} W_{it}^{\pm}}$$

$$\delta_t^{\pm} = \frac{\sum_{i=1}^{I}\sum_{t=1}^{T} W_{it}^{\pm} \cdot WN_{it}^{\pm}}{\sum_{i=1}^{I}\sum_{t=1}^{T} W_{it}^{\pm}}$$

$$\lambda_t^{\pm} = f\left(\alpha_t^{\pm}\right)$$

$$\lambda_t^{\pm} = f\left(\delta_t^{\pm}\right)$$

(4) Working population constraints.

In order to ensure that the region has enough population to support economic development, working population constraints establish the correlation relationship between population and output value.

$$\sum_{i=1}^{I} W_{it}^{\pm} \cdot WUP_{it}^{\pm} \leq UTP_t^{\pm} \cdot Q_t^{\pm}$$

(5) Industrial development will constraints.

To prevent excessive growth or the recession of various industries, industrial development will constraints reflect the actual situation of capacity change and simultaneously ensure the relative stability of the industrial structure, where $q_1 \geq 1 \geq q_2 \geq 0$.

$$q_1 W_{i,t-1}^{\pm} \geq W_{it}^{\pm} \geq q_2 W_{i,t-1}^{\pm}, \quad \forall i, t$$

(6) Output value constraints.

Output value constraints are set for the purpose of ensuring the healthy and reasonable development of the regional economy, preventing government managers from one-sided pursuit of output value growth while in the meantime ensuring a certain minimum development speed.

$$WTV_t^{\pm} \geq \sum_{i=1}^{I} W_{it}^{\pm} \geq DTV_t^{\pm}, \quad \forall t$$

(7) Arable land area constraint.

Arable land area constraints meet the basic needs of farmland security.

$SL_t^{\pm} \cdot RL_t^{\pm} \geq W_{i=1,t}^{\pm} \geq ML_t^{\pm} \cdot RL_t^{\pm}, \quad \forall t$

where i denotes different industries. Related to the current industrial structure characteristics and future development plan of Qingpu and relying on the merger of similar industries, typical key industries are selected as variables. Where i = 1 for the agriculture, i = 2 for the manufacturing industry, i = 3 for the construction industry, i = 4 for wholesale and retail industry, i = 5 for the transportation industry, i = 6 for the accommodation and catering industry, i = 7 for the communications industry, i = 8 for the financial industry, i = 9 for the real estate industry, i = 10 for other service industry.

Here t denotes the planning period, where t = 1 for the first planning period (2021–2025), t = 2 for the second planning period (2026–2030), t = 3 for the third planning period (2031–2035); k denotes different water pollutants, where k = 1 for COD, k = 2 for NH_3-N, k = 3 for TP; j denotes different air pollutants, where j = 1 for SO_2, j = 2 for NO_x, j = 3 for PM. Thus, $W_{it}^{\pm}$ = the output value from industry i in period t;

$WC_{it}^{\pm}$ = the water resources consumption per unit of output value from industry i in period t;

$WN_{it}^{\pm}$ = the energy consumption per unit of output value from industry i in period t;
$WP_{it}^{\pm}$ = the price of water resources per unit from industry i in period t;
$NP_{it}^{\pm}$ = the price of energy per unit from industry i in period t;
$PE_{itk}^{\pm}$ = the production coefficient of pollutant k per unit of output value from industry i in period t;
$PN_{itj}^{\pm}$ = the production coefficient of pollutant j per unit of output value from industry i in period t;
$RN_{itj}^{\pm}$ = the removal efficiency of pollutant k from industry i in period t;
$TN_{tj}^{\pm}$ = the environmental capacity of air pollutants j in period t;
$PC_{itk}^{\pm}$ = the removal cost of pollutant k from industry i in period t;
$NC_{itj}^{\pm}$ = the removal cost of pollutant j from industry i in period t;
$UPE_{tk}^{\pm}$ = the emission intensity of pollutant k from population in period t;
$PUP_{tk}^{\pm}$ = the removal cost of pollutant k from population in period t.
$f(\alpha^{\pm})$ = the satisfaction membership function;
$\alpha_t^{\pm}$ = water resources consumption function per unit output value;
$\delta_t^{\pm}$ = energy consumption function per unit of output value;
$\lambda_t^{\pm}$ = the satisfactory degree of water resources consumption per unit of output value;
$WUP_{it}^{\pm}$ = the working population per unit of output value from industry i in period t;
$UTP_t^{\pm}$ = the population gross in period t;
$Q_t^{\pm}$ = the proportion of working population in period t;
$PTW_t^{\pm}$ = the maximum amount of the domestic water in period t;
$EWT_t^{\pm}$ = the maximum amount of ecological water in period t;
$TTW_t^{\pm}$ = the maximum amount of water resources in period t;
$TNW_t^{\pm}$ = the maximum amount of energy in period t;
$OW_t^{\pm}$ = the maximum amount of transferred outside water in period t;
$RP_{itk}^{\pm}$ = The removal efficiency of pollutant k from industry i in period t;
$UPR_{tk}^{\pm}$ = The removal efficiency of pollutant from domestic sewage in period t;
$TP_{tk}^{\pm}$ = The total allowable emissions of pollutant k in period t;
$DTV_t^{\pm}$ = The minimum objective system output value in period t;
$WTV_t^{\pm}$ = The maximum objective system output value in period t;
$SL_t^{\pm}$ = The minimum area of arable land in period t;
$RL_t^{\pm}$ = the output value per unit of arable land area in period t;
$ML_t^{\pm}$ = The maximum area of arable land in period t.

The model is split by interactive algorithm, and the upper bound model and lower bound model are obtained respectively.

3.3. Data Collection

To obtain the relevant data on the economic and environmental systems in Qingpu District to be used in this research, we collected them from the Shanghai statistical yearbook of Qingpu District, the statistical bulletin of national economic and social development, the environmental quality report, the handbook of discharge coefficient of industrial sources, the manual of discharge coefficient of urban domestic sources, the outline of the 13th Shanghai five-year Plan of National Economic and Social Development, the 13th Shanghai five-year Environmental Protection Plan, Shanghai Water Resources Bulletin, Qingpu District pollution Source list and other related materials, literature review.

The model considers key industries such as agriculture, manufacturing, construction, wholesale and retail, transportation, accommodation and catering, communications, finance, real estate, and other service industries. Water pollutants include COD, NH_3-N and TP, while air pollutants include SO_2, NO_x and PM. The relevant research can be calculated according to the specific research direction and the constraints of the data selection model.

4. Results, Analysis and Discussion

In this study, the objective of the optimization model established was to minimize the cost of the energy-water resource system in Qingpu district of Shanghai during the planning period. The optimal solutions of the model could closely combine the established energy and environment policy, resource planning and its industrial economic impact. In addition, the solution results, including certain values, interval values and fuzzy distribution information, fully reflect the various forms of uncertainty existing in the model. Specifically, the interval solution of the model could help the decision-maker to obtain multiple decision schemes; at the same time, it could make possible deep tradeoff analysis between the system cost and different fuzzy membership degrees. Three planning periods are under consideration, one of which is five years. At the same time, a multi-scenario analysis method was adopted to obtain results under different satisfaction scenarios by assigning different minimum values to satisfaction constraints $\lambda_t^{\pm}$. According to the relevant formulas, we take $\lambda_t^{\pm} \geq 0.3$ as the low satisfaction scenario and $\lambda_t^{\pm} \geq 0.7$ as the high satisfaction scenario.

4.1. Water Environmental Capacity

Qingpu District has four water control units, namely Dianfeng, Huangdu, Linjiang and Taipu River Bridge. The discharge status and capacity are shown in Table 2. The water environmental capacities of NH_3-N were 0.016, 0.094, 0.227 and 0.009 $\times$ 10^4 tonnes, the water environmental capacities of TP were 0.008, 0.033, 0.076 and 0.004 $\times$ 10^4 tonnes, and the water environmental capacities of COD were 0.414, 2.040, 4.875 and 0.167 $\times$ 10^4 tonnes. The water environment in Qingpu district is generally overloaded. With the development of industry in the future, regional water environment governance should be strengthened to provide support for the improvement of the regional water environment.

Table 2. Water control unit main indicators discharge status and capacity (unit: 10^4 tone).

Control Unit	NH_3-N		TP		COD	
	Discharge Status	Capacity	Discharge Status	Capacity	Discharge Status	Capacity
Dianfeng	0.022	0.016	0.009	0.008	0.488	0.414
Huangdu	0.126	0.094	0.038	0.033	2.382	2.040
Linjiang	0.305	0.227	0.088	0.076	5.694	4.875
Taipu River Bridge	0.012	0.009	0.004	0.004	0.195	0.167
total	0.465	0.346	0.139	0.121	8.759	7.496

4.2. Atmospheric Capacity

Considering that $PM_{2.5}$ concentration in Qingpu district have not reached the safe value recommended by WHO, the atmospheric environmental quality targets for different stages ($PM_{2.5}$ concentration target is 33 $\mu g/m^3$ in 2025 and 25 $\mu g/m^3$ in 2035) were set in the calculation process for atmospheric environmental capacity, and calculated for the atmospheric environmental capacity at different stages. This part of the work mainly relies on the "third line and one permit" policy of Shanghai. Considering the requirements of atmospheric environment quality improvement in Shanghai, the atmospheric environment capacity of Qingpu District in each stage was calculated.

The atmospheric capacities of SO_2 were 0.04×10^4 tonnes in 2025, 0.035×10^4 tonnes in 2030 and 0.03×10^4 tonnes in 2035, the atmospheric capacities of NO_x were 0.03×10^4 tonnes in 2025, 0.02×10^4 tonnes in 2030 and 0.01×10^4 tonnes in 2035, and the atmospheric capacities of PM were 0.02×10^4 tonnes in 2025, 0.015×10^4 tonnes in 2030 and 0.01×10^4 tonnes in 2035.

4.3. Low Satisfaction Scenario Results

Figure 3 shows the upper and lower limits of output value of various sectors in Qingpu District in different planning periods under the low satisfaction scenario $\lambda_t^{\pm} \geq 0.3$. The results reveal that industry will continue to occupy the position of pillar sector in Qingpu District in the future, which will be $[38.65, 50.04] \times 10^9$ yuan, $[43.82, 51.32] \times 10^9$ yuan and $[45.81, 49.06] \times 10^9$ yuan, respectively, in different planning periods. However, from the change in the upper limit of the output value, the future industrial output value will firstly increase and then decrease. The wholesale and retail sector and transportation sector will also increase, and their output value in the third planning period can reach $[26.07, 33.14] \times 10^9$ yuan and $[21.04, 26.75] \times 10^9$ yuan respectively. Agriculture and the catering and accommodation sector will be the sectors with the most obvious decline in output value, in which the output value of agriculture in different planning periods are $[0.41, 0.49] \times 10^9$ yuan, $[0.20, 0.30] \times 10^9$ yuan and $[0.10, 0.18] \times 10^9$ yuan, respectively and the output value of catering and accommodation sector in different planning periods is $[1.06, 1.27] \times 10^9$ yuan, $[0.53, 0.76] \times 10^9$ yuan and $[0.26, 0.46] \times 10^9$ yuan, respectively. Additionally, the upper and lower limits of the output value of the construction sector show the opposite trend, that is, with the passage of time, the output value of the construction sector has a large space for change, which will reach $[0.79, 7.54] \times 10^9$ yuan in the third planning period. Other sectors in the tertiary industry, including information transmission, finance, real estate and other service sectors, all show a certain growth trend in different planning periods.

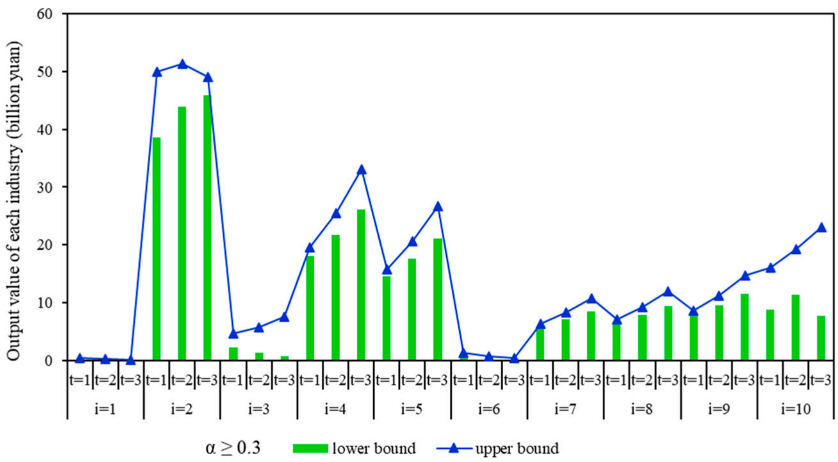


Figure 3. Output value of various sectors in Qingpu District in different planning periods under the low satisfaction scenario.

Figure 4 shows the upper and lower limits of water resource consumption of various sectors in Qingpu District in different planning periods under the low satisfaction scenario. In the upper limit results, although the industrial water consumption decreases year by year it will still be the sector with the largest water resource consumption in the region, reaching [29.83, 42.49] $\times$ 10^6 m^3, [32.14, 41.40] $\times$ 10^6 m^3 and [31.92, 37.60] $\times$ 10^6 m^3 in different planning periods. With the shrinking agricultural scale the water consumption of agriculture will decrease in the future, reaching [7.34, 8.01] $\times$ 10^6 m^3, [3.49, 4.65] $\times$ 10^6 m^3 and [1.66, 2.60] $\times$ 10^6 m^3 in different planning periods. The water resource consumption of the construction and catering and accommodation sectors will show a trend of continuous decrease in the three planning periods. Contrarily, the water resource consumption of the wholesale and retail, transportation, information and financial sectors shows an upward trend in different planning periods. In the third planning period, the water resource consumption of these four sectors will reach [4.16, 5.82] $\times$ 10^6 m^3, [4.06, 5.72] $\times$ 10^6 m^3, [8.46, 10.76] $\times$ 10^6 m^3 and [9.40, 11.95] $\times$ 10^6 m^3, respectively.

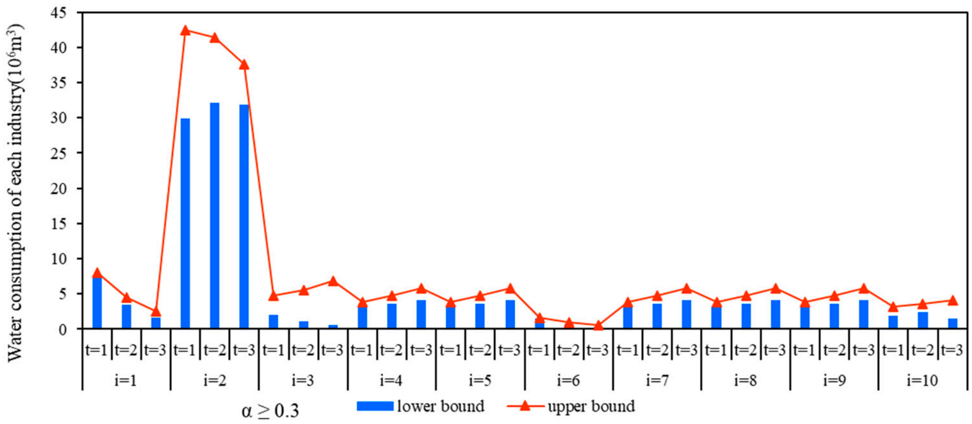


Figure 4. Water resource consumption of various sectors in Qingpu District in different planning periods under the low satisfaction scenario.

Figure 5 shows the upper and lower limits of energy consumption of various sectors in different planning periods under the scenario of low satisfaction in Qingpu District. The results suggest that the industry, wholesale and retail and transportation sectors are those with the highest energy consumption, but they all show a trend of decreasing energy consumption during the planning period. The energy consumption of the three sectors in the third period are [162.68, 191.65] $\times$ 10^3 t^3, [208.13, 291.08] $\times$ 10^3 t^3 and [167.99, 234.94] $\times$ 10^3 t^3, respectively. Additionally, the energy consumption of the agriculture, construction and accommodation and catering sectors also show an obvious trend of reduction. Integrally, tertiary industry will continue to occupy the main share of energy consumption, and the change in energy consumption of the information transmission, financial, real estate and other service sectors will be stable. In the third period, the energy consumption of each sector will reach [67.56, 94.49] $\times$ 10^3 t^3, [75.05, 104.97] $\times$ 10^3 t^3, [91.96, 128.62] $\times$ 10^3 t^3 and [67.46, 184.49] $\times$ 10^3 t^3, respectively.

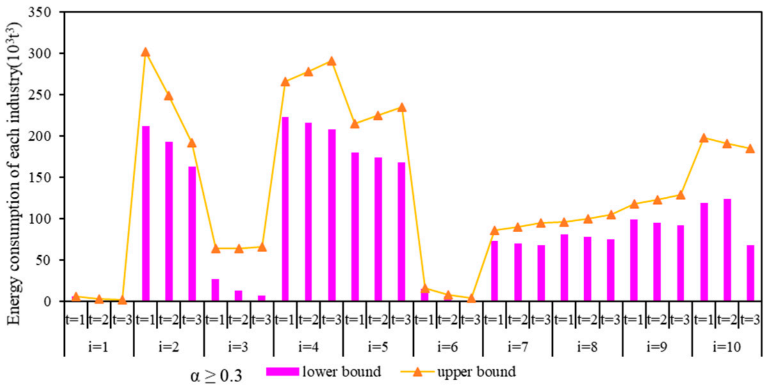
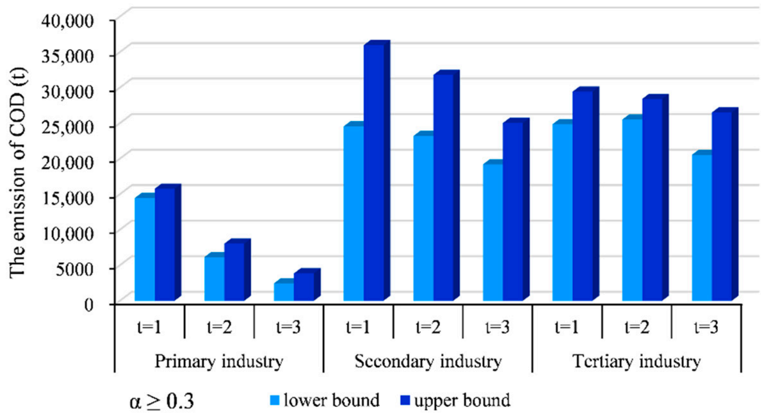


Figure 5. Energy consumption in Qingpu District in different planning periods under the low satisfaction scenario.

Figure 6 shows the emissions of COD, ammonia nitrogen and total phosphorus in different planning periods under the low satisfaction scenario. The distribution of different pollutants in tertiary industry has the same trend, which means the emissions of all pollutants show a decreasing trend with the passing of the planning period, and they are mainly concentrated in secondary industry in the early stage and tertiary industry in the long term. In the first planning period, the emissions of COD, ammonia nitrogen and total phosphorus are mainly concentrated in secondary industry, and the emissions of the three pollutants reach [14,452.35, 15,766.20]t, [767.25, 837.00]t and [229.35, 250.20]t, respectively. In the third planning period, the discharge of COD, ammonia nitrogen and total phosphorus are mainly concentrated in tertiary industry, and the discharge of three pollutants reach [20,530.54, 26,502.35]t, [1089.93, 1406.96]t and [325.81, 420.58]t, respectively. With the development of the high-tech and service sectors, the main objects of water environmental pressure faced by Qingpu District will also alter in the future.

Figure 7 shows the emissions of air pollutants, including sulfur dioxide, nitrogen oxides and dust, in different planning periods under the low satisfaction scenario. Among the three sectors, the discharge of air pollutants in primary industry is always at a low level. In the third planning period, the emissions of sulfur dioxide, nitrogen oxides and particulate matter are only [0.21, 0.33]t, [0.20, 0.34]t and [0.06, 0.11]t, respectively. Among the sulfur dioxide emission sources secondary industry occupies a dominant position, showing an upward trend and then a downward trend in three planning periods, [245.47, 337.99]t, [262.05, 331.32]t and [259.11, 304.95]t, respectively. Similarly, the main source of particulate matter is secondary industry, [142.47, 195.01]t, [152.74, 160.37]t and [151.34, 174.37]t, respectively. Tertiary industry, as the main source of NO_x, shows a trend of continuous increase in the three planning periods, [151.57, 152.14]t, [171.23, 186.08]t and [194.31, 214.51]t, respectively.



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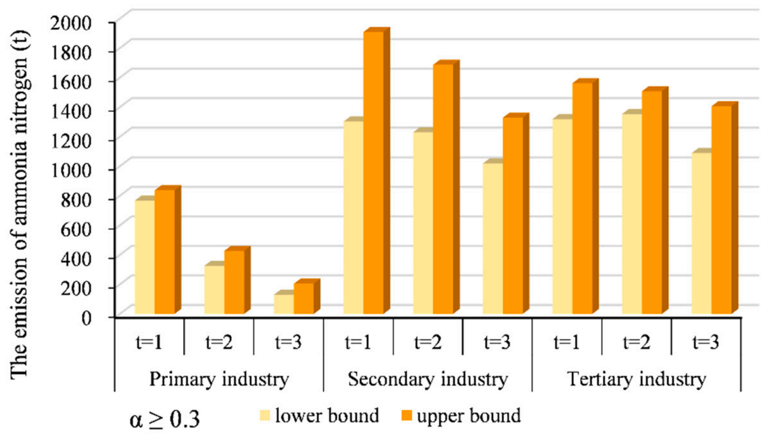

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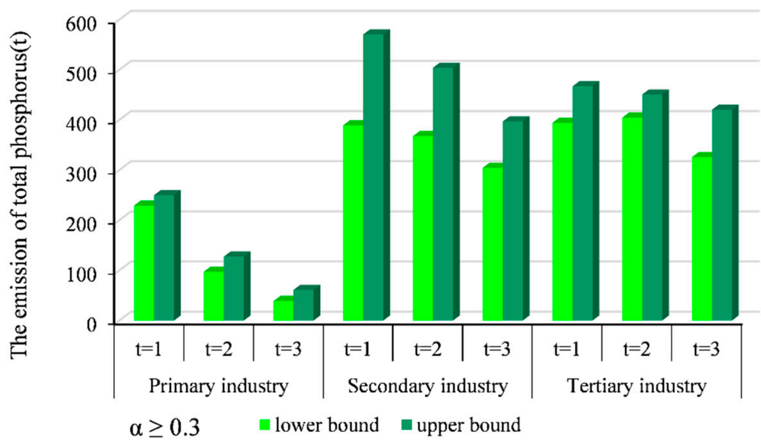

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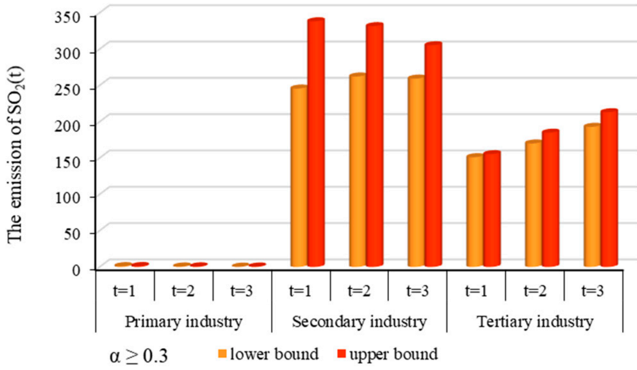
Figure 6. Emission of water environmental pollutants in Qingpu District in different planning periods under the low satisfaction scenario. (**a**) the emission of TOD; (**b**) the emission of ammonia nitrogen; (**c**) the emission of total phosphorus.



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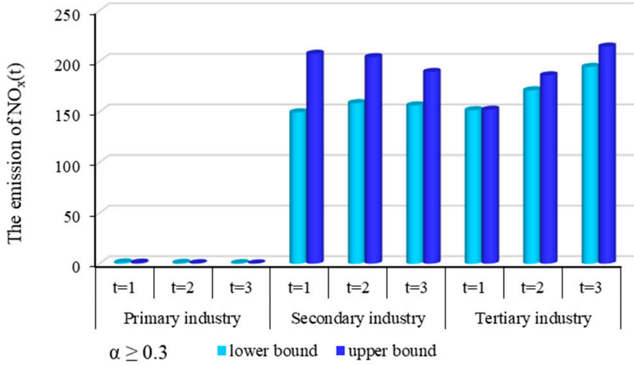

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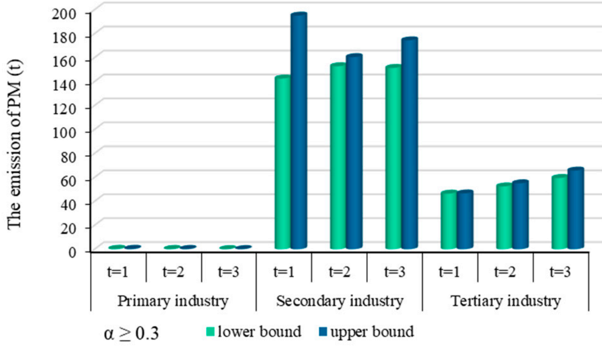

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Figure 7. Emissions of air pollutants in Qingpu District in different planning periods under the low satisfaction scenario. (**a**) the emission of SO_2; (**b**) the emission of NO_x; (**c**) the emission of PM.

4.4. High Satisfaction Scenario Results

Figure 8 shows the upper and lower limits of output value of various sectors in Qingpu District in different planning periods under the scenario of high satisfaction ($\lambda_t^{\pm} \geq 0.7$). The results reveal that industry will continue to occupy the position of pillar sector in Qingpu District in the future under the high satisfaction scenario. In different planning periods, it will be [35.57, 38.65] $\times$ 10^9 yuan, [42.68, 46.35] $\times$ 10^9 yuan and [42.39, 45.13] $\times$ 10^9 yuan, respectively. In the three planning periods, the future industrial output value has a trend of increasing first and then decreasing. The wholesale and retail and transportation sectors will also increase, and their output value in the third planning period could reach [26.07, 33.14] $\times$ 10^9 yuan and [21.04, 26.75] $\times$ 10^9 yuan, respectively. Agriculture and the catering and accommodation sector will be the sectors with the most obvious decline in output value, in which the output value of agriculture in different planning periods is [0.49, 0.57] × 10^9 yuan, [0.29, 0.40] × 10^9 yuan and [0.17, 0.28] × 10^9 yuan, respectively, and the output value of the catering and accommodation sector in different planning periods are [1.27, 1.48] × 10^9 yuan, [0.76, 1.03] × 10^9 yuan and [0.45, 0.72] × 10^9 yuan, respectively.

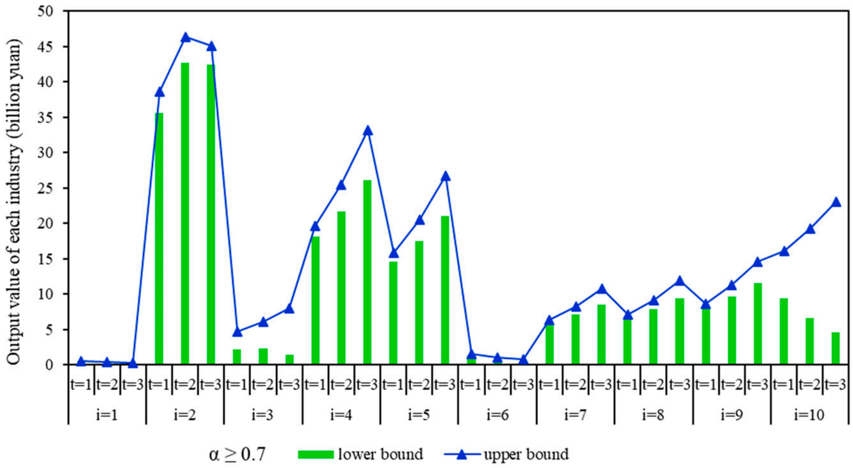


Figure 8. Output value of various sectors in Qingpu District in different planning periods under the high satisfaction scenario.

Figure 9 shows the upper and lower limits of water resource consumption of various sectors in Qingpu District during different planning periods under the high satisfaction scenario. With the high satisfaction ceiling, although industrial water consumption decreases year over year, it would still be the sector with the largest water resource consumption in the whole region, reaching [27.46, 32.82] × 10^6 m^3, [31.30, 37.39] × 10^6 m^3 and [31.44, 32.49] × 10^6 m^3 in the different planning periods. With the shrinking of agricultural scale, the water consumption of agriculture will decrease in the future, reaching [8.01, 10.28] × 10^6 m^3, [4.56, 6.83] × 10^6 m^3 and [2.60, 4.54] × 10^6 m^3 in different planning periods. The water resource consumption of the construction and catering and accommodation sectors will show a trend of continuous decrease in the three planning periods. Contrarily, the water resource consumption of the wholesale and retail, transportation, information and financial sectors show an upward trend in different planning periods. In the third planning period, the combined water resource consumption of these four sectors will reach [4.16, 5.82] × 10^6 m^3, [4.06, 5.72] × 10^6 m^3, [4.16, 5.82] × 10^6 m^3 and [4.16, 5.82] × 10^6 m^3, respectively.

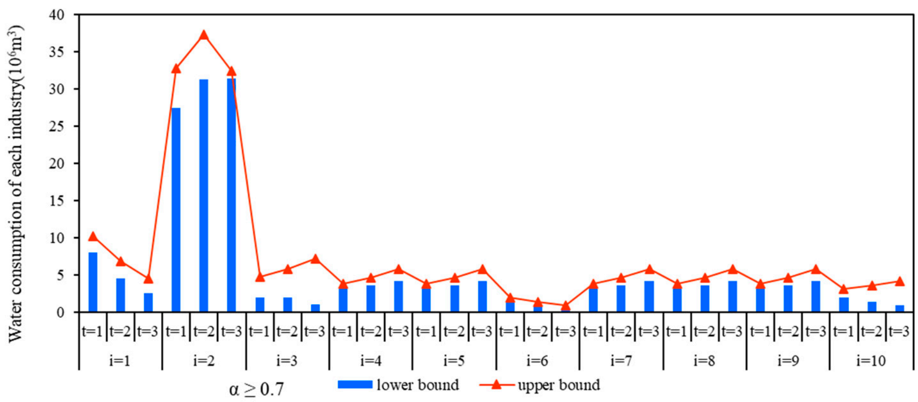


Figure 9. Water resource consumption of various sectors in Qingpu District in different planning periods under the high satisfaction scenario.

Figure 10 shows the upper and lower limits of energy consumption of various sectors in Qingpu District in different planning periods under the high satisfaction scenario. The results suggest that the industry, wholesale and retail and transportation sectors are the sectors with the highest energy consumption, but they all show a trend of decreasing energy consumption during the planning period. The energy consumption of the three sectors in the third period are [160.26, 165.58] × 10^3 t^3, [208.13, 291.08] × 10^3 t^3 and [167.99, 234.94] × 10^3 t^3, respectively. In addition, the energy consumption of the agriculture, construction and accommodation and catering sectors also show an obvious trend towards reduction. Integrally, tertiary industry will continue to occupy the main share of energy consumption, and the change in energy consumption of the information transmission, financial, real estate and other service sectors tends to be stable. In the third period, the energy consumption of each sector will reach [67.56, 94.49] × 10^3 t^3, [75.05, 104.97] × 10^3 t^3, [91.96, 128.62] × 10^3 t^3 and [40.28, 184.49] × 10^3 t^3.

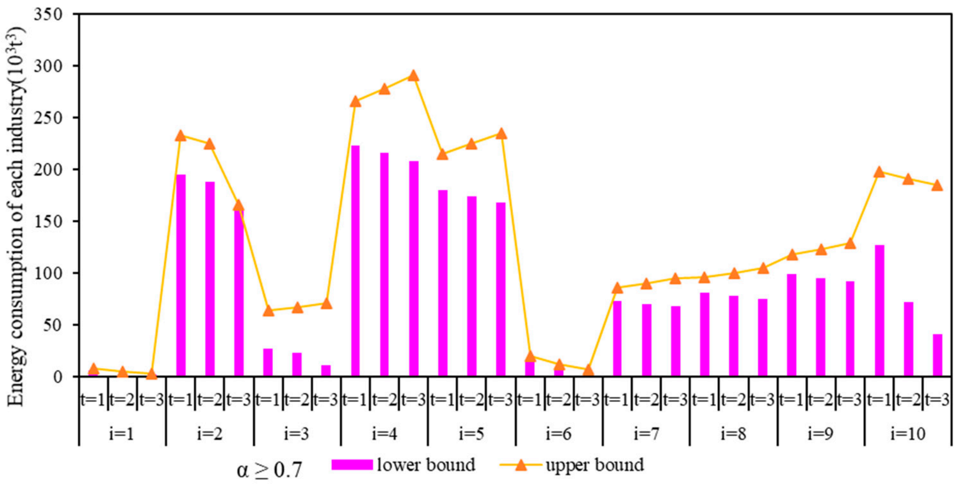
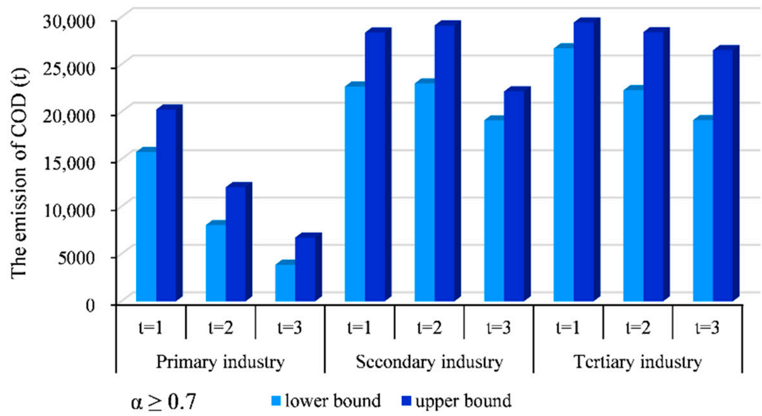


Figure 10. Energy consumption in Qingpu District in different planning periods under the high satisfaction scenario.

Figure 11 shows the emissions of COD, ammonia nitrogen and total phosphorus in different planning periods under the high satisfaction scenario. Different pollutants have the same trend in the distribution of the three industries. The emissions of pollutants in primary and tertiary industry all show a decreasing trend with the passing of the planning period, but the emissions of pollutants in secondary industry increase first and then decline. In the first planning period, the emissions of COD, ammonia nitrogen and total phosphorus are mainly concentrated in tertiary industry, and the emissions of the three pollutants reach [26,688.67, 29,430.24]t, [1416.85, 1562.40]t and [423.53, 467.04]t, respectively. In the second planning period, the emissions of COD, ammonia nitrogen and total phosphorus are mainly concentrated in secondary industry, and the emissions of the three pollutants reach [29,115.46, 22,986.39]t, [1220.31, 1545.68]t and [364.78, 462.04]t, respectively. In the third planning period, the emissions of COD, ammonia nitrogen and total phosphorus are concentrated in tertiary industry, and the emissions of the three pollutants reach [19,113.36, 26,502.35]t, [1014.69, 1406.96]t and [303.32, 420.58]t, respectively. With the development of the high-tech and service sectors, the main targets of water environmental pressure faced by Qingpu District in the future will also change.



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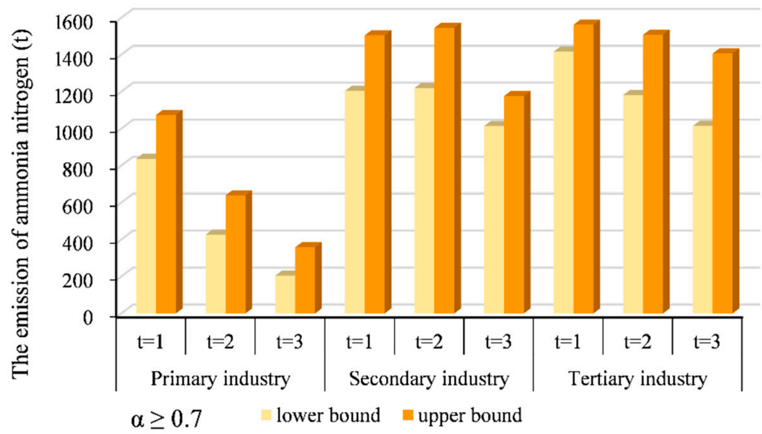

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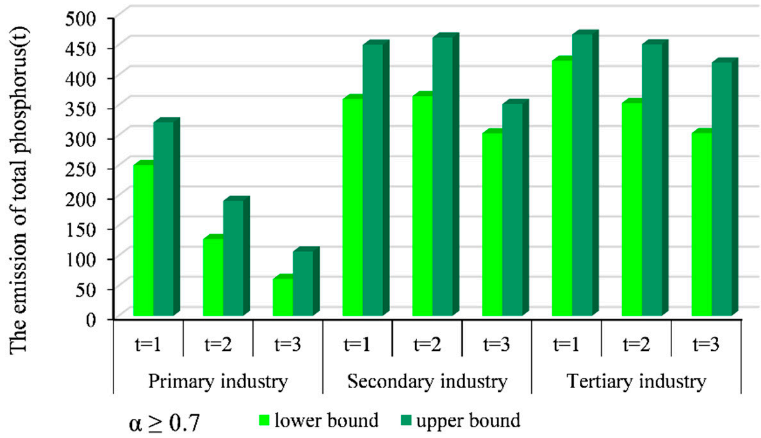

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Figure 11. Emission of water environmental pollutants in Qingpu District in different planning periods under the high satisfaction scenario. (**a**) the emission of TOD; (**b**) the emission of ammonia nitrogen; (**c**) the emission of total phosphorus.

Figure 12 shows the emissions of air pollutants, including sulfur dioxide, nitrogen oxides and dust, in different planning periods under the high satisfaction scenario. Among the three sectors, the emission of air pollutants in primary industry is always at a low level. In the third planning period, the emissions of sulfur dioxide, nitrogen oxides and particulate matter are only [0.34, 0.56]t, [0.33, 0.57]t and [0.32, 0.39]t, respectively. Among the sulfur dioxide emission sources, secondary industry always plays a dominant role, showing an upward trend and then a downward trend in the three planning periods, which are [226.32, 263.50]t, [257.28, 301.19]t and [256.40, 266.49]t, respectively. Similarly, the main source of particulate matter is secondary industry, [131.26, 151.38]t, [149.41, 156.88]t and [149.44, 151.58]t, respectively. Tertiary industry, as the main source of NO_x, shows a trend of continuous increase in the three planning periods, [151.57, 154.52]t, [171.23, 176.87]t and [194.31, 209.14]t, respectively.

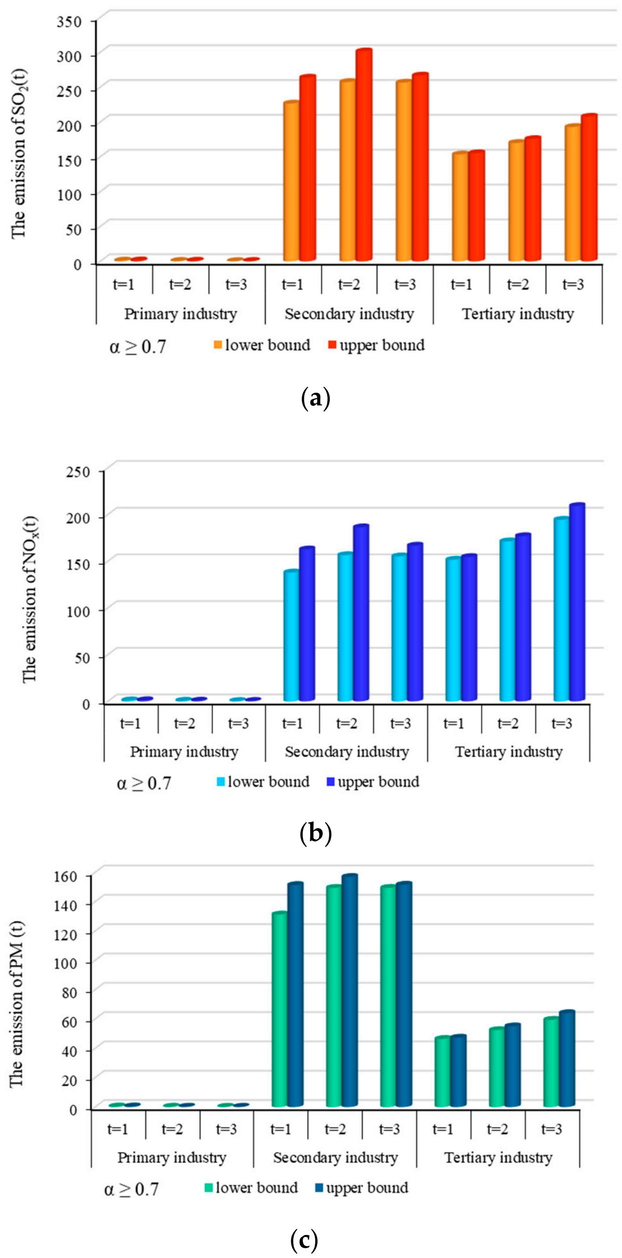

Figure 12. Emission of air pollutants in Qingpu District in different planning periods under the high satisfaction scenario. (**a**) the emission of SO_2; (**b**) the emission of NO_x; (**c**) the emission of PM.

4.5. Discussion

Various sources of uncertainty are important for the regional development planning system, and they were expressed as uncertain parameters and credibility levels, such as the performance of constraints for resources and energy. Although all Chinese cities have put forward binding targets for resources and energy, some cities still face the risk of failing to meet them. The accurate accounting of the potential effect of these uncertainties is significant for understanding the risks that will come with regional development. In order to better understand the system, Figures 3 and 8 show the output value of various sectors in Qingpu District under different credibility levels. It can be found that higher credibility levels are associated with lower violation risk of credibility constraints as well as lower economic growth. When the credibility level increases, the system first changes the growth of industry (which is the key sector for meeting the energy efficiency constraint), then changes the growth of the agriculture and catering and accommodation sectors, which is important to achieve the constraint on water resources. For example in the low satisfaction scenario, the output value of industry will be [38.65, 50.04] $\times 10^9$ yuan, [43.82, 51.32] $\times 10^9$ yuan and [45.81, 49.06] $\times 10^9$ yuan, respectively, in different planning periods with $\lambda_t^{\pm} \geq 0.3$; however, when $\lambda_t^{\pm} \geq 0.7$, the output value of industry will be [35.57, 38.65] $\times 10^9$ yuan, [42.68, 46.35] $\times 10^9$ yuan and [42.39, 45.13] $\times 10^9$ yuan, respectively, which is lower than the value with $\lambda_t^{\pm} \geq 0.3$. The agriculture and catering and accommodation sectors follow the same trend as industry. The wholesale and retail sector has the same output with different credibility levels. Thus, in the scenarios with different credibility levels, Qingpu District can meet the requirement of resource and energy constraints by adjusting the structure of key industries. The results of the model provide the direction of industrial structure adjustment with different credibility levels in the future, and decisionmakers can determine the direction of industrial structure adjustment according to the violation risks of credibility constraints and economic development benefits.

The energy increment of Qingpu District mainly comes from electricity in the future, and the increase of fossil energy is limited. In the future, efforts to ensure the carbon peak will mainly rely on the external transmission power grid to improve the proportion of renewable energy, as it is difficult to change the energy structure of the local power grid. Regional green development should improve energy efficiency at first, and increase economic trends in the aggregate while consuming the same energy. Therefore, with the change of energy structure in power grid, Qingpu District can truly achieve carbon peak and carbon neutrality. Thus, in this study, energy efficiency constraint was set as the low carbon development constraint on the system. In addition to the measures given by the model to adjust industrial structure, improving energy efficiency requires joint efforts in many areas, such as upgrading production technology, promoting green building, transformation of old communities, and so forth, which are reflected in the model by changing the energy coefficient.

Due to the complex nature of regional development systems, there exist some limitations for this study. The model provides optimal results for the maximization of economic growth. System benefit is considered as the most important factor in the model. Therefore, industries with relatively high energy consumption but relatively low economic contribution will be adjusted first. However, in reality, the existence of many industries is closely related to local peoples' livelihood and employment. For example, industrial development creates jobs, and the increase in employment population promotes the development of catering, accommodation and other industries nearby. Before adjusting one industry, decisionmakers need to consider the impact on other industries and peoples' livelihoods. In further studies, the interlinkages between industries need to be taken into account to ensure that the adjustment measures are more feasible.

In past studies of optimization models, the pollutant discharge gross quantity in the constraint conditions is often seen as a fixed value based on the management indicator given by the government. However, in the real world, the environmental capacity that can be used is affected by many factors, such as hydrological conditions and meteorological conditions. Thus, it is important to integrate the environmental quality model into the optimization model. The real environmental capacity of the region can be more accurately calculated by the established environmental quality model. At the same time, carbon peak is currently a key work in China, and carbon peak requirements should be included as targets or constraints in regional optimization studies. In this way, studies will have more practical significance and provide better support for regional development.

5. Conclusions

This study proposed an IFP-EQ model, combining an environmental quality model and an interval fuzzy optimization model, and then applied it to the regional development planning of Qingpu District along with different satisfaction level scenarios set to indicate the policy preference of decisionmakers. The uncertainties were presented as interval values and satisfaction levels in the model. The environmental quality model considered the water environmental quality model and atmosphere environmental quality model. The tradeoffs between economic development, resource management, pollution emission and population planning were analyzed. The results suggest that the methodology was applicable for the regional development planning system within the planning period. The developed model could be used for generating a series of optimization schema under multiple credibility levels, ensuring that the regional development planning system could meet societal demand and environmental quality requirements, considering a proper balance between expected system benefits and the risks of violating the resource and low carbon development constraints. A higher satisfaction level means that the violation risk of fuzzy credibility constraints is lower, as is economic growth. Decisionmakers can determine the direction of industrial structure adjustment according to the violation risks of fuzzy credibility constraints and economic development benefits.

The IFP-EQ model has been proven to be effective in the case study. However, there are still some aspects to be improved. Firstly, carbon peak target of Qingpu District mainly relies on increasing the proportion of new energy in the power supply of the input power grid. But in the actual process of model calculation, this part is not well considered because of a lack of data. The contribution of local new energy development to changes in the regional power grid structure is not clear. The model still has room for improvement in accounting for efforts to achieve the carbon peak target by changes to the local energy structure. Additionally, the interlinkages between industries need to be taken into account to ensure that the adjustment measures are more feasible. Furthermore, the selection of environmental quality models is mainly based on the actual situation of Qingpu District. In the process of practical application, corresponding models such as one-dimensional and two-dimensional water quality models can be replaced on a regional working basis. Finally, extreme climate has a certain impact on regional environmental quality, and it is necessary to add climate change into the model. Furthermore, although the risk of the method was considered under maximizing the expected value of the objective function, further study about risk is still needed. Thus, some topics concerning risk deserve future research, for instance fuzzy statistics used as a proxy for risk.

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References

1. Solomon, S.; Plattner, G.K.; Knutti, R.; Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 1704–1709. [CrossRef] [PubMed]
2. Fu, Z.H.; Zhao, H.J.; Wang, H.; Lu, W.T.; Wang, J.; Guo, H.C. Integrated planning for regional development planning and water resources management under uncertainty: A case study of Xining, China. *J. Hydrol.* **2017**, *554*, 623–634. [CrossRef]
3. Bahrami, S.; Therrien, F.; Wong, S.; Jatskevich, J. Semidefinite relaxation of optimal power flow for ac–dc grids. *IEEE Trans. Power Syst.* **2017**, *99*, 1–16. [CrossRef]
4. Samimi, A.; Nikzad, M.; Siano, P. Scenario-based stochastic framework for coupled active and reactive power market in smart distribution systems with demand response programs. *Renew. Energy* **2017**, *109*, 20–44. [CrossRef]
5. Chen, C.; Li, Y.P.; Huang, G.H. An inexact robust optimization method for supporting carbon dioxide emissions management in regional electric-power systems. *Energy Econ.* **2013**, *40*, 441–456. [CrossRef]
6. Mi, Z.F.; Pan, S.Y.; Yu, H.; Wei, Y.M. Potential impacts of industrial structure on energy consumption and CO_2 emission: A case study of Beijing. *CEEP-BIT Work. Pap.* **2014**, *103*, 455–462. [CrossRef]
7. Cheng, Z.; Li, L.; Liu, J. Industrial structure, technical progress and carbon intensity in China's provinces. *Renew. Sustain. Energy Rev.* **2017**, *81*, 2935–2946. [CrossRef]
8. Stoyan, S.J.; Dessouky, M.M. A stochastic mixed-integer programming approach to the energy-technology management problem. *Comput. Ind. Eng.* **2012**, *63*, 594–606. [CrossRef]
9. Santos, H.L.; Legey, L.F.L. A model for long-term electricity expansion planning with endogenous environmental costs. *Int. J. Electr. Power* **2013**, *51*, 98–105. [CrossRef]
10. Zhang, Y.; Fu, Z.; Xie, Y.; Li, Z.; Liu, Y.; Hu, Q.; Guo, H. Multi-objective programming for energy system based on the decomposition of carbon emission driving forces: A case study of Guangdong, China. *J. Clean. Prod.* **2021**, *309*, 127410. [CrossRef]
11. Lu, W.T.; Dai, C.; Fu, Z.H.; Liang, Z.Y.; Guo, H.C. An interval-fuzzy possibilistic programming model to optimize china energy management system with co2 emission constraint. *Energy* **2018**, *142*, 1023–1039. [CrossRef]
12. Yang, L.; Lahr, M.L. The Drivers of China's Regional Carbon Emission Change—A Structural Decomposition Analysis from 1997 to 2007. *Sustainability* **2019**, *11*, 3254. [CrossRef]
13. Fahimnia, B.; Sarkis, J.; Choudhary, A.; Eshragh, A. Tactical supply chain planning under a carbon tax policy scheme: A case study. *Int. J. Prod. Econ.* **2015**, *164*, 206–215. [CrossRef]
14. Song, A.; Yang, X.; Zhang, X.; Wang, F.; Huang, W. Ecology environment research about carbon emission efficiency in china based on a novel super epsilon-based measures (sebm) model. *Appl. Ecol. Environ. Res.* **2019**, *17*, 1109–1128. [CrossRef]
15. Lu, S.; Wang, J.; Shang, Y.; Bao, H.; Chen, H. Potential assessment of optimizing energy structure in the city of carbon intensity target. *Appl. Energy* **2016**, *194*, 765–773. [CrossRef]
16. Han, S.; Lin, C.; Zhang, B.; Farnoosh, A. Projections and Recommendations for Energy Structure and Industrial Structure Development in China through 2030: A System Dynamics Model. *Sustainability* **2019**, *11*, 4901. [CrossRef]
17. Huang, G.H. A hybrid inexact-stochastic water management model. *Eur. J. Oper. Res.* **1998**, *107*, 137–158. [CrossRef]
18. Inuiguchi, M.; Greco, S.; Owinski, R.; Tanino, T. Possibility and necessity measure specification using modifiers for decision making under fuzziness. *Fuzzy Sets Syst.* **2003**, *137*, 151–175. [CrossRef]
19. Mather, J.H.; Brune, W.H. Heterogeneous chemistry on liquid sulfate aerosols - a comparison of in situ measurements with zero-dimensional model calculations. *Geophys. Res. Lett.* **1990**, *17*, 1283–1286. [CrossRef]
20. Lin, W.Y.; Hsiao, M.C.; Wu, P.C.; Fu, J.S.; Lai, L.W.; Lai, H.C. Analysis of air quality and health Co-benefits regarding electric vehicle promotion coupled with power plant emissions. *J. Clean. Prod.* **2019**, *247*, 119–152. [CrossRef]
21. Skamarock, W.C.; Klemp, J.B.; Dudhia, J.; Gill, D.O.; Barker, D.M.; Duda, M.G.; Huang, X.-Y.; Wang, W.; Powers, J.G. A Description of Advanced Research WRF Version 3. NCAR Technical Note NCAR/TN–475+STR. 2008. Available online: https://opensky.ucar.edu/islandora/object/technotes%3A500/datastream/PDF/view (accessed on 20 August 2021).