Forecasting China's marine scientific research and education, marine industrial structure upgrading and marine economy growth based on the AWBO-MGM(1,m) model

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Abstract

Purpose – The purpose of this paper is to explore the internal interaction mechanism of marine scientific research and education, industrial structure upgrading and marine economic growth from a systematic perspective, based on which this work forecasts their future development trends.

Design/methodology/approach – In this study, a multivariate grey model is applied to the prediction of marine scientific research and education, industrial structure upgrading and marine economic growth. Considering the impact of the COVID-19 on marine development, this paper introduces the weakening buffer operator into MGM(1,m) and constructs the AWBO-MGM(1,m) model. To verify the validity and accuracy of the new model, this paper uses AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), back propagation neural network and linear regression models for simulation and prediction based on the data from 2010 to 2021, respectively.

Findings – From the theoretical perspective, the development of marine scientific research and education can accelerate industrial upgrading and promote marine economic growth by providing high-quality talents, promoting marine science and technology progress and reducing transaction costs; while the upgrading of marine industrial structure and marine economic growth can promote the development of marine scientific research and education by guiding social capital, enhancing talent demand and stimulating market vitality. From the empirical analysis, the AWBO-MGM(1,m) model can effectively deal with epidemic shocks and has higher fitting and prediction accuracy than the other five comparative models.

Practical implications – The government should pay attention to the construction of marine scientific research and education, so as to provide high-quality talents and advanced scientific research results for the high-quality development of marine economy. On the basis of using science and technology to firmly build the primary and secondary marine industries, the government should actively guide the labor, capital and other factors of production to the tertiary industry, thereby promoting the optimization and upgrading of marine industrial structure.

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Originality/value – On the one hand, the interplay mechanism of marine scientific research and education, industrial structure upgrading and marine economic growth is analyzed from a systematic perspective; on the other hand, the enhanced AWBO-MGM(1,m) possesses higher forecasting performance and is applicable to the systemic multivariate forecasting problem in the presence of outstanding external shocks.

Keywords Marine economic growth, Marine scientific research and education, Industrial structure upgrading, MGM(1,m), Weakening buffer operator

Paper type Research paper

1. Introduction

1.1 Study background

It is stated in *The State Council's Approval of the 14th Five-Year Plan for the Development of the Marine Economy* that the development of the marine economy should be based on the new development stage and comprehensive implementation of the new development concept. Since 2012, with the support of the Maritime Power Strategy, China's gross ocean product (GOP) has grown rapidly, but the structural problems of the marine economy still exist: high energy consumption and high pollution industries are still in a dominant position, the development of new marine industries is relatively slow, the asymmetry between the employment structure and the output value structure, the large industrial deviation and other problems are still prominent, and the problem of unreasonable industrial structure restricts the further development of China's marine economy (An and Li, 2020). In the context of the "New Normal" economy, it is a common problem of overcapacity and it is necessary to abandon the crude development pattern with growth rate as the primary goal. Continuously optimizing the marine industrial structure and improving the quality of marine economic development are keys to tackling.

High-quality development of the marine economy cannot be achieved without scientific and technological innovation to optimize industrial structure, promote supply-side reform and inject new growth momentum into the marine economy. Marine scientific research and education is the basis for promoting the progress of marine science and technology, and is also a key factor driving the development of marine economy: on the one hand, marine scientific research and education provide high-level talents and scientific and technological achievements for updating and transforming existing industries, and promoting emerging ones; on the other hand, marine scientific research and education can provide marine resource management services for enterprises, and promote the upgrading of marine industry structure by improving management efficiency and reducing transaction costs. On the contrary, the upgrading of marine industry structure and the growth of marine economy will expand the demand for marine scientific research and education, while guiding more funds, policies and talent resources to grow marine scientific research and education, thus further promoting the development of marine industry and forming a virtuous cycle. Therefore, exploring the dynamic interaction among marine scientific research and education, industrial structure upgrading and marine economic growth, and predicting their future development trends can provide implications for realizing high-quality development of China's marine economy.

1.2 Literature review

Industrial structural transformation and upgrading is an important driver of economic growth (Gan *et al.*, 2011; Adom *et al.*, 2012; Dong *et al.*, 2020). Erumban *et al.* (2019) showed that upgrading of industrial structure can increase labor productivity and has a positive effect on economic growth. In the field of marine research, many scholars have conducted studies and obtained similar results using methods such as principal component analysis, panel regression models, vector autoregressive (VAR) models and grey correlations, and concluded that the upgrading of marine industry structure has a significant contribution to marine economic growth (Di *et al.*, 2014; Zhai, 2020; Liu *et al.*, 2021a). Specifically, the upgrading of marine industry structure will affect the spatial and temporal evolution of the marine economy by influencing production factor inputs and improving the effect of financial support (Wang and Han, 2017; Fei, 2020), and there is a significant spatial dependence between the upgrading of marine industry structure and coastal economic growth, showing nonuniform distribution characteristics (Wang and Zhai, 2020). Some works split the upgrading of marine industrial structure into two aspects: industrial structure advancement and industrial structure rationalization, and argue that the above two ways of industrial structure adjustments can have a differential impact on marine economic growth. Xie *et al.* (2019), Yu *et al.* (2021) and Wang *et al.*, 2021a found that rationalization of marine industrial structure can have a positive impact on the marine economy, while the advancement of marine industrial structure shows a negative correlation with marine economy growth. In addition, it has also been noted in the literature that the upgrading of marine industries has failed to generate a driving mechanism for marine economic growth (Shao *et al.*, 2021).

In recent years, high-quality marine development has gradually become a hot topic. High-quality marine development is inseparable from marine education and technological innovation. Few studies have explored the impact of marine scientific research and education on the marine economy, and the role of marine technology innovation in promoting the development of marine economy has become a hot spot for researchers' attention. Many works have explored the impact of the marine science and technology innovation on the marine economy growth by using the dynamic interactive, factor contribution, coordination relationship and influence paths as entry angles, respectively. The results showed that science and technology innovation can promote the growth of China's marine economy through various ways, and there is a long-term stable equilibrium relationship between the two subjects (Liu *et al.*, 2021b; Shao *et al.*, 2021; Li *et al.*, 2023a, b, c). In particular, there are long-term and short-term differences in the impact of basic research, application research, exploitation research and industrialization in marine technological innovation on the marine economic development (Wu *et al.*, 2020). Some scholars have explored the inverse effect of marine economic growth on the progress of marine science and technology, for example, Yu *et al.* (2021), by constructing a vector autoregressive model, found that the increase in marine research personnel and marine research funding is the Granger cause of marine economic growth, which in turn drives the growth in the number of research personnel. Marine science and technology innovation is also an important motivation for the upgrading of marine industrial structure, playing an important role in promoting ecologization, rationalization and advancedization of marine industrial structure (Qin *et al.*, 2018; Wang *et al.*, 2021b), and the industrial structure upgrading will in turn have a significant positive impact on marine science and technology innovation (Li *et al.*, 2021a, b).

In terms of marine economic prediction, most of the relevant literature uses grey models, time series models and VAR models to numerically forecast the GOP, the scale of various marine industries and the number of marine employees (Raman *et al.*, 2017; Ma *et al.*, 2020; Liu, 2020; Li *et al.*, 2021a, b; Shan and Cao, 2022). Among above methods, GM(1,1) and ARIMA models are limited to univariate forecasting and cannot consider the influence relationship among multiple variables; GM(1,N) models can incorporate multiple variables into the model but only focus on the unidirectional impact of multiple variables on a single variable; VAR models can present the bidirectional effects between multiple variables but have high requirements on the length of data samples. MGM(1,m) is an important prediction model in grey system theory with the feature of small sample requirement and high prediction accuracy. MGM(1,m) models can unify the description of each variable from the system perspective, better reflect the relationship between the variables in the system with mutual influence and constraints, and use it as the basis for the prediction of each variable, which can get more scientific and accurate prediction results. MGM(1,m) models have been widely used for poor data, multivariate forecasting problems (Zhai *et al.*, 1997; Dai *et al.*, 2018; Wu *et al.*, 2022).

In summary, many useful results have been developed on the interplay of marine industrial structure upgrading, marine science and technology innovation and marine economic growth, and previous studies have shown that there are mutual influences among the above factors, which provides a solid research basis for this study. However, there are different opinions about the relationship between the upgrading of marine industrial structure and the marine economy growth. Moreover, few scholars have explored the realistic effects of marine scientific research and education on the development of marine economy. In terms of marine economic forecasting, most of the previous methods have the limitations of univariate forecasting or high sample size requirements, and there is a lack of forecasting for marine scientific research and education. The development process of marine scientific research and education, industrial structure upgrading and marine economic growth is complex and involves various aspects of human society and natural environment. Under the circumstances that the boundaries of relevant influencing factors are difficult to be determined, some information is difficult to be obtained and the sample interval is short, the study using MGM(1,m) model may be more advantageous than other measurement methods. In view of the above considerations, this paper uses the grey MGM(1,m) model to explore the role relationship between marine research and education, industrial structure upgrading and economic growth based on China's marine economic data from 2008 to 2019, and to predict and foresee their future development trends, so as to provide reference for promoting the transformation and upgrading of the marine industry, and then achieving high-quality development of the marine economy.

1.3 Contributions and organization

This paper identifies the inherent interaction among marine economic growth, marine scientific research and education and marine industrial structure upgrading, and builds a multivariate interactive grey model to predict their future development trends. Moreover, to consider the impact of the COVID-19 shock on variables, this paper introduces the weakening buffer operator into MGM(1,m) and constructs the AWBO-MGM(1,m). The validity of the model is verified through the prediction of the above three research subjects. The contributions of this paper are as follows:

(1) The growth of marine economy, the development of marine scientific research and education, and the upgrading of marine industry structure mutually affect and promote each other. Based on the reality of China, this paper discerns the inner interaction mechanism of the above research objects from a systematic perspective, and provides a theoretical basis for the formulation of policies to adjust the structure of marine industry and promote marine scientific research and education.

(2) The outbreak of the COVID-19 has had a significant negative impact on the development of China's marine economy. The MGM(1,m) with model calibration based on observations is difficult to predict the impact of external shocks on the system itself, which results in unacceptable prediction results and is not conducive to a true understanding of the development trend of the system itself. Therefore, the AWBO-MGM(1,m) model proposed in this paper can eliminate the interference of shocks on the system behavior sequence to a certain extent and improve the prediction accuracy.

(3) The prediction results of the AWBO-MGM(1,m) model are compared with those of grey models such as MGM(1,m), GM(1,N) and GM(1,1), and non-grey models such as back propagation neural network (BPNN) and linear regression (LR). It is indicated that the new model has obvious advantages and can effectively predict the future trends of marine economic growth, marine scientific research and education and marine industrial structure upgrading.

The rest of this paper is organized as follows. Section 2 discusses the interaction of marine economic growth, marine scientific research and education and marine industrial structure upgrading from the theoretical perspective and shows the construction process of AWBO-MGM(1,m). Section 3 compares the prediction performance of the AWBO-MGM(1,m) with the MGM(1,m), GM(1,N), GM(1,1), BPNN and LR, and uses the new model to make future prediction of the above research objects. Section 4 summarizes the findings of this paper.

2. Theoretical analysis and methodology

2.1 Theoretical analysis

The development of marine scientific research and education can accelerate the upgrading of marine industry structure, thus driving the growth of marine economy. At present, the development of high-quality marine economy in China has been obstructed by shortages in the number of senior marine talents and comprehensive quality of human resources. Marine scientific research and education can provide sufficient talent guarantee for the development of green, low-carbon and efficient, high value-added marine industries and strategic emerging marine industries, thereby helping the marine economy change the status quo of high energy-consuming and low value-added industries, and ultimately promoting marine economy growth. On the other hand, the construction of marine disciplines and the improvement of marine scientific research investment can guarantee the marine scientific and technological innovation, accelerate the application of new scientific research results and then stimulate the advanced and knowledge-based marine industrial structure, enhancing the long-term and steady growth of the marine economy. Finally, marine knowledge-intensive industries are usually sensitive to transaction costs. Marine scientific research and education can promote effective flow of various marine resources by improving the management level of marine economic entities. Thus, the development of marine scientific research and education can reduce various types of transaction costs, benefit the development of marine industries, especially knowledge-intensive industries, and promote industrial structure upgrading and economic growth.

While marine scientific research and education promote the upgrading of industrial structure and economic growth, the latter in turn promotes the former. First, the field of marine scientific research and education is usually characterized by high risks and long return cycles, which do not easily attract social capital, so marine scientific research and education is usually led by the government and has a strong policy dependence. By providing lucrative economic returns, the high-quality development of the marine economy can attract social capital investment, so as to provide financial support for the development of marine scientific research and education, and finally promote innovations and transformation of scientific and technological achievements. Second, the specialization and refinement of marine industries will expand the demand for marine talents, especially high-level talents, and the shortage of supply in the talent market is bound to enhance the remuneration of marine talents, attract more talents to enter the marine field and help the progress of marine scientific research and education. Third, industrial restructuring also provides a broad platform for science and technology innovation. The upgrading of industrial structure will give rise to new industrial sectors, opening up the flow of factors, releasing the market vitality and giving sufficient use to marine scientific research. In summary, there is interplay of marine research and education, marine industrial upgrading and marine economic growth. The above factors mutually promote and form a virtuous cycle, ultimately promoting high-quality development of the marine economy.

2.2 AWBO-MGM(1,m) model

As the basis and core of grey forecasting theory, the GM(1,1) model reveals the inner development law of variables through the cumulative generation of original series and the construction of first-order differential equations, but the model is limited to the modeling and forecasting of a single time series. In practical problems, there are relationships among variables that affect and constrain each other. In this regard, the MGM(1,m) model is a unified description of each variable from the system perspective, which can better reflect the interplay variables in the system that affect and constrain each other. The COVID-19 outbreak has had a negative impact on the sustainable development of China's marine economy. The MGM(1,m) model with model calibration based on observations is difficult to predict the impact of external shocks on the system, which leads to unacceptable prediction results and is not conducive to a true understanding of the trend of the system itself. Therefore, this paper proposes an *AWBO-MGM(1,m)* model, which can, to a certain extent, eliminate the interference of shocks on the system behavior sequence and improve the prediction accuracy. The modeling process of the *AWBO-MGM(1,m)* is as follows:

Let $\boldsymbol{X}_i^{(0)}$ be the original sequence:

$$\boldsymbol{X}_i = \left(x_i^{(0)}(1), x_i^{(0)}(2), \cdots, x_i^{(0)}(n)\right), i = 1, 2, \cdots, m \tag{1}$$

The sequence of first-order weakening buffer operators is obtained by introducing the first-order weakening buffer operator (*1-AWBO*) into the original sequence:

$$\boldsymbol{X}_i^{(0)}D = \left(x_i^{(0)}(1)d, x_i^{(0)}(2)d, \cdots, x_i^{(0)}(n)d\right), i = 1, 2, \cdots, m \tag{2}$$

where D denotes the AWBO and its series can act many times. $\boldsymbol{X}_i^{(0)}D$ represents the 1-AWBO (Chen *et al.*, 2021).

$$x_i^{(0)}(k)d = \frac{1}{n-k+1}\left(x_i^{(0)}(k) + x_i^{(0)}(k+1) + \cdots + x_i^{(0)}(n)\right), i = 1, 2, \cdots, m, k = 1, 2, \cdots, n \tag{3}$$

$\boldsymbol{X}_i^{(1)}D$ is a sequence of cumulative generation of $\boldsymbol{X}_i^{(0)}D$, i.e.

$$x_i^{(1)}(k)d = \sum_{j=1}^{k} x_i^{(0)}(j)d, i = 1, 2, \cdots, m, k = 1, 2, \cdots, n \tag{4}$$

$\boldsymbol{Z}_i^{(1)}D$ is the sequence of immediately adjacent mean generators of $\boldsymbol{X}_i^{(1)}D$, where $\boldsymbol{Z}_i^{(1)}D = \left(z_i^{(1)}(2)d, z_i^{(1)}(3)d, \cdots, z_i^{(1)}(n)d\right)^T$, and

$$z_i^{(1)}(k)d = 0.5\left(x_i^{(1)}(k-1)d + x_i^{(1)}(k)d\right), k = 2, 3, \cdots, n \tag{5}$$

Then the expression of the *AWBO-MGM(1,m)* model is

$$\begin{cases} \dfrac{dx_1^{(1)}(t)d}{dt} = a_{11}x_1^{(1)}(t)d + a_{12}x_2^{(1)}(t)d + \cdots + a_{1m}x_m^{(1)}(t)d + b_1 \\ \dfrac{dx_2^{(1)}(t)d}{dt} = a_{21}x_1^{(1)}(t)d + a_{22}x_2^{(1)}(t)d + \cdots + a_{2m}x_m^{(1)}(t)d + b_2 \\ \vdots \\ \dfrac{dx_m^{(1)}(t)d}{dt} = a_{m1}x_1^{(1)}(t)d + a_{m2}x_2^{(1)}(t)d + \cdots + a_{mm}x_m^{(1)}(t)d + b_m \end{cases} \tag{6}$$

Assuming that

$$\boldsymbol{A}=\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{pmatrix}, \boldsymbol{B}=\begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix} \tag{7}$$

The matrix expression of *AWBO-MGM(1,m)* is

$$\frac{d\boldsymbol{X}^{(1)}(t)D}{dt}=\boldsymbol{A}\boldsymbol{X}^{(1)}(t)D+\boldsymbol{B} \tag{8}$$

The corresponding time response function is

$$\boldsymbol{X}^{(1)}(t)D=e^{\boldsymbol{A}(t-1)}\left(\boldsymbol{X}^{(1)}(1)D+\boldsymbol{A}^{-1}\boldsymbol{B}\right)-\boldsymbol{A}^{-1}\boldsymbol{B} \tag{9}$$

The differential expression of *AWBO-MGM(1,m)* is given by

$$\boldsymbol{X}^{(0)}(k)D=\boldsymbol{A}\boldsymbol{Z}^{(1)}(k)D+\boldsymbol{B} \tag{10}$$

Let $\alpha_i=(a_{i1},a_{i2},\cdots,a_{im},b_i)^T,(i=1,2,\cdots,m)$, then the estimation of α_i can be generated by the least squares method:

$$\widehat{\alpha}_i=\begin{pmatrix} \widehat{a}_{i1} \\ \widehat{a}_{i2} \\ \vdots \\ \widehat{a}_{im} \\ \widehat{b}_i \end{pmatrix}=\left(\boldsymbol{P}^T\boldsymbol{P}\right)^{-1}\boldsymbol{P}^T\boldsymbol{Y}_i \tag{11}$$

where

$$\boldsymbol{P}=\begin{bmatrix} z_1^{(1)}(2)d & z_2^{(1)}(2)d & \cdots & z_m^{(1)}(2)d & 1 \\ z_1^{(1)}(3)d & z_2^{(1)}(3)d & \cdots & z_m^{(1)}(3)d & 1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ z_1^{(1)}(n)d & z_2^{(1)}(n)d & \cdots & z_m^{(1)}(n)d & 1 \end{bmatrix}, \boldsymbol{Y}_i=\begin{pmatrix} x_i^{(0)}(2)d \\ x_i^{(0)}(3)d \\ \vdots \\ x_i^{(0)}(n)d \end{pmatrix}, i=1,2,\cdots,m \tag{12}$$

Then the estimated values of matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ are obtained. The corresponding time response functions are

$$\widehat{\boldsymbol{X}}^{(1)}(k)D=e^{\widehat{\boldsymbol{A}}(k-1)}\left(\boldsymbol{X}^{(1)}(1)D+\widehat{\boldsymbol{A}}^{-1}\widehat{\boldsymbol{B}}\right)-\widehat{\boldsymbol{A}}^{-1}\widehat{\boldsymbol{B}} \tag{13}$$

The predicted value of the original sequence $\boldsymbol{X}^{(0)}$ is

$$\widehat{X}^{(0)}(k)D = \widehat{X}^{(1)}(k)D - \widehat{X}^{(1)}(k-1)D, k = 2,3,\cdots,n \tag{14}$$

The above modeling process of the *A WBO-MGM(1,m)* model can be summarized as Figure 1.

2.3 Model-performance metrics

In this study, the root-mean-square error (RMSE), mean absolute error (MAE), average percent error (APE) and mean absolute percentage error (MAPE) are selected to compare accuracies of different models. The smaller the values thereof, the greater the accuracy.

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(x_j - \widehat{x}_j\right)^2} \tag{15}$$

$$MAE = \frac{1}{n}\sum_{j=1}^{n}\left|x_j - \widehat{x}_j\right| \tag{16}$$

$$APE = \left|\frac{x_j - \widehat{x}_j}{x_j}\right| \times 100\% \tag{17}$$

$$MAPE = \frac{1}{n}\sum_{j=1}^{n}\left|\frac{x_j - \widehat{x}_j}{x_j}\right| \times 100\% \tag{18}$$

where x_j is the actual and $\widehat{x}_j$ is the predicted value. The equivalent evaluation criteria for forecast with the MAPE are listed in Table 1 (Li *et al.*, 2023a, b, c).

3. The analytics of prediction

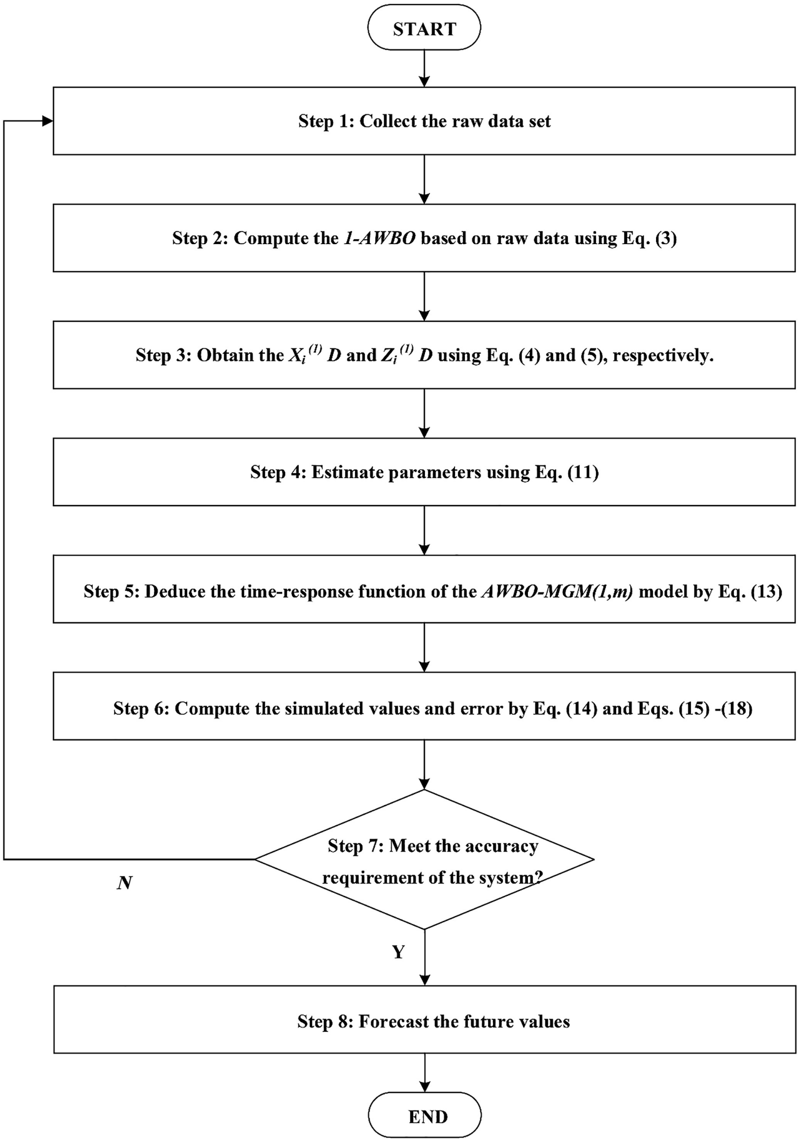
3.1 Collecting raw data and selecting variables

In order to explore the role of marine scientific research and education in the development of marine economy, the ratio of the added value of Marine Scientific Research, Education, Management and Services to GOP is chosen as a proxy variable to measure the development level of marine scientific research and education, and is denoted as Marine Scientific Research and Education (*MSRE*).

The upgrading of marine industrial structure refers to the process or trend of the transformation of industrial structure from low-level form to high-level form, which is the inherent requirement and external expression of high-quality development of marine economy. The increase of the ratio of secondary and tertiary industries is an important symbol of the upgrading of marine industrial structure. In particular, the increase of the ratio of tertiary industries means higher input-output efficiency, broader employment market and stronger capital attraction, which is of great significance to the high-quality development of marine economy.

In order to scientifically measure the level of China's marine industrial structure upgrading, this paper constructs the marine industrial structure upgrading (MISU) index as follows, which is denoted as *MISU*:

$$MISU_t = \sum\nolimits_{i=1}^{3} W_{it} \times i \tag{19}$$



Source(s): Authors' own work

Figure 1. Modeling process of the AWBO-MGM(1,m)

where $i = 1, 2, 3$ represents marine primary, secondary and tertiary industries, W_{it} is the share of value added of the three industries in GOP in year t separately and $MISU_t$ then measures the level of structural upgrading of the marine industry in year t.

The growth of GOP is one of the goals of China's ocean strategy, which directly shows the development results of China's marine economy. In this paper, we adopt the conventional method and select China's GOP for measuring the growth level of China's marine economy, which is denoted as *GOP*.

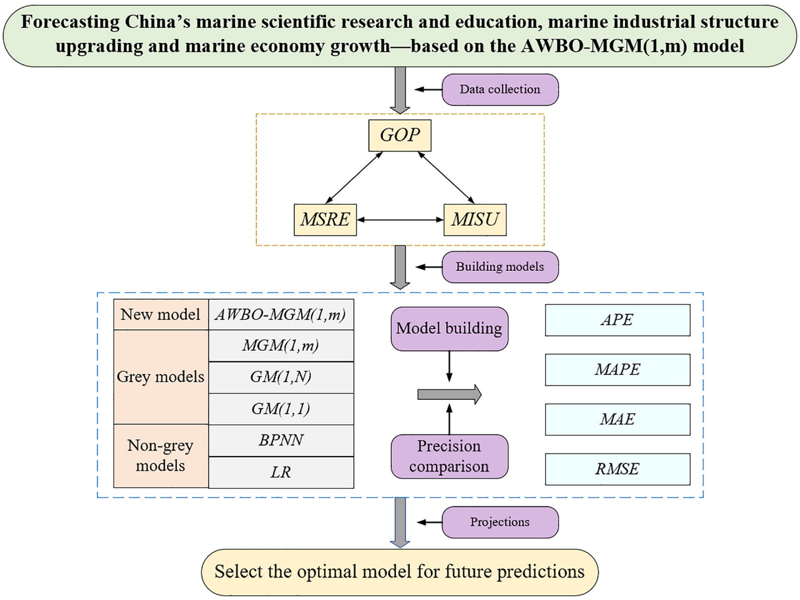
In this paper, the national marine economic data from 2010 to 2021 are selected as the sample set, and the research data are obtained from the *China Marine Economic Bulletin (2010–2021)* and the *China Marine Statistical Yearbook (2010–2020)*. Among them, 2010–2018 is used as the training set for model calibration, and 2019–2021 is used as the prediction set to judge the prediction accuracy of different models. The unit of GOP value is 100 million RMB, and MSRE and MISU are ratios with unit of 1.

In this paper, the prediction accuracy of the new model is compared with five popular models, including three grey models (MGM(1,m), GM(1,N) and GM(1,1) models), one artificial intelligence (BPNN model) and one econometric model (Linear regression model or LR model). In order to avoid the errors caused by the magnitude difference among the variables and the risk of singular matrix that may occur in the calculation process, the data corresponding to each variable are initialized before modeling, i.e. each variable is divided by the first data of the corresponding variable, respectively (Yin *et al.*, 2023). Finally, the data is restored to its initial value for intuitiveness. Figure 2 shows a visualization of the case analysis process.

Table 1.
The MAPE criterion for model examination

MAPE (%)	Prediction accuracy
0–10	High accuracy
10–20	Good accuracy
20–50	Reasonable accuracy
>50	Weak accuracy

Source(s): Li *et al.* (2023a, b, c)



Source(s): Authors' own work

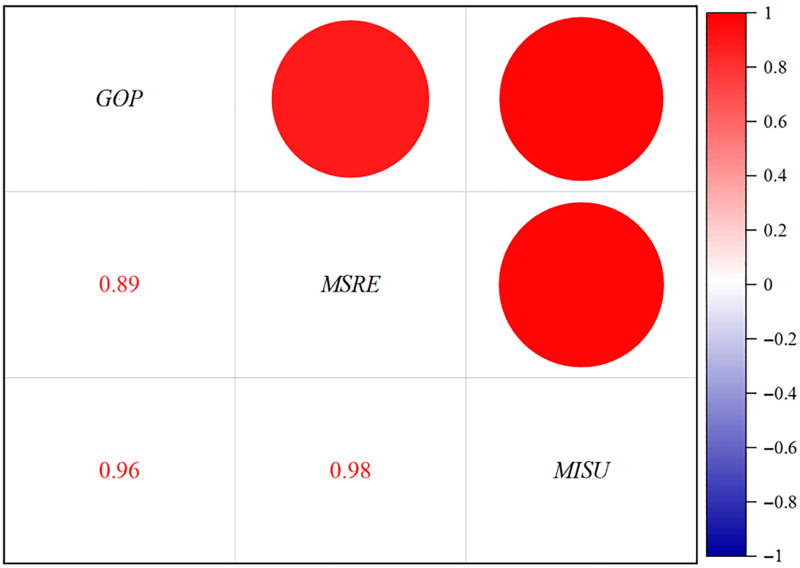
Figure 2.
Case study flow chart

3.2 Modeling process and comparison with alternative models

Figure 3 shows the heat map of correlation coefficients of the three variables, the positive diagonal area of the matrix is labeled with the variable names, the lower left triangular area shows the correlation coefficient values and the upper right triangular area visualizes the magnitude and direction of the correlation coefficients, where red represents positive correlation and blue represents negative correlation, and the larger the absolute correlation coefficient, the more circular the graph is. From the map, we can see that the correlation coefficients of GOP, MSRE and MISU are all greater than or equal to 0.89, indicating that the variables show significant correlations, so there are likely to be interactions among the three subjects.

To compare the simulation and prediction accuracy of the six models for the GOP, this paper first analyzes the errors generated when using the six models (Table 2 and Figure 4). For the training sets, the minimum APEs of the six models, i.e. AWBO-MGM(1,m), GM(1,1), GM(1,N), MGM(1,m), BPNN and LR are 0.00%, 0.08%, 0.41%, 0.02%, 0.13% and 0.46%; the maximum APEs are 0.25%, 0.92%, 72.84%, 0.88%, 8.44% and 6.10%; and the MAPEs are 0.07%, 0.40%, 11.96%, 0.37%, 4.38% and 3.16%, respectively. For the test sets, the minimum APEs of the six models are 2.95%, 2.21%, 3.44%, 1.57%, 7.68% and 3.87%; the maximum APEs are 12.61%, 24.51%, 38.18%, 23.21%, 36.11% and 31.21%; and the MAPEs are 6.33%, 15.62%, 21.05%, 14.36%, 23.74% and 21.10%, respectively. Comparing the results of APE and MAPE, the AWBO-MGM(1,m) model has the best fitting accuracy and prediction accuracy for GOP, and MGM(1,m) is suboptimal.

To compare the simulation and prediction accuracy of the six models for the MSRE, this paper analyzes the errors generated when using the six models (Table 3 and Figure 5). For the training sets, the minimum APEs of the six models, i.e. AWBO-MGM(1,m), GM(1,1), GM(1,N), MGM(1,m), BPNN and LR are 0.05%, 0.78%, 0.39%, 0.01%, 0.13% and 0.16%; the maximum APEs are 0.66%, 6.55%, 115.70%, 3.34%, 8.03% and 2.22%; and the MAPEs are 0.27%, 3.14%, 17.18%, 1.43%, 2.57% and 1.10%, respectively. For the test sets, the minimum APEs



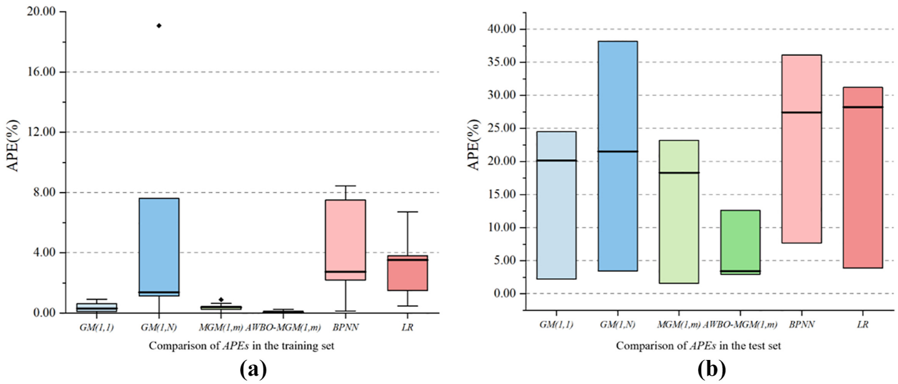
Source(s): Calculated based on data from the China Marine Economic Bulletin (2010-2021) and the China Marine Statistical Yearbook (2010-2020)

Figure 3. Correlation coefficient heat map

Table 2.
Forecasts and APE of the GOP

Time Training set	Actual value	GM(1,1) Forecasts	GM(1,1) APE	GM(1,N) Forecasts	GM(1,N) APE	MGM(1,m) Forecasts	MGM(1,m) APE	AWBO-MGM(1,m) X(0)D	AWBO-MGM(1,m) Forecasts	AWBO-MGM(1,m) APE	BPNN Forecasts	BPNN APE	LR Forecasts	LR APE
2010	38439	38439	0.00%	38439	0.00%	38439	0.00%	60505.22	60505.22	0.00%	35363.88	8.00%	41018.03	6.71%
2011	45570	45850.85	0.62%	12377.31	72.84%	45560.12	0.02%	63263.5	63255.91	0.01%	41723.09	8.44%	44889.07	1.49%
2012	50087	49979.3	0.22%	50293.3	0.41%	49900.45	0.37%	65791.14	65740.35	0.08%	50152.26	0.13%	50549.56	0.92%
2013	54313	54479.48	0.31%	64679.18	19.09%	54555.94	0.45%	68408.5	68407.62	0.00%	50332.01	7.33%	54060.62	0.46%
2014	59936	59384.86	0.92%	64496.92	7.61%	59555.38	0.64%	71227.6	71222.11	0.01%	55436.01	7.51%	56277.94	6.10%
2015	64669	64731.92	0.10%	65397.9	1.13%	64928.81	0.40%	74050.5	74157.27	0.14%	62895.84	2.74%	67129.89	3.81%
2016	70507	70560.44	0.08%	71473.06	1.37%	70707.82	0.28%	77177.67	77193.3	0.02%	72055.97	2.20%	68019.82	3.53%
2017	77611	76913.76	0.90%	80699.94	3.98%	76925.77	0.88%	80513	80315.35	0.25%	77044.77	0.73%	80537.17	3.77%
2018	83415	83839.14	0.51%	82428.65	1.18%	83618.12	0.24%	83415	83512.22	0.12%	85366.09	2.34%	82065.79	1.62%
MAPE		0.40%		11.96%		<u>0.37%</u>			*0.07%*		4.38%		3.16%	
Test set														
2019	89415	91388.09	2.21%	92489.92	3.44%	90822.68	1.57%		86775.45	2.95%	82547.65	7.68%	85956.9	3.87%
2020	80010	99616.76	24.51%	97228.69	21.52%	98579.84	23.21%		90098.55	12.61%	58071.36	27.42%	57428.94	28.22%
2021	90385	108586.34	20.14%	124891.53	38.18%	106932.84	18.31%		93476.5	3.42%	57743.53	36.11%	62177.15	31.21%
MAPE		15.62%		21.05%		<u>14.36%</u>			*6.33%*		23.74%		21.10%	

Note(s): Italic ones are the best choice, underline ones are the second-best choice
Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR



Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR

Figure 4.
APE box line chart for the GOP

of the six models are 0.77%, 2.46%, 8.94%, 4.18%, 2.32% and 2.26%; the maximum APEs are 14.90%, 15.24%, 23.25%, 6.25%, 19.06% and 14.75%; and the MAPEs are 8.17%, 8.56%, 17.85%, 5.33%, 12.52% and 10.10%, respectively. Comparing the results of APE and MAPE, the AWBO-MGM(1,m) model has excellent fitting and prediction accuracy for MSRE.

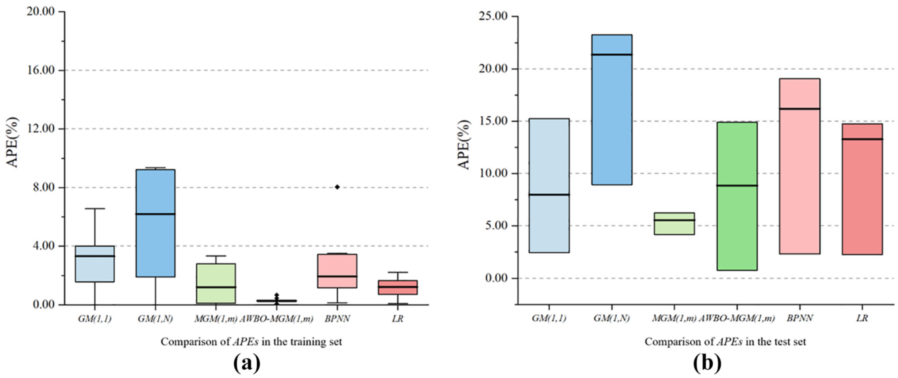
To compare the simulation and prediction accuracy of the six models for the MISU, this paper analyzes the errors generated when using the six models (Table 4 and Figure 6). For the training sets, the minimum APEs of the six models, i.e. AWBO-MGM(1,m), GM(1,1), GM(1,N), MGM(1,m), BPNN and LR are 0.00%, 0.07%, 0.97%, 0.07%, 0.00% and 0.01%; the maximum APEs are 0.05%, 0.79%, 73.44%, 0.39%, 0.60% and 0.20%; and the MAPEs are 0.07%, 0.40%, 11.96%, 0.37%, 4.38% and 3.16%, respectively. For the test sets, the minimum APEs of the six models are 0.12%, 0.08%, 4.80%, 0.68%, 1.03% and 0.22%; the maximum APEs are 0.40%, 0.95%, 91.72%, 3.15%, 7.03% and 1.87%; and the MAPEs are 6.33%, 15.62%, 21.05%, 14.36%, 23.74% and 21.10%, respectively. Comparing the results of APE and MAPE, the AWBO-MGM(1,m) model has the best fitting accuracy and prediction accuracy for MISU.

Comparing the three different measures of prediction accuracy (RMSE, MAE and MAPE) for the three variables and for the six models, as shown in Tables 5–7, it can be seen that for the GOP (Table 5), MAPE values of the AWBO-MGM(1,m) model and the MGM(1,m) model are 0.02% and 0.15% for the training set, and 6.33% and 14.36% for the test set, respectively; for the MISU (Table 7), MAPE values of the AWBO-MGM(1,m) model and the MGM(1,m) model are 0.07% and 0.37% for the training set, and 0.23% and 1.81% for the test set, respectively. Therefore, in terms of the above two variables, MAPE values of the MGM(1,m), GM(1,N), GM(1,1), BPNN, and LR models were larger than those of the AWBO-MGM(1,m) for both the training and test sets. For the test set of MSRE (Table 6), although the RMSE, MAE and MAPE values of the AWBO-MGM(1,m) model are higher than those of the MGM(1,m) model, the MAPE of the AWBO-MGM(1,m) model is 8.17%, which is less than 10%, and still belongs to the category of high precision prediction. Besides, each error value of the AWBO-MGM(1,m) model for the training set is smaller than that of the MGM(1,m) model. Figure 7 shows the overall comparison of the performance of the six models, and it can be seen that the AWBO-MGM(1,m) model proposed in this paper does better in simulating and predicting GOP, MSRE and MISU as a system.

Table 3.
Forecasts and APE of the MSRE

Time Training set	Actual value	GM(1,1) Forecasts	GM(1,1) APE	GM(1,N) Forecasts	GM(1,N) APE	MGM(1,m) Forecasts	MGM(1,m) APE	X(0) D	AWBO-MGM(1,m) Forecasts	AWBO-MGM(1,m) APE	BPNN Forecasts	BPNN APE	LR Forecasts	LR APE
2010	0.178	0.178	0.00%	0.178	0.00%	0.178	0.00%	0.19	0.19	0.00%	0.172	3.50%	0.178	0.09%
2011	0.17	0.161	5.16%	−0.027	115.70%	0.171	0.85%	0.192	0.191	0.05%	0.172	1.15%	0.169	0.71%
2012	0.176	0.169	4.01%	0.16	9.37%	0.17	3.34%	0.195	0.194	0.27%	0.176	0.28%	0.176	0.16%
2013	0.171	0.177	3.66%	0.168	1.89%	0.173	1.20%	0.198	0.198	0.27%	0.176	3.11%	0.172	0.71%
2014	0.174	0.186	6.55%	0.174	0.39%	0.179	2.80%	0.203	0.204	0.22%	0.18	3.45%	0.172	1.22%
2015	0.189	0.195	3.31%	0.182	3.46%	0.189	0.01%	0.21	0.21	0.27%	0.192	1.94%	0.193	2.22%
2016	0.208	0.204	1.57%	0.19	8.39%	0.201	3.33%	0.217	0.216	0.44%	0.208	0.13%	0.204	1.64%
2017	0.213	0.214	0.78%	0.199	6.19%	0.215	1.26%	0.222	0.224	0.66%	0.23	8.03%	0.217	1.90%
2018	0.232	0.225	3.19%	0.211	9.23%	0.232	0.09%	0.232	0.232	0.22%	0.236	1.56%	0.229	1.22%
MAPE		3.14%		17.18%		1.43%			*0.27%*		2.57%		1.10%	
Test set														
2019	0.241	0.236	2.46%	0.22	8.94%	0.252	4.18%		0.24	0.77%	0.236	2.32%	0.236	2.26%
2020	0.291	0.247	15.24%	0.229	21.35%	0.273	6.25%		0.248	14.90%	0.236	19.06%	0.253	13.28%
2021	0.281	0.259	7.99%	0.216	23.25%	0.297	5.55%		0.257	8.84%	0.236	16.19%	0.24	14.75%
MAPE		8.56%		17.85%		5.33%			8.17%		12.52%		10.10%	

Note(s): Italic ones are the best choice, underline ones are the second-best choice
Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR



Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR

Figure 5. APE box line chart for the MRSE

3.3 Future forecasting

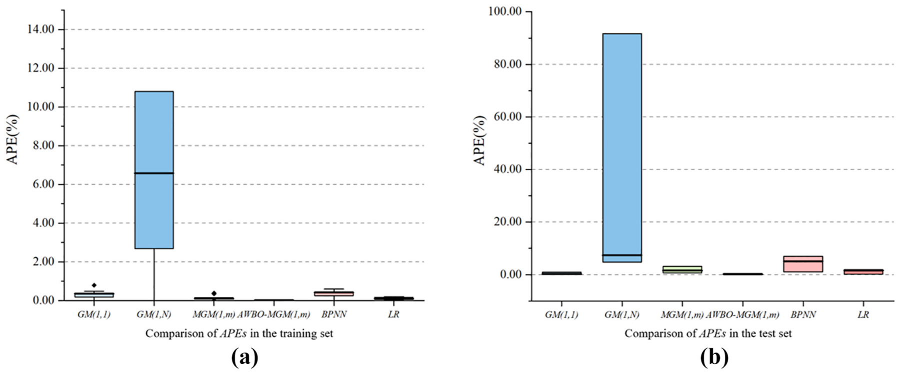
The above empirical results show that the AWBO-MGM(1,m) model is more suitable than the five comparison models to predict the future values of GOP, MSRE and MISU in China. With the rapid recovery of China's economy from the epidemic, China's marine economy is expected to resume its previous development trend. Therefore, in order to obtain more accurate prediction results considering the COVID-19 shock, we use the data from 2010 to 2019 for the AWBO-MGM(1,m) model calibration, based on which the values of GOP, MSRE and MISU of 2022–2025 is predicted. Table 8 shows the prediction results, where the red lines indicate actual values and the green lines to the right of the dotted line are forecasted values. According to the *China Marine Economy Statistical Bulletin (2022)* released by the Ministry of Natural Resources of China, the actual value of China's GOP in 2022 is 9,462.8 billion RMB, and the error of the predicted value of GOP in 2022 in the table is only 4.7%; the value of the MISU in 2022 is 2.543, and the error of the predicted value in the table is only 1.8%, which indicates that the AWBO-MGM(1,m) model has good performance and the prediction results have a high degree of confidence.

Figure 8 shows the actual values of GOP, MSRE and MISU from 2010 to 2019 and the predicted values of each variable from 2010 to 2025 obtained by the AWBO-MGM(1,m) model. It can be seen that China's GOP, the level of marine scientific research and education, and the level of upgrading of marine industry structure continue to maintain the growth trend in 2022–2025. The result is consistent with the actual: on the one hand, China's marine economy has shown good development momentum in recent years, and in 2021, China's GOP exceeded 9 trillion RMB for the first time, with a growth rate of 8.3%, exceeding the GDP growth rate by 0.3 percentage points, and the GOP accounted for 15% of GDP in coastal areas, contributing 8.0% of the year-on-year increase in China's GDP. Despite the impact of the COVID-19, the structural upgrading of China's marine industry has been steadily progressing in recent years, and the proportions of the product of three industries to GOP in 2021 were 5.0%, 33.4% and 61.6%, separately. The innovation of marine science and technology promotes the high-quality development of marine industry. From 2007 to 2021, China's marine patents have continued to grow, with an average annual year-on-year growth rate of nearly 20%, and the conversion rate of marine science and technology has increased significantly. So, the marine economy has been gradually transformed from factor-driven to science and technology-driven, and the sustainable development force has been enhanced. On the other hand, the top-level design of the development of the marine economy has been optimized. The 14th Five-Year Plan pointed out that we should further build a modern marine

Table 4. Forecasts and APE of the MISU

Time Training set	Actual value	GM(1,1) Forecasts	GM(1,1) APE	GM(1,N) Forecasts	GM(1,N) APE	MGM(1,m) Forecasts	MGM(1,m) APE	AWBO-MGM(1,m) X(0)D	AWBO-MGM(1,m) Forecasts	AWBO-MGM(1,m) APE	BPNN Forecasts	BPNN APE	LR Forecasts	LR APE
2010	2.421	2.421	0.00%	2.421	0.00%	2.421	0.00%	2.464	2.464	0.00%	2.411	0.44%	2.42	0.06%
2011	2.419	2.407	0.48%	0.642	73.44%	2.421	0.09%	2.47	2.47	0.00%	2.408	0.44%	2.42	0.06%
2012	2.434	2.425	0.38%	2.594	6.58%	2.426	0.35%	2.477	2.476	0.04%	2.419	0.60%	2.434	0.01%
2013	2.434	2.442	0.35%	3.055	25.52%	2.436	0.07%	2.484	2.485	0.02%	2.423	0.44%	2.433	0.02%
2014	2.441	2.46	0.79%	2.705	10.80%	2.451	0.39%	2.494	2.495	0.05%	2.441	0.00%	2.445	0.17%
2015	2.473	2.478	0.22%	2.407	2.68%	2.469	0.15%	2.508	2.507	0.02%	2.464	0.38%	2.468	0.19%
2016	2.495	2.497	0.07%	2.519	0.97%	2.492	0.13%	2.519	2.519	0.00%	2.501	0.24%	2.499	0.16%
2017	2.52	2.515	0.18%	2.752	9.24%	2.517	0.10%	2.531	2.531	0.00%	2.53	0.41%	2.514	0.20%
2018	2.543	2.533	0.37%	2.464	3.08%	2.545	0.10%	2.543	2.543	0.01%	2.544	0.04%	2.545	0.10%
MAPE		0.32%		14.70%		0.15%			*0.02%*		0.33%		<u>0.11%</u>	
Test set														
2019	2.559	2.552	0.27%	2.747	7.36%	2.576	0.68%		2.555	0.17%	2.585	1.03%	2.565	0.22%
2020	2.568	2.571	0.08%	2.692	4.80%	2.61	1.61%		2.565	0.12%	2.388	7.03%	2.611	1.64%
2021	2.565	2.589	0.95%	4.918	91.72%	2.646	3.15%		2.575	0.40%	2.434	5.10%	2.613	1.87%
MAPE		<u>0.44%</u>		34.63%		1.81%			*0.23%*		4.38%		1.24%	

Note(s): Italic ones are the best choice, underline ones are the second-best choice
Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR



Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR

Figure 6. APE box line chart for the MISU

	RMSE	MAE	MAPE
Training set			
GM(1,1)	348.78	260.43	0.40%
GM(1,N)	11747.51	6010.71	11.96%
MGM(1,m)	308.66	241	0.37%
AWBO-MGM(1,m)	*83.55*	*53.56*	*0.07%*
BPNN	2789.43	2367.52	4.38%
LR	2195.93	1872.94	3.16%
Test set			
GM(1,1)	15487.7	13260.4	15.62%
GM(1,N)	22335.61	18266.71	21.05%
MGM(1,m)	14383.46	12175.12	14.36%
AWBO-MGM(1,m)	*6279.69*	*5273.2*	*6.33%*
BPNN	23050.16	20482.49	23.74%
LR	20956.67	18082.34	21.10%

Note(s): Italic ones are the best choice
Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR

Table 5. Accuracy comparison of models (GOP)

industry system, break through a number of core technologies in marine engineering, marine resources utilizing and marine environment protection, stimulate the marine cultural tourism development, and continuously improve the marine economic development quality. The 20th CPC National Congress emphasized the importance of the marine economy to promote regional economic development and to maintain national security, and provided clear direction and strong support for marine economy growth, industrial structure upgrading and the development of marine scientific research and education.

4. Conclusion and future work

This paper explores the interactions of marine economic growth, marine industrial structure optimization and marine scientific research and education development at the theoretical level, and predicts the future development trends of the three subjects. Considering that the COVID-19 shock will adversely affect the development of marine economy, using the traditional MGM(1,m) model will lead to poor forecasting performance, so this paper

	RMSE	MAE	MAPE(%)
Training set			
GM(1,1)	0.007	0.006	3.14%
GM(1,N)	0.067	0.031	17.18%
MGM(1,m)	0.004	0.003	1.43%
AWBO-MGM(1,m)	*0.001*	*0.001*	*0.27%*
BPNN	0.007	0.005	2.57%
LR	0.003	0.002	1.10%
Test set			
GM(1,1)	0.029	0.024	8.56%
GM(1,N)	0.054	0.05	17.85%
MGM(1,m)	*0.015*	*0.015*	*5.33%*
AWBO-MGM(1,m)	0.029	0.023	8.17%
BPNN	0.042	0.036	12.52%
LR	0.033	0.029	10.10%

Note(s): Italic ones are the best choice
Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR

Table 6.
Accuracy comparison of models (MSRE)

	RMSE	MAE	MAPE(%)
Training set			
GM(1,1)	0.009	0.008	0.32%
GM(1,N)	0.641	0.358	14.70%
MGM(1,m)	0.005	0.004	0.15%
AWBO-MGM(1,m)	*0.001*	*0*	*0.02%*
BPNN	0.009	0.008	0.33%
LR	0.003	0.003	0.11%
Test set			
GM(1,1)	0.015	0.011	0.44%
GM(1,N)	1.364	0.888	34.63%
MGM(1,m)	0.053	0.047	1.81%
AWBO-MGM(1,m)	*0.007*	*0.006*	*0.23%*
BPNN	0.13	0.112	4.38%
LR	0.037	0.032	1.24%

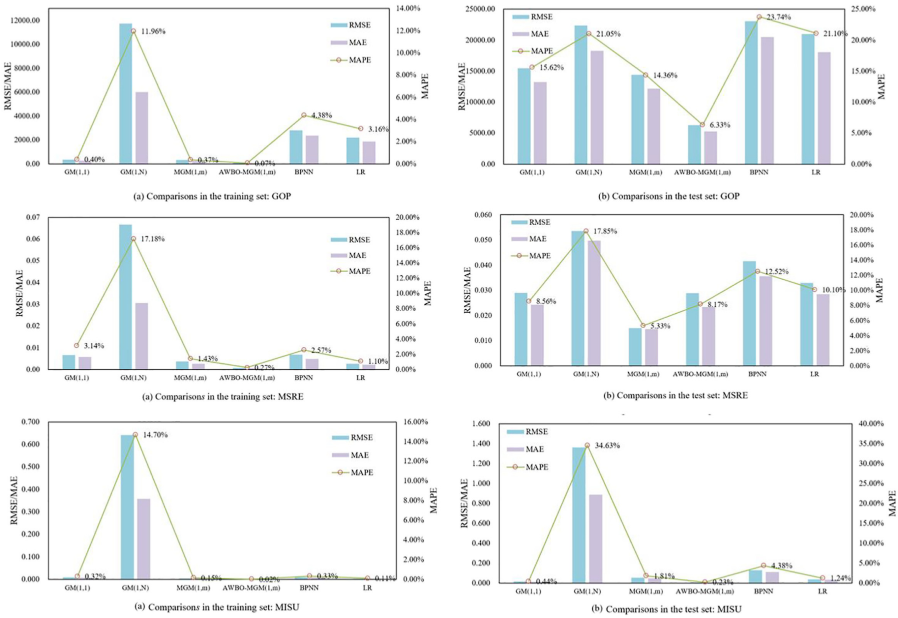
Note(s): Italic ones are the best choice
Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR

Table 7.
Accuracy comparison of models (MISU)

incorporates the weakening buffer operator into the MGM(1,m) model and innovatively proposes the AWBO-MGM(1,m) model. Based on the theoretical analysis and the prediction results of the AWBO-MGM(1,m) model, the following conclusions are obtained:

(1) From the theoretical point of view, the development of marine scientific research and education can accelerate industrial upgrading and promote marine economic growth by providing high-quality talents, promoting the progress of marine science and technology and reducing transaction costs. Moreover, the upgrading of marine industry structure and the growth of marine economy can promote the development of marine research and education by guiding social funds, enhancing the demand for talents and stimulating market vitality in return.

(2) The new model is empirically compared with MGM(1,m), GM(1,N), GM(1,1), BPNN and LR models. The results show that the prediction accuracy of the AWBO-



Source(s): Calculated based on AWBO-MGM(1,m), MGM(1,m), GM(1,N), GM(1,1), BPNN and LR

Figure 7. Comparison of performance evaluation of the models

Variables	2022	2023	2024	2025
GOP	99265.91	102606.83	105996.42	109435
MSRE	0.263	0.27	0.278	0.285
MISU	2.59	2.599	2.608	2.616

Source(s): Calculated based on AWBO-MGM(1,m)

Table 8. The forecasts of GOP, MSRE and MISU with AWBO-MGM(1,m)

MGM(1,m) model in both the training and test sets falls into the category of high-precision prediction, and the prediction results are more reliable than those of the other five models. In addition, the AWBO-MGM(1,m) model can effectively deal with the influence of unanticipated shocks on variables such as COVID-19, and thus obtain more accurate prediction results.

(3) The AWBO-MGM(1,m) model was used to forecast the GOP, the level of marine industrial structure upgrading and the development of marine scientific research and education in China from 2022 to 2025, and the results showed that the three subjects will continue to maintain a stable growth after the essential end of the COVID-19 shock. By 2025, the values of GOP, MSRE and MISU will be expected to reach 10.94 trillion, 0.29 and 2.61.

Based on the above conclusions, this paper puts forward the following policy implications. First, the government should pay attention to the construction of marine scientific research and education, and closely integrate the "Strategy of Invigorating China through the

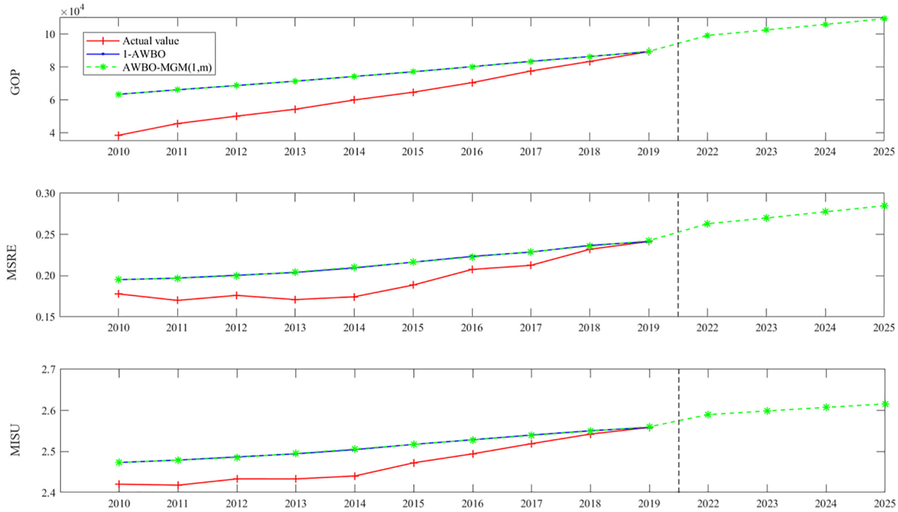


Figure 8.
The forecasts of the GOP, MSRE and MISU

Source(s): Calculated based on AWBO-MGM(1,m)

Development of Science and Education" with the "Maritime Power Strategy", so as to provide high-quality talents and advanced scientific research results for the high-quality development of marine economy. Second, the government should actively guide the labor, capital and other factors of production to the tertiary industry, thereby promoting the optimization and upgrading of marine industrial structure. Third, the government should pay attention to the solid foundation of the marine industry and increase policy support of scientific research and education for the first and second marine industries, to avoid the hollowing out of the industry to shake the foundation of the marine industry.

AWBO-MGM(1,m) has good predictive performance for China's marine economy growth, marine industrial structure upgrading, and marine scientific research and education development under the influence of the COVID-19, which indicates that the model is suitable for systematic variables forecasting problems in the presence of significant unanticipated external shocks. However, the buffer operator selected in this paper is based on fixed weights, which fails to reflect the importance of new information for numerical prediction and probably weakens the prediction performance of the model. In future researches, the new information priority criterion can be considered to further enhance the model by introducing a buffer operator with variable weights, thus giving more weight to the new information and improve prediction accuracy.

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