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The Digital: A Catalyst for Accelerating the Quality Improvement and Sustainable Development of China's Marine Industry

Gang Zhou [1], Li Zhang [1], Yao Xu [2,*], Lewei Hong [3,*] and Yi Zhang [2]

[1] School of Economics, Ocean University of China, Qingdao 266100, China
[2] Business School, Qingdao University of Technology, Qingdao 266520, China
[3] School of Marxism, Tsinghua University, Beijing 100084, China
* Correspondence: xuyao@qut.edu.cn (Y.X.); honglewei@126.com (L.H.)

Abstract

The sustainable development of the marine industry is a vital pillar for achieving global ecological balance and economic prosperity. As a crucial repository of resources and a vital regulator of climate, the ocean plays an irreplaceable role in supporting humanity's long-term development. Against this backdrop, digital technology drives modern development, supporting decision-making and resource allocation while profoundly transforming industrial models. The resulting digital economy has become one of the core drivers of sustainable global economic growth. Given the close connection between the marine industry and the digital economy, attention has been drawn to whether a correlation exists between their respective growth rates. This study employs a Panel Vector Autoregression (PVAR) model based on panel data from China's coastal provinces between 2012 and 2023. The empirical analysis reveals: (1) After a certain period, the growth rates of the digital economy and the quality development of the marine industry exhibit a mutually reinforcing trend. Furthermore, the innovation coupling coordination rate and the upgrading rate within the marine industry also strengthen each other, injecting endogenous momentum into the sustainable development of the marine sector. (2) When simulating external shocks through local government expenditure, it was found that while local government spending positively impacts the growth rate of the digital economy, its effect on the quality development rate of marine industries is limited, exhibiting a "single-helix" upward trend. This suggests the need to optimize the precision of policy support to better balance the coordinated sustainable development of the digital economy and marine industries. (3) The growth rate of the digital economy exerts a dual threshold effect on the quality development of marine industries. That is, there are two thresholds: 0.0099 and 0.0725. Initially, the promotion effect is relatively small with a positive and significant coefficient of 0.120. When exceeding the first threshold, the coefficient becomes 0.416, which is positively significant. When exceeding the second threshold, the promotion effect disappears. This necessitates differentiated strategies tailored to distinct developmental stages to propel marine industries toward high-quality, sustainable development empowered by the digital economy. Based on these findings, this study focuses on the relationship between the growth rates of the digital economy and marine industries, offering actionable recommendations for marine nations like China to advance high-level sustainable industrial development.

Keywords: the digital; marine industry quality; acceleration mechanism; threshold effect; sustainable development

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Academic Editor: Tim Gray

Received: 8 September 2025
Revised: 16 October 2025
Accepted: 19 October 2025
Published: 24 October 2025

Citation: Zhou, G.; Zhang, L.; Xu, Y.; Hong, L.; Zhang, Y. The Digital: A Catalyst for Accelerating the Quality Improvement and Sustainable Development of China's Marine Industry. *Sustainability* **2025**, *17*, 9464. https://doi.org/10.3390/su17219464

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1. Introduction

With the rapid development of the economy, humanity's demand for resources has intensified. To meet the resource needs of social development and alleviate the pressure on land resource exploitation, the development of marine resources has been continuously deepened, and it has been found that marine resource development shows enormous potential in aspects such as resource replenishment and industrial promotion [1–3].

Marine resource development has led to increasingly apparent challenges within the marine industry, including lagging infrastructure development, industrial chain vulnerability, and high energy consumption. To fully leverage the economic value of marine resources, some countries have introduced policies aimed at enhancing the maritime sector standards. The United States has emphasized policies regarding marine science research, environmental protection, and higher education. It has introduced medium- and long-term plans for marine industry development, including the "21st Century Marine Blueprint," the "U.S. Marine Action Plan," and the "Marine Spatial Planning Framework." The South Korean government has increased its financial investments in the industry as outlined in its Ocean Korea (OK) 21 strategic vision, which proposes a "blue revolution" to strengthen the country's maritime power. Australia has designated the marine industry as one of its pillar industries, established a marine development strategy, and formulated the Marine Research and Innovation Strategic Framework to establish a unified and coordinated national marine industry research and development (R&D) network. The EU has adopted the Integrated Maritime Policy and Action Plan, increasing investment in marine research and technology to propel its maritime industry to the forefront of global development. In 2017, China established high-quality development as the foundation for the marine industry.

Meanwhile, digital technology is permeating various industrial sectors with unprecedented force, and its role in optimizing resource allocation and innovating development models is becoming increasingly prominent. Moreover, the digital economy has become a key engine driving the transformation and upgrading of the global economy. It also plays a significant role in integrating and optimizing marine industrial chains. Thus, governments worldwide are increasingly adopting digital tools to boost high-quality advancement in the marine sector. The United States is seeking to uncover how digital twin technology can drive sustainable growth in the marine sector by examining four key thematic areas, along with the challenges within them and possible ways to address these challenges [4]. The EU uses digital technologies to make decisions regarding marine-related industrial policies, including fisheries, shipping, and offshore energy production [5]. Australia is using artificial intelligence to develop a new multipurpose Multi-Purpose Offshore Production Platform (MPOP) to ensure that offshore oil and gas facilities are safer and more reliable [6]. China is applying digital technology to marine fisheries as a means of promoting green development and sustainability [7]. Although studies highlight the digital economy's role in fueling the high-quality growth of the marine economy, this paper identifies a gap in the literature: the mutual influence between their respective development rates.

All major maritime powers employ digital technologies to boost the development of their marine sectors and improve quality. However, the link between the growth rate of the digital economy and marine industry quality, as well as the underlying causal mechanisms, requires more thorough investigation. Developed countries apply digital technology extensively, which allows for thorough investigation of causal relationships in their development processes; therefore, this paper selects a developing country, China, to rigorously assess the intrinsic causal relationship between these two sectors.

2. Literature Review

2.1. Rate of Digital Economic Development

Over the past decade, the digital economy has emerged as a pivotal force behind global economic expansion [8] and encompasses all economic activities propelled by digital computing technologies [9]. Currently, digital economy measurement systems primarily use index construction and production efficiency methods. The index construction method integrates multi-dimensional indicators, quantitative analysis, and dynamic comparison, becoming the core method for systematically assessing the development level and impact. The index construction method is widely used for measuring the digital economy because it is comprehensive and objective. He et al. constructed a digital development index covering five aspects using the entropy method: digital infrastructure, digital industrialization, industrial digitization, digital governance, and digital innovation capabilities [10]. Su et al. developed a K-means-SA algorithm by combining K-means, GRA, and SA to create a comprehensive digital economy index system with four dimensions: infrastructure, applications, innovation, and benefits [11]. Chen developed a digital economy indicator system using AHP and FCE. The system consists of four primary indicators and 15 sub-indicators, which were used to score and compare Japan's digital economy with that of 11 regions in China [12]. Zhang and Ma employed the entropy-weighted TOPSIS method to comprehensively assess the development level of the digital economy across Chinese provinces from 2015 to 2019 and then used the BCC-DEA and Malmquist models to analyze output efficiency from static and dynamic dimensions, respectively. Their study revealed that Guangdong Province has made significant strides in digital economic development [13]. By contrast, Ma et al. integrated the digital financial inclusion index into a digital economy measurement system to achieve a more comprehensive measurement of digital economy indicators [14]. However, studies on the growth rate of the digital economy remain scarce. Two methods exist for measuring it: the first uses the change rates of various basic indicators to build an index, and the second builds a digital economy index system and applies a growth rate adjustment, which reflects the actual growth rate more accurately. This paper adopts the second method, building on existing research, to measure the digital economy and apply growth rate adjustments.

2.2. Quality Development Rate of Marine Industries

Numerous scholars have conducted in-depth research on the quality and development of the marine industry to meet the dual demands of economic development and marine ecological conservation. Research on indicators of marine industry quality development can be categorized into two approaches: one involves constructing marine industry quality indicators using specific metrics, and the other employs total factor productivity (TFP) as the primary indicator. For example, Liu et al. employed SBM-Undesirable and Super SBM-Undesirable models to gauge the growth of marine green TFP, using this as a proxy for the marine industry quality development index. However, compared to the indicator construction method, the TFP method does not provide a comprehensive picture [15]. Consequently, numerous scholars have constructed indicator systems to measure the quality development index of the marine industry. Wang et al. used a combination of network DEA methods to divide the marine industry into four major areas: production, distribution, consumption, and investment. They calculated efficiency-weighted production measures and found that financial development contributed to the high-quality development of the marine industry [16]. Sun et al. developed a "2 + 6 + 4" framework for measuring the quality index of the marine industry, combining the five development concepts with six safety-centered concepts and four systems [17]. An et al. constructed six indicators and combined entropy, kernel density estimation, and partial spatial autocorrelation analysis to

find that the quality of marine industry development declined from east to south to north and that there were spatial differences between provinces and cities [18]. Similarly to digital economy research, few studies have investigated the growth rate of quality development in the marine industry. Building on existing research, this paper constructs an indicator system to measure the marine industry quality development and then applies a growth-rate transformation to the resulting index to obtain its growth rate.

2.3. The Rates of Digital Economic Development and Quality Development in the Marine Industry

As the digital economy is becoming increasingly integrated into the global economic landscape, technological applications in sectors like marine fisheries, marine manufacturing, and marine high-tech industries are growing. Numerous studies have examined the quality development of a single marine industry sector. He et al. examined the impact of the digital economy on the sustainable development of China's marine equipment manufacturing industry. They found that the digital economy has a positive effect on the sustainable growth of the industry, with digital trade playing a partial mediating role. They also found that the development of digital application capabilities was imbalanced across China's coastal regions. Tianjin and Guangdong have strong sustainable development capabilities compared to Guangxi and Hainan [19]. Nham and Hoa studied the function of digital technology in the sustainable development of marine mineral resources and found that its application can notably enhance resource utilization efficiency and sustainability [20].

Several scholars have conducted comprehensive analyses of the impact of the digital economy on the marine industry. Zhou et al. applied the PLS-SEM model and found that the digital economy can significantly improve the quality of the marine industry. They further noted that its effects are most evident in the dimensions of innovation and openness, while there remains considerable room for improvement regarding coordination and green development [21]. Fang et al. employed a panel fixed-effects model and the Dagum-Kini coefficient to evaluate the spatiotemporal characteristics, interrelationships, and underlying mechanisms of regional marine industry sustainability in relation to digital technology. They found that both the digital technology and green development levels of China's marine industry showed a steady upward trend, with significant regional disparities and a hierarchical structure. They proposed enhancing the application of digital technologies through technological innovations [22]. Ding et al. conducted a bidirectional assessment of coastal provinces and municipalities in China. They found that marine resources, environmental systems, and coordination concepts were important breakthroughs in narrowing the regional development gaps [23].

While scholars have focused on the one-way promotional effect of the digital economy on the quality development of the marine industry, the impact of the digital economy's growth rate on the quality of the marine industry has received limited attention. Building on previous research, this paper constructs a panel vector autoregressive (PVAR) model to examine the development rates of the digital economy and marine industry quality to reveal their mutual influence on each other's growth rates. It also introduces the marine industry's upgrading rate and innovation coupling coordination rate to provide new perspectives and policy recommendations for the quality development of the marine industry. The research process used in this paper is illustrated in Figure 1.

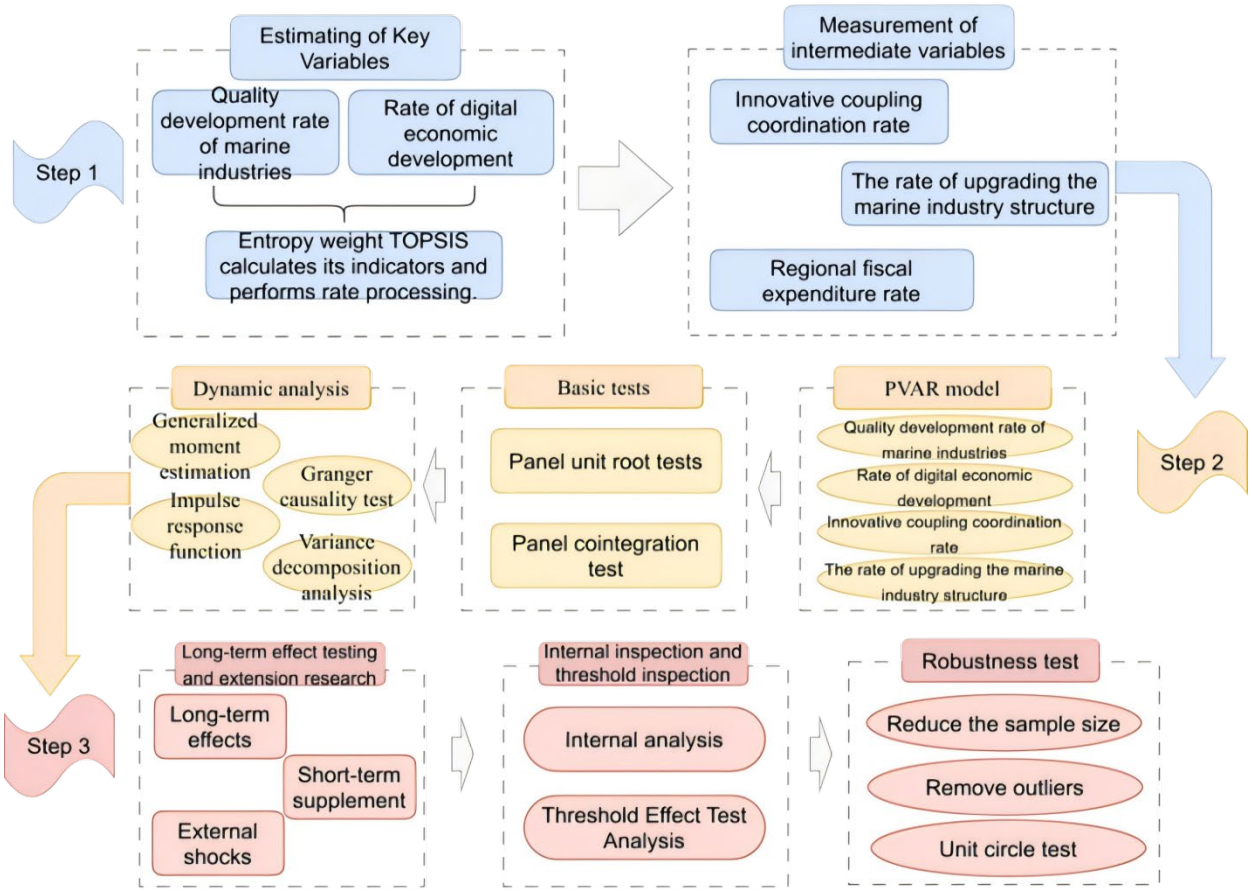


Figure 1. Research flow chart.

3. Theoretical Basis and Research Hypotheses

3.1. The Rate of Digital Economic Development and the Rate of Quality Development in the Marine Industry

Digital technology can improve the quality of the marine industry by facilitating digital economic development. Digital technologies are changing the maritime industry and making it more automated and effective [24]. A policy paper by Stevens et al. argued that digital technologies will reshape the marine industry's performance and effectiveness in the future [25]. Thus, the digital economy can exert an influence on the quality of the marine industry.

The influence of the marine industry's quality development on the growth of the digital economy stems from the expansion of the scope of application and the rise in digital demand. Liu et al. demonstrated that sustainable growth in the marine industry engenders a proliferation of novel application scenarios for the digital economy. This provides significant application targets for the advancement of digital technology and offers considerable potential for market growth, talent development, resource optimization, and information exchange [26]. The continuous development of the marine industry will generate high-end and varied demands, drive digital technological innovation, and enhance digital capabilities.

This paper builds on existing research and considers whether a development mechanism influences growth rates. Accordingly, Hypothesis 1 is proposed.

Hypothesis 1. *There exists a mutual influence mechanism between the growth rate of the digital economy and the quality development rate of the marine industry.*

3.2. The Mediating Mechanism Between the Digital Economy's Growth Rate and the Marine Industry's Quality Development Rate

A review of the literature on the digital economy and marine industries focuses on the coupling between innovation and the upgrading of marine industry structures. For example, Liu et al. used the entropy value method and CCDM to assess the coupling coordination between the two. They found that digital technology development significantly impacts marine industry quality improvement, particularly in industrial structure upgrading, digital infrastructure, and marine innovation capacity [26]. Building on their findings, this paper considers coordinated and innovative development between the two and examines whether an innovative coupling coordination index acts as an intermediary in fostering mutual influence on their development rates. Therefore, Hypothesis 2 is proposed.

Hypothesis 2. *The coordinated development rate of innovation coupling indirectly promotes the growth rates of the two industries*.

As noted by Hou and Zhao, optimizing the marine industry structure facilitates its shift from traditional sectors to informatization, digitization, and intelligence, thereby promoting quality development [27]. Therefore, this paper posits that the upgrading of structural rates in the marine industry may affect development rates. Therefore, Hypothesis 3 is proposed.

Hypothesis 3. *The marine industry's structural upgrading rate indirectly promotes the development rate of both industries*.

Meanwhile, the pace of technological advancement in the marine industry is relatively slow, which necessitates a longer cycle for the diffusion of advanced technologies. For instance, Jin et al. found that the impact of the digital economy on the marine industry exhibits a significantly positive effect after a certain lag period [28]. Therefore, this paper argues that there is a certain lag in the impact of the digital economy on the development of the marine industry, and there is also a certain lag in the transformation of digital technologies into marine-specific technologies. On this basis, this paper proposes the following hypothesis.

Therefore, Hypotheses 4 and 5 are proposed.

Hypothesis 4. *The boosting effect of the marine industry's rate of structural upgrading on the digital economy's growth rate has a relatively long lag*.

Hypothesis 5. *The promotional effect of the digital economy's growth rate on the innovation coupling coordination rate has a relatively long lag*.

3.3. External Shock Variables Affecting the Rate of Quality Development in the Digital Economy and Marine Industries

Local government expenditure serves as a tool for regulating industrial development in both the digital economy and the marine industry, influencing the efficiency of resource allocation and, in turn, overall industrial growth. Keynesian fiscal theory shows that local government spending can directly stimulate industrial development and influence the economic growth of related industries by increasing capital expenditure [29]. Furthermore, relevant studies by Liu and Xia indicate that local fiscal expenditure can effectively promote the digital innovation of enterprises within a region, thereby enhancing the regional digitalization level and the development of the digital economy [30]. Moreover, fiscal expenditure can also promote digital economy innovation and the application level of

the digital economy in a region [31]. In recent years, the Chinese government has issued many policy documents to promote the development of the digital economy, including the "14th Five-Year Plan for the Development of the Digital Economy" in 2021, the "Overall Plan for the Construction of a Digital China" in 2023, and the "Action Plan for Accelerating the Cultivation of Digital Talent to Support the Development of the Digital Economy (2024–2026)" in 2024. Since the national government is prioritizing the digital economy, local governments are also expected to increase their expenditures in this area. However, this focus may come at the expense of other industries. Thus, Hypothesis 6 is proposed.

Hypothesis 6. *The growth rate of local fiscal expenditures will accelerate the development of the digital economy but will not directly promote the quality development rate of the marine industry.*

3.4. The Threshold Effect of Digital Economic Growth Rate on Marine Industry Quality Development Rate

The growth of the digital economy impacts the expansion of other industries, but it involves prerequisites. For example, it is essential to build infrastructure for the digital industry to meet hardware demands for the free flow of digital information. Software requirements in the digital industry require many highly skilled workers with data knowledge. Furthermore, there is a time lag between the hardware and software in the digital industry, as the dissemination of software knowledge lags behind the construction of infrastructure to meet the hardware demand [27]. Therefore, this paper holds that the digital economy's influence on other industries is conditional and specifically features a threshold effect. The impact of the digital economy's growth rate on the development rates of other industries may also have a similar effect. Thus, Hypothesis 7 is proposed.

Hypothesis 7. *The growth rate of the digital economy has a threshold effect on the quality development rate of the marine industry.*

As shown in Figure 2, most existing studies use a one-way approach. By contrast, this paper expands the research assumptions, as shown in Figure 3, and illustrates them in Figure 4.

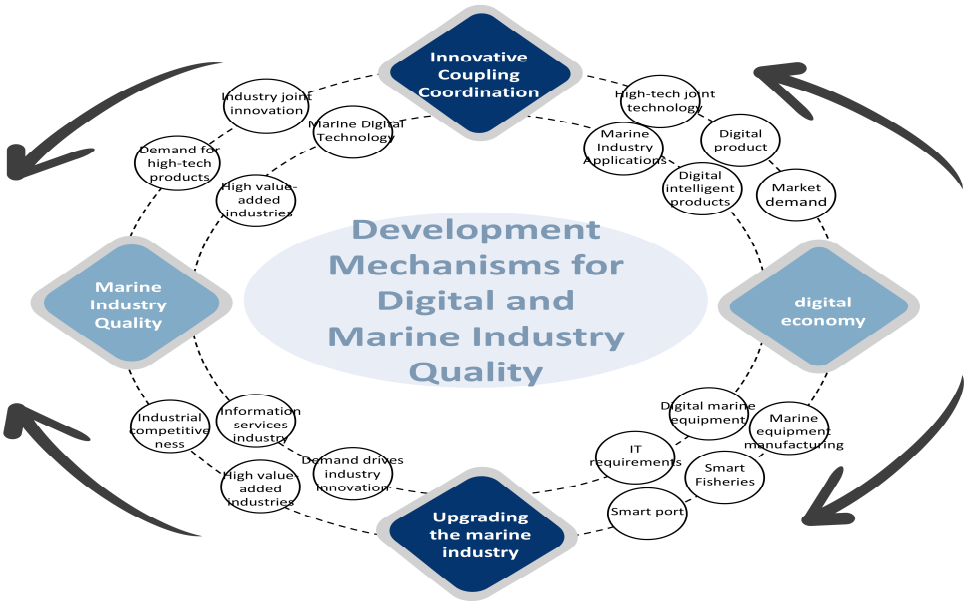


Figure 2. One-way research mechanism diagram. Note: The arrows indicate the direction of action, i.e., the direction between the research variables.

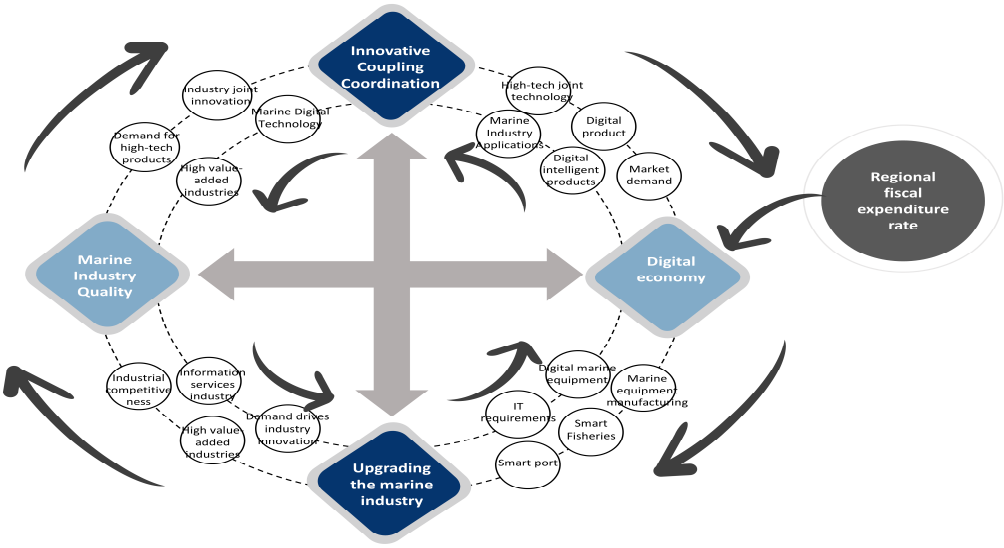


Figure 3. Expected two-way mechanism of the study. Note: The arrows indicate the direction of action, i.e., the direction between the research variables.

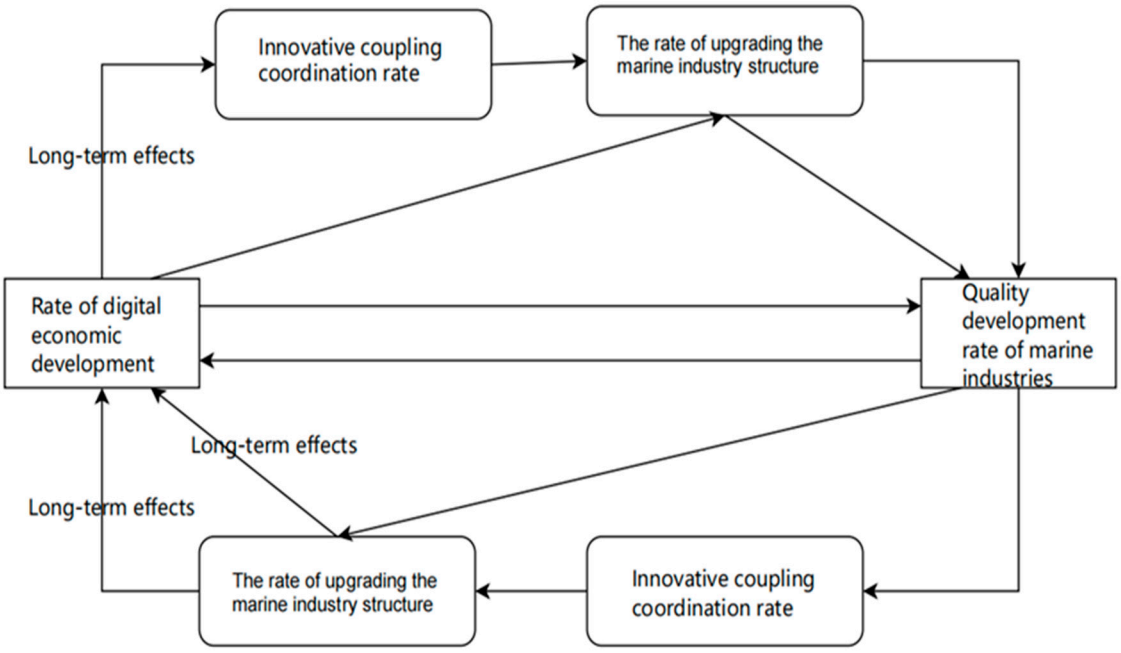


Figure 4. Expected research hypothesis mechanism diagram.

4. Variable Selection and Model Construction

4.1. Variable Selection

4.1.1. Explained Variable: RATE of Development of Marine Industry Quality

Building on the studies by Wang et al. [16], Zhou et al. [32], Ding et al. [23]., Liu et al. [15] and Sun et al. [17] as well as the new development philosophy outlined in the 13th Five-Year Plan for the Development of China's Marine Industry, this paper constructs five primary indicators and 22 secondary indicators, and adopts the entropy-weighted TOPSIS method to assess the quality development level of the marine industry. After obtaining the quality level of the marine industry, this study calculates the growth rate of the index. Further details are presented in Table 1.

Table 1. Marine Industry Quality Development Index.

Primary	Secondary	Tertiary
Marine Industry Quality Development Index	Innovation	Internal R&D expenditure in coastal areas Number of R&D projects in coastal areas Number of scientific research institutions in coastal areas Number of scientific research personnel in coastal areas Percentage of master's and doctoral degree holders in coastal areas Number of marine patents granted in coastal areas
	Coordination	Total value of marine fishery production in coastal areas Percentage of total marine production value in coastal areas relative to regional GDP Fixed asset investment in coastal regions' society Percentage of marine tertiary industry in coastal areas relative to total marine production value Percentage of total marine production value in coastal areas relative to national total marine production value
	Green	Per capita aquatic product production in coastal areas General industrial solid waste generation in coastal areas Comprehensive utilization rate of general industrial solid waste in coastal areas Energy consumption per unit of marine gross product in coastal areas
	Open	Number of international standard containers at coastal ports Total import and export trade volume in coastal areas Foreign capital utilization intensity in coastal regions
	Sharing	Number of people employed in the fishing industry in coastal areas Percentage of urban and rural residents' income in coastal areas Number of hospital beds per 10,000 people in coastal areas Number of marine-related higher education institutions (organizations) in coastal areas Per capita marine gross domestic product in coastal areas

4.1.2. Explanatory Variable: Rate of Digital Industry Development

Incorporating the national government's digital economic development requirements into existing research [33,34], this paper constructs four secondary indicators, seven tertiary indicators, and 17 quaternary indicators to assess four aspects of digital industry development: digital support systems, digital communication and service capabilities, digital information and transactions, and digital R&D ecosystems. The same method is used to convert the indicators into rates. Further details are presented in Table 2.

4.1.3. Intermediate Variables: Innovation Coupling Coordination Rate and Marine Industry Structural Upgrading Rate

Kim et al. and Bouma studied innovation coupling measures using indices, such as PMI, NMI, and NPMI, to calculate the level of innovation coupling coordination [35,36]. Tang and Liu et al. used another method to measure the level of coupling coordination by measuring the degree of dynamic coupling between industries [37,38]. This paper uses data from the National Patent Statistics Bureau related to the marine industry and digital economy and avoids subjective errors to enhance objectivity. First, the patent data are processed using Python software 3.12.7. and mapped using the "Correlation Table between the Classification of Core Industries in the Digital Economy and the International Patent Classification (2023)," which references the International Patent Classification (IPC). Patents belonging to the digital economy are assigned a value of one, whereas others are assigned a value of zero. This paper selects marine industry patent topics from the Qingdao Patent

Office database of the National Patent Database based on the research of Guo Jianke and matches the data using "application numbers" [39]. Ultimately, we obtain digital, marine, and common patent data. The study applies the entropy value method, TOPSIS, and gray correlation to calculate the degree of coupling between industries in terms of innovation coordination and set the corresponding weights. Finally, the dataset is processed to cover the period from 2012 to 2023.

Table 2. Digital Economy Index.

Primary	Secondary	Tertiary	Indicator Attributes
Digital Economy Index	Digital support system	Traditional digital infrastructure	Total length of long-haul optical fiber cable lines Mobile phone penetration rate
		Network information infrastructure	Number of domain names Internet broadband access ports Number of Internet broadband access users
	Digital communications and service capabilities	Digital communication capabilities	Total telecommunications business volume Total postal business volume
		digital service capabilities	Software business revenue Digital inclusive finance index
	Digital Informatization and Transactions	Level of enterprise informatization	Number of computers used per 100 employees Number of websites owned per 100 companies
		Digital transaction level	Number of enterprises engaged in e-commerce Percentage of enterprises engaged in e-commerce transactions
	Digital R&D Ecosystem	Research and development ecosystem of large-scale enterprises	Full-time equivalent of R&D personnel in industrial enterprises above designated size R&D expenditure in industrial enterprises above designated size R&D projects in industrial enterprises above designated size Number of patent applications for R&D by industrial enterprises above designated size

The rate of upgrading the marine industry structure is based on existing research [27]. The index is constructed by assigning weights of one, two, and three to the proportions of the primary, secondary, and tertiary industries, respectively. These ratios are added to obtain the marine industry structure upgrade index. The index is subsequently converted into a rate to derive the marine industry structural upgrading rate.

4.1.4. External Shock Variable: Regional Fiscal Expenditure Rate

Regarding the mutually reinforcing relationship between the growth rates of digital economic development and the quality of the marine industry, we select the growth rate of local government expenditure as a variable representing external shocks. This is because external shocks originate from multiple sources, such as local education, healthcare, and urbanization. Local fiscal expenditures include education, healthcare, tax incentives, and

policy subsidies. Therefore, this paper selects the local fiscal expenditure rate as the external shock variable to avoid omitting important external shock variables and to reflect a more comprehensive overall external shock.

4.1.5. Data Description

Given the availability and comparability of the data, we selected the data from 2012 to 2023 and focused on China's coastal provinces (cities) with the exception of Hong Kong, Macao, and Taiwan (as shown in the Figure 5 below). Panel data was used to analyze the interaction between the rates of development of the digital economy and the quality of the marine industry. The primary data sources for this paper included the China Statistical Yearbook (2011–2023), China Marine Economy Statistical Yearbook, Marine Economy Blue Book, China Marine Development Report, data from provincial marine bureaus, data from the First National Marine Industry Survey, and the National Patent Database (Qingdao Patent Database). To address the limitations of the marine industry data and ensure the rationality of the research content, this paper adopts the interpolation method with reference to the relevant research by Hou Yi et al. to conduct interpolation estimation for some of the data from 2022 to 2023 [27]. The final research results cover the data from 2012 to 2023. The map of the study area is shown in the figure below. The specific data content can be retrieved in the Supplementary Materials.

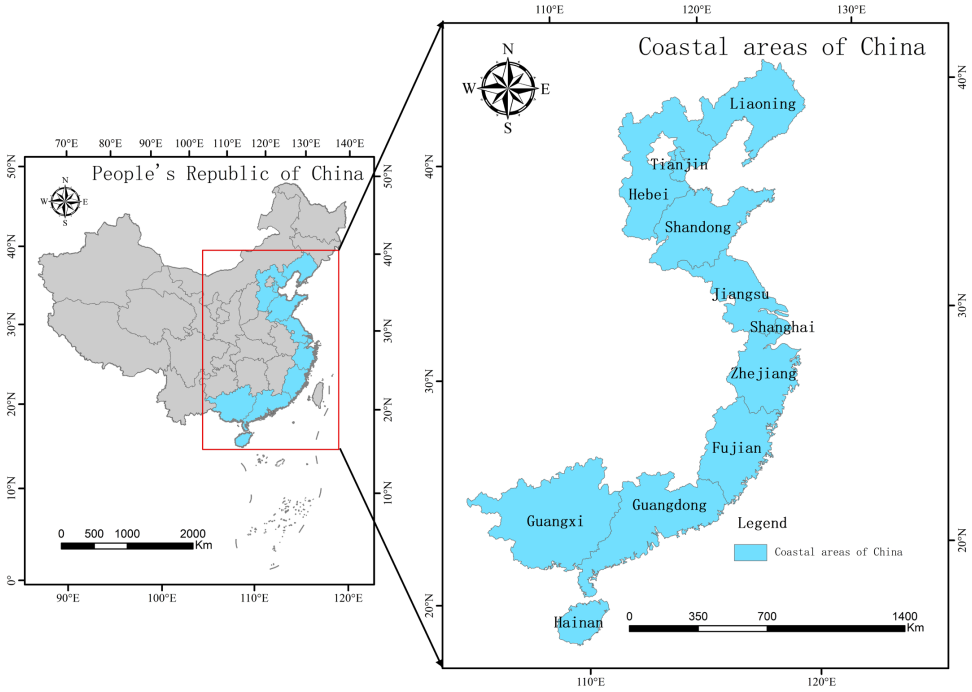


Figure 5. Map of the study area.

4.2. Model Construction

The PVAR model can well meet the research hypothesis of studying the mutually promoting effect in this paper and can also overcome the endogeneity problem well. Therefore, this paper chooses the PVAR model for the research. This paper constructed the following model, which is based on the above research hypotheses and references Charfeddine and Kahia [40] and Dogan et al. [41].

$$\begin{bmatrix} OE_{it} \\ DE_{it} \\ IS_{it} \\ CI_{it} \end{bmatrix} = \begin{bmatrix} \alpha_{10} \\ \alpha_{20} \\ \alpha_{30} \\ \alpha_{40} \end{bmatrix} + \sum_{p=1}^{P} \begin{bmatrix} \alpha_{11p} & \alpha_{12p} & \alpha_{13p} & \alpha_{14p} \\ \alpha_{21p} & \alpha_{22p} & \alpha_{23p} & \alpha_{24p} \\ \alpha_{31p} & \alpha_{32p} & \alpha_{33p} & \alpha_{34p} \\ \alpha_{41p} & \alpha_{42p} & \alpha_{43p} & \alpha_{44p} \end{bmatrix} \begin{bmatrix} OE_{i,t-p} \\ DE_{i,t-p} \\ IS_{i,t-p} \\ CI_{i,t-p} \end{bmatrix} + \begin{bmatrix} \mu_{1it} \\ \mu_{2it} \\ \mu_{3it} \\ \mu_{4it} \end{bmatrix}$$

where i and t represent the region and year, respectively; OE_{it} represents the growth rate of the quality of the marine industry; DE_{it} represents the growth rate of the digital economy; IS_{it} represents the growth rate of the structure of the marine industry; and CI_{it} represents the growth rate of innovation coupling coordination. $OE_{i,t-p}$, $DE_{i,t-p}$, $IS_{i,t-p}$, $CI_{i,t-p}$ represent the lagged variables of the four variables at period p, respectively, with the former being the lagged coefficients and μ_{it} being the random disturbance term. A descriptive analysis is presented in Figure 6.

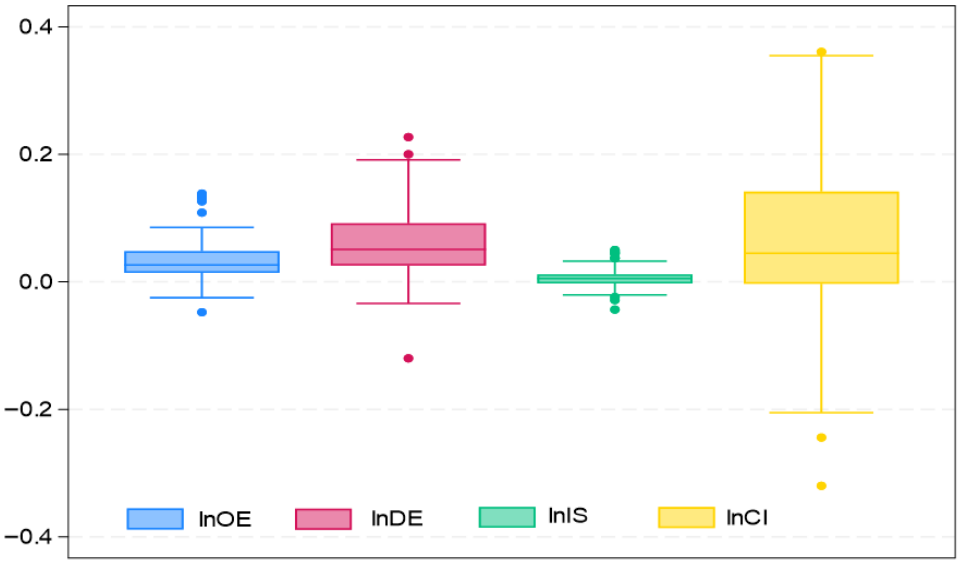


Figure 6. Descriptive analysis.

5. Empirical Results and Analysis

5.1. Short-Term Effects Within the Industry

5.1.1. Stability Test

Five testing methods were employed to ensure the accuracy of the model estimates. These tests were used to prevent spurious regressions. The results of these tests were presented in Table 3. Based on the test results, lnOE, lnDE, lnIS, and lnCI were found to be stationary after smoothing.

Table 3. Stability Test.

Variable	LLC	IPS	HT	ADF-Fisher	PP-Fisher	Result
lnOE	−8.4222 ***	−4.6408 ***	−0.3318 ***	103.6590 ***	187.0940 ***	smooth
lnDE	−4.5596 ***	−3.2052 ***	−0.2161 ***	32.6750 ***	79.0626 ***	smooth
lnIS	−5.8151 ***	−3.1652 ***	−0.0943 ***	41.7761 ***	63.4170 ***	smooth
lnCI	−5.8994 ***	−2.8361 ***	0.0223 ***	37.8336 **	44.8836 ***	smooth

Note: ***, and ** indicate significance levels of 1% and 5%, respectively; the values in parentheses are robust standard errors.

Furthermore, this paper performed cointegration tests; the Pedroni and Kao tests rejected the null hypothesis. Therefore, this paper concludes that there is a long-term relationship between these variables. Thus, a PVAR model was established.

5.1.2. Determination of the Optimal Lag Order

The lag order of the PVAR model was determined using CMMSC Stata 18 [42]. This paper used a five-order lag, and the results were reported in Table 4. The optimal lag order was found to be one according to AIC, BIC, and HQIC. Therefore, the lag order of the PVAR model was set to one.

Table 4. Determination of the optimal lag order.

Lag	AIC	BIC	HQIC
1	−14.0514 *	−12.5785 *	−13.454 *
2	−13.8126	−11.8203	−13.0065
3	−13.6258	−11.0359	−12.5824
4	−13.1513	−9.86393	−11.8364
5	8.8728	12.9867	10.4984

Note: * denotes the optimal lag order.

5.1.3. Analysis of Generalized Method of Moments (GMM) Estimation Results

This paper constructed a PVAR model using lnOE, lnDE, lnIS, and lnCI as endogenous variables to perform a GMM estimation. Table 5 reports the estimation results.

Table 5, Equation (1), shows the effects of DE, IS, and CI (all lagged by one period) on OE. Lagged DE and IS have a substantial influence on OE, while lagged CI does not. Equation (2) shows that lagged OE has a substantial influence on DE. Equation (3) explains that lagged DE and CI have a significant positive impact on IS. Equation (4) explains that lagged OE and IS have a substantial influence on CI. These results align with the expectations and assumptions in the previous section, confirming Hypotheses 1 and 2.

Table 5. GMM estimation results of the PVAR model.

Equation	(1)	(2)	(3)	(4)
Variable	**h_lnOE**	**h_lnDE**	**h_lnIS**	**h_lnCI**
L1.h_lnOE	0.161	0.311 **	0.034	0.909 **
	(1.27)	(2.69)	(0.66)	(2.39)
L1.h_lnDE	0.113 **	0.535 ***	0.048 *	0.147
	(2.01)	(7.16)	(1.85)	(0.52)
L1.h_lnIS	0.387 **	−0.189	0.088	2.069 **
	(2.28)	(−0.73)	(0.78)	(2.85)
L1.h_lnCI	−0.025	−0.009	0.026 **	0.353 ***
	(−1.12)	(−0.37)	(2.76)	(3.18)

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively; the values in parentheses are robust standard errors.

5.1.4. Granger Causality Test

We conducted a Granger causality test to examine the causal relationships among the variables.

As shown in Table 6, the *p*-values corresponding to digital economy development (DE) and marine industrial structure upgrading (IS) are both less than 0.05, which indicates that digital economy development and marine industrial structure upgrading are Granger causes of the improvement of marine industrial quality development (OE). The *p*-value corresponding to marine industrial quality development (OE) is less than 0.05, suggesting that marine industrial quality development is a Granger cause of digital economy development (DE). Regarding the impact of digital economy development (DE) and innovation coupling coordination (CI) on marine industrial structure upgrading (IS), the *p*-value corresponding to the former (DE) is less than 0.1, while that corresponding to the latter (CI) is less than 0.01. Due to model constraints, the significance level corresponding to DE was relatively low in the previous analysis. Therefore, this study conducted a supplementary test for this issue, and the results are presented in Table 7. The *p*-value in Table 7 is less than 0.05, which confirms that both digital economy development (DE) and innovation coupling coordination (CI) are Granger causes of marine industrial structure upgrading (IS). Additionally, the *p*-value corresponding to marine industrial quality development (OE)

is less than 0.05, and the *p*-value corresponding to marine industrial structure upgrading (IS) is less than 0.01, indicating that both marine industrial quality development (OE) and marine industrial structure upgrading (IS) are Granger causes of innovation coupling coordination (CI).

Table 6. Granger Causality Test.

Equation	Excluded	*p*-Value	Result
h_lnOE	h_lnDE	0.045	Reject
	h_lnIS	0.022	Reject
	h_lnCI	0.264	Accept
	ALL	0.016	Reject
h_lnDE	h_lnOE	0.007	Reject
	h_lnIS	0.468	Accept
	h_lnCI	0.709	Accept
	ALL	0.039	Reject
h_lnIS	h_lnOE	0.510	Accept
	h_lnDE	0.064	Reject
	h_lnCI	0.006	Reject
	ALL	0.008	Reject
h_lnCI	h_lnOE	0.017	Reject
	h_lnDE	0.606	Accept
	h_lnIS	0.005	Reject
	ALL	0.004	Reject

Table 7. Granger causality supplementary test.

Equation	Excluded	*p*-Value	Result
h_lnDE	h_lnIS	0.689	Accept
	ALL	0.689	Accept
h_lnIS	h_lnDE	0.023	Reject
	ALL	0.023	Reject

5.1.5. Impulse Response Analysis

The impulse response is the impact on another variable when a standard deviation shock is imposed on the error term of that variable, while holding all other factors constant. Figure 7 shows the results for lnOE, lnDE, lnIS, and lnCD.

In Figure 7(2), DE's initial positive impact on OE diminishes over time, suggesting that the growth rate of the digital economy can provide a short-term boost to the marine industry's quality development rate by offering new technologies and business models, although this effect gradually fades. As shown in Figure 7(3), IS exerts a similar impact on OE; the rate of structural upgrading of the marine industry can drive growth in the industry's quality development rate in the short term. This is because resources are transferred to efficient industries and gradually level off over time.

In Figure 7(5), the OE responds strongly to the DE shock at the beginning and then decays, indicating that the development rate of the quality of the marine industry is significantly positively correlated with the development rate of the digital industry, after which the relationship gradually flattens. Figure 7(9,10) shows the impact responses of OE and DE on the IS, respectively. Both impacts are positive, indicating that the initial rates of marine industry quality and the digital economy are conducive to the rate of structural upgrading in the marine industry. Digital technology facilitates industrial upgrading by creating new application scenarios for the digital industry. Figure 7(12) shows that the CI positively impacts IS, demonstrating that the coordinated development of innovation

coupling can enhance structural optimization in the marine industry. Figure 7(13,15) shows the impacts of OE and IS on the CI, respectively. Initially, a substantial positive response is observed, indicating the accelerated development of the marine industry and its concomitant structural upgrading, which imparted a marked impetus to the collaborative advancement of innovation coupling. The development of the marine industry has a robust self-reinforcing effect in the short term, ultimately reaching a state of equilibrium over time.

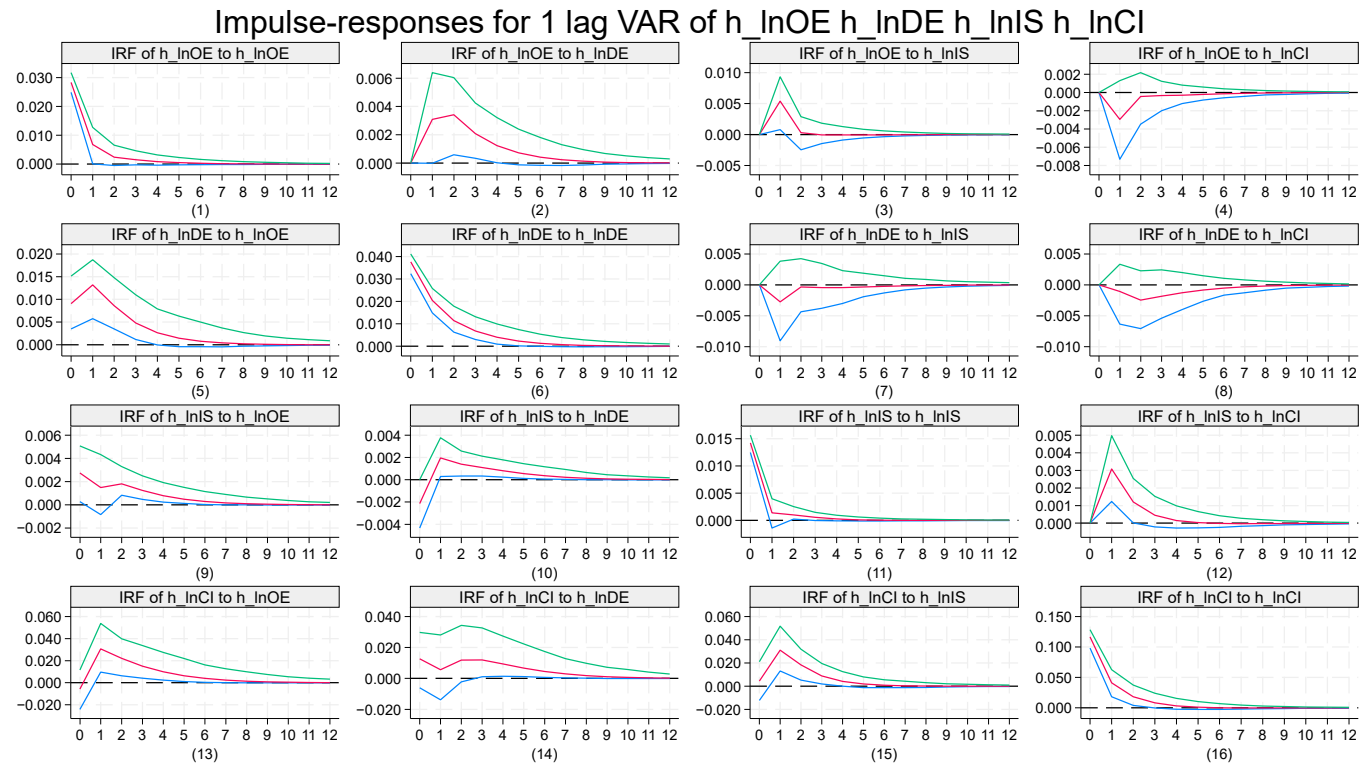


Figure 7. Pulse response analysis. Note: Figures (**1**–**4**), (**5**–**8**), (**9**–**12**), and (**13**–**16**) respectively show the impulse responses of h_lnOE, h_lnDE, h_lnIS, and h_lnCI to themselves and the other three variables. The red lines in the figures represent impulse fluctuations, while the green and blue lines indicate the upper and lower bounds of the 5% confidence interval, respectively.

5.1.6. Variance Decomposition

This paper employed a variance decomposition analysis of the quality of the marine industry. The findings indicate a gradual decline in the effect of the lagging five periods on itself, while the growth rate of digital economic development exhibits an upward trend. The other two variables remain at a certain level and do not change thereafter because of the long period, which allows only data from a certain number of years to be captured.

5.2. Long-Term Effect Testing and Extension Research

5.2.1. Testing TWO Sets of Long-Term Effects

This paper finds that upgrading marine industrial structures and innovation coordination have long-term effects on digital and quality development in the marine industry. However, marine industrial upgrading must occur first to promote digital economic development. Although digital economic development covers a broad scope, it is barely integrated into the marine industry and is incremental in practice, making the dual-pronged approach of the present paper essential. The first set of tests examines the long-term effects of upgrading the marine industry's structure and digital economic development. The

second set examines the effects of innovation and digital economic development. See Table 8 for details.

Table 8. Variance decomposition.

Periods	h_lnOE	h_lnDE	h_lnIS	h_lnCI
1	1	0	0	0
2	0.947	0.011	0.033	0.010
3	0.935	0.023	0.032	0.010
4	0.931	0.028	0.033	0.010
5	0.929	0.029	0.033	0.010
6	0.928	0.029	0.033	0.010
7	0.928	0.030	0.033	0.010
8	0.928	0.030	0.033	0.010
9	0.928	0.030	0.033	0.010
10	0.928	0.030	0.033	0.010
11	0.928	0.030	0.033	0.010
12	0.928	0.030	0.033	0.010
13	0.928	0.030	0.033	0.010

Efforts to incorporate digital technology in the context of industrial upgrading have led to an increase in the demand for such technology. In turn, this boosts the growth of the digital economy. However, the initial mismatch among digital products, digital technology, and other data elements, as well as internal friction within the industry, leads to an increase in "wrong delivery costs," causing negative fluctuations in the apparent coordination of the digital industry. However, the essence of this is a transitional and localized contradiction in the process of transformation and adjustment that has not yet formed a stable negative causal relationship. Therefore, while the respective coefficient demonstrates a negative value, it is ultimately deemed statistically insignificant. After upgrading the marine industry structure, the infrastructure for marine industries specializing in high technology has improved. At this stage, there is an increased demand for digital services such as smart ports, smart fisheries, and marine big data services. Enterprises have already developed targeted R&D plans, further increasing the demand for digital services. Consequently, a promotional correlation exists between the upgrade rate of the marine industry and the development rate of the digital economy. Once past the promotional period, diminishing marginal returns in the marine industry's structural upgrading may result in suppressed yet insignificant growth. This fluctuation in coefficients is an inevitable process of dynamic adaptation between the marine industry and the digital economy: from the initial stage of "attempting collaboration but with weak foundations," to the intermediate stage of "transformation pains causing friction," then to "adaptation taking shape and forming strong collaboration," and finally to "rebalancing toward a new stage of upgrading." This reflects the combined effects of industrial structure transformation, technological synergy efficiency, and the matching degree of supply and demand at different stages as well as the complexity and stage-specific patterns of the marine industry's integration with the digital economy. Therefore, Hypotheses 4 and 5 are established (Table 9).

5.2.2. The Marine Industry's Quality Growth Rate and Its Structural Upgrading Rate

To supplement the above conclusions, we conducted a separate analysis of the two variables, as the large number of variables in the original model and their interrelationships may have led to suboptimal results. According to Table 10, we found that in the lagging period, the quality development rate of the marine industry and the up-

grading rate of the marine industry structure had a mutually reinforcing effect. Therefore, Hypothesis 3 is established.

Table 9. Long-term effect test.

Variable	h_lnDE	h_lnCI
L1.h_lnIS	−0.428 (−1.32)	
L1.h_lnDE	0.186 ** (2.16)	0.736 *** (3.65)
L2.h_lnIS	0.249 (0.99)	
L2.h_lnDE	0.328 ** (2.06)	0.173 (0.53)
L3.h_lnIS	−0.351 (−0.11)	
L3.h_lnDE	−0.233 (−1.51)	0.385 (1.11)
fulllength L4.h_lnIS	−0.308 (−1.02)	
L4.h_lnDE	0.311 (0.108	0.624 ** (2.53)
L5.h_lnIS	0.445 ** (1.96)	
L5.h_lnDE	−0.005 (−0.004)	0.123 (0.60)
L6.h_lnIS	−0.318 (−1.27)	
L6.h_lnDE	−0.077 (−0.93)	0.573 ** (2.42)

Note: ***, and ** indicate significance levels of 1%, and 5%, respectively; the values in parentheses are robust standard errors.

Table 10. Supplementary tests.

Variable	h_lnOE	h_lnIS
L1.h_lnOE	0.261 * (1.85)	0.103 ** (1.97)
L1.h_lnIS	0.378 ** (2.09)	0.122 (1.04)

Note: **, and * indicate significance levels of 5%, and 10%, respectively; the values in parentheses are robust standard errors.

5.3. External Shock Effect

The present paper aimed to verify the spiral acceleration mechanism linking these two entities. To this end, we propose that external shocks accelerate the mutually promoting development of the two sectors. The results are presented in Table 11.

Table 11. External Shock Test.

Variable	h_lnOE	h_lnDE
L1.h_Local fiscal growth rate	−0.03 (−0.85)	0.106 ** (2.17)

Note: ** indicate significance levels of 5%, respectively; the values in parentheses are robust standard errors.

As shown in Table 10, the growth rate of local government finances has no substantial influence on the development rate of the quality of the marine industry. However, it

has a beneficial promotional effect on the growth of the digital economy. The rationale underlying this phenomenon is that the digital industry receives substantial support from local governments in terms of R&D subsidies and infrastructure development, whereas the marine industry, which is predominantly traditional, may face insufficient fiscal investment or a bias toward short-term infrastructure projects, resulting in limited long-term support for industrial quality improvement. In some cases, a resource allocation imbalance may even exert a mild inhibitory effect. Second, there is a time lag between industrial growth and the fiscal effects. Digital technology R&D cycles are relatively brief and can rapidly impact the digital industry, allowing a promotional effect to be observed over a shorter period. However, the marine industry's supply chain is extensive. The technology conversion cycle was protracted. The impact of fiscal expenditure on quality enhancement becomes evident only after a considerable interval. In the short term, it may show a slight inhibitory trend owing to lag growth. According to the "triple-helix" theory, there is a complex interdependent relationship among the three variables, forming a triple-helix upward development trend. However, the results indicate that the external shocks in this paper do not exhibit an interdependent mechanism among the three variables but rather follow a "single-helix" trend. Therefore, Hypothesis 6 is established.

5.4. Internal Mechanism

To explore the acceleration mechanisms inherent in the digital economy and marine industry quality, this paper analyzed the subsystems of both sectors. Specifically, it used the digital support system, digital communication and service capabilities, digital informatization and transactions, and digital R&D ecosystem of the digital economy to analyze the five subsystems of marine industry quality. Based on the optimal lag order and effect, this paper applied a second-order lag to the digital communication and service capabilities, openness and digital economy, and sharing and digital industry subsystems and a first-order lag to the remaining subsystems. All subsystems underwent rate-based processing.

Figure 8 shows that innovation has a weak negative impact on digital support systems. Innovation leads to a relatively concentrated allocation of resources, resulting in reduced investment in infrastructure, thereby exerting a suppressive effect. It also has a weak promotional effect on digital communication and service capabilities. Coordination and green initiatives have a positive promotional effect on digital communication and service capabilities, as well as digital informatization and transactions. Openness has a positive effect on digital informatization and transactions, as well as the digital R&D ecosystem, sharing has a strong negative correlation with the digital R&D ecosystem, as the latter requires a large concentration of resources, while sharing implies the dispersion of resources, thus inhibiting the digital R&D ecosystem.

As shown in Figure 9, the digital support system significantly promotes innovation and coordination but is negatively correlated with green and openness. The construction of a digital support system requires the consumption of natural resources, which inhibit green development. Meanwhile, the improvement in the digital support system facilitated domestic logistics and transportation, making it easier to sell products that were previously exported abroad, thereby inhibiting openness to a certain extent. Digital communication and service capabilities have no obvious effect on green and openness but have a positive effect on coordination. Digital information technology and transactions, and the digital R&D ecosystem, are negatively correlated with sharing. Digital information technology and transactions generate increased income for talent in the IT industry. However, the employment threshold for related industries is high, hindering sharing. The digital R&D ecosystem requires research resources, which hinder sharing.

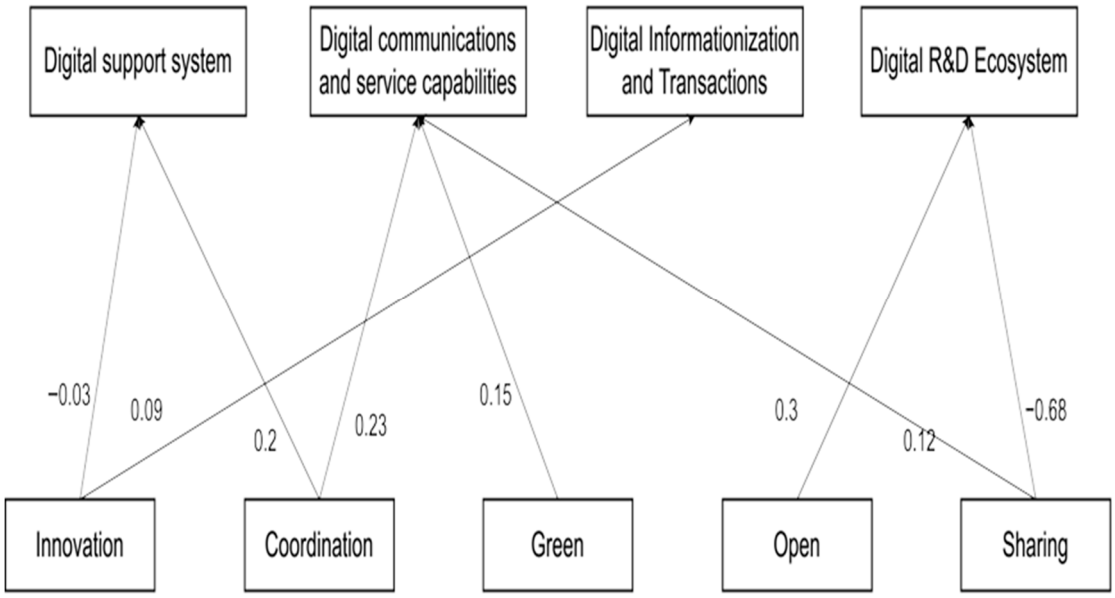


Figure 8. Analysis of the marine industry subsystem on the digital economy subsystem.

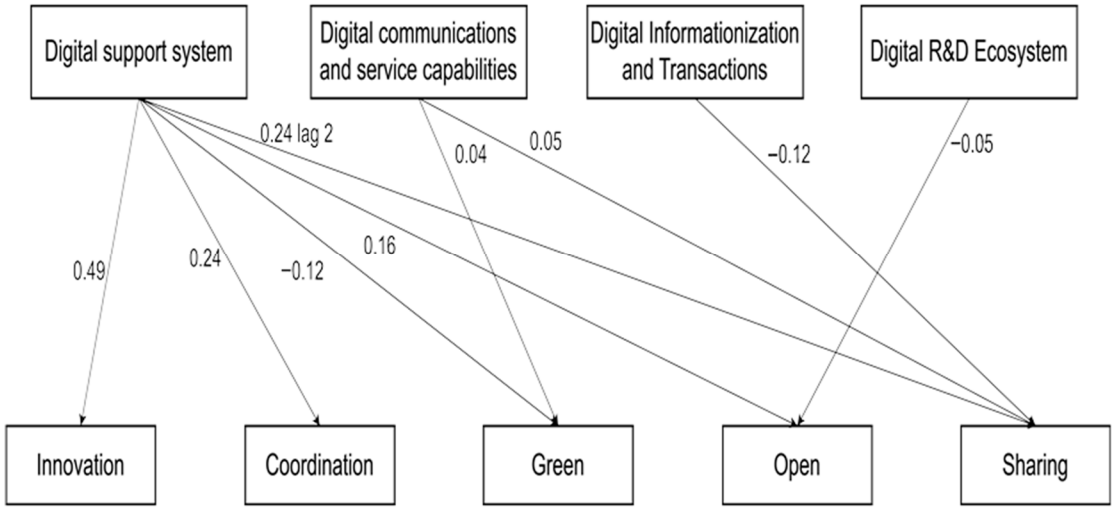


Figure 9. Analysis of the marine industry subsystem by the digital economy subsystem.

5.5. Threshold Effect Test

First, we tested for the threshold effect on the coordination rate of innovation coupling. The test results are presented in Table 11 and Figure 10. These findings suggest the presence of a double threshold for the coordination effects of innovation coupling.

Table 12 presents the results of the threshold effect estimation. When the innovation coupling coordination rate does not exceed 0.0099, the rate of digital economic development positively affects the rate of marine industry quality development. The impact coefficient is 0.120. The innovation coupling coordination rate was relatively low. At this stage, establishing preliminary connections can improve the marine industry's quality development rate through cost reduction and efficiency improvement; however, the depth of integration is insufficient, and the enabling effect is limited. When the innovation coupling coordination rate exceeds 0.0099, but does not exceed 0.0725, the positive correlation between digital economic development and marine industry quality increases, with the influence coefficient rising from 0.120 to 0.416. At this point, integration has broken through the "foundational stage," with the integration speed significantly increasing and entering the stages of technological penetration and model reconstruction. The digital economy has transformed from

an "auxiliary tool" into an "innovation engine," thereby greatly boosting the growth rate of the marine industry's quality development. Once the innovation coupling coordination rate exceeds 0.0725, the growth rate of the digital economy no longer has a significant impact on the quality of the marine industry. This finding indicates that once technological integration reaches the standardization stage, it enters a "standardization bottleneck period."

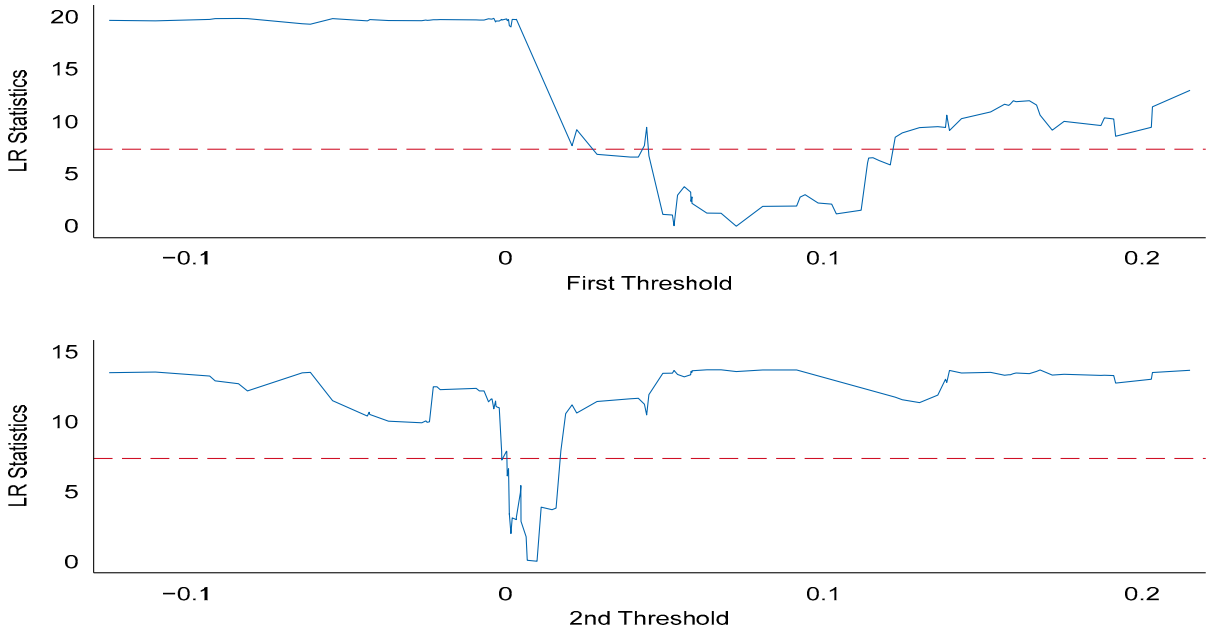


Figure 10. Threshold estimates and confidence intervals. Note: The blue line is first used to determine whether a threshold effect exists. The red line represents the critical value for the threshold effect. When the blue line is below the red line, it indicates that a threshold effect exists.

Table 12. Threshold Effect Test.

Model	F-Value	*p*-Value	BS	Threshold		
				1%	5%	10%
Single	5.88	0.2100	300	7.4165	8.7571	12.7079
Double	15.27 ***	0.0000	300	6.3733	7.4355	13.5604
Triple	1.82	0.9400	300	10.1230	13.7290	20.8368

Note: *** indicate significance levels of 1%, respectively; the values in parentheses are robust standard errors.

It highlights that as the marine industry's adoption of digital technologies, digital products, and digital talents deepens, its own data analysis capabilities, data processing capabilities, and operational decision-making have also accelerated significantly. This has played an accelerating role in the quality development of the marine industry in different periods; however, this accelerating effect is not static. In the initial stage, due to the incomplete construction of digital infrastructure, the accelerating effect was relatively weak. With the improvement of digital equipment, the accelerating effect increased. Finally, restricted by the spatial constraints of the industry itself, the effect stabilized and eventually disappeared. Therefore, Hypothesis 7 is established.

5.6. Robustness Test

5.6.1. Change Sample Size

To ensure the validity of the results, this paper conducted a robustness test by reducing the number of years included in the analysis. It further verified data reliability by excluding data from 2022 and 2023 and retaining the 10 years of data needed for the regression analysis (see Tables 13 and 14 for details).

Table 13. Threshold estimation results.

	Threshold range	Coefficient value	*t*-Statistic	*p*-Value
lnIS	lnIS $\leq$ 0.0099	0.120 **	2.43	0.017
	0.0099 < lnIS $\leq$ 0.0725	0.416 ***	5.58	0.000
	lnIS > 0.0725	0.069	1.11	0.269

Note: ***, and ** indicate significance levels of 1%, and 5%, respectively; the values in parentheses are robust standard errors.

Table 14. Regression results of robustness test 1.

Variable	h_lnOE	h_lnDE	h_lnIS	h_lnCI
L1.h_lnOE	0.182	0.381 ***	0.068	0.903 **
	(1.42)	(3.18)	(1.36)	(1.98)
L1.h_lnDE	0.118 **	0.593 ***	0.054 **	0.156
	(1.97)	(7.55)	(2.02)	(0.50)
L1.h_lnIS	0.506 **	−0.219	0.201	3.498 ***
	(1.99)	(−0.65)	(1.49)	(2.93)
L1.h_lnCI	−0.028	−0.011	0.023 ***	0.329 ***
	(−1.12)	(−0.46)	(2.62)	(2.93)

Note: ***, and ** indicate significance levels of 1%, and 5%, respectively; the values in parentheses are robust standard errors.

The results of the GMM tests and Granger causality tests herein are consistent with those of the previous studies; therefore, this paper concludes that the results presented earlier are robust.

5.6.2. Robustness Test for Extreme Value Treatment

To avoid the impact of extreme values on the conclusions of this study. We conducted the aforementioned test by applying 1% and 99% quantile shrinkage to the four variables. The results are presented in Tables 15–17, respectively.

The results of the GMM tests and Granger causality tests herein are consistent with those of the previous studies; therefore, this paper concludes that the results presented earlier are robust.

5.6.3. Unit Circle Test

To verify whether the statistical characteristics of the data remain invariant over time—i.e., to validate the stationarity of the time series—this study employs the unit root test. As presented in Figure 11, the test results demonstrate that all unit roots lie within the unit circle, indicating the absence of a unit root in the series. Consequently, the null hypothesis that "the series contains a unit root (i.e., the statistical characteristics of the data vary with time)" is rejected. It is ultimately determined that the statistical characteristics of the data do not change over time, which is equivalent to confirming the stationarity of the time series. This confirms the robustness of the aforementioned conclusions.

Table 15. Robust Granger test 1.

Equation	Excluded	*p*-Value	Result
h_lnOE	h_lnDE	0.048	Reject
	h_lnIS	0.047	Reject
	h_lnCI	0.222	Accept
	ALL	0.019	Reject
h_lnDE	h_lnOE	0.001	Reject
	h_lnIS	0.513	Accept
	h_lnCI	0.645	Accept
	ALL	0.009	Reject
h_lnIS	h_lnOE	0.174	Accept
	h_lnDE	0.044	Reject
	h_lnCI	0.009	Reject
	ALL	0.005	Reject
h_lnCI	h_lnOE	0.048	Reject
	h_lnDE	0.619	Accept
	h_lnIS	0.003	Reject
	ALL	0.003	Reject

Table 16. Regression results of robustness test 2.

Variable	h_lnOE	h_lnDE	h_lnIS	h_lnCI
L1.h_lnOE	0.159	0.329 ***	0.039	0.895 **
	(1.26)	(2.86)	(0.77)	(2.36)
L1.h_lnDE	0.112 *	0.538 ***	0.048 **	0.173
	(1.90)	(6.75)	(1.81)	(0.59)
L1.h_lnIS	0.400 **	−0.257	0.101	2.175 ***
	(2.23)	(−0.93)	(0.91)	(2.79)
L1.h_lnCI	−0.026	−0.013	0.025 ***	0.375 ***
	(−1.13)	(−0.52)	(2.72)	(3.48)

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively; the values in parentheses are robust standard errors.

Table 17. Robust Granger test 2.

Equation	Excluded	*p*-Value	Result
h_lnOE	h_lnDE	0.058	Reject
	h_lnIS	0.026	Reject
	h_lnCI	0.260	Accept
	ALL	0.022	Reject
h_lnDE	h_lnOE	0.004	Reject
	h_lnIS	0.352	Accept
	h_lnCI	0.605	Accept
	ALL	0.020	Reject
h_lnIS	h_lnOE	0.439	Accept
	h_lnDE	0.070	Reject
	h_lnCI	0.007	Reject
	ALL	0.010	Reject
h_lnCI	h_lnOE	0.018	Reject
	h_lnDE	0.553	Accept
	h_lnIS	0.005	Reject
	ALL	0.004	Reject

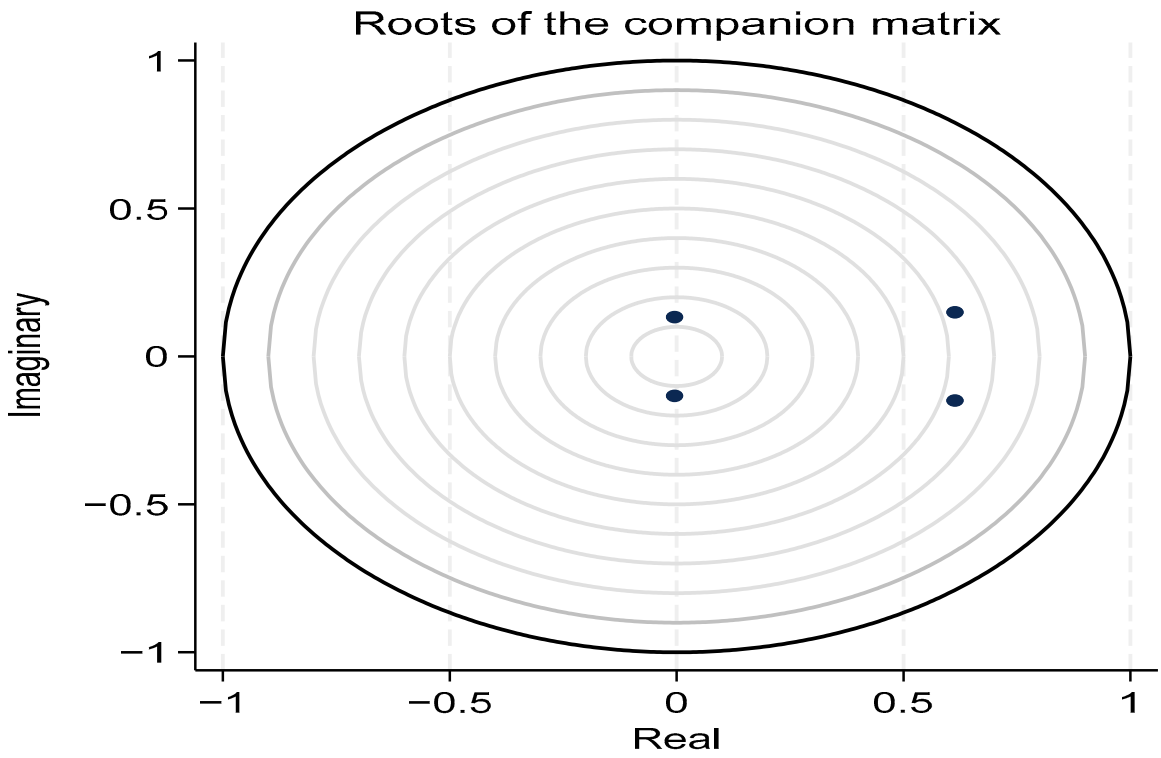


Figure 11. Unit circle test. Note: The big dot is used to determine whether the model is stable. When all the roots are concentrated within the unit circle, it indicates that the model is stable.

6. Discussion

This paper examines the mutual influence of the growth rates of the digital economy and marine industry quality, with the core question being whether a mutually reinforcing and accelerating development mechanism exists between the two.

The conclusions of this paper differ from those of Xia et al. [8], He et al. [10], Zhou et al. [21], Fang et al. [22], Ding et al. [23]. The latter studies primarily focused on unidirectional analyses of digital economy-intermediary variable-marine industry quality relationships, neglecting the mutual influence of their development speeds. This paper found that the growth rates of the digital economy and the quality of the marine industry reinforce each other. This difference is mainly due to the fact that this paper focuses on the mutual influence of development rates, as well as the different lag effects existing in the digital application of traditional marine industries and marine high-tech industries. Furthermore, the rate of change in the marine industry's structural upgrading and the innovation coupling index, both acting as intermediate variables, are shown to function as mechanisms driving this mutual reinforcement. Furthermore, based on the characteristics of the industry, this interaction involved a time lag. Some effects can be quickly observed after a short-term application, whereas others, such as feedback from the rate of the marine industry's structural upgrading to the digital economy and feedback from the application of digital technology to the marine industry, involve a relatively long lag. This is mainly due to the rapid integrated development of marine high-tech industries and digital technologies. However, the digital application and digital demand of traditional industries face certain difficulties. It may be necessary to build certain digital equipment or upgrade existing power equipment to meet the application requirements of digital technologies.

This paper makes three significant contributions to the literature. It explores the dynamic interaction mechanism between the growth rates of the digital economy and marine industry quality from the perspective of "development rate," thereby filling the research gap concerning "rate interaction." Second, to address endogeneity issues, this paper em-

ploys a PVAR model and a GMM for regression estimation, which helps predict future trends and offers development recommendations. Third, this paper finds that the growth rate of the digital economy exerts a "double-threshold" effect on the growth rate of marine industry quality, clarifying the moderating role of the technology integration stage in their relationship and enriching the stage-based theory of industrial collaborative development.

By broadening the range of policy instruments, data, and economic indicators that can be used to assess the development of the digital marine industry, this paper provides a comprehensive framework for Chinese marine government departments to make informed decisions regarding marine planning and investment.

Limitations of the Paper and Future Directions

This paper has two limitations. First, the relatively short data period from 2012 to 2023 may limit the comprehensiveness of the conclusions. Second, the marine industry subsectors (i.e., fisheries, shipping, and engineering) have not been studied and may be affected differently. Third, this study focuses on China, and relying solely on data from one country may have limitations. China's unique development stage, institutional environment, and industrial characteristics may make it difficult for the conclusions to be directly applicable to other types of countries, and also fail to fully reveal the common laws and differences in the interaction between the two in cross-country contexts.

In the future, data from a longer period will be used to obtain more comprehensive insights into long-term effects. Second, it is necessary to delve deeper into marine industry subsectors to explore the specific impacts of their development rates in different fields. For example, focusing on internal interaction mechanisms between industries, thereby achieving joint and coordinated development across multiple industries. Additionally, analyzing the internal interactions between the digital industry and various sectors within the marine industry, including the fisheries, manufacturing, and resource development sectors, as well as the mechanisms of mutual acceleration and development would be of interest.

7. Conclusions and Policy Recommendations

7.1. Conclusions

As the marine economies continue to develop globally, countries are increasingly incorporating digital technology to realize the "win-win" development of both socioeconomic growth and ecological conservation through data analysis and monitoring. Therefore, a comprehensive paper is crucial for strategic decision-making.

This paper draws the following main conclusions: (1) The digital economy and marine industry benefit from each other. The digital economy has accelerated the quality development of the marine industry with a lag period. The digital economy's growth rate and the structural upgrade rate of the marine industry exert a positive driving effect on the quality development rate of the latter. The quality development of the marine industry feeds back into the digital economy, thereby creating cyclical growth. (2) Digital economic growth indirectly promotes marine industry development quality by increasing the growth rate of marine industry upgrades. (3) A virtuous cycle of mutual promotion exists between the rate of innovation coupling, coordination, and structural upgrading of the marine industry. (4) Local government spending can drive digital economy development. This directly promotes the mutual facilitation between the development rates of the two sectors, creating a "single spiral" upward trend. (5) The digital economy's growth rate affects the marine industry's quality development rate. In the early stages of technological integration and maturation, the growth of the digital economy can significantly promote marine industry development. This effect increases when the rates of innovation, coupling, and

coordination improve. However, once the innovation coupling coordination rate exceeds a certain threshold and enters standardization, this promotional effect is less significant. This indicates that, during specific stages, the digital economy may possess significant potential to accelerate the quality-oriented development of the marine industry.

7.2. Policy Recommendations

In the short term, the focus should be placed on supporting projects that rapidly implement digital technologies, such as smart port monitoring, offshore wind power, and smart salmon farming, by providing tiered subsidies based on project investment growth rates. In the medium-to-long term, the focus should be on the construction of marine big data centers, underwater observation networks, and other projects, including China's "Transparent Ocean" project, the UK's British Oceanographic Data Centre, and the U.S. National Oceanographic Data Center. Additionally, a proportion of funds could be allocated to projects whose annual construction progress exceeds expectations. A feedback mechanism would ensure that the growth targets are met. If the growth rate of the two industries surpasses expectations by one percentage point, a proportionate share would be returned to the local government for investment.

To upgrade traditional industries, a "growth rate ladder incentive" could be adopted. For example, enterprises that have achieved a digital transformation growth rate of 10% can enjoy VAT refunds upon collection. For emerging sectors, a "scale-growth leverage" approach could be considered where, for every 5% increase in the digital coverage rate of deep-sea aquaculture, enterprises are permitted to expand their marine aquaculture area by 10%. For marine digital service enterprises with revenue growth exceeding 20%, an R&D subsidy of 3% of the incremental portion may be provided. Examples include the maritime intelligent navigation system developed by Zhejiang E-Navigation Information Technology Co., Ltd., which serves tens of thousands of fishing vessels across China via its "Marine E-Navigation Smart Version" platform, as well as the digital transformation of the fishery industry in Wuxing District, Huzhou City, Zhejiang Province, China. By applying digital technologies and leveraging policy incentives, Zhejiang E-Navigation Information Technology Co., Ltd. achieved a 26% year-on-year growth in operating revenue in 2024, while the number of newly served fishing vessels further increased in 2025. Meanwhile, the fishery breeding scale in Wuxing District was further expanded, and the revenue per unit area also grew.

Countries can consider additional incentives to drive digital–marine cross-disciplinary patents, promote a "school-enterprise joint growth ranking" to significantly shorten the industrialization cycle of cooperative projects and reward their R&D teams; optimize the transmission mechanism of fiscal expenditures by implementing a digital-first and marine-follow-up fiscal investment strategy; and establish a marine digitalization special fund for regions that meet digital economic development targets.

Ultimately, these policies must prioritize the sustainable development of marine industries as their core objective. By integrating digital transformation with ecological conservation, we can transform short-term growth drivers into long-term resilience for marine industries, thereby safeguarding the ocean's capacity to support development for both present and future generations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17219464/s1.

Author Contributions: Conceptualization, G.Z. and L.Z.; methodology, L.Z.; software, L.H. and Y.Z.; validation, G.Z. and Y.X.; formal analysis, L.Z., L.H. and Y.Z.; visualization, Y.X.; resources, Y.X.; data

curation, L.Z., Y.X. and G.Z.; writing—review and editing, G.Z. and Y.X. All authors have read and agreed to the published version of the manuscript.

Funding: The work is supported by the Shandong Office of Philosophy and Social Science (Grant No. 24CSDJ49).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are available upon request from the readers.

Acknowledgments: The authors thank the editor and the anonymous reviewers for providing constructive suggestions and comments on this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

PVAR	Panel Vector Autoregression
OK	Ocean Korea
EU	European Union
MPOP	Multi-Purpose Offshore Production Platform
K-means-SA	K-means Clustering and Simulated Annealing Hybrid Algorithm
AHP	Analytic Hierarchy Process
FCE	Fuzzy Comprehensive Evaluation
BBC-DEA	Banker-Charnes-Cooper Model—Data Envelopment Analysis
TFP	Total Factor Productivity
PLS-SEM	Partial Least Squares Structural Equation Modeling
CCDM	Coupled Coordination Degree Model
IPC	International Patent Classification
CMMSC	Combined Marginal Social Cost
IT	Information Technology
US	United States
UK	United Kingdom
VAT	Value-Added Tax

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