A relative interval-regret analysis method for regional ecosystem planning – a case study of Dongying, China

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A relative interval-regret analysis (RIRA) method is developed for regional ecosystem management under uncertainty through incorporating interval-parameter programming (IPP) and minimax relative regret (MRR) analysis techniques within a general framework. RIRA can handle uncertainties expressed as intervals and random variables without knowing probability distributions and only needs a list of possible scenarios that may occur; it can also incorporate ecosystem services valuation approaches directly into the optimization process, such that an effective linkage between eco-compensation costs and ecosystem service losses can be provided. The RIRA method is applied to a real case of planning regional ecosystem of Dongying, where the natural ecosystem has suffered the severe degradation due to large-scale land reclamation projects. Results of land-use pattern, ecological compensation strategy, and industrial pollution-mitigation scheme can be obtained. The results reveal that, although large-scale reclamation projects can bring benefits and make a significant contribution to local economic development, they can also result in many negative effects to the coastal ecosystem, such as endangering animals and plants, changing intrinsic gas regulation, as well as altering natural nutrient cycling. Moreover, the results indicate that eco-compensation cost is much higher than the cost for reclaimed land use, disclosing that eco-compensation mechanism is desired for curbing excessive reclamation activities. These findings can facilitate the local decision makers in not only considering regional ecosystem integrity but also gaining insights into the tradeoff between socio-economic development and eco-environmental sustainability.

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1. Introduction

Most of disasters are derived from human activities; hazards may be natural in origin, but it is the way in which socio-economy has been developed that causes them to become disasters (Brien et al., 2006). Ecological disasters are great obstacles to sustainable development, which can significantly affect the long-term viability of society and economy and thus lead to serious adverse impacts on eco-environment as well as human life. Effective planning plays an important role for promoting regional ecosystem protection as well as developing socio-economic sustainability. However, achieving an efficient strategy is difficult since many conflicting factors have to be balanced due to complexities of the real-world problems. Ecological destruction, environmental deterioration, and resources shortage often become serious issues when development of economy is over stressed (Li et al., 2011a,b). For example, reclamation in China has caused a sharp drop in the national coastal wetlands, such that the cumulative loss has reached 22,000 km² since 1949 (i.e., around 51.2% of the total area of coastal wetlands in China) (An et al., 2007). The total mangrove area has lost 69% to the current 151 km² and the total area of coral reefs has declined by about 80% (Zhang et al., 2005). Besides, many other human activities (e.g., deforestation, livestock pasturing, and overfishing) also bring about profound negative effects on ecosystems as well as ecosystem services that they provide. Therefore, it is desired that effective planning and management strategies be advanced to coordinate the relationship between human activity and natural ecosystem.

Previously, a wide range of mathematical techniques were proposed for planning regional ecosystems with a sustainable development manner (Higgins et al., 1997; Su et al., 2007; Erol
Randhir, 2013; Gumiero et al., 2013; Natuhara, 2013; Recknagel, 2013; Yang and Chen, 2013; Yu et al., 2013; Ling et al., 2014; Mao et al., 2014). Curtis (2004) proposed a multiple criteria analysis method to estimate forest ecological service value in multiple forest management policies and analyze the multiple strategies of ecological compensation. Sanon et al. (2012) employed multi-criteria decision analysis approach to quantify the explicit tradeoffs between the stakeholder’s objectives related to key ecosystem services of the Lobau floodplain of Vienna. Vidal-Legaz et al. (2013) advanced a dynamic ecosystem simulation model to analyze the tradeoffs between the ecosystem service loss and the rural economic development under different land uses. Pinto et al. (2014) formulated an ecological assessment model to link biodiversity indicators, ecosystem functioning, provision of services and human well-being in estuarine system, and assess such links in a spatially and temporally explicit manner. In general, the aforementioned conventional methods were effective for analyzing and planning regional ecosystems with consideration of ecosystem service quantification and the relationship between human activities and natural ecosystems. However, ecosystem is very complicated, in which multiple processes and multiple factors should be considered by decision makers, involving the diversity of system components, the combination of generic and site-specific features, the dynamic transformation of matter or energy, and the temporal/spatial evolutions of parameters; moreover, these processes/factors as well as their interactions are of uncertain features. In real-world ecosystem management problems, the requirements for specifying the parameters’ probability distributions are often associated with difficulties due to the absence of the related information and then affect their practical applicability.

Minimax regret (MMR) analysis technique is effective for determining the hedging strategy under uncertainty, which only needs a list of possible scenarios that may occur without any assumption on their probabilities or distributions, and then seeks to identify the optimal alternatives with the minimized maximum regret across all scenarios (Savage, 1954). The MMR analysis method has an advantage in providing effective decision support under uncertainty, which only needs a list of possible scenarios (Li et al., 2011a,b). Generally, there are two regret criteria: absolute regret and relative regret. The absolute regret reflects the difference of objective-function value between the chosen strategy and the optimal one under each scenario, while the relative regret is defined as a ratio of the absolute regret to the optimal objective-function value (Averbakh 2005; Assis et al., 2009). The relative regret is less conservative than the absolute regret, particularly in situations in which the optimal objective function values differ significantly among possible scenarios. Previously, a number of research works based on the MMR analysis techniques were conducted for resources and environmental decision making problems (Kanudia and Lou lou, 1998; Hoaga et al., 2002; Yager 2004; Kasperski and Zielinski, 2006; Chang and Davila, 2007; Li et al., 2011a,b). Unfortunately, there have been few studies focusing on employing this technique to regional ecosystems management and planning under uncertainty. In fact, in real-world ecosystem management problems, there are many sources of uncertainties exist in a number of ecosystem components and their inter-relationships. Some parameters may present simply as intervals, while the others may be associated with random and/or fuzzy information; moreover, it is often unreliable to obtain the distribution of a random event with probability fit when data are not enough. Most of the previous studies rely on individual systems analysis method to deal with uncertainty, such that robustness of the optimization results may be significantly influenced due to the problems of over-simplification for uncertainties.

Therefore, the objective of this study is to advance a relative interval-regret analysis (RIRA) method for planning regional ecosystem under uncertainty. The RIRA method will be a hybrid of interval-parameter programming (IPP) and minimax-relative regret (MRR) analysis techniques, which can not only address uncertainties expressed as intervals but also determine alternatives without probability information for the states of the world. Then, the RIRA method is applied to a real case of planning regional ecosystem of Dongying (in China), where a variety of ecosystem service losses induced by large-scale land-reclamation projects are quantitatively evaluated and the relevant eco-compensation standard is established to coordinate economic development and eco-environmental protection. The results obtained will be valuable for local decision makers to identify optimal alternatives for reclaimed land-use pattern under different scenarios.

2. Methodology

Firstly, consider a deterministic linear programming (LP) problem as follows:

\[
\text{Minf} = \sum_{j=1}^{n} c_j x_j \quad (1a)
\]

subject to:

\[
\sum_{j=1}^{n} a_{ij} x_j \leq b_i, \quad i = 1, 2, ..., m \quad (1b)
\]

\[
x_j \geq 0, \quad \forall j \quad (1c)
\]

where \(c_j, a_{ij}, b_i\) are sets of deterministic parameters. However, in many real-world problems, the quality of information that can be obtained is mostly not satisfactory enough to be known with precision. Consequently, when uncertainties exist as possible scenarios with unknown probabilistic distributions, the above problem can be converted into:

\[
\text{Minf} = \sum_{j=1}^{n} c_j x_j \quad (2a)
\]

subject to:

\[
\sum_{j=1}^{n} a_{ij} x_j \leq b_i, \quad r = 1, 2, ..., m_1 \quad (2b)
\]

\[
\sum_{j=1}^{n} a_{ij} x_j \leq b_i, \quad r = m_1 + 1, m_1 + 2, ..., m \quad (2c)
\]

\[
x_j \geq 0, \quad \forall j \quad (2d)
\]

where \(b_i\) is a set of uncertain parameters, and decision has to be made under such a condition. The minimax relative regret (MRR) analysis is devoted to handling such problems where the worst-case ratio of the loss (in the objective function) is to be minimized while the prior probabilistic function of random variables is unavailable (Averbakh, 2005; Li and Huang, 2006). In practical applications of MRR, the matrix should be converted to a regret one. Thus, we have:

\[
r_j = C(s_i, o_j) - \min_{o \in O} C(s_i, o) \quad (3)
\]

where \(S\) is a strategy space and \(S = \{s_1, s_2, s_3, ..., s_p\}\); \(O\) is an outcome space and \(O = \{o_1, o_2, o_3, ..., o_q\}\); \(U\) is a real-valued objective function.
defined as $S \times O$ for a problem of decision analysis under uncertainty; $C(s, o_j)$ is the cost incurred when strategy $s_j$ is used while outcome $o_j$ occurs; $r_{ij}$ is the regret of joint strategy $(s_j, o_j)$, which is defined as a ratio of the absolute regret to the optimal objective-function value. Let $r_{ij}$ be elements of matrix $R$. A regret matrix $R(s, o_j)$ can be defined as follows:

$$R(s, o_j) = \{r_{ij}| i, j \}$$

(4)

Then, the MRR criterion can be determined as follows:

$$\text{MRR} = \min_{s \in S} \max_{o_j \in O} |R(s, o_j)| = \{r_{ij}| s_i \in S; o_j \in O \}$$

(5)

A regret $r_{ij}$ is always non-negative. An alternative that satisfies Eq. (5) is desired. Obviously, the MRR has an advantage in providing effective decision support under uncertainty; however, more uncertainties that exist in the left-hand sides and the objective function of model (2) may also need to be reflected. Interval-parameter programming (IPP) is an alternative for tackling uncertainties expressed as intervals that exist in the model’s left-hand and right-hand sides as well as the objective function (Suo et al., 2013). The IPP has advantages such that (i) it allows uncertainties to be directly communicated into the optimization process, (ii) it does not lead to more complicated intermediate models, and thus has a relatively low computational requirement and (iii) it does not require distributional information for model parameters, which is particularly meaningful for practical applications because it is typically much more difficult for planners/engineers to specify distributions than to obtain intervals (Huang et al., 1995; Zhang et al., 2014). An IPP model can be formulated as follows:

$$\text{Min}_{x} \sum_{j=1}^{n} c_j^x x_j$$

subject to:

$$\sum_{j=1}^{n} a_{ij}^x x_j \leq b_{ij}^x, i = 1, 2, ..., m \tag{6b}$$

$$x_j \geq 0, \forall j \tag{6c}$$

where $c_j^x$, $a_{ij}^x$, and $b_{ij}^x$ form a set of interval values with deterministic lower and upper bounds but unknown distribution information. The lower and upper bounds represent the minimum and maximum value of parameters, which can tackle uncertainties that generally cannot be quantified as either distribution functions or membership functions, since interval numbers are acceptable as its uncertain inputs (Suo et al., 2013). Consequently, to determine the hedging alternatives accounting for uncertainties expressed as discrete intervals, the concepts of IPP and MRR will be incorporated into a general framework. This leads to an interval minimax regret (IMMR) analysis model as follows:

$$\text{Min}_{s \in S} \left\{ \max_{o_j \in O} R(s, o_j) \right\}$$

subject to:

$$\sum_{j=1}^{m} \left[ a_{ij}^x x_j \right] \leq b_{ij}^x, r = 1, 2, ..., m; s_i \in S; o_j \in O \tag{7b}$$

$$\sum_{j=1}^{m} \left[ a_{ij}^x x_j \right] \leq b_{ij}^x, r = m+1, m+2, ..., m; s_i \in S; o_j \in O \tag{7c}$$

$$x_j \geq 0, j = 1, 2, ..., n_1 \tag{7d}$$

$$x_j \geq 0, j = 1, 2, ..., n_2 \tag{7e}$$

where $b_{ij}^x$ may take $q$ sets of fuzzy-interval numbers $(b_{ij,0}^x, b_{ij,1}^x, ..., b_{ij,q}^x)$, the objective is to minimize the worst-case regret value under uncertainty. A two-step method is proposed for solving the IMMR model. When the objective is to be minimized, a set of submodels corresponding to $f^r$ can be formulated firstly; then, the other set of submodels corresponding to $f^r$ can be formulated based on the solutions obtained from the first set of submodels (Li and Huang, 2008). Interval solutions for the IMMR model can then be obtained through integration of the solutions of the two sets of submodels. In detail, for each $b_{ij}^x$, the submodel (corresponding to $f^r$) can be formulated as follows:

$$\text{Min}_{x} \sum_{j=1}^{n} c_j^x x_j$$

subject to:

$$\sum_{j=1}^{m} \left[ a_{ij}^x \text{Sign}(a_{ij}^x) x_j \right] + \sum_{j=k+1}^{n} \left[ a_{ij}^x \text{Sign}(a_{ij}^x) x_j \right] + \sum_{j=1}^{n} \left[ a_{ij}^x \text{Sign}(a_{ij}^x) x_j \right]^2 \leq b_{ij}^x, \forall r; s_i \in S; o_j \in O \tag{8a}$$

$$\sum_{j=1}^{m} \left[ a_{ij}^x \text{Sign}(a_{ij}^x) x_j \right] + \sum_{j=k+1}^{n} \left[ a_{ij}^x \text{Sign}(a_{ij}^x) x_j \right] + \sum_{j=1}^{n} \left[ a_{ij}^x \text{Sign}(a_{ij}^x) x_j \right]^2 \leq b_{ij}^x, \forall r; s_i \in S; o_j \in O \tag{8b}$$

where

$$x_j^r \geq 0, j = 1, 2, ..., k_1 \tag{8d}$$

$$x_j^r \geq 0, j = k_1 + 1, k_1 + 2, ..., n_1 \tag{8e}$$

$$x_{j,so}^r \geq 0, j = 1, 2, ..., n_2; s_i \in S; o_j \in O \tag{8f}$$

$$x_{j,so}^r \geq 0, j = k_2 + 1, k_2 + 2, ..., n_2; s_i \in S; o_j \in O \tag{8g}$$

where $x_j^r (j = 1, 2, ..., k_1)$ and $x_{j,so}^r (j = 1, 2, ..., k_2)$ are the lower bounds of interval variables with positive coefficients in the objective function; $x_j^r (j = k_1 + 1, k_1 + 2, ..., n_1)$ and $x_{j,so}^r (j = k_2 + 1, k_2 + 2, ..., n_2)$ are upper bounds of interval variables with negative coefficients. Through solving the above $p \times q$ submodels (under different combinations of strategies and outcomes), a set of lower-bound objective-function values can be generated. Thus, a matrix of lower-bound system costs can be obtained as follows:

$$F_{so} = \begin{bmatrix} f_{s_1, o_1}^{r_1} & \cdots & f_{s_1, o_q}^{r_1} \\ \vdots & \ddots & \vdots \\ f_{s_n, o_1}^{r_1} & \cdots & f_{s_n, o_q}^{r_1} \end{bmatrix}$$

(9)

Based on the solutions obtained from the lower-bound submodels, a set of submodels (corresponding to $f^r$) can be formulated as follows:
Min \[ f_{so}^+ = \frac{k_1}{j-1} c_j^+ x_j^+ + \sum_{j=k_1+1}^{n_1} c_j^+ x_j^+ + \frac{k_2}{j-1} c_j^+ x_j^+ + \sum_{j=k_2+1}^{n_2} c_j^+ x_j^+ \]  (10a)

Subject to:

\[ \sum_{j=1}^{k_1} |a_{ij}| \text{Sign}(a_{ij}) x_j^+ + \sum_{j=k_1+1}^{n_1} |a_{ij}| \text{Sign}(a_{ij}) x_j^- + \frac{k_2}{j-1} |a_{ij}| \text{Sign}(a_{ij}) x_j^+ + \sum_{j=k_2+1}^{n_2} |a_{ij}| \text{Sign}(a_{ij}) x_j^+ \leq b_j^+, \forall r,s_i \in S, o_j \in O \]  (10b)

\[ x_j^+ \geq x_j^+ \text{opt}, j = 1, 2, ..., k_1 \]  (10c)

\[ 0 \leq x_j^- \leq x_j^+ \text{opt}, j = k_1 + 1, k_1 + 2, ..., n_1 \]  (10d)

\[ x_{so}^+ \geq x_{so}^+ \text{opt}, j = 1, 2, ..., k_2; s_i \in S, o_j \in O \]  (10e)

\[ 0 \leq x_{so}^- \leq x_{so}^+ \text{opt}, j = k_2 + 1, k_2 + 2, ..., n_2; s_i \in S, o_j \in O \]  (10f)

By solving the above submodels, the matrix of upper-bound system costs can be obtained as follows:

\[ F_{so}^+ = \begin{bmatrix} f_{s_1 o_1}^+ f_{s_1 o_2}^+ \cdots f_{s_1 o_k}^+ \\ f_{s_2 o_1}^+ f_{s_2 o_2}^+ \cdots f_{s_2 o_k}^+ \\ \vdots \\ f_{s_n o_1}^+ f_{s_n o_2}^+ \cdots f_{s_n o_k}^+ \end{bmatrix} \]  (11)

Eqs. (9) and (10) can be integrated to generate the matrix of interval system benefits across all possible scenarios as follows:

\[ F_{so}^- = \begin{bmatrix} f_{s_1 o_1}^- f_{s_1 o_2}^- \cdots f_{s_1 o_k}^- \\ f_{s_2 o_1}^- f_{s_2 o_2}^- \cdots f_{s_2 o_k}^- \\ \vdots \\ f_{s_n o_1}^- f_{s_n o_2}^- \cdots f_{s_n o_k}^- \end{bmatrix} \]  (12)

where \( F_{so}^+ = [F_{so}^+ F_{so}^-] \), with \( s_i \in S \) and \( o_j \in O \). Then, the matrix of interval costs can be transformed into a regret matrix with interval elements. Interval-parameters regret can provide underlying differences in perceived regret and be directly comparable in different scenarios. Let \( f_{so}^- f_{so}^+ \cdots f_{so}^- \) be the least lower-bound costs of the best strategy among all possible outcomes of \( O = \{o_1, o_2, o_3, ..., o_k\} \), respectively. Thus, the following relative interval regret matrix can be obtained:

\[ R_{so} \begin{bmatrix} f_{s_1 o_1} - f_{s_1 o_1} & f_{s_1 o_2} - f_{s_1 o_2} & \cdots & f_{s_1 o_k} - f_{s_1 o_k} \\ f_{s_2 o_1} - f_{s_2 o_1} & f_{s_2 o_2} - f_{s_2 o_2} & \cdots & f_{s_2 o_k} - f_{s_2 o_k} \\ \vdots & \vdots & \ddots & \vdots \\ f_{s_n o_1} - f_{s_n o_1} & f_{s_n o_2} - f_{s_n o_2} & \cdots & f_{s_n o_k} - f_{s_n o_k} \end{bmatrix} \]  (13)

The predesigned strategy with the relative regret value satisfying Eq. (14) is desired for decision makers. The proposed IMRR method can deal with complex problems for regional ecosystem management and planning. Particularly, it can minimize the maximum regret value incurred under the targets pre-regulated by authority and handle uncertainties expressed as intervals without known probabilistic distributions. The seeking procedure of the global optimum solution for regional ecosystem planning problem is easy, such that it is possible to apply the IMRR method to large-scale practical problems.

3. The study system

The City of Dongying is located in the northern part of Shandong Province (China), and lies in the downstream of the Yellow River Basin, which is close to Binzhou, Zibo and Weifang cities. The study city is an important part of Circum-Bohai-Sea region and Jiaodong Peninsula. Its area is around 7923 km² (Fig. 1) and includes two districts (i.e., Dongying and Hekou) and three counties (i.e., Guangrao, Lijin and Kenli). In 1970s, the city was an important base of petroleum production and possesses single-structure industry. The gross industrial output was only RMB¥ 5.54 × 10⁶, which was fell far behind the national average level of industrialization. With the growth of local population and the shift of industrial structure, the local land resources have been unable to meet the increasing land demand from the industry development and resident growth. Correspondingly, a number of reclamation projects have been implemented along the coastal line to mitigate the shortage of land resources. In the study area, land reclamation can date back to the end of 1970s. The reclamation land was firstly used as saltpans before the economic reform policy was implemented. In 1980s, a variety of small bays and lagoons were enclosed to raise shrimp or economic fishery, leading to that these small bays and lagoons were disappeared due to sedimentation (Wu et al., 2012). Since 1990s, reclaimed land was transformed into industrial districts and harbor/port sections.

Currently, the coastal land reclamation has become an important manner for the local government to acquire land resources for supporting its socio-economic development. In the past decades, the city has become one industrial center and driving force for economic stimulus in Shandong Peninsula, including
machinery, marine chemical industry, petroleum chemical industry, fine chemical industry, energy, and food production. Among them, petrochemical and energy-related industries are the primary ones. In 2012, the yield of petroleum of local Shengli Oil Field is among the top three in China, which reached 33.55 million tonne; while the gross industrial output was RMB¥ 1.81 × 10^{12}, with approximately 80% of the total value being from the chemical industry. Besides, the population was approximately 2.03 million in 2011, with a growth rate of around 1.27% per year (SYD, 2012). Obviously, land reclamation projects have brought huge benefit and make a significant contribution to local economic development and urbanization level.

Although the city has achieved rapid economic development in recent decades, the coastal land reclamation projects have resulted in a series of damages to coastal ecosystems as well as the ecological services they provide. In the past 30 years, the total area of natural wetland, mudflat and tidal flat has disappeared about 37.89% in the study area, with an increase from 0.24 to 0.32 in the landscape fragmentation index (Zhang et al., 2009). Land reclamation occupies marine space, permanently change the intrinsic natural quality (e.g., topography, physiognomy and shoreline), and alter the hydrodynamic effect of sediment transport or inshore current systems, as well as endanger the animals and plants (e.g., benthic organisms and mangroves) (Lu et al., 2002). For example, phytoplankton, the major producer of organic matter in marine, plays an important role in gas regulation service through photosynthesis. According to Liang and Zhang (2011), the Shannon-Weaver diversity index of phytoplankton decreased about 50% from 1983 to 2004. Besides, land reclamation projects have severely threatened to the surrounding wetlands. Be regarded as the “kidneys” of the earth, wetland ecosystem is famous for maintaining regional ecological balance, protecting biological diversity. However, fast population growth, long term clearance of natural resource, rapid expansion of built-up areas and cultivated lands, degrade the local wetland ecological conditions, and impair its ability to regulate runoff and increase the damage caused by marine disasters. After reclamation, the vast patches of the natural coastal wetlands are turned into croplands or urban and industrial zones. With the urbanization of surrounding areas, the wetland area is continuing to decrease.

In order to maintain regional ecosystem sustainability, local decision makers have advanced a series of market-based control measures to mitigate the conflict between economic development and eco-environmental protection (You et al., 2014). Among them, ecological compensation mechanism is one of key tools to protect and sustainable use ecosystem services, and to adjust the distribution of costs and benefits between the interests of different actors and stakeholders, mainly through economic measures (Liu et al., 2014). The basic idea is to make decision makes consider the full costs associated with land reclamation projects, including damages to the coastal and wetland ecosystems (SOA, 2009). Without ecological compensation, the stakeholders only pay private costs (e.g., construction and operating costs). The ecological compensation mechanism is designed to internalize the externalities of different land use patterns such that excessive development activities can be curbed effectively (CICED, 2012). In general, with the effect of land reclamation projects, decision makers desire to develop a sound ecosystem management plan to promote regional development in a sustainable manner.

4. Modeling formulation

A relative interval-regret analysis (RIRA) model is to be formulated for planning the regional ecosystem sustainability. Land reclamation could make a significant contribution to local economic development; however, the surplus land reclamation could lead to waste of land resources if the land cannot be utilized effectively. Moreover, more wetland and marine space are occupied, leading to huge ecological compensation costs as well as serious eco-environmental problems. Thus, the objective of study system is to maximize system benefit through planning the limited land resources for diversiform use patterns (i.e., industrial districts and port section). The objective function can be formulated as:

\[
\text{Max } f_{SO} = \sum_{i=1}^{5} NB_{i}^{z} \times X_{i,50} + \sum_{i=1}^{5} EC_{i}^{z} \times Y_{i,50} \times B_{1,50} + \sum_{i=1}^{5} E_{i}^{z} \times Z_{i,50} \times B_{2,50}
\]

(15-1a)

In this study, four main industrial districts (i.e., petrochemical, marine chemical, fine chemical and energy-related industries) and
local port section are mainly considered. These industries could bring huge benefit and make a significant contribution to local economic development. However, chemical industry and energy production contribute significantly to the local environmental pollution. In order to satisfy the environmental and ecological requirements and reduce the penalty due to excess emission, it is imperative to mitigate pollutant emissions. A number of pollutants such as sewage, particulate matter with particle size below 10 μm (PM_{10}), sulfur dioxide (SO_{2}), and solid waste are taken into consideration. The amount of each pollutant is determined by various conversion, process and transforming activities and the associated emission rates. These pollutant treatment costs should also be incorporated into the optimization process. Then, the net benefit (industrial income minus treatment cost of pollutant emissions) obtained from a variety of industrial activities can be presented as:

\[
NB_{i}^{±} = P_{i}^{±} × PW_{i}^{±} × PI_{i}^{±} × WC_{i}^{±} - PPM_{i}^{±} × PH_{i}^{±} × PMC_{i}^{±} - PSO_{i}^{±} × PI_{i}^{±} × SOC_{i}^{±} + PSF_{i}^{±} × PI_{i}^{±} × \eta_{i} × SK_{i}^{±} - PS_{i}^{±} × PI_{i}^{±} × (1 - \eta_{i}) × SC_{i}^{±},
\]

(15-1b) Since different ecosystems may have varied ecological structures and functions that provide different ecosystem services and the severity of damages to the coastal ecosystems could also vary with land uses, the ecological compensation standard can be obtained through evaluation of ecosystem service losses for different reclaimed land use patterns. In this study, eleven ecosystem services are taken into account, including three direct services (production of hay, reed and seafood) and eight indirect services (gas regulation, water supply, wastewater treatment, soil retention, nutrient regulation, air pollutant absorption, recreation and ecotourism). These service values are evaluated using two approaches: (1) direct market approach is used where market prices of outputs (and inputs) are available, which includes productivity loss and public pricing methods; (2) surrogate market approach is used to establish a surrogate market from which the shadow prices can be derived, including substitute cost, restoration cost and travel cost methods (Wang et al., 2010). For example, timber is valued at local market prices net of input costs and extraction costs; besides, the values of absorbing CO_{2} and releasing O_{2} can be evaluated using surrogate market approach. According to the formula of photosynthesis and respiration, when wetland ecological park absorbs 1 g CO_{2}, 0.73 g O_{2} can be released (Chen et al., 2004). The value of gas regulation services can be estimated by investigating the costs associated with fixing CO_{2} and supplying O_{2} and the amount of CO_{2} absorbed by ecosystems per unit area and time. Similarly, other ecosystem services can be evaluated based on benefit transfer. Therefore, the ecological compensation cost (EC_{i}^{±}) can be estimated as follows:

\[
EC_{i}^{±} = PHA_{i}^{±} × HA_{i}^{±} + PRE_{i}^{±} × RE_{i}^{±} + PSF_{i}^{±} × SF_{i}^{±} + CP_{i}^{±} × C + 0.73 × CP_{i}^{±} × O + PW_{i}^{±} × WC_{i}^{±} + RP_{i}^{±} × RO × RCI + ZP_{i}^{±} × ZC_{i}^{±} + ZP_{i}^{±} × \left(\sum_{p=1}^{s} OL_{p}^{±} × PI_{p}^{±} + I_{p}^{±}\right) × FP_{i}^{±} × PMC_{i}^{±} + 365 × YCT_{i}^{±} × YM_{i}^{±}.
\]

If the actual reclaimed land is lower than the value anticipated by decision makers, a shortage could be thus generated and the industrial production may be reduced arising from land scarcity. To guarantee the basic demands, land shortage from reclaimed land resources should be supplemented through purchasing available land in the study area. Besides, more manpower and material resources are needed, leading to more land use cost. Accordingly, the economic losses (EL_{i}^{±}) due to reclaimed land shortage can be expressed as:

\[
EL_{i}^{±} = LU_{i}^{±} + \sigma × (MA_{i}^{±} + MR_{i}^{±})
\]

(15-1d) Constraints of the RIRA model can help define the interrelationship among decision variables, available resources, pollutant treatment capacities, environmental requirement and ecosystem threshold. These constraints include a number of inequalities which describe various impact factors and their interactions. Thus, we have:

(1) Constraints of available land resources:

\[
\sum_{i=1}^{5} X_{i,50}^{±} = T_{5,i}^{±}, s \in S
\]

(15-2a)

\[
\sum_{i=1}^{5} X_{i,50}^{±} + \sum_{i=1}^{5} Y_{i,50}^{±} × B_{1,50} - \sum_{i=1}^{5} Z_{i,50}^{±} × B_{2,50} \leq Q_{5}, o \in O
\]

(15-2b)

(2) Constraint of available water resources:

\[
\sum_{i=1}^{4} P_{i}^{±} × PW_{i}^{±} × \left(X_{i,150}^{±} + Y_{i,150}^{±} × B_{1,50} - Z_{i,150}^{±} × B_{2,50}\right) (1 - TR_{i}^{±} × GW_{i}^{±}) ≤ AVW_{i}^{±}
\]

(15-2c)

(3) Capacity constraint of wastewater treatment:

\[
\sum_{i=1}^{4} P_{i}^{±} × PW_{i}^{±} × \left(X_{i,150}^{±} + Y_{i,150}^{±} × B_{1,50} - Z_{i,150}^{±} × B_{2,50}\right) - WT_{i}^{±} ≤ TPC_{i}^{±}
\]

(15-2d)

(4) Constraint of COD-discharge allowance:

\[
TR_{i}^{±} × (1 - GW_{i}^{±}) × GBCOD × \sum_{i=1}^{4} P_{i}^{±} × CODF_{i}^{±} × \left(X_{i,150}^{±} - Y_{i,150}^{±} × B_{1,50} + Z_{i,150}^{±} × B_{2,50}\right) + (1 - TR_{i}^{±}) × \sum_{i=1}^{4} P_{i}^{±} × CODF_{i}^{±} × \left(X_{i,150}^{±} - Y_{i,150}^{±} × B_{1,50} + Z_{i,150}^{±} × B_{2,50}\right) ≤ AVCOD_{i}^{±}
\]

(15-2e)

(5) Constraint of PM_{10} emission allowance:

\[
\sum_{i=1}^{4} P_{i}^{±} × PPM_{i}^{±} × \left(X_{i,150}^{±} - Y_{i,150}^{±} × B_{1,50} + Z_{i,150}^{±} × B_{2,50}\right) × (1 - PO_{i}^{±}) ≤ TPM_{i}^{±}
\]

(15-2f)

(6) Constraint of SO_{2} emission allowance:

\[
\sum_{i=1}^{4} P_{i}^{±} × PSO_{i}^{±} × \left(X_{i,150}^{±} - Y_{i,150}^{±} × B_{1,50} + Z_{i,150}^{±} × B_{2,50}\right) × (1 - SO_{i}^{±}) ≤ SEC_{i}^{±}
\]

(15-2g)
(7) Constraint of solid waste discharge allowance:

\[
\sum_{i=1}^{4} p_{f_i}^{+} \times PSO_{j}^{+} \times \left( X_{x, i}^{+} - Y_{x, i}^{+} \times B_{1,i} + Z_{x, i}^{+} \times B_{2,i} \right) \times (1 - \eta_i) \leq TSV^{+} \tag{15-2h}
\]

(8) Soil erosion constraint:

\[
\sum_{j=1}^{5} Z_{j}^{+} \times \left( X_{x, j}^{+} - Y_{x, j}^{+} \times B_{1,j} + Z_{x, j}^{+} \times B_{2,j} \right) \leq TSL^{+} \tag{15-2i}
\]

(9) Constraint of water resources demand of wetland:

\[
(1 - \alpha) \times R_{Ei}^{+} \times RO \times \frac{K}{n} \times X_{i} \times \sum_{e=1}^{E} Q_{e\min} \leq \frac{K}{n} \times X_{i} \times \sum_{e=1}^{E} Q_{e\min} \tag{15-2j}
\]

(10) Land reclamation intensity constraint:

\[
\frac{\left( \sum_{j=1}^{5} X_{j, s}^{+} - \sum_{j=1}^{5} Y_{j, s}^{+} \times B_{1,j} + \sum_{j=1}^{5} Z_{j, s}^{+} \times B_{2,j} \right)}{CL} \leq (1 - \mu) \times TL^{+} \tag{15-2k}
\]

(11) Nonnegative constraint:

\[
X_{x, s}^{+} \geq Z_{x, s}^{+} \quad \forall i, j, s \in S, o \in O \tag{15-2l}
\]

\[
Y_{j, s}^{+}, Z_{j, s}^{+} \geq 0 \quad \forall i, j, s \in S, o \in O \tag{15-2m}
\]

(12) Binary constraint:

\[
B_{1,s} \begin{cases} 
1 & \text{if land area shortage occurs} \\
0 & \text{if otherwise} 
\end{cases} \tag{15-2n}
\]

\[
B_{2,s} \begin{cases} 
1 & \text{if land area surplus occurs} \\
0 & \text{if otherwise} 
\end{cases} \tag{15-2o}
\]

\[
0 \leq B_{1,s} + B_{2,s} \leq 1, s \in S, o \in O \tag{15-2p}
\]

The detailed nomenclatures for the variables and parameters are provided in Appendix. The uncertain information for system components may exist in terms of intervals without knowing their probabilities. Land availability for different uses is divided into six intervals, they are [45.71, 85.04] × 10³, [58.55, 100.64] × 10³, [77.55, 116.64] × 10³, [91.54, 131.61] × 10³, [106.01, 146.05] × 10³, and [119.82, 162.05] × 10³ m². Under such a condition, decision makers have to determine the amount of land allocated to each industrial district when the reclaimed land availability is of uncertain feature. They can make a decision in advance based on each possible level, and then six land-use strategies are predesigned in this study. Consequently, thirty-six scenarios examined that are combinations from different strategies of land reclamation and various outcomes of available land would be generated.

The representative data are investigated based on a number of government reports and a variety of related literature. Table 1 presents the modeling inputs for the petrochemical, marine chemical, fine chemical and energy-related industries, including product benefit, water consumption rate, wastewater discharge, COD-generation rate and PM_{10} generation rate. In the study area, available water resources include surface water, groundwater, sea water, desalination, and recycled water. The water supply of Dongying would be [96.11, 108.65] × 10³ m³. According to the water resource planning, the annual water resources for industry are planned to be [32.67, 55.41] × 10³ m³. The percentage for concentrated wastewater and the recycle of treated wastewater would be 81% and 87%, respectively. Meanwhile, a new sewage discharge standard was promulgated in 2008, and the concentration of COD discharged has a more stringent restrict for [50.60] mg/L (Dongying Environmental Protection Agency, 2008). In addition, a number of policies would be implemented to reduce the air-pollutant emissions and guarantee air quality. The centralized treatment ratio for PM_{10} and sulfur dioxide was 87,89% in 2013 and it is expected to increase up to 91% at the end of planning horizon. The local existing landfill, incineration and composting facilities are not available to serve the industrial solid waste treatment needs, the local decision makers plan to develop a large-scale industrial solid waste treatment plan with the capacities of [80.50, 105.55] tonne/day and the comprehensive reutilization ratio of 85%.

Land reclamation would result in variable ecosystem and natural resource losses at different spatial scales. Table 2 lists the ecosystem service losses for different land use patterns. For example, around 81% of COD input was removed due to sedimentation in the ditch and accumulation and mineralization in the wetland soil. The biochemical degradation capacity of COD is [0.14, 0.33] tonne/m², while the average cost for treating sewage is [5.4, 6.2] RMB/tonne. Related modeling inputs are expressed as interval values due to the uncertain features and inaccurate information. For example, soil erosion modulus may depend on many factors such as topography, soil properties, rainfalls and vegetation coverage. These factors cause the variation of soil erosion modulus in a range. Thus, the soil erosion modulus has difficulties in being expressed as a deterministic value; instead, it can be presented as intervals. In addition, the data of planned and reclaimed land area are collected from Dongying Twelfth Five-Year

| Land use pattern | Product benefit (10^{9} RMBs/ ton) | COD generation rate (kg/ tonne) | Water consumption rate (kg/ tonne) | Wastewater discharge (kg/ tonne) | PM_{10} generation rate (kg/ tonne) |
|------------------|----------------------------------|---------------------------------|---------------------------------|---------------------------------|----------------------------------|
| PC               | [5.42, 7.67]                     | [0.87, 1.07]                    | [13.25, 16.19]                  | [0.99, 1.21]                    | [0.14, 0.19]                      |
| FC               | [4.45, 5.58]                     | [7.19, 8.79]                    | [10.11, 12.35]                  | [3.35, 4.09]                    | [0.19, 0.25]                      |
| MC               | [8.10, 9.20]                     | [1.21, 1.48]                    | [2.11, 2.58]                    | [0.94, 1.15]                    | [0.07, 0.10]                      |
| ER               | [3.64, 4.05]                     | [0.65, 0.79]                    | [4.31, 5.27]                    | [2.84, 3.47]                    | [0.38, 0.52]                      |
Table 2  
Ecosystem service losses for different land use patterns.

| Land use pattern | PC        | FC        | MC        | ER        |
|------------------|-----------|-----------|-----------|-----------|
| Hay production (tonne/m²) | [0.13, 0.22] | [0.24, 0.34] | [0.15, 0.21] | [0.17, 0.29] |
| Reed production (tonne/m²) | [0.52, 0.66] | [0.21, 0.27] | [0.49, 0.70] | [0.18, 0.25] |
| Carbon absorption (tonne/m²) | [0.04, 0.07] | [0.07, 0.10] | [0.02, 0.06] | [0.07, 0.11] |
| Purification of water (tonne/m²) | [0.31, 0.32] | [0.32, 0.33] | [0.14, 0.16] | [0.22, 0.28] |
| Water conservation (tonne/m²) | [0.57, 0.62] | [0.38, 0.44] | [0.68, 0.80] | [0.34, 0.39] |
| Soil erosion module (kg/m²) | [3.32, 5.66] | [3.65, 4.67] | [2.68, 2.70] | [3.48, 3.70] |
| Content of P elements (%) | 0.42 | 0.42 | 0.41 | 0.42 |
| Content of N elements (%) | 0.12 | 0.14 | 0.16 | 0.19 |
| Content of K elements (%) | 0.85 | 0.91 | 0.76 | 0.82 |
| Soil organic matter (%) | 7.02 | 7.02 | 7.09 | 7.11 |
| Air-pollutant absorption (tonne/m²) | [0.12, 0.16] | [0.15, 0.17] | [0.17, 0.22] | [0.21, 0.24] |

Plan (2012), Dongying municipality’s ecosystem construction master plan (2003–2020) and Dongying land reclamation projects planning outline (2010).

5. Results analysis

In this study, 36 scenarios were examined based on six strategies and six outcomes under different land reclamation levels. Table 3 shows the resulting system benefits and relative regret values under all scenarios, demonstrating a tradeoff between the maximized system benefit and maximized system feasibility (or minimized system risk). The relative regret would be generated when the difference between the anticipated and actual land availability exists, and the relative regret matrix with interval elements could reflect the disparity not only between the system benefit of each chosen strategy and the optimal one, but also between the lower and upper bounds of the system benefit. The results indicate that variations in predefined strategies and actual land reclamation outcomes would lead to varied system benefits. Moreover, the maximum relative regret would be [0.64, 0.97], demonstrating the largest disparity would occur under strategy 1. The interval regret matrix can reflect not only the distance between the objective function values under the chosen and ideal alternatives, but also the difference between lower and upper bounds of the objective function value.

Fig. 2 reveals the variations of relative regrets with land reclamation strategies under different outcomes of available land. Results imply that the relative regret would increase along with a raised disparity between the anticipated and actual land availability. For the lower-bound curve, the maximum disparity of relative regret would exist if strategy 1 (corresponding to the lowest target anticipated) is adopted; for the upper-bound curve, the maximum disparity of relative regret would occur under strategy 6 (corresponding to the highest target anticipated). It is concluded that both a too-low and a too-high anticipated target would lead to a large fluctuation of relative regret with outcomes and poor system feasibility. Fig. 3 presents the maximum relative regrets under different land reclamation strategies. The minimal lower-bound regret level would be 0.34 under strategy 3; the minimax upper-bound regret level would 0.73 under strategy 4.
According to IMRR criterion analysis, the optimal land reclamation target would be in the range of $[77.55, 131.61] \times 10^6 \text{m}^2$, where $77.55 \times 10^6 \text{m}^2$ corresponds to demanding conditions and $131.61 \times 10^6 \text{m}^2$ is related to more advantageous conditions. If such an optimal alternative is adopted, the system would achieve a minimized maximum relative regret, and the penalties caused by overestimation or underestimation for land availability could also be minimized.

The optimal decision alternative for land use patterns could be obtained, which provides an effective linkage between regional economic development and eco-environmental protection. Under the optimal alternative, the total area of $[77.55, 130.56] \times 10^6 \text{m}^2$ of the coastal wetland and tidal flat would be reclaimed into industrial districts or port sections. Among them, the optimized land use targets for the petroleum chemical, marine chemical, fine chemical, energy-related industries and ports would be $[11.61, 18.45], [5.64, 13.52], [8.48, 21.91], [30.69, 58.03]$ and $[18.58, 18.65] \times 10^6 \text{m}^2$, respectively. Table 4 shows the optimized land-use schemes of different activities. The deficits are related to land availability and land use target, which would occur if the available land do not meet the targets. For example, when the actual land reclamation level is low, the available land area would be $[44.97, 85.01] \text{m}^2$. When strategy 3 (S3) is adopted, the available land would be delivered to petroleum chemical and marine chemical industries, demonstrating a priority of land use to these industries. Land shortage would occur for energy-related industries (i.e., $24.35 \times 10^6 \text{m}^2$), which is restricted to the fact that the benefit is relatively low associated with the more pollutant emissions. The optimal allocation to fine chemical industries is equal to zero, indicating that no land would be delivered. Compared with S3, energy-related industries would obtain $26.09 \times 10^6 \text{m}^2$ land resources from the reclamation projects, followed by port section with a share of $18.65 \times 10^6 \text{m}^2$ when strategy 4 (S4) is adopted. However, although more available land can be used, the shortage is raised. To maximize the system benefit, there would be $18.35 \times 10^6 \text{m}^2$ and $24.86 \times 10^6 \text{m}^2$ land shortages to fine chemical and energy-related industries, respectively. The land use target of marine chemical industries is guaranteed under such a situation. The solutions under the other reclamation levels can be similarly analyzed.

Land shortage and surplus to different use patterns under optimal strategies are shown in Fig. 4. Land shortage (with negative sign) would be generated if the available land area is lower than the target anticipated; conversely, surplus would occur when land availability is greater than the planning target. When S4 is adopted, shortage tends to be generated. The results imply that the land demands of fine chemical and energy-related industries should be first curtailed in the case of insufficient land availability. By contrast, the land planned to marine chemical industries and/or ports should be first guaranteed since they would contribute higher benefits for local economy and discharge relatively less pollutant when the targets are satisfied. The surplus may occur under the high and very-high land reclamation level, and excess land would be used to port construction. When S3 is accepted, land surplus would be likely to occur, and most of the surplus would be used to petroleum chemical industries.

Fig. 5 presents the solutions of evaluation ecosystem service losses when the optimal decision alternatives are undertaken. Under the optimal strategies, the total ecosystem service losses caused by the excessive reclamation would be RMB $[1.40, 2.64] \times 10^8$. Results indicate that the land reclamation in the study area would cause significant damages to the soil retention and nutrient regulation services, accounting for around $[18.06, 33.28]\%$ of the total losses of ecosystem services. The soil retention and nutrient regulation services mainly depend on the structural aspects of ecosystems, especially vegetation cover and root system, which is contributed to protecting soil organic and inorganic fertility. Besides, reclamation would change seaside and sandy beaches which provide the esthetic and recreational service. The values of recreation and ecotourism occupy $[9.12, 11.45]\%$ of the total ecosystem service value. With the increasing visitors, the demand for recreation in natural areas (‘eco-tourism’) will most likely continue to increase in the future. Moreover, if properly managed, the natural wetland would continuously provide ecosystem services into the future without decreasing their productivity. Unfortunately, in the study area, the ecosystem system services would also suffer the severe shrink induced by large-scale land reclamation projects along the coastal line.

In the model, pollutant-emission reduction (i.e., COD and SO$_2$) was taken into consideration to satisfy the environmental and
Table 4
Land use targets and solutions under the optimal strategy.

| Outcome | User | Strategy 3 (10^6 m²) | Strategy 4 (10^6 m²) |
|---------|------|----------------------|----------------------|
|         |      | Optimal allocation   | Optimal allocation   |
| L       | PC   | 11.63                | 11.63                |
|         | FC   | 5.64                 | 0                    |
|         | MC   | 12.74                | 12.74                |
|         | ER   | 26.43                | 2.08                 |
|         | PO   | 18.55                | 18.55                |
|         |      |                      |                      |
| L-M     | PC   | 10.75                | 10.75                |
|         | FC   | 5.64                 | 0                    |
|         | MC   | 14.56                | 14.56                |
|         | ER   | 27.94                | 18.59                |
|         | PO   | 16.11                | 16.11                |
| M       | PC   | 11.61                | 11.61                |
|         | FC   | 5.64                 | 5.64                 |
|         | MC   | 8.48                 | 8.48                 |
|         | ER   | 30.69                | 30.69                |
|         | PO   | 18.55                | 18.55                |
| M-H     | PC   | 17.05                | 31.55                |
|         | FC   | 5.64                 | 5.64                 |
|         | MC   | 18.50                | 18.50                |
|         | ER   | 15.25                | 15.25                |
|         | PO   | 18.55                | 18.55                |
| H       | PC   | 17.05                | 35.14                |
|         | FC   | 5.64                 | 5.64                 |
|         | MC   | 18.50                | 28.01                |
|         | ER   | 15.25                | 15.25                |
|         | PO   | 18.55                | 20.96                |
| V-H     | PC   | 17.05                | 33.99                |
|         | FC   | 5.64                 | 5.64                 |
|         | MC   | 18.50                | 27.17                |
|         | ER   | 15.25                | 24.91                |
|         | PO   | 18.55                | 28.28                |

For the excessive land reclamation, the eco-compensation cost would be undertaken to promote regional ecosystem protection and develop socio-economic sustainability, which can be concluded by evaluating ecosystem service losses. The solutions of ecological compensation cost under medium-high, high and very-high outcomes. Results indicate that the ecological compensation costs would increase along with a raised land reclamation level. For example, when strategy 1 is adopted, the ecological compensation cost of petroleum chemical industry would be RMB [5.51, 9.37] × 10^5 and RMB [9.06, 17.11] × 10^5 under the reclaimed level of H and V-H, respectively. Similarly, under strategy 3, the ecological compensation cost of marine chemical industry would be RMB [2.68, 3.46] × 10^5 and RMB [3.65, 3.98] × 10^5 under the reclaimed level of H and V-H, respectively. Besides, the reclamation projects for port construction would undertake the higher eco-compensation cost than other land use patterns, which reveals local marine ecosystem has suffered the severe degradation induced by port construction.

**Fig. 6** shows the lower and upper values of COD from various chemical industry activities under the optimal decision alternatives, indicating that the amount of COD discharged from petrochemical industry is the highest. For example, when the actual land reclamation level is low, the amount of COD discharged from petrochemical industries would be [9.78, 13.83] tonne per year, accounting for around [54.12, 58.59]% of the total regional industrial emissions. In addition, the results indicate that, the total amount of COD emissions would have a pronounced tendency to increase, which is mainly because the surplus land would be used to the industries of high-pollution discharge. Currently, the centralized COD treatment ratio would be [81.92, 84.41]% in the study area. In order to improve the local water quality, it would increase the efficiency and intensity of centralized wastewater treatment, and formulate the corresponding standards to strictly control and manage the sewage to be discharged. **Fig. 7** presents the amount of SO₂ emission from various industries. The amount of SO₂ generated by energy-related industries would be highest, with the amount of [8.27, 21.88] tonne per year. In order to control regional SO₂ emission, small-scale energy-related facilities should be closed. Besides, advanced industrial pollutant treatment technologies must be installed to reduce the pollution emissions and to satisfy the stricter environmental requirements.

**For the excessive land reclamation, the eco-compensation cost would be undertaken to promote regional ecosystem protection and develop socio-economic sustainability, which can be concluded by evaluating ecosystem service losses. Fig. 8** presents the ecological requirement and reduce the penalty due to excess emission. **Fig. 6** shows the lower and upper values of COD from various chemical industry activities under the optimal decision alternatives, indicating that the amount of COD discharged from petrochemical industry is the highest. For example, when the actual land reclamation level is low, the amount of COD discharged from petrochemical industries would be [9.78, 13.83] tonne per year, accounting for around [54.12, 58.59]% of the total regional industrial emissions. In addition, the results indicate that, the total amount of COD emissions would have a pronounced tendency to increase, which is mainly because the surplus land would be used to the industries of high-pollution discharge. Currently, the centralized COD treatment ratio would be [81.92, 84.41]% in the study area. In order to improve the local water quality, it would increase the efficiency and intensity of centralized wastewater treatment, and formulate the corresponding standards to strictly control and manage the sewage to be discharged. **Fig. 7** presents the amount of SO₂ emission from various industries. The amount of SO₂ generated by energy-related industries would be highest, with the amount of [8.27, 21.88] tonne per year. In order to control regional SO₂ emission, small-scale energy-related facilities should be closed. Besides, advanced industrial pollutant treatment technologies must be installed to reduce the pollution emissions and to satisfy the stricter environmental requirements.
If the reclamation target is pre-regulated too low (e.g., the decision maker has a conservative attitude towards ecosystem planning), the corresponding policy may result in less shortage and thus lower land use cost but, at the same time, more ecological compensation costs would be needed when future reclamation level is high. Conversely, under a strategy for high land reclamation target, a plan with high reclamation level would be generated, resulting in a high system benefit; but, at the same time, a high risk of penalty would generate when the promised land is not delivered under demanding conditions (e.g., when future reclamation level is low). Therefore, different regional ecosystem plannings for the reclamation projects are associated with different levels of economic benefit and system-failure risk.

**Fig. 4.** Optimized land shortage or surplus under different outcomes [(a) lower bound, (b) upper bound].

**Fig. 5.** Ecosystem service losses under the optimal decision alternative.

**Fig. 6.** The amount of COD under the optimal decision alternative [(a) lower bound, (b) upper bound].
6. Discussion

In this study, eleven ecosystem services were taken into account, including three direct services (production of hay, reed and seafood) and eight indirect services (gas regulation, water supply, wastewater treatment, soil retention, nutrient regulation, air pollutant absorption, recreation and ecotourism). Among them, gas regulation, water supply and soil retention are the pivotal ecosystem services and functions for local coastal ecosystem sustainability, which could be estimated by the ecological factors of carbon sequestration coefficient, runoff coefficient and soil erosion module, respectively. Accordingly, sensitivity analysis was conducted to investigate the effects of different ecological factors (i.e., CP, RO and ZP) on the ecosystem service losses and system benefits. The statistic results of ecological factors (CP, RO and ZP) indicate that their fluctuation intervals would be [0.02, 0.10] tonne/m², [30.60, 60.68] kg/m² based on the lower and upper order statistic values. Each of ecological factors of CP, RO and ZP can be designed to vary conspicuously under the three conditions. For example, soil erosion module of ZP may equal 2.66 kg/m² (low), 4.17 kg/m² (medium), or 5.68 kg/m² (high). Correspondingly, there would be 27 combinations (i.e., 3 × 3 × 3 = 27) for the system benefits associate with the three sensitive factors.

Fig. 10 presents the system benefits under different ecological factors. When CP, RO and ZP values are 0.02 tonne/m², 30% and 2.66 kg/m², respectively, the system benefit would be RMB [241.7, 589.6] × 10⁵. When CP, RO and ZP are 0.10 tonne/m², 60% and 5.68 kg/m², respectively, the system benefit would be RMB [208.6, 535.5] × 10⁵. The results reveal that higher CP, RO and ZP would yield more ecosystem services losses, which would result in more eco-compensation costs in the study area. Besides, the variations of other ecological factors can also lead to different system benefits. For example, when the CR value decreases 1%, the system benefit could reduce RMB [3.7, 6.1] × 10⁴; the system benefit could cut down by RMB [1.1, 3.5] × 10⁶ as the RO value decreases 1%; when

Fig. 7. The amount of SO₂ emission under the optimal decision alternative [(a) lower bound, (b) upper bound].

Fig. 8. Ecological compensation cost under medium-high, high and very-high outcomes [(a) lower bound, (b) upper bound].
the ZP value reduces 1%, the system benefit would decrease RMB¥ $[21.6, 43.2] \times 10^6$. Therefore, much more eco-compensation cost could be saved as the ZP value decreases 1%, which indicates that soil erosion is the most sensitive ecological factor in the process of estimating the ecosystem service losses and calculating the system benefit.

Therefore, for the local regional ecosystem management, controlling the soil erosion of coastal wetland is the most important factor for reducing eco-compensation cost. Ecosystems maintain their functional integrity through a natural balance of materials and energy flowing through, cycling within, and leaving them. This equilibrium is supported by natural, physical, chemical and biological processes. The soil retention and nutrient regulation services mainly depend on the structural aspects of ecosystems, especially vegetation cover and root system, which is contributed to protecting soil organic and inorganic fertility. The presence of coastal ecosystems such as mangroves and coral reefs can prevent and alleviate damages caused by flooding and storm events in coastal zones. Meanwhile, carbon sequestration coefficient and runoff coefficient are also the significant ecological factors for the final decisions.

7. Conclusions

In this study, a relative interval-regret analysis (RIRA) method has been developed for regional ecosystem management under uncertainty by incorporating interval-parameter programming (IPP) and minimax relative regret (MRR) analysis within a general framework. Compared with the conventional systems analysis techniques, RIRA can handle uncertainties expressed as intervals and random variables without knowing probabilistic distributions and only needs a list of possible scenarios that may occur. Through converting an interval system cost/benefit matrix into a relative regret matrix, the economic consequences can be analyzed and the optimal alternative can be identified. The relative regret is less conservative than the absolute regret value, particularly in the situations in which the optimal objective function values differ significantly among all possible scenarios.

The RIRA method has been applied to a real case of regional ecosystem planning in Dongying, where the natural ecosystem has suffered the severe degradation induced by large-scale land reclamation projects along the coastal line. Modeling formulation can incorporate ecosystem service valuation techniques directly into its optimization process, such that an effective linkage between eco-compensation costs and ecosystem service losses can be provided. Thirty-six possible scenarios have been examined, demonstrating that complex tradeoffs among system benefit, ecological compensation cost, and relative regret value exist. Variations in outcomes of reclaimed land use strategies and ecological compensation schemes could lead to varied system benefits and relative regret values. Additionally, the relative regret value could increase along with a raised disparity between the anticipated and actual land availability. With the aid of the model, several findings can be disclosed based on the results in terms of regional ecosystem planning, land use pattern, ecological compensation analysis, and industrial pollution-mitigation scheme. Firstly, owing to higher product benefits and less pollutant emissions, a priority of land use to petrochemical and marine chemical industrial districts exists; the scales of fine chemical and energy-related industries should be systematically limited. Second, eco-compensation mechanism is indispensable to regional ecosystem management, which is designed to internalize the externalities of different land use patterns so that excessive development activities can be curbed effectively. For the excessive
reclamation, the eco-compensation cost is estimated as RMB¥ [563.05, 912.58] per m², which is much higher than current reclaimed land use charge of RMB¥ 180 per m². Thus, it is urgent to establish eco-compensation that covers wide range of ocean uses and is easy for coastal managers to implement. The compensation payments can be used to restore the damaged coastal ecosystem, as well as constructing the natural protection zones and the wetland ecological parks. Thirdly, land reclamation projects could bring huge benefits and make a significant contribution to local economic development, associated with large amount of pollutants discharging into nearby river, mudflat and tidal flat. Wastewater emissions are the main obstacles to regional eco-environmental sustainability, which are generated primarily from petrochemical industrial processes. Therefore, pollutant mitigation schemes are effective for decision makers to gain insight into the tradeoffs between economic objective and local environmental requirement. Correspondingly, the specific suggestions to the authorities can be summarized as follows: (i) advanced industrial pollutant treatment technologies (e.g., tertiary wastewater treatment and depth processing technologies) should be recommended to further improve pollutant removal efficiency; (ii) the investment for local ecological restoration should be further expanded to achieve regional economic-ecological sustainability; and (iii) while it may not be feasible to stop all reclamation activities in this area, it is imperative that future large-scale land reclamation projects should be systematically limited and based on rigorous eco-environmental impact analyses.

The interactions between coastal ecosystems and the human system are extremely complex, involving multiple pathways and feedbacks. Although this study is the first attempt to manage regional ecosystems through the IRRA method, there is still much space for improvement of the proposed method. For example, the ecosystem service losses calculated using direct market approach and surrogate market approach are all subject to the well-known imperfections, including the questionable assumption of perfect substitutability between ecosystem services and manmade alternatives, which has difficulties in obtaining more accurate ecosystem service functions. Besides, ecosystem can provide more service functions (e.g., genetic sources, biological control and biodiversity maintenance), such that other types of ecosystem services, as well as the non-use value, should be considered. These services play the significant roles in maintaining ecosystem

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**Fig. 10.** Benefits under different ecological factors of CP, RO and ZP with (a) 2.66 kg/m², (b) 4.17 kg/m² and (c) 5.68 kg/m².
functional integrity; therefore, it is necessary to advance more sophisticated methods to evaluate these services. Moreover, the ecological thresholds in the study area cannot be accurately evaluated and considered, when a system crossing a threshold, a small change in economic activity can have enormous impacts and result in irreversible loss of critical natural capital. On the other hand, the proposed model can only deal with uncertainties expressed as discrete intervals linearly related to its factors; many of these costs are nonlinear due to non-linear interactions in the natural systems. Therefore, the model could be further strengthened by considering of more uncertainties well as improving of its practical application to regional ecosystem planning.

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Appendix.

\[ f^+ \]
\[ i \]
Main reclaimed land use pattern benefit (RMBY) in the study area, \( i = 1, 2, \ldots, 5 \) (for petrochemical, marine chemical, fine chemical, energy-related industries and port transportation)

\[ X_{ij}^+ \]
Area of promised land to use pattern \( i \) when decision makers adopt strategy \( s \) under outcome of available land \( o \) (m²)

\[ Y_{ij}^+ \]
Area of land surplus under strategy \( s \) and outcome \( o \) (m²)

\[ Z_{ij}^+ \]
Area of land shortage under strategy \( s \) and outcome \( o \) (m²)

\[ NB_i \]
Net benefit for land use pattern \( i \) per unit area (RMBY/m²)

\[ EC_i \]
Ecological compensation cost for land use pattern \( i \) per unit area (RMBY/m²)

\[ EL_i \]
Shortage penalty for land use pattern \( i \) per unit area (RMBY/m²)

\[ B1_{ij} \]
Binary variable, identifying whether or not land surplus would occur under strategy \( s \) and outcome \( o \)

\[ B2_{ij} \]
Binary variable, identifying whether or not the water shortage would be undertaken under strategy \( s \) and outcome \( o \)

\[ P1_{ij} \]
Production of pattern \( i \) per unit area (tonne/m²/year)

\[ PP_{ij} \]
Product price of pattern \( i \) (RMBY/tonne)

\[ PW_{ij} \]
Sewage discharge of per production of land use pattern \( i \) (m³/tonne)

\[ WC \]
Sewage treatment cost (RMBY/m³)

\[ PPM_i \]
PM₁₀ emissions of per production of land use pattern \( i \) (tonne/tonne)

\[ PMC_i \]
PM₁₀ treatment cost (RMBY/tonne)

\[ PSO_i \]
SO₂ emissions of per production of land use pattern \( i \) (tonne/tonne)

\[ SOC_i \]
SO₂ treatment cost (RMBY/tonne)

\[ PS_i \]
Solid waste generation from per production of land use pattern \( i \) (tonne/tonne)

\[ \eta_{1_i} \]
Recycle rate of solid waste of land use pattern \( i \) (%)

\[ SR_i \]
Benefit for recyclable solid waste of land use pattern \( i \) (RMBY/tonne)

\[ SC_i \]
Solid waste treatment cost (RMBY/tonne)

\[ PHA_i \]
Loss of hay production per unit area of land use pattern \( i \) (tonne/m²/year)

\[ PRE_i \]
Loss of reed production per unit area of land use pattern \( i \) (tonne/m²/year)

\[ PSF_i \]
Loss of seafood production per unit area of land use pattern \( i \) (tonne/m²/year)

\[ HA_i \]
Hay price (RMBY/tonne)

\[ RE_i \]
Reed price (RMBY/tonne)

\[ SF_i \]
Seafood average price (RMBY/tonne)

\[ CP_i \]
Loss of carbon sequestration service per unit area of land use pattern \( i \) (tonne/m²/year)

\[ C \]
Carbon tax (RMBY/tonne)

\[ O \]
Oxygen price (RMBY/tonne)

\[ WP_i \]
Loss of water purification service per unit area of land use pattern \( i \) (tonne/m²/year)

\[ RP_i \]
Loss of water conservation service per unit area of land use pattern \( i \) (tonne/m²/year)

\[ RO \]
Rainfall runoff coefficient (%)

\[ RCI \]
Water price (RMBY/m³)

\[ ZI_i \]
Soil erosion index (tonne/m²/year)

\[ ZCI_i \]
Price of river dredging and cleaning (RMBY/tonne)

\[ OL_i \]
Soil element content (p %)

\[ PL_i \]
Soil elements in proportion of fertilizer (%)

\[ PF_i \]
Price of fertilizer (RMBY/tonne)

\[ FFP_i \]
Loss of pollutant absorption service per unit area of land use pattern \( i \) (tonne/m²/year)

\[ YCI \]
Per capital tourism consumption (RMB)

\[ YP \]
Tourism arrivals of ecotourism per unit area (per capita/m²)

\[ LU_i \]
Land use cost of Dongying (RMBY/m²)

\[ \sigma \]
Cost adjustment coefficient for more manpower and material resources

\[ MA_i \]
Manpower resources for land use pattern \( i \) per unit area (RMBY/m²)

\[ MR_i \]
Material resources for land use pattern \( i \) per unit area (RMBY/m²)

\[ T_i \]
Land use target estimated by decision makers under strategy \( s \) (m²)

\[ Q_i \]
Actual water availability under outcome \( o \) (m³)

\[ PW_i \]
Water consumption of per unit production of land use pattern \( i \) (m³/tonne)

\[ TR_i \]
Concentrated sewage treatment rate (%) (RMBY/m³)

\[ GW_i \]
Recycling rate of treated water from the sewage treating plants (%) (RMBY/m³)

\[ AVW_i \]
Regional total available water resources (m³/year)

\[ WT_i \]
Purification of sewage for wetland ecosystem (m³)

\[ TPC_i \]
Capacity of sewage treatment plant (m³/year)

\[ GBCOD \]
COD concentration of wastewater discharge in emission standard (tonne/m³)

\[ CODE_i \]
COD emissions of per unit production of land use pattern \( i \) (kg/tonne)

\[ AVCOD_i \]
Allowable amount of industrial COD emissions (kg/year)

\[ PO_i \]
Average PM₁₀ exhausting efficiency of collecting PM₁₀ facilities (%)

\[ TPM_i \]
Allowable amount of industrial PM₁₀ emissions (tonne/day)

\[ SO_i \]
Average SO₂ exhausting efficiency of collecting SO₂ facilities (%)

\[ SEC_i \]
Allowable amount of industrial SO₂ emissions (tonne/day)

\[ TSV_i \]
Allowable amount of industrial solid waste emissions (tonne/day)

\[ TSL_i \]
Allowable soil erosion area (m²)

\[ \alpha \]
Wetland hydrating coefficient (%)

\[ \eta \]
Statistical number of year

\[ e \]
Statistical number of month

\[ K \]
Conversion coefficient, value is 31.54 × 10⁶

\[ Q_{min} \]
Minimum monthly average runoff (m³/s)
CL Length of the coastline (m)
μ Ecological conservation level
TL Reclamation intensity coefficient (m)

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