Utilization effectiveness of marine functional zones using system dynamics for China: modeling and assessment

A case study of Qingdao Mariculture Functional Zones

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Abstract The marine functional zoning(MFZ) for China is a new large-scale, ecosystem-based zoning policy for management of development and use in the marine environment. The system dynamic (SD) method is used to evaluate the utilization effectiveness of existed marine functional zones (MFZs) quantitatively for China. As a case study, an impact assessment system is constructed to obtain the cause and effect feedback chart of the mariculture functional zones in Qingdao city, China. A feedback SD model and the main control loops are developed to analyze the utilization effectiveness of the mariculture functional zones. Vensim software is applied to the assessment for the mariculture functional zones of Qingdao. The results provide an effective support for policies and legislation for the division of MFZs. Analysis results and simulations are presented to verify and validate the proposed model.

Keywords Marine functional zoning · System dynamics · Utilization effectiveness · Marine policy

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Introduction

In recent years, the need for balancing the various demands on marine areas and resources has become critical. The health of ocean resources is vital for both economic and environmental sustainability. Comprehensive planning is required to protect marine resources. Protection can be achieved through MFZ, which is an integrated, multi-sector (e.g., fisheries, energy, transport) and multi-disciplinary (e.g., engineers, scientists, policy analysts, planners) process of the allocation and assessment of anthropogenic ocean uses to achieve and meet ecological, economic, and social objectives (Luan and Ke 2002). MFZ enables the country to have better control of its marine areas, protect and improve its marine environment, ensure the rational exploitation of its marine resources, and allow for the sustainable development of the marine economy.

The division of MFZs is directly related to the rational development and sustainable use of the oceans. Therefore, assessing the effectiveness of existing MFZs is of great importance. However, accessing the utilization effectiveness of MFZs can be difficult because the systems need to deal with complex data often seen in most facets of anthropogenic ocean uses, such as marine ecology and biological modeling, mapping, and associated analyses, using a variety of modeling and data management tools. The impact assessment of MFZs is a complicate system involving many factors and constraints, which require a variety of modeling and data management tools (Xu et al. 2010; Wang and Xu 2009).

Qingdao historically known as Tsingtao is a major city in eastern Shandong province, Eastern China, with a population of over 8.715 million (2010 census). Lying across the Shandong Peninsula while looking out to the Yellow Sea, Qingdao is a major seaport, naval base, and industrial centre. Qingdao has abundant marine resources and a good industrial base. In 2004, Qingdao designated a total of 191 MFZs in nine categories. Of the 191 MFZs, 33 are fisheries resource utilization

zones and conservation zones (including fishing ports and fishing facilities, fishing bases, breeding areas, proliferation areas, and fishing area). The total area is 385.1585 km^2 in Qingdao, and comprises 29.2 % of the entire MFZs of Qingdao. Qingdao fishery output value accounted for 22.3 % of the marine economy, whereas marine aquaculture production accounted for 73 % of the total output of aquatic products in 2009. However, with the booming marine economy and tourism, and the rapid development of port and shipping services, the aquaculture area is shrinking (Zhang and Li 2006). Since aquaculture has expanded and intensified in almost all regions of the world and has grown to about 43% of current global fish consumption, an inevitable question arises: how one can knows the polices are right for keeping an sustainable development while conserving places that are critical for the health of the marine environment and its biodiversity? Therefore, analyzing the utilization effectiveness of the marine aquaculture is of great importance.

At present, most studies are focused on the principles, methods, and zoning processes of MFZs. Division methods of MFZs in China are more concentrated in the indicator method, superposition method, and coordination method (Xu et al. 2010; Wang and Xu 2009; Zhang and Li 2006; Miao and Li 2005). For example, a project with the marine and MFZ compliance criteria is studied in (Wang and Xu 2009). An analytic hierarchy process is proposed to establish the assessment indices systems for the exploration potential of MFZs (Wang and Liu 2011). Analyzes marine environmental impacts of the ports and establishes the indicators of functional characteristics of ports.

Worldwide marine spatial plans (MSP) have been prepared with various objectives, similar to Chinese MFZ. MSP is a process that brings together multiple users of the ocean-including energy, industry, government, conservation and recreation-to make informed and coordinated decisions about how to use marine resources sustainably (Vince 2006; Hall 2011; Gopnik et al. 2012; Douvere and Ehler 2009; Qiu and Jones 2013; Wang and Miao 2008). In Australia Marine bioregional plans are developed as a new focus for marine planning and have been developed for four of Australia's marine regions (Vince 2006). Canada provides an integrated ocean management through marine spatial planning based on the national legislative and policy context (Hall 2011). In the United States, marine spatial planning is being addressed at the national, regional, and state levels (Halpern et al. 2012). In 2002, EU Recommendations on Integrated Coastal Zone Management, the EU issued the EU Green Paper on Future Maritime Policy. In 2006, the EU Marine integrated Policy Blue Book in 2007, respectively (Douvere and Ehler 2009). Above the EU policy to promote, a number of European countries carried out the management of marine spatial planning and achieved good results (Qiu and Jones 2013). The North Sea, Belgium, Netherlands, Germany, the United

Kingdom has been initially completed the proposal of sea-use planning and the zoning within the scope of the territorial sea (Wang and Miao 2008; Gimpel et al. 2013; Suárez de Vivero and Rodríguez Mateos 2012), One may refer to (Collie et al. 2013; Halpern et al. 2012) and the references therein for some other introduction about MSP in practice.

In all the initiatives taken in MFZ or MSP, most studies and research tools are focused on the principles, methods, and zoning processes (Stelzenmüller et al. 2013) no clear socio-economic factors and assessment models have been considered. Recently, evaluation is generally recognised as an essential step for learning and improvement in MSP, Practical guidance and experience relative to evaluation in MSP is, however, very limited. The division methods of MFZs in China most focus on the fuzzy method, quantitative method, and analytic hierarchy method (Zhang and Li 2006; Miao and Li 2005; Stelzenmüller et al. 2013). Moreover, these initiatives were implemented before the division of the MFZs. The utilization effectiveness and impacts of MFZs are not considered in China (Gao et al. 2011).

The present paper aims at assessing and modeling the utilization effectiveness for MFZs in Qingdao using the SD method. SD is an approach used to understand the behavior of complex systems over time and created in the mid-1950s by Professor Jay Forrester of the Massachusetts Institute of Technology, The approach is very useful to conceptualize a comprehensive understanding and explanation of human interactions and complicated phenomena (Sterman 2001). The impact assessment system is constructed to obtain the cause and effect feedback chart of the marine culture functional zone. Data are processed using statistical method and geographic information system. A feedback SD model and the main control loops for the utilization effects evaluation are presented based on the obtained results. Simulations are conducted to verify the proposed model. The models are implemented with Vensim and the programs use stock and flow icons to help one see where the accumulations of the system take place.

Impact assessment of the utilization effectiveness of MFZs

The price of aquatic products is the most important factor in determining the extent of breeding activities in MFZs (Suárez de Vivero and Rodríguez Mateos 2012). In addition, the price of aquatic products production is also affected by aquiculture, catching costs, social economic conditions, per capital annual expenditure on consumption, and consumption habits. However, these factors also affect the fishery price in 1 or 2 years, depending on the growth cycle of aquiculture products.

Even among the same aquatic products, the price of edible fish in the lowest category is far less affected by the economic situation than that of the high quality seafood. Many marine economic function zones, such

as mariculture zones, tourism zones, and others, are also affected by the regional marine environment, marine weather conditions, and other major environmental conditions. Thus, the unitization effectiveness of MFZs should be taken into account.

In addition, various types of MFZs affect each other. In creating MFZs, the authorities need to consider the cumulative effect of maritime industries on the seas, seek to make industries more sustainable, and proactively minimize conflicts between industries seeking to utilize the same sea area, and promote the economic development of the zones that are closely related to the key industries. Wastewater and pollution in ports and sailing areas can affect nearby breeding areas. The sediment and water power also affect the tourist zones.

To summarize, the system state variables are selected according to urban population, aquatic products price, energy cost, production materials cost, feed cost, human resource cost, consumption desire, and marine capture production, shipping throughout, tourism income, marine aquaculture area, and marine aquaculture production.

The system decision variables include the growth rates of the following: urban population, first industry, second industry, third industry, agricultural products price, aquaculture cost, consumption per capita, expected consumption, marine capture, freshwater aquaculture, and freshwater capture.

SD model for the utilization effectiveness of Qingdao mariculture functional zone

The causal loop diagram can express the feedbacks in the system better than the causal relation model. The price of aquatic products is divided into six categories, and each category is refined. Each system branch description is analyzed based on the categories divided before. The causal loop diagrams are then obtained using Vensim.

The branch circuits of SD modeling Qingdao MFZ are as follows:

1) GDP (branch circuit: Total population, urban population, total values).
2) Per capita aquatic consumption (branch circuit: GDP, per capita GDP, per capita income, per capita aquatic consumption).
3) Average price of aquatic products (branch circuit: calculated using aquatic products cost, per capita aquatic consumption, the difference between expected yield and actual yield).
4) Aquatic products cost (branch circuit: decided by energy, production materials, feed and human resource costs).
5) Expected consumption of aquatic products (branch circuit: calculated using per capita aquatic consumption and price).

6) Expected yield of aquatic products (branch circuit: marine aquaculture area, expected mariculture yield, expected consumption of aquatic products, freshwater aquaculture/fishing yield).

Not all the variables can be used in this model. Hence, only some important factors are selected to build the model, as shown in Fig. 1. By adjusting the loop parameter, the future economic benefits can be predicted using historical data. Figure 2 shows the SD model of the utilization effectiveness of Qingdao MFZs, where GDP is gross domestic product which consist of the primary industry(GDP1), the secondary industry(GDP2) and tertiary industrial (GDP3).

The causal loop diagram in Fig. 1 can express the feedbacks in the system better than the causal relation model. Figure 2 expresses all relationships and effects in a series of functions. In analyzing the feedbacks and relations, the model is established (see Fig. 2).

In the model proposed as Fig. 2, all the data are derived from Shandong province statistical information website, China fishery statistical yearbooks and China marine statistical yearbooks (2000–2011). According to the branch circuits proposed, the model consists of the following seven sectors which the main equations in model presented in Fig. 2 are as follows:

(1) Population
The total population at any time (t) in the region is given by

$$P(t) = P(t-dt) + (P_{gr}-P_{dl})dt \tag{1}$$

where $P(t)$ is the total population at time t, P_{gr} is the growth of total population in time (dt), P_{dl} is population decline in time (dt). The total population is due to births, immigration, death and emigrations, immigrations rate, emigrations rate, death rate and birth rate. Urban population is one of the major driving factors behind the amount of aquatic products consumed in the region, and it is modeled as

$$P_u(t) = P_u(t-dt) + (P_{ugr}-P_{udl})dt \tag{2}$$

where $P_u(t)$ is the urban population at time t, P_{ugr} is the growth of urban population in time (dt), P_{udl} is the decline of urban population in time (dt).

(2) Aquatic Products Cost
The Prices of aquatic products are closely related to the Costs of aquatic products, and the aquatic products cost $C_{aq}(t)$ is computed as

$$C_{aq}(t) = C_{en}(t-h_{en})F_{en} + C_{hr}(t-h_{pm})F_{pm} \\ + C_{pm}(t-h_{pm})F_{pm} \tag{3}$$
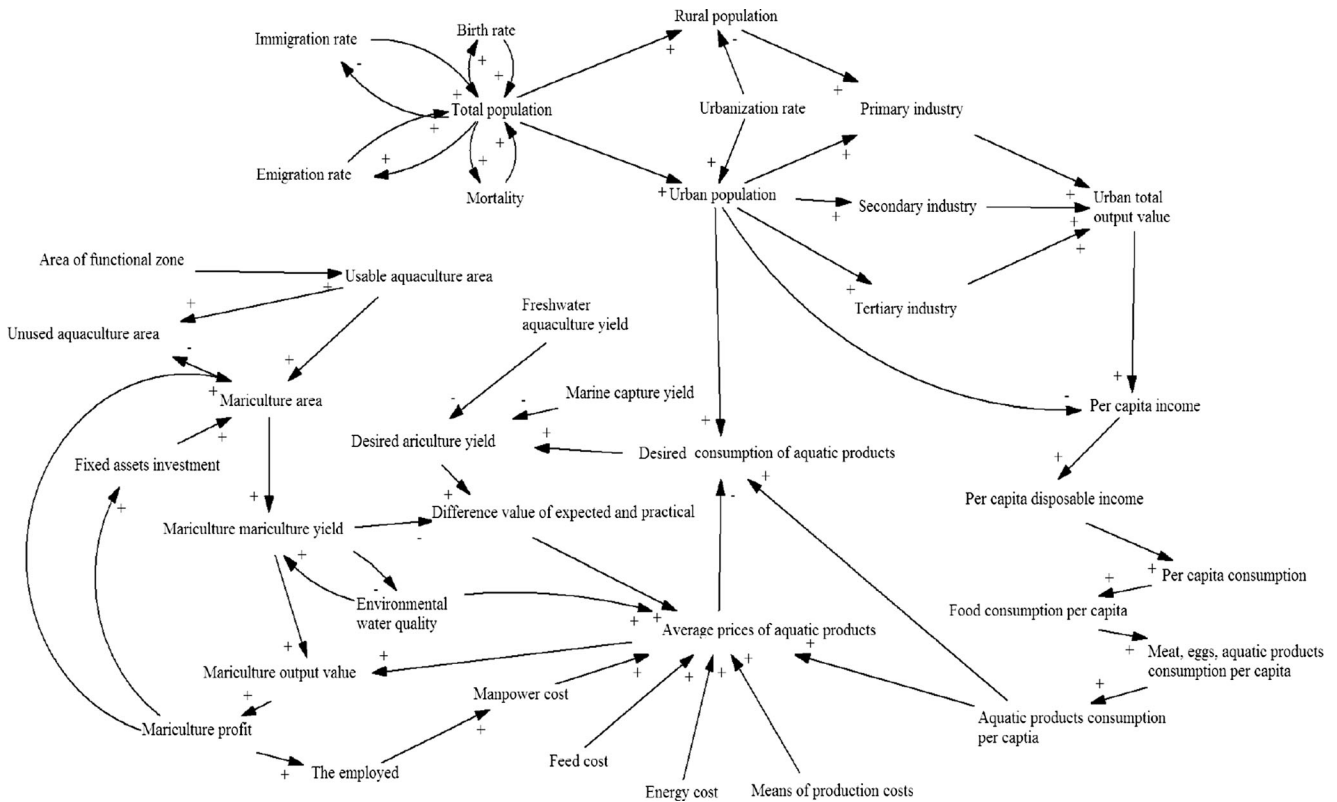
Fig. 1 Feedback structure for the utilization effectiveness of Qingdao MFZs

where $C_{aq}(t)$ is aquatic products cost at time t, $C_{en}(t)$ is Energy Cost at time t, $C_{hr}(t)$ is human resource cost at time t, $C_{pm}(t)$ is production materials cost at time t. F_{en}, F_{pm} and F_{pm} are impact factors of energy, human resource, and production materials and human resource, respectively. h_{en}, h_{pm} and h_{pm} are delays of the impact of energy cost, human resource cost, and production materials cost and human resource cost, respectively.
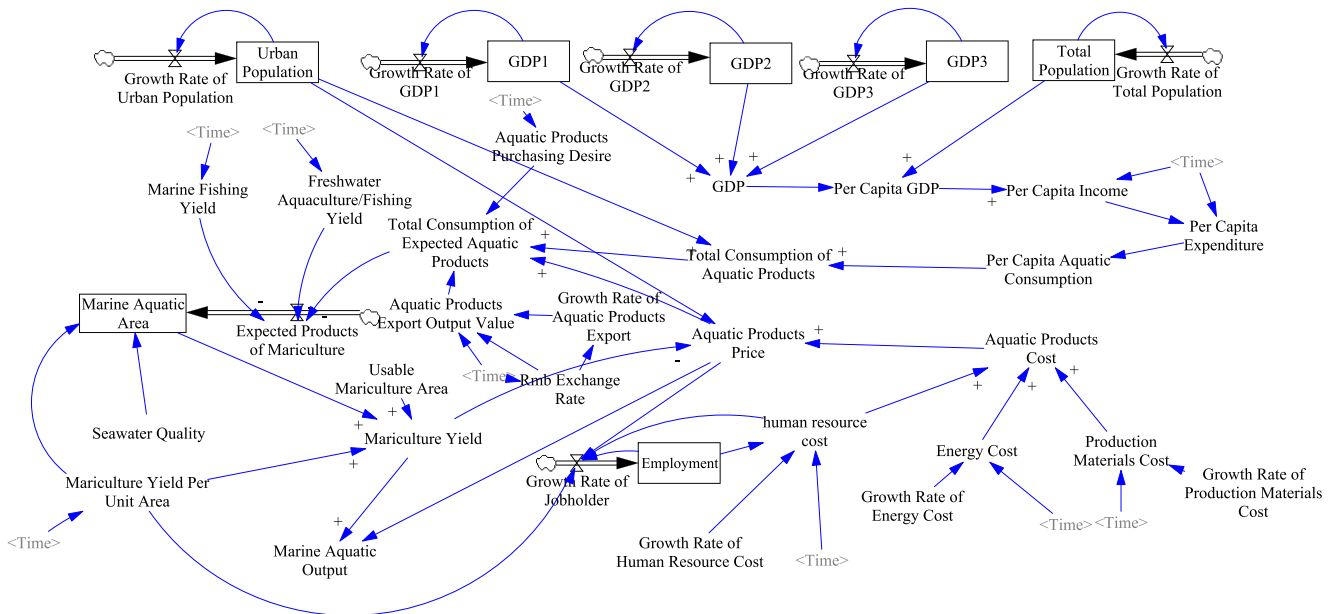
Fig. 2 System flow diagram of the utilization effectiveness of Qingdao MFZs

Table 1 Simulation errors of the SD model of Qingdao MFZs between mariculture area and production

Year	Mariculture area (Ha)			Mariculture yield (Ton)		
	Actual value	Simulation value	Error (%)	Actual value	Simulation value	Error (%)
2000	55387	57584.6	3.97	783503	829955.6	5.93
2001	59456	66025.0	8.6	827228	906583.4	8.6
2002	58355	63902.5	2.52	858536	896189.2	2.52
2003	42460	42621.37	0.86	817176	826577.8	0.86
2004	44789	47494.39	5.75	821744	854998.5	5.75
2005	45368	50757.68	7.26	806198	851189.2	7.26
2006	45602	49586.66	6.83	800482	893560	6.83
2007	41416	44197.38	1.93	755466	763008	1.93
2008	35954	36324.74	6.8	755843	804455.8	6.8
2009	37098	41319.45	7.75	794168	809608.1	7.75
2010	40101	41831.3	4.31	812642	840947.9	3.48
2011	38743	41542.2	7.23	823080	896998.2	8.98

(3) Prices of aquatic products

The prices of aquatic products are

$$P_{ap}(t) = F_{aq}C_{aq}(t-h_{aq})Y_a(t-h_{ya})\big/P_u(t) \qquad (4)$$

where $P_{ap}(t)$ is aquatic products price at time t, $Y_a(t)$ is mariculure yield at time t and the impact factor of aquatic products cost. h_{aq} and h_{ya} are delays of the impact of aquatic products cost and mariculure yield, respectively.

(4) GDP

$$G(t) = G_1(t) + G_2(t) + G_3(t) \qquad (5)$$

where $G(t)$ is GDP1 at time t, $G_1(t)$ is GDP2 at time t, $G_3(t)$ is GDP3 at time t.

(5) Aquatic Consumption

$$T(t) = P_u(t)T_p(t) \qquad (6)$$

where $T(t)$ is total consumption of aquatic products, and $T_p(t)$ is per capita aquatic consumption.

(6) Effective mariculture area

With the change of the aquatic products price, the yield and seawater quality, the effective mariculture area will change accordingly.

The amount of effective mariculture area $A(t)$ in the distinct is

$$A(t) = A(t-dt) + \Big(E_m(t-h_{dm})Q_s(t-h_{qs})F_{sq}\big/Y_{pu}(t-h_{ypu})\Big)dt \qquad (7)$$

where Y_{pu} is mariculture yield per unit Area, $Q_s(t)$ is seawater quality at time t, h_{dm}, h_{qs} and h_{ypu} are delays in E_m, Q_s and Y_{pu}

respectively. $E_m(t)$ is the expected consumption of aquatic products, and decided by

$$E_m(t) = T(t-h_t) + E_{gr}Y_a(t)\big/T(t) \qquad (8)$$

where $E_{gr}(t)$ is the growth of expected aquatic consumption at time t, $Y_a(t)$ is marine fishing yield.

(7) Employment

$$J(t) = J(t-dt) + \big(J_{gr}-J_{dl}\big)dt \qquad (9)$$

where $J(t)$ is the employment number of related industries at time t, J_{gr} is the growth of the employment number in time (dt), J_{dl} is employment decline in time (dt). J_{gr} is proportional to the price of aquatic products and effective mariculture area, is inversely proportional to the aquatic products cost.

Simulations

Mathematically, the basic structure of a formal SD computer simulation model is a system of coupled, nonlinear, first-order differential (or integral) equations. The simulation of such systems is easily accomplished by partitioning simulated time into discrete intervals. State variable is computed from its previous value and its net rate of change.

Verifications by historical data

To validate the simulation model, the historical data from year 2000 to 2011 in Qingdao are used. Five subsystems are established to simulate three main state variables, namely, human resource costs, production costs, and energy costs. In addition, urban population, aquatic products price, marine aquaculture production, and per capital consumption costs are verified. The

Table 2 Simulation errors of the SD model of Qingdao MFZs between mariculture area and production

Year	Mariculture output value(Ton)			Aquatic products price index		
	Actual value	Simulation value	Error (%)	Actual value	Simulation value	Error (%)
2000	323160	359422.5	1.12	106.6	117.69	10.4
2001	392665	435245.7	8.6	108.09	119.41	10.4
2002	438711	460379.2	2.52	103.55	104.01	0.44
2003	471366	502171.2	0.86	105.73	116.67	10.3
2004	487952	517848.7	5.75	116.62	123.05	5.51
2005	511659	563390.5	7.26	120.58	133.67	10.8
2006	584037	589848.3	6.83	124.68	138.58	11.1
2007	570395	610289.2	1.93	130.79	144.74	10.6
2008	571171	587435.9	6.80	147.53	148.01	0.33
2009	646790	662769.9	7.75	150.93	152.29	0.90
2010	751788	795264.03	5.78	161.19	171.27	6.25
2011	862643	905685.16	4.99	184.41	197.29	6.98

verified data are shown in Tables 1 and 2. Table 1 describes the errors between marine aquaculture area and marine aquaculture production from 2000 to 2011. Table 1 shows that the main factors will change even in the same year; the actual errors are more obvious if using the same single parameter matrix in the model. Table 2 describes the errors between aquatic products price and marine aquaculture production from 2000 to 2011. Actual Values in Tables 1 and 2 are derived from China fishery statistical yearbooks and China marine statistical yearbooks (2000–2011). Tables 1 and 2 show that the prediction accuracy of the SD model can be guaranteed (more than 91 %) even if the annual main parameters and impact index matrix are unchanged. Verifying variables for the proposed model is satisfied.

Sensitivity analysis

Sensitivity analysis shows how a particular scenario may be affected by multiple variables. For example, in modeling a home mortgage, sensitivity analysis could forecast situations if interest rates rise and/or property values decline. From a different point of view, the sensitivity of the model can be divided into three types, namely, value sensitivity, behavior sensitivity, and policy sensitivity, all of which can determine the robustness of the model.
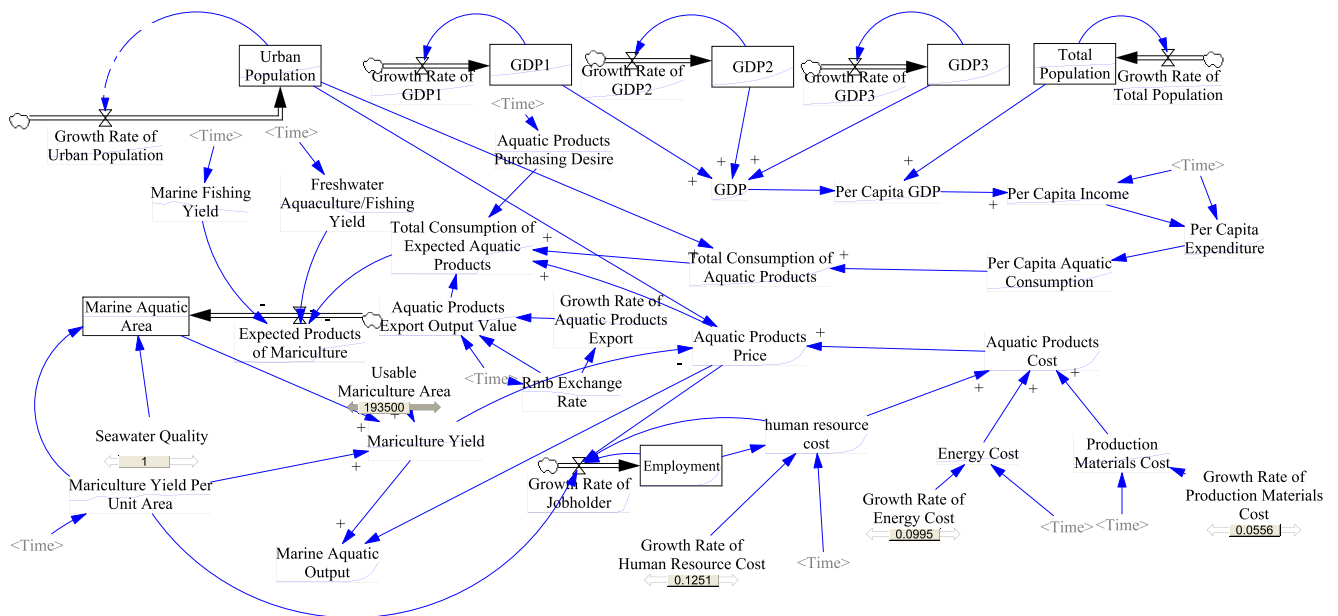
Fig. 3 Sensitivity analysis of the utilization effects for Qingdao MFZ

Fig. 4 Simulation curves of average aquatic products price in Qingdao at different growth rates of human resource costs (Aquatic Price 1 when human resource costs growth rate is 0.1, Aquatic Price 2 represents the simulation curves when human resource costs growth rate is 0.11)
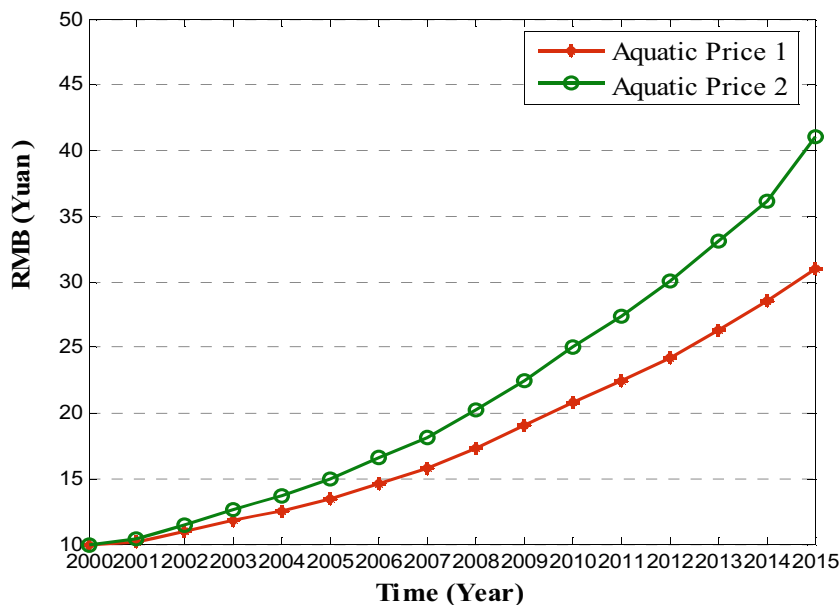

Figure 3 shows the sensitivity analysis results of the utilization effects for Qingdao MFZ. The simulation curve in each variable bracket means the trends from 2000 to 2011. And the variables in blue background such as marine fishing products, freshwater fishing products and expected consumption of aquatic products are influenced by time. The variation of the variables with a slider can cause changes with its associated variables in the feedbacks, or even to the whole system.
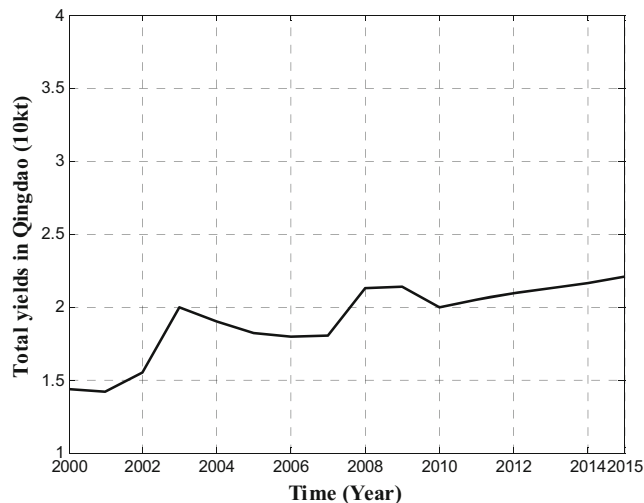
The main factors of the aquatic products cost include human resource, production, and energy costs. The first two factors are regular. The curve of energy costs is growth, but the changes are irregular. The change rate is used in the calculations of the cost of human resources, and the look-up table method is used in energy fuel costs calculations.

As the production cost has increased significantly in 2011, the increasing rate of the production materials costs in the sliding model is set as about 10 % in the simulation data. Figure 4 shows the simulation curves of average aquatic products price in Qingdao at different growth rates of human resource costs and Fig. 5 shows the simulation curves of expected consumption of aquatic products in Qingdao at different growth rates of human resource costs. In Fig. 4 Aquatic price represents the average market price per year of daily aquatic products excluding precious seafood. From Figs. 4, and 5 and Table 1 we conclude that with the increasing price of aquatic products, the expected consumption is reduced.
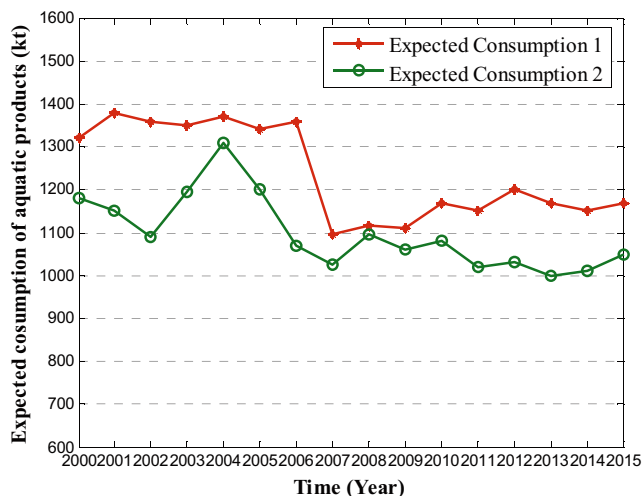
Fig. 5 Comparison chart of expected consumption of aquatic products in Qingdao (Expected consumption 1 represents the simulation curves when human resource costs growth rate is 0.1; Expected consumption 2 represents the simulation curves when human resource costs growth rate is 0.11)

Fig. 6 Simulation of the total mariculture yields of Qingdao (The mariculture yields of Qingdao in 2014 and 2015 are predictive values)

From the analysis above, the impact factors of aquatic products is more than scientific-technological progress and prices. Scientific and technological progress is a long process. The price of aquatic products and the level of consumption are processes of continuous volatility. Under the influence of aquatic growth cycle, the trend in information delay and the aquatic price undergoes fluctuation for 4 to 5 years per period. In order to further verify the conclusions above, we add a ratio factor y which represents "purchasing desire of aquatic product" in the model proposed. The initial value $y_0 = 1$. When a similar marine culture quality incidents happen, the ratio factor is adjusted to $(0, 1)$ depending on the influence of the incident, when the other similar products (meat and eggs) quality incidents happen, y is increased to $(1, 2)$ depends on the influence. y may be the largest when some incidents happens, and in the second year, third year, y moves down accordingly. Figure 6 is the simulation and prediction curve of the total marine culture production after two mariculture quality accident in 2003 and 2008, and Fig. 6 shows that the lag affects of the yield changes obviously.

In summary, the detailed conclusions obtained are as follows:

1) Qingdao mariculture area is reduced by 33 % in the past decade, and aquaculture production would not change much.
2) The effect of the aquatic products price and other factors translates to an aquaculture fluctuation period of 5 to 6 years.
3) The aquatic production and output value of Qingdao have been increasing recently. However, this surge is not a real performance boost affected by the increasing energy price, production materials, feed and human resource costs. With the economic development of Qingdao and the extension of the city, aquaculture will be further marginalized. Therefore, factory aquaculture will be very important for the future development of aquaculture.

Conclusions

This paper provides an integrated assessment model on the utilization effectiveness of Qingdao MFZs using SD. The impact assessment system is established. Simulations are conducted using historical data from year 2000 to 2011. The results indicate that simulations can assess the utilization effectiveness and predict the development trend of Qingdao MFZs with satisfactory accuracy. The model may be more effective if the values of the assessment system are changed annually. The proposed model provides an effective means to analyze the MFZs quantitatively.

References

Collie JS, Adamowicz WL, Beck MW et al (2013) Marine spatial planning in practice. Estuar Coast Shelf Sci 117:1–11

Douvere F, Ehler CN (2009) New perspectives on sea use management: initial findings from European experience with marine spatial planning. J Environ Manage 9:77–88

Gao YM, Zhou L, Qu P (2011) Evaluations on the utilization effects of marine functional zones based on system dynamics. J Ocean Univ China (Social Sciences) 4:15–20

Gimpel A, Stelzenmüller V, Cormier et al. (2013) A spatially explicit risk approach to support marine spatial planning in the German EEZ. Mar Environ Res 86:56–69

Gopnik M, Fieseler C, Cantral L et al (2012) Coming to the table: early stakeholder engagement in marine spatial planning. Mar Policy 36(5):1139–1149

Hall T (2011) Advancing objectives-based, integrated ocean management through marine spatial planning: current and future directions on the Scotian shelf off Nova Scotia, Canada. J Coast Conserv 15:247–255

Halpern BS, Diamond J, Gaines S (2012) Near-term priorities for the science, policy and practice of coastal and marine spatial planning (CMSP). Mar Policy 36:198–205

Luan WX, Ke D (2002) The functional programs of marine functional division of China. Hum Geogr 17:93–95

Miao LJ, Li SY (2005) A discussion of method of classified sea area use grading. Manag Geol Sci Technol 22:75–77

Qiu WF, Jones PJ (2013) The emerging policy landscape for marine spatial planning in Europe. Mar Policy 39:182–190

Stelzenmüller V, Lee J, South A et al (2013) Practical tools to support marine spatial planning: a review and some prototype tools. Mar Policy 38:214–227

Sterman JD (2001) System dynamics modeling. Calif Manag Rev 43:8–25

Suárez de Vivero JL, Rodríguez Mateos JC (2012) The spanish approach to marine spatial planning. Marine strategy framework directive vs. EU integrated maritime policy. Mar Policy 36:18–27

Vince J (2006) The south east regional marine plan: implementing Australia's oceans policy. Mar Policy 30:420–430

Wang JJT, Liu BQ (2011) Preliminary study on the compatibility discrimination methods of marine function zoning: a case study of port functional zones. Mar Sci Bull 30:496–501

Wang QM, Miao FM (2008) Overview of foreign marine spatial planning and its impact on Chinese marine functional zoning. Ocean Dev Manag 25:45–49

Wang JT, Xu W (2009) Construction and evaluation of the assessment indicator system of exploration potential of marine functional zone. Mar Sci Bull 6:1–6

Xu W, Deng WX, Liu DH et al (2010) On the determination standards of the compliance between sea areas for developing projects and marine functional zoning. Ocean Dev Manag 7:4–7

Zhang GH, Li X (2006) Marine functional division in Qingdao City. Terr Nat Res Study 4:5–7