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ESTABLISHMENT OF SYSTEMATIC GREEN SHIP DEVELOPMENT PROCESS BY INTERPRETATIVE STRUCTURAL MODEL

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Abstract

With the continuous development of the global economy, port and shipping logistics occupy an important position in today's international trade. Consequently, the greenhouse gases emitted by ships also cause serious pollution in the ecological environment. In the face of such situation, the International Maritime Organization has formulated relevant conventions to prevent and control the pollution caused by ship operations, navigation, and dismantling. However, the implementation of these conventions poses serious challenges to China's shipbuilding and shipping industries. Therefore, the green ship industry is one of the important directions for the transformation and upgrading of China's shipbuilding industry. In this paper, 20 green ship indicators are summarized on the basis of the characteristics of a ship's life cycle stages. The concurrent engineering concept is used in this study to shorten the R&D cycle time of green ships effectively. Then, the interpretative structural model (ISM) is applied to decompose and reorganize the green ship indicators in the various stages of the original ship life cycle. Finally, the five stages of green ship development are established on the basis of the ISM analysis results, which can provide the shipping company as reference for the development of green ships to promote the environmental protection of ports and oceans and assist the sustainable development of port and shipping logistics.

Keywords: green ship, concurrent engineering, interpretative structural model

1. Introduction

With the continuous economic development, port and shipping logistics occupies an important position in today's trade, as ship transportation has the advantages of large volume and low cost; hence, approximately 90% of the country's internal and foreign trade transactions use port and shipping logistics (Yuan, 2006). In addition, the port has become a bridge connecting domestic and international economic and trade exchanges between domestic and foreign enterprises. The port industry has become an important part of the modern logistics industry and an important link in our country's modern logistics system. According to the "2020 Global Top 20 Container Port Forecast Report," China still accounts for nearly half of the world's top 20 container ports, and 7 of the world's top 10 container ports are from China (China brand, 2020). Although port and shipping logistics brings cargo exchange and economic growth, it also immensely increases the levels of air pollution in ports and their surrounding areas. According to the China Motor Vehicle Environmental Management Annual Report in 2017, ships emitted 853,000 tons of sulfur dioxide (SO2), 79,000 tons of hydrocarbons (HC), 13.46 million tons of nitrogen oxides (NOx), and 1.310 million tons of particulate matter (Ministry of Ecology and Environment of the People's Republic of China, 2018).

As the port air and ocean pollution problems are becoming increasingly serious, the port pollution control problem has received extensive attention from the government, thus giving rise to the concept of green ships. Green ships refer to the use of environmentally friendly, advanced, and reliable technologies to improve or eradicate ship pollution from the source during a ship's life cycle. Green ships are the route for the development of the shipbuilding industry, and China is still in its infancy in the manufacture and application of green ships. In recent years, the International Maritime Organization's (IMO) Pollution Prevention Convention, Ballast Water Discharge Convention, and Ship Recycling Convention have also paid increasing attention to the development of integrated marine and the prevention of land and air pollution. They have proposed nine major emission limit requirements for ships and a green index. At the same time, the continuous implementation of these conventions has brought severe challenges to China's shipbuilding and shipping industries. Therefore, earlier recognition and attention to low-carbon development and environmental protection can effectively promote the technological development of low-carbon and energy-saving green ships. At the same time, China's shipping industry can seize the opportunities of future industry competition and be in a favorable position in such race.

According to the ship life cycle (design→manufacturing→operation→dismantling) and corresponding environmental factors, relevant green ship indicators can be classified into design indicators, manufacturing indicators, operation indicators, and dismantling indicators. From the beginning of the ship design to the completion of the ship dismantling, green ship indicators can be introduced to ensure that the ship meets environmental friendliness during its life cycle. Generally speaking, product design and development methods include Sequential Engineering (SE) and Concurrent Engineering (CE). Compared with serial engineering, concurrent engineering considers all elements of the product life cycle at the same time. It emphasizes the full participation and collaboration of personnel in various fields during the design and development process by considering the product design, manufacturability, maintainability, and quality control. Moreover, it can reduce the blindness of early product design, prevent the influence of unreasonable factors as early as possible, and shorten the product design and development cycle. Therefore, in accordance with the concept of concurrent engineering, this article focuses on green ship indicators and ship life cycle processes, including the design, manufacturing, operation, and dismantling processes and their corresponding environmental

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factors, so that the green ship indicators can be combined with the ship's life cycle to establish a systematic development process.

2. Literature review

The Method section describes in detail how the study was conducted, including conceptual and operational definitions of the variables used in the study, Different types of studies will rely on different methodologies; however, a complete description of the methods used enables the reader to evaluate the appropriateness of your methods and the reliability and the validity of your results, It also permits experienced investigators to replicate the study, If your manuscript is an update of an ongoing or earlier study and the method has been published in detail elsewhere, you may refer the reader to that source and simply give a brief synopsis of the method in this section.

2.1 Basic concepts and development of green ships

Green ships refer to the entire life cycle of ships from design, manufacturing, operation, scrapping, to dismantling. The use of optimized green technology can effectively meet the needs of users for functions and performance, improve the safety performance of ships, minimize the consumption of resources and energy, and reduce environmental pollution. The ultimate goal of green ships is to become pollution-free and emission-free. They also aim to promote the sound development of the global environment, shipbuilding, and shipping industries. In the design of green ships, the entire life cycle of the ship should be considered, and the ship, the environment, and humans should be linked together (Wang, 2013). The key to green ship technology is friendliness and energy saving. Given the current technical conditions, ship power technology still has difficulty achieving truly pollution-free and zero-emission green technology. Therefore, it generally needs to go through three stages. The first stage involves saving energy, conserving resources, and reducing emissions; the second stage includes producing high-efficiency energy, high-efficiency resources, and light pollution; the third stage aims to have renewable energy, recycling resources, and no pollution (Wu, 2010). To undergo these three stages, ship research and development has continued to introduce new technologies that meet the needs of green ships, from the development of basic energy-efficient ship types, the research and development of low-emission and high-efficiency power propulsion devices, and to the development of environmentally friendly non-polluting paints and lightweight materials to build the green ships and the green environment needed in the future in all aspects (Yu, 2010).

2.2 Ship life cycle and green ship indicators

Product life cycle refers to the beginning of product design, raw material collection, processing, and production; the product transportation, sales and use, and product scrap or recycling; and the final treatment and the end of the environmental load process related to the entire life cycle system (Wang et al., 1999). Therefore, the entire process from the initial design and manufacture of the ship to the start of the operation, final disposal, recycling, and green dismantling is the ship's life cycle, as shown in Figure 1.

According to Figure 1, the green ship indicators are divided into five categories, as presented in Table 1. In the design stage, the required factors are taken into consideration according to the needs and purposes of each stage of the ship's life cycle, and each link is optimized to maximize benefits (Wang, 2014). In the manufacturing stage, the theoretical design of ships is transformed into actual products, covering the entire life cycle. Economic, environmental, and social benefits should be fully considered, thus minimizing pollution and damage to the environment and energy consumption and also improving resource utilization and low carbon green benefits (Zhang, 2016). With the increase in freight volume in the operation stage, total amount of carbon dioxide emissions produced by ships during navigation and transportation continues to increase. It should focus on the research of green energy saving and emission reduction technologies and accelerate the development of green series of ship types (Shang, 2010; Hao et al., 2012). The dismantling stage is the reverse process of shipbuilding, which mainly entails recycling the reusable materials and equipment in old ships (Shi, 2012). Thus, the ship breaking industry is a resource-friendly and environmentally friendly industry. This sector will be beneficial to the common development of its related industries (Zhang, 2010). Finally, from design to dismantling, green ships require low emissions, low pollution, high efficiency, and high benefit to the environment (Gao, 2011).

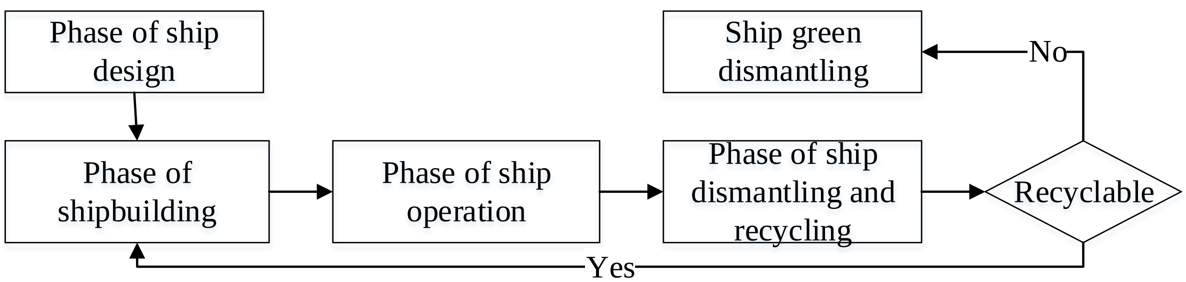

Figure 1. Life cycle of the ship

3. Questionnaire design and methodology of research

This article adopts a questionnaire survey, the objects of which are filled in by relevant ship operators and logistics scholars. Then, the questionnaires are distributed by snowball sampling. The questionnaire is designed to conduct a correlation survey based on the 20 green ship indicators in Table 1. The purpose of the survey is to determine whether the two indicators will affect each other. The interpretative structural model (ISM) is used to analyze and establish a systematic development process.

3.1 Questionnaire design

The questionnaire for the relevance survey of green ship indicators is a survey of the relevance between pair-wise indicators. According to the proportion of answers to "yes" and "no," it is judged whether a subordination relationship exists between the indicators. "0" means no impact, and "1" indicates an impact as an assessment. The way of narrating the question is "Which of the following indicator factors do you think will be affected by indicator factor A when developing green ships?" If an impact exists, "Yes" should be checked. Otherwise, "No" should be selected. The questionnaire URL is as follows:
https://www.wjx.cn/pq/24477772.aspx?t=636910077559721750.

Table 1. Indicators of green ship

Classification	Indicator	Definition	Reference
Design phase	Optimization of ship form	New technology is uses to optimize the design of the hull shape, various performance indicators of the ship, and related physical factors of the ship to improve the efficiency of ship navigation and reduce pollution emissions.	Liu et al. (2010)
	Ships without ballast water	Under normal operations, ships need only a small amount or no ships with ballast water.	Zhang et al. (2016)
	Ship parallel collaborative design technology	In the design phase, the design, manufacturing, operation, dismantling, and recycling of the ship are incorporated into the integrated design, thus reducing unnecessary research and development steps, shortening the ship research and development cycle, and cutting research and development costs.	Liu and Su (2011)
	Recyclable design	At the beginning of the ship design, full consideration should be given to the possibility of various resource recovery, dismantling treatment methods, and costs to minimize the waste of resources and the pollution impact on the environment.	Ye et al. (2011)
	Standardized design	Computer technology is used to carry out the standardized design of the entire ship, make the ship easy to use, modify, and maintain, thereby improving the efficiency and life of the ship.	Wang and Zhu (2012)
Manufacturing phase	Green processing technology	Through the net shape forming manufacturing technology, dry cutting, processing simulation technique, virtual reality technology, and agile manufacturing, the consumption of raw materials and energy in the ship's manufacturing process are reduced, or the ship development cycle is shortened.	Ding (2011), Mao (2008)
	Green welding technology	Advanced welding equipment is used to reduce the pollution of toxic gas, arc light, and smoke generated during the welding of the hull.	Ding (2011), Mao (2008)
	Green coating process	To improve the coating quality and work efficiency of ships while reducing the consumption of resources and the emission of harmful substances, green and environmentally friendly coating processes and coating equipment must be used.	Wang and Zhu (2012)
	Ship weight reduction	The weight of the ship can be reduced from the perspective of materials (such as hull structure optimization and the use of lightweight composite materials), manufacturing process perspective, and structural optimization design perspective.	Zhang et al. (2016), Jia (2016)
	Ship noise control	With low-noise mechanical equipment and power plants, the noise generated by the ship's engine room or ventilation system, deck machinery, steering gear, and propulsion system can be reduced.	Ding (2011), Wu et al. (2013)
	Ship powerplant	New energy ship power technology is used and ship power system is built on to achieve zero pollution and zero emission of ships.	Wu (2010), Chen (2013)

Table 1. Indicators of green ship (cont.)

Classification	Indicator	Definition	Reference
Manufacturing phase	Ship drag reduction technology	The ship drag reduction technology can reduce the frictional resistance of the ship during the voyage, decrease the cost of fuel consumption, and improve the economy of ship operation.	Yuan et al. (2013)
Operational phase	Ship energy consumption detection system	During the ship's operation, the ship's energy consumption online detection system can record and analyze the ship's fuel consumption and other related data in real time, thus providing scientific basis and analysis for energy conservation and emission reduction.	Wang et al. (2015), Wei (2016)
	Ship operation optimization	From the aspects of ship equipment, management, and operation, the implementation guidelines for ship operation performance are formulated, optimized, and improved to enhance the ship energy efficiency design index (EEDI).	Yu (2010), Gao (2011)
	International regulations and policies	Through the formulation of the law, ships are regulated to use clean energy to replace petroleum fuels and reduce ships' greenhouse gas emissions.	Eworldship.com (2014)
Dismantling phase	Improve sewage treatment technology	The sewage discharged from ships is processed and filtered into recyclable and pollution-free water. The current technology mainly uses the membrane bio-reactor (MBR) to treat sewage.	Jiang et al. (2011)
	Recycling and utilization of waste	Ship waste can be divided into general waste and hazardous waste. General waste can be recycled for secondary processing and reuse or can be sold. To avoid harm to the environment, hazardous waste must be handed over to a professional external unit with a hazardous waste business license for disposal.	Xu and Liu (2015)
	Harmless dismantling of ship	A plan is made before ship dismantling; the waste pollutants of the ship are analyzed; then, they are classified, decomposed, prevented, and recycled one by one to eliminate pollution to the environment and to recycle the dismantled materials during the ship dismantling process.	Gao (2012), Zheng (2013)
Environmental factor	Energy saving and emission reduction	The main purpose is to adopt feasible, reliable, and reasonable technologies to reduce energy consumption and pollutant emissions, reduce unnecessary losses and waste, and use resources rationally.	Shang (2010), Hao et al. (2012)
	Renewable energy	Renewable energy sources, such as solar energy, wind energy, and ocean energy, have low pollution and can be reused to achieve the effect of energy saving and emission reduction.	Zhu (2017)

3.2 Methodology of research

To judge the affiliation of various green ship indicators, this study uses ISM as an analysis tool. The analysis results of ISM can summarize the hierarchical relationships and graph of various elements. They can also be used as the framework to propose a systematic execution procedure, thereby reducing errors and risks in the decision-making and planning promotion process. At present, ISM has a wide range of applications. For example, by using ISM and combining it with examples, the scientific analysis and evaluation of the technological innovation capabilities of high-tech enterprises have been carried out. The key research discusses the application of the method and the analysis of the results and then gives the ideas and methods to solve the problem (Chang et al., 2003). Therefore, this study adopts ISM to construct a set of standard operating procedures for the development of green ship indicators and provides reference and implementation basis for the ship industry to develop green ships. The seven steps proposed by Olsen (1982) to explain the calculation of ISM are described in order as follows:

Step 1. Determine the factors related to the research: Related factors are collected according to the research theme, expressed as a_i, i=1, 2, …, k.

Step 2. Determine the subordination relationship between pair-wise factors: Questionnaire surveys are used according to the opinions of experts and scholars to measure the subordination relationship between pair-wise factors and the situation of mutual influence.

Step 3. Determine the relation matrix: The relationship between pair-wise factors has the following four situations. Therefore, the relation matrix (**A**) can be expressed as Equation (1).

(1) If factor i directly affects factor j, then a_{ij}=1 and a_{ji}=0.

(2) If factor j directly affects factor i, then a_{ji}=0 and a_{ij}=1.

(3) If factor i and factor j influence each other, then a_{ij}=1 and a_{ji}=1.

(4) If factor i and factor j do not affect each other, then a_{ij}=0 and a_{ji}=0.

$$\mathbf{A} = \begin{bmatrix} a_{11} & \cdots & a_{1k} \\ \vdots & \ddots & \vdots \\ a_{k1} & \cdots & a_{kk} \end{bmatrix} = \left[a_{ij} \right] \quad i = 1, 2, 3, \cdots k, \; j = 1, 2, 3, \cdots k \qquad (1)$$

Step 4. Determine the adjacent matrix (**M**): The relation matrix (**A**) and the identity matrix (**I**) are added to obtain **M**.

Step 5. Convert the adjacent matrix (**M**) into the reachable matrix (**M***): ISM has transitivity, that is, if factor A is related to factor B and factor B is related to factor C, then factor A and factor C will also be related. Therefore, the adjacent matrix can be called the reachable matrix after it satisfies the transitivity property.

Step 6. Convert the reachable matrix into the hierarchy matrix: The hierarchy matrix includes the reachability set (**R**(a_i)) and the antecedent set (**A**(a_i)). The intersection of the two is (**R**(a_i)∩**A**(a_i)).

(1) Reachable set ($\mathbf{R}(a_i)$): With the horizontal axis taken as the main axis, the corresponding factors are extracted if the intersection value of the horizontal and vertical axis factors in the reachable matrix is 1.

(2) Antecedent set ($\mathbf{A}(a_i)$): With the vertical axis taken as the main axis, the corresponding factors are extracted if the intersection value of the horizontal and vertical axis factors in the reachable matrix is 1.

Step 7. Use the hierarchy matrix to draw the ISM hierarchical relationship graph: The factors that are exactly the same as $\mathbf{R}(a_i)$ and $\mathbf{R}(a_i)\cap\mathbf{A}(a_i)$ are extracted and placed on the first layer. Then, the extracted factors are deleted. The remaining factors find the second-level factors in the same way, and so on. After finding the factors of each level, arrows are drawn to show the subordination of each factor according to the relationship between pair-wise factors presented in the relationship matrix (**A**) relationship, that is, the hierarchical relationship graph of ISM is completed.

4. Data analysis

ISM analysis has seven steps. The first step is presented in Table 1. The corresponding numbers of each factor are shown in Table 2. The analysis results of the remaining steps are described as follows.

4.1 Analysis results of ISM

First, the relationship between pair-wise factors are determined. A total of 12 valid questionnaires have been collected in this questionnaire survey. If 10 respondents (80% as the threshold) believe that the pair-wise factors have a subordination relationship, these factors will be deemed to have a subordination relationship, as shown in Table 3. Then, according to Step 3 to Step 6, the relation matrix (**A**) is shown in Table 4. The adjacent matrix (**M**) is shown in Table 5, while the reachable matrix (**M***) is shown in Table 6. Next, the hierarchy matrix is shown in Table 7.

Table 2. Correspondence table of each factor and number symbol

No.	Indicator	No.	Indicator	No.	Indicator	No.	Indicator
1	Optimization of ship form	2	Ships without ballast water	3	Green welding technology	4	Ship parallel collaborative design technology
5	Ship noise control	6	Recyclable design	7	Ship drag reduction technology	8	Green processing technology
9	Green coating process	10	Ship weight reduction	11	Ship powerplant	12	Standardized design
13	Ship energy consumption detection system	14	Ship operation optimization	15	International regulations and policies	16	Improve sewage treatment technology
17	Recycling and utilization of waste	18	Harmless dismantling of ship	19	Renewable energy	20	Energy saving and emission reduction

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Finally, according to Step 7, the hierarchical relationship graph can be obtained, combined with the subordination results in Table 3, as shown in Figure 2. Table 7 demonstrates that the $\mathbf{R}(a_i)$ and $\mathbf{R}(a_i)\cap\mathbf{A}(a_i)$ of factor 3, factor 6, factor 8, factor 9, factor 12, factor 14, factor 15, factor 16, factor 17, factor 18, factor 19, and factor 20 are exactly the same. Thus, these factors are selected as the first layer of the hierarchy relationship graph. After deleting the selected factors, the same method is used to choose factors that are exactly the same as $\mathbf{R}(a_i)$ and $\mathbf{R}(a_i)\cap\mathbf{A}(a_i)$ as the second layer. Consequently, factor 4 and factor 11 are selected as the second layer. By analogy, factor 2, factor 5, factor 10, and factor 13 are chosen as the third layer; factor 1 as the fourth layer; and finally factor 7 as the fifth layer.

Table 3. Subordination relationship between pair-wise factors

1[1]→4[2]	1→10	1→11	1→12	2↔10[3]	2→11	3↔8	3↔9	4↔6
4↔12	4↔14	5→11	6↔16	6↔17	6↔18	7→1	7↔11	8↔9
10→4	10→7	10↔11	10→12	12→6	12↔14	13→4	15↔20	16↔17
16↔19	16↔20	17↔19	17↔20	18→17	19→6	19↔20	20→6	

Remarks: [1]Refer to Table 2 for each indicator number, [2]A→B means that factor A directly affects factor B ; [3]A↔B means that factor A and factor B influence each other.

Table 4. Relation matrix

No[1]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1		0[2]	0	1[3]	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0
2	0		0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
3	0	0		0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0		0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0
5	0	0	0	0		0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	1	0		0	0	0	0	0	0	0	0	0	1	1	1	0	0
7	1	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0	0	0
8	0	0	1	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0
9	0	0	1	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0	0
10	0	1	0	1	0	0	1	0	0		1	1	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	1	0	0	1		0	0	0	0	0	0	0	0	0
12	0	0	0	1	0	1	0	0	0	0	0		0	1	0	0	0	0	0	0
13	0	0	0	1	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
14	0	0	0	1	0	0	0	0	0	0	0	1	0		0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	1
16	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0		1	0	1	1
17	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1		0	1	1
18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1		0	0
19	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0		1
20	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	

Remarks: [1]Refer to Table 2 for each indicator number, [2]A→B means that factor A directly affects factor B ; [3]A↔B means that factor A and factor B influence each other.

Table 5. Adjacent matrix

No1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	02	0	13	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0
7	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
8	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
9	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
10	0	1	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0
12	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0
13	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
14	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
16	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	1	1
17	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	1	1
18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0
19	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	1	1
20	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	1

Remarks: [1]Refer to Table 2 for each indicator number, [2]A→B means that factor A directly affects factor B；[3]A↔B means that factor A and factor B influence each other.

Table 6. Reachable matrix

No[1]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1[2]	0[3]	0	1	0	1*	0	0	0	1	1	1	0	1*	0	1*	1*	1*	1*	1*
2	0	1	0	0	0	0	0	0	0	1	1	1*	0	1*	0	0	0	0	0	0
3	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	1*	1*	1*	1*	1*
5	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	1	0	1	0	0	0	0	0	1*	0	1*	0	1	1	1	1*	1*
7	1	0	0	1*	0	1*	1	0	0	1*	1	1*	0	1*	0	1*	1*	1*	1*	1*
8	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
9	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
10	0	1	0	1	0	1*	1	0	0	1	1	1	0	1*	0	1*	1*	1*	1*	1*
11	0	0	0	0	0	0	1	0	0	1	1	1*	0	1*	0	1*	1*	1*	1*	1*
12	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	1*	1*	1*	1*	1*
13	0	0	0	1	0	1*	0	0	0	0	0	1*	1	1*	0	1*	1*	1*	1*	1*
14	0	0	0	1	0	1*	0	0	0	0	0	1	0	1	0	1*	1*	1*	1*	1*
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
16	0	0	0	0	0	1	0	0	0	0	0	1*	0	1*	0	1	1	1*	1	1
17	0	0	0	0	0	1	0	0	0	0	0	1*	0	1*	0	1	1	1*	1	1
18	0	0	0	0	0	1	0	0	0	0	0	1*	0	1*	0	1*	1	1	1*	1*
19	0	0	0	0	0	1	0	0	0	0	0	1*	0	1*	0	1	1	1*	1	1
20	0	0	0	0	0	1	0	0	0	0	0	1*	0	1*	1	1	1	1*	1	1

Remarks: [1]Refer to Table 2 for each indicator number, [2]A→B means that factor A directly affects factor B；[3]A↔B means that factor A and factor B influence each other, *means that there is no subordination relationship, but it has a subordination relationship because of the transitivity property.

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Table 7. Hierarchy matrix

No[1]	Reachability Set R(a_i)[2]	Antecedent Set A(a_i)[3]	R(a_i)∩A(a_i)[4]
1	1, 4, 6, 10, 11, 12, 14, 16, 17, 18, 19, 20	1, 7	1
2	2, 10, 11, 12, 14	2, 10	2, 10
3	3, 8, 9	3, 8, 9	3, 8, 9
4	4, 6, 12, 14, 16, 17, 18, 19, 20	1, 4, 6, 7, 10, 12, 13, 14	4, 6
5	5, 11	5	5
6	4, 6, 12, 14, 16, 17, 18, 19, 20	1, 4, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	4, 6, 12, 14, 16, 17, 18, 19, 20
7	1, 4, 6, 7, 10, 11, 12, 14, 16, 17, 18, 19, 20	7, 10, 11	7, 10, 11
8	3, 8, 9	3, 8, 9	3, 8, 9
9	3, 8, 9	3, 8, 9	3, 8, 9
10	2, 4, 6, 7, 10, 11, 12, 14, 16, 17, 18, 19, 20	1, 2, 7, 10, 11	2, 7, 10, 11
11	7, 10, 11, 12, 14, 16, 17, 18, 19, 20	1, 2, 5, 7, 10, 11	7, 10, 11
12	4, 6, 12, 14, 16, 17, 18, 19, 20	1, 2, 4, 6, 7, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20	4, 6, 12, 14, 16, 17, 18, 19, 20
13	4, 6, 12, 13, 14, 16, 17, 18, 19, 20	13	13
14	4, 6, 12, 14, 16, 17, 18, 19, 20	1, 2, 4, 6, 7, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20	4, 6, 12, 14, 16, 17, 18, 19, 20
15	15, 20	15, 20	15, 20
16	6, 12, 14, 16, 17, 18, 19, 20	1, 4, 6, 7, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20	6, 12, 14, 16, 17, 18, 19, 20
17	6, 12, 14, 16, 17, 18, 19, 20	1, 4, 6, 7, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20	6, 12, 14, 16, 17, 18, 19, 20
18	6, 12, 14, 16, 17, 18, 19, 20	1, 4, 6, 7, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20	6, 12, 14, 16, 17, 18, 19, 20
19	6, 12, 14, 16, 17, 18, 19, 20	1, 4, 6, 7, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20	6, 12, 14, 16, 17, 18, 19, 20
20	6, 12, 14, 15, 16, 17, 18, 19, 20	1, 4, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	6, 12, 14, 15, 16, 17, 18, 19, 20

Remarks: [1]Refer to Table 2 for each indicator number

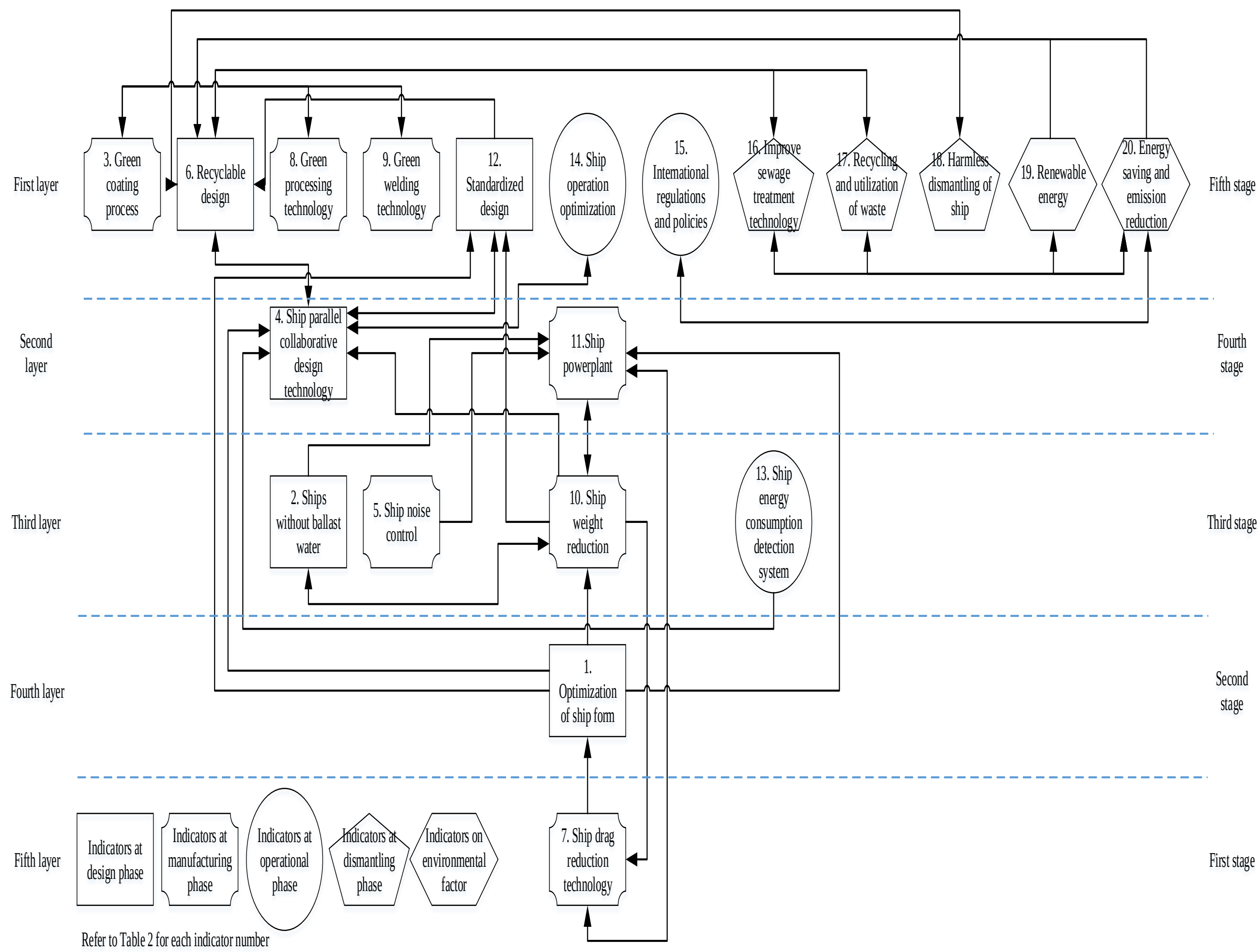

Figure 2. Hierarchical relationship graph

4.2 Analysis of hierarchical relationship graph

According to Figure 2, when establishing a systematic green ship development process, the first stage that should be built is “7. Ship drag reduction technology” of the fifth layer. Given that the ship drag reduction technology can help the ship effectively reduce the fuel consumption during the sailing process and increase the ship’s sailing speed, it has important economic benefits in operation. Therefore, the research on ship drag reduction technology can be used as an important basis for the research and design of green ships.

In the second stage, “1. Ship type optimization” of the fourth layer should be carried out. Figure 2 demonstrates that “7. Ship drag reduction technology” directly affects “1. Ship type optimization.” Ships sailing in the ocean need to overcome the frictional resistance caused by seawater friction. The research and development of ship drag reduction technology to optimize

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the ship form will reduce the frictional resistance during the ship's navigation, minimize the loss of ship fuel, and improve the economics of ship operations.

In the third stage, "2. Ships without ballast water," "5. Ship noise control," "10. Ship weight reduction," and "13. Ship energy consumption monitoring system" should be carried out, as shown in Figure 2.

(1) "10. Ship weight reduction" is affected by "1. Ship type optimization" of the second stage. Therefore, in the optimization design of the ship type, the factors affecting the weight of the ship are taken into consideration, and the structure of the hull is optimized as a whole to reduce the weight of the ship.

(2) "2. Ship without ballast water" and "10. Ship weight reduction" have mutual influence. Traditional ships have ballast tanks at the bottom. To consider the weight of the ship when sailing empty, the water tanks will be filled with seawater at the port of departure to maintain the balance of the ship. When the ship arrives at the port of destination to load the cargo, the water in the water tank will be discharged. However, when the ship sails on an empty ship, the water tank will be filled with seawater, which will increase the weight of the ship, thus causing an increase in fuel consumption when an empty ship sails (Cao, 2010). Therefore, the design of ships without ballast water will reduce the load on the ship and ensure the stability of the ship during navigation.

(3) "10. Ship weight reduction" will also affect the "7. Ship drag reduction technology" of the first stage. After the weight of the ship is reduced, the resistance to seawater during the voyage will be reduced, which will increase the power of the ship. At the same speed, the fuel consumption will be reduced.

In the fourth stage, "4. Ship parallel collaborative design technology" and "11. Ship powerplant" should be implemented, as shown in Figure 2.

(1) "4. Ship parallel collaborative design technology" is simultaneously affected by "1. Optimization of ship form" of the second stage and "10. Ship weight reduction" and "13. Ship energy consumption detection system" of the third stage. Through the optimization of the shape of the ship in the design process, the reduction of ship weight during the manufacturing process, and the improvement of the ship energy consumption monitoring system in the operation process, the overall design phase of ship parallel collaboration technology is improved. In addition, the cost of research and development is reduced, and the cycle of research and development of ships is shortened.

(2) "11. Ship power plant" is affected by "1. Optimization of ship form" of the second stage and "2. Ships without ballast water" and "5. Ship noise control" of the third stage. Through the optimization of the ship type, high-tech ship power plants can be installed effectively. The non-ballast water technology saves the main body space of the ship. It can allocate the saved main body space of the ship to the power plant, which improves the overall benefits of the ship and can allow the ship to travel stably at sea. At the same time, the main source of the noise of the ship comes from the power plant. Moreover, the use of low-noise mechanical

equipment can reduce the noise generated by the power plant, thus reducing its impact on the surrounding environment and ship personnel and achieving zero pollution and zero emissions.

(3) "11. Ship power plant" and "7. Ship drag reduction technology" of the first stage and "10. Ship weight reduction" of the third stage have mutual influence. When the resistance of the ship is decreased, the power of the ship will increase. Reducing the weight of the ship can also increase the power of the ship, shorten its navigation cycle, and save fuel consumption. At the same time, with the advancement of science and technology, the performance of the ship's power plant has also been improved, thus increasing the power of the ship and minimizing the resistance when the ship is running. The weight and volume of the ship's power plant will also be reduced, thereby lightening the weight of the ship.

In the fifth stage, "3. Green welding technology," "6. Recyclable design," "8. Green processing technology," "9. Green coating process," "12. Standardized design," "14. Ship operation optimization," "15. International regulations and policies," "16. Improve sewage treatment technology," "17. Recycling and utilization of waste," "18. Harmless dismantling of ship," "19. Renewable energy," and "20. Energy saving and emission reduction" should be implemented, as can be seen from Figure 2.

(1) Given that "3. Green welding technology," "8. Green processing technology," and "9. Green coating process" are all manufacturing index factors, these three factors influence one another during the manufacturing process and are not related to other factors. They all jointly promote the low-carbon emission of ships, improve the operating efficiency, and protect the environment.

(2) "14. Ship operation optimization" and "15. International regulations and policies" are both operational indicators. "14. Ship operation optimization" and "12. Standardized design" interact with "4. Ship parallel collaborative design technology" of the fourth stage. Therefore, computers can be used to standardize the design of ships and their equipment. At the same time, they can also regulate ship operations and parallel collaboration technologies, systematize operating procedures, improve ship operating efficiency, and reduce friction among factors due to uncoordinated elements. Moreover, a green design concept for designers must be established, and the research and optimization of ship types must be strengthened; a series of ship types with excellent technical and economic performance must also be formed, and the entire green process of shipbuilding from the initial design stage of the ship must be established (Xie, 2009).

(3) "15. International regulations and policies" and "20. Energy saving and emission reduction" also influence each other. For example, the European Union stipulates that before 2020, the upper limit of the global ship sulfur content is 0.5%, which is a sound interpretation of ship energy saving and emission reduction. This concept reduces the overall consumption of ships and the emission of harmful substances. It is precise because of this concept of energy-saving and emission reduction that the effective implementation of current international laws and policies has been achieved [28].

(4) "6. Recyclable design" and "12. Standardized design" are both design indicators. "6. Recyclable design," "16. Improve sewage treatment technology," "17. Recycling and utilization of waste," and "18. Harmless dismantling of ship" interact with "4. Ship parallel collaborative design technology" of the fourth stage. Given that "16. Improve sewage treatment technology," "17. Recycling and utilization of waste," and "18. Harmless dismantling of ship" are all dismantling indicators, the recyclable design plays a very important role in the dismantling process. Through the use of parallel collaboration technology, at the beginning of the design, the dismantling and recycling of the ship after scrapping and the subsequent processing work are considered to make better use of resources, reduce pollution, and have a beneficial impact on the entire life cycle of the ship and the environment.

(5) "6. Recyclable design" is also affected by "19. Renewable energy" and "20. Energy saving and emission reduction." Substituting renewable energy for ordinary energy can reduce or eliminate the emission of harmful pollutants. For example, the use of solar energy and wind energy will greatly increase the recyclability ratio of ships. At the same time, the use of technically feasible, economical, and reasonable energy-saving and emission-reduction methods will increase the recyclable ratio to solve port and marine pollution [10][33].

(6) "6. Recyclable design" is also affected by "12. Standardized design." Therefore, a standardized design can be implemented in the entire recycling process to shorten the recycling cycle of ship waste and reduce unnecessary resource consumption to achieve an effective and reasonable utilization of resources.

(7) "12. Standardized design" is affected by "1. Ship type optimization" of the second stage and "10. Reduce ship weight" of the third stage. The optimization of the ship type and the reduction of the weight of the ship can also promote a smoother standardized design.

(8) "16. Improve sewage treatment technology," "17. Recycling and utilization of waste," and "18. Harmless dismantling of ship" are all dismantling indicators. Among them, "16. Improve sewage treatment technology," "17. Recycling and utilization of waste," "19. Renewable energy," and "20. Energy saving and emission reduction" interact with one another. "19. Renewable energy" and "20. Energy saving and emission reduction" are both environmental indicators, and the improvement of sewage treatment technology and waste recycling and utilization is at the final dismantling stage of the ship's life cycle. By increasing the recycling rate, the emission of harmful substances can be reduced, thus effectively promoting energy saving and emission reduction. Given the use of clean renewable energy, the dismantling process to deal with the pollution caused by the use of non-clean energy has been shortened, thereby better solving the waste of resources.

(9) "17. Recycling and utilization of waste" is also affected by "18. Harmless dismantling of ships." The harmless dismantling of ships aims to realize the recycling of ships. Each part of the dismantling is processed one by one, recycled, and utilized, and the recyclable materials are effectively recovered. Non-recyclable substances need to be addressed by relevant departments for special pollution-free treatment.

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5. Conclusions

With the growing prosperity of the shipping industry, the environmental pollution generated is increasing. At the same time, the global shipping industry's policies and regulations for limiting sulfur are introduced, and the environmental protection standards are becoming increasingly stringent, thus bringing severe challenges to the shipping and shipping industries. At present, green ship indicators are mainly divided into five categories: design, manufacturing, operation, dismantling, and environment. In the process of developing green ships, the requirements of green ship indicators must be met. Therefore, a systematic standard operating process for the development of green ship indicators must be established. Such process determines green ship indicators that need to be gradually completed at each stage, as a reference basis for the shipping industry to implement green ship indicators during the green ship development stage. On the basis of the hierarchical relationship of the ISM analysis results, a five-stage standard operating procedure for green ship development is established, which is expected to be used as a reference and implementation basis for the shipbuilding industry when developing green ships.

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