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**Research Article**

# Determining the Main Criteria Required for the Green Transition of the Maritime Industry

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## Abstract

Today, the importance of green transition in the maritime sector is increasing. In this study, the main criteria for the green transition of the maritime industry have been determined, taking into account the International Maritime Organization (IMO) regulations for the year 2050 and beyond. The criteria were prioritized using a Fuzzy AHP-Based Approach and calculated the cause-effectiveness of each criterion applying the DEMATEL Technique. The aim of the study is to determine whether the green conversion can meet the operational requirements of merchant ships. For this purpose, quantitative and qualitative research techniques were used as a hybrid. The ultimate goal of the study is to evaluate the impact of merchant ships, which will be built in the green concept, on the operational needs, within the framework of maritime transport operation engineering (MTME). At the end of the study, a gradual roadmap was presented to the maritime industry, which will prepare a strategic target plan within the scope of the green transition of the maritime industry.

**Keywords:** MTME, Green Transition, Merchant Ships, Maritime Industry

## Introduction

The shipping industry is an essential element of global trade and has a significant impact on the environment. This environmental impact is equivalent to the release of 1.2 billion tons of CO2 in 2020 and accounts for about 3% of total global greenhouse gas emissions. Flag states and port states, especially the International Maritime Organization (IMO), take preventive measures to control greenhouse gas emissions and issue strict regulations for this purpose. For this reason, the maritime industry focuses on green technologies that will not only reduce emissions from ships but also minimize the environmental impact of shipyards, organized industrial zones, and subsidiaries. Although national and international institutions and organizations and port and flag states have adopted IMO's targets for 2050 and beyond, a common international standard has not been determined for classification societies and green technologies in the maritime industry.
The maritime industry on green technologies; it focuses on smart technologies such as energy efficiency, biodiversity, digitalization, automation, and robotic applications, as well as clean technologies and waste disposal systems.

A "green" merchant ship in the future will be one with a minimal negative impact on the environment. Green ships will be designed to minimize their carbon footprint using advanced technology and energy-efficient systems, using alternative sources such as biofuels, hydrogen fuel cells, or electric propulsion systems instead of traditional fossil fuels. A green merchant ship will have an efficient hull design and provide lower fuel consumption. Within the scope of renewable energy sources, the ship will be equipped with intermediate systems that can be embedded in the fuel system of dual-fuel engines by producing hydrogen from seawater in addition to solar panels or wind turbines to generate electricity and reduce dependence on traditional fuel sources. Within the scope of zero emission and zero waste targets, green ships will have advanced waste management systems that will be able to recycle the wastes they produce on board or process these wastes. It will use advanced emission control systems such as scrubbers or catalytic converters to reduce emissions of harmful pollutants such as sulphur oxides (SOx) and nitrogen oxides (NOx) within the framework of reduced emissions. European Community Shipowners' Associations (ECSA) and the European Shipbuilders and Marine Equipment Manufacturers Association (SEA Europe) within the framework of the Green Ship Incentive Program and the Environmental Ship Index-ESI developed by the International Association of Ports and Harbours (IAPH) works are being handled. Similar initiatives are underway around the world regarding green technologies. The Environmental Ship Index (ESI) criteria cover a range of environmental issues such as emissions, noise, water discharges, waste management, and energy efficiency. Ratings are calculated based on data reported by ship operators, verified, and approved by independent third-party organizations. Thus, the performances of the ships can be displayed in a transparent way and comparisons can be made with other ships. However, all these efforts are still distributed. They must be consolidated and meet international standards. The ESI Portal, run by the IAPH, gives ports and other interested parties the ability to encourage ships to use cleaner fuels or, prevent polluters through discounts on port dues, or other incentives corresponding to a certain level of cleanliness (Notteboom et.al., 2022). ESI Incentive Provider Ports are listed in Table-1.

As seen in Table-1, although ESI Countries try to protect an important environmental area around their ports, 2.4 percent of the annual 40 billion cubic meters of pollution caused by the production of commercial goods originates from merchant ships and the prevention of this mobile pollution requires serious initial investments.

Table 1: ESI Incentive Provider Ports (created by authors)

| Continental | Country | Port Authority |
|---|---|---|
| North America | Canada | Prince Rupert, Halifax, Vancouver Fraser, Saint John, |
| | USA | Los Angeles, New York, New Jersey, Long Beach |
| Central America | Panama | Panama Canal |
| South America | Brazil | Pecém, Açu, Suave, Itaqui |
| Europe | Netherland | Amsterdam, Rotterdam, Gröningen Seaports, Green Award Foundation, Tata Steel Ijmuiden Terminal, North Sea Port |
| | UK | Port of London |
| | Italy | Autorità Portuale di Civitavecchia |
| | Spain | Port Authority of Barcelona |
| | Denmark | Port of Aarhus, Port of Kolding |
| | Norway | Port of Kristiansand, Norwegian Costal Administration (Kystverket), Port of Stravanger, Port of Bergen, Port of Florø (Alben), Karmsund Port Authority, Port of Drammen, Port Authority of Fredrikstad & Sarpsborg, Port of Oslo |
| | Sweden | Port of Gothenburg, Port of Stockholm, |
| | Finland | Port of Helsinki Ltd. |
| | Slovenia | Port of Koper |
| | Estonia | Port of Tallinm |
| | Belgium | Port of Antwerb, Port of Zeebruggee |
| | France | Grand Port Maritime de la Rèunion |
| | Germany | Hamburg Port Authortity, Bremerhaven, Brunnsbüttel Port GMBH, Port of Rostock, Niedersachsen Port, Jade Wesser Port |
| Asia | Oman | Port of Sohar |
| | South Korea | Ulsan Port Authority |
| | Japan | Port of Tokyo, Port of Yokohoma, Tomakomai Port Authority, Nagoya Port Authority |
| Oceania | Australia | NSW Ports |
| | New Zealand | Port Nelson Limited |

***.***https://www.environmentalshipindex.org/*

***Literature Review***

When the literature is reviewed, there are very few studies on the green transformation of shipyards or the shipping industry, while there are many individual studies on the sustainability of ships. Also, there are mentioned some categories such as green, blue, clean, smart, etc. which are not common standards and are incompatible with each other worldwide. An environmentally sensitive approach alone is not a rational solution and unreasonable standards cannot maintain as a field of application. First of all, the regulations of the International Maritime Organization should be focused on, and in this context, it should be considered the requirements of the classification societies that certify compliance with the regulations. Subsequently, industrial applications in the world and academic or sectoral studies in this field should be taken into account. IMO's post-2050 goals gradually forced zero waste and zero emissions. This target forces all parties involved in the maritime industry to transform.

Since the initial costs are high in the transformation of new, sustainable, and environmentally friendly technologies into industrial products, it is not possible to make a profitable and sustainable transformation in the fragile markets of maritime trade, and it is necessary to realize the transformation gradually over time. However, the date of entry into force of the regulations creates time pressure, the economic conditions due to the recession in the world create negative conditions for the transformation process, and it is necessary to put forward a meticulous approach to strategic investments. For this reason, all the criteria affecting the issue in a wide range were taken into consideration while scanning the literature, and the main criteria were determined by clustering the mentioned criteria among themselves. While environmental criteria come to the fore in the literature, it is stated that digital transformation will strengthen green innovation as well as compliance with regulations, reduction of emissions, and energy efficiency (Xue et.al., 2022). Similarly, it is encouraged that digital finance will also be effective in green technology innovation and depending on the governance capacity of local governments, especially in regions with high pollutant emission intensity (Feng et.al., 2022). Shan et.al., come to the conclusion that the effect of green technology innovation and renewable energy on carbon dioxide emissions is negative in the long run, while the effect of energy consumption, population, and per capita income is positive for carbon dioxide emissions (Shan, 2021). Weber and Neuhoff concluded that technological innovation creates energy-efficient technologies that are less important for environmental pollution (Weber and Neuhoff, 2010). However, due to the developments in the past 13 years, it is thought that the importance of energy efficiency approaches the other two criteria. Ganda, on the other hand, implied that technological innovation increases emissions to pollute the atmosphere (Ganda, 2019). In Environmental Protection, the cleanship and green passport notations of Bureau Veritas come to the fore. In this context, Cleanship, Cleanship Super, Advanced Wastewater Treatment (AWT-A, AWT-B, AWT A/B, Biofuel Ready, Ballast Water Exchange (BWE), Ballast Water Treatment (BWT), Continuous Emissions Monitoring System (CEMS), It has fields of activity in areas such as Exhaust Gas Cleaning System Using Scrubber(s) (EGCS-SCRUBBER), Fast Oil Recovery System (FORS), Gray Waters Treatment (GWT), etc. However, green passport is related to hazardous material inventory and includes preparation for recycling (Bureau Veritas, 2022). The notation of the BIOFUEL READY aims to assist shipowners in being ready to use biofuels or its blends (Leblanc, 2022). Within the scope of The European Green Deal, fresh air, clean water, renovated, and energy-efficient buildings, cleaner energy and cutting-edge clean technological innovation, longer lasting products that can be repaired, recycled, and re-used, future-proof jobs and skills training for the transition globally competitive and resilient industry is aimed at the development of green technologies (EU, 2023). In addition, smart shipping ensures to be more sustainable for ship owners and managers by improving the energy efficiency of the ship (Joley, 2023). For example, shipyards with zero environmental impact in terms of energy use and pollution are defined as green. As the scope only considers the operational lifecycle, a green shipyard only takes into account the sustainable production of vessels and the repairs made (Janson, 2016). In the results of the research regarding green ships before last decades, there was no hesitation to control $NO_X$ and $SO_X$ emissions, but in terms of reducing $CO_2$ emissions, it was considered that the operating speed of the ships should be decreased by 2 knots below operation speed (Schnack, 2009). Although the suggestions were a logical solution in terms of protecting the environment, reducing speed was not reasonable for shipowners and ship operators. Although this is not a desired solution for container ships where speed is important, slowing down bulk carriers and tankers, whose economic speed is already low, would not be an appropriate approach in terms of navigational safety either. The concept studies carried out by Lloyd's Register on green shipping, it aims to create green corridors by concentrating on alternative fuels and establishing a silk alliance in terms of access to strong financial resources and risk sharing. For this reason, it concentrates its work on IMO's decarbonization targets. Within the scope of the green corridor initiative, green technologies, ship types, as well as the selection of alternative fuels, are considered the entire global supply chain, including initiatives of public and private institutions and the development of the ports' facilities and infrastructures (Raucci et.al., 2022). The American Bureau of Shipping (ABS) has been focused on four fundamental elements (ABS, 2023) regarding green corridors mentioned below;

- cross value chain collaboration among the owners/operators, cargo owners, ports, and marine fuel producers
- viable fuel pathways regarding zero emissions.
- shipping, and logistical impact on market forces demanding green shipping at scale
- policies and regulations related to incentives, penalties, and enabling support from the government.

The European Marine Equipment Council has focused on seven main issues regarding green ships. These are; Reduction of Gas Emissions (NOx, $CO_2$, $SO_x$, Soot, Smoke, and Particulate Matter), Ship Waste Disposal, Bilge Water Treatment, Black Waste Water Treatment, Gray Waste Water Treatment, Ballast Water Treatment, and Underwater Coatings (EMEC, 2010). Green shipping practices (GSPs) can be conceptualized along six environmental management aspects in shipping operations, according to Lai et al. These are "Company policy and procedure (CPP), Shipping documentation (SD), Shipper cooperation (SC), Shipping equipment (SE), Shipping materials (SM) and Shipping design and compliance (SDC)" (Lai et.al., 2011).

One of the key components of the environmental management groups in question is shipping equipment (SE) because shipyards and maritime equipment are both involved in shipbuilding. All products and services used in the operation, construction, conversion, and maintenance of ships as well as technical services for engineering, installation and commissioning, and lifecycle management of ships are considered to be marine equipment (EMEC, 2009).

**Competitiveness of Green Ships**

An incentive program focused only on environmental pollution cannot fully meet the green ship concept. Technologies already realized are not yet sustainable in a cost-effective manner. Because producing green ships requires primarily that the shipyards or manufacturing facilities be green. Compared to the construction of conventional ships in terms of initial investment costs, green ships are unable to compete in the short run. IMO regulations necessitate the construction of green ships, and it is necessary to equip ships that will meet IMO criteria gradually, at the minimum level, and in a timely manner that will allow the technology to produce a cost-effective industrial product.

***What should be the transition criteria of the shipyards that will build the green ships?***

To develop and encourage the use of clean technologies and energy-efficient processes in the shipbuilding industry and repair activities, the following actions should be taken.

- promoting the use of environmentally friendly materials such as recycling or sustainable materials,
- reducing the amount of waste produced,
- implementing waste management practices at shipbuilding
- repairing sites to minimize the impact on the environment.
- promoting the use of renewable energy sources such as solar or wind energy,
- supporting R&D initiatives
- improving the environmental performance of the shipbuilding and R&M industry.

Five main criteria come to the fore to ensure the purpose above. These include institutional, economic, technological, occupational health & safety, and environmental criteria. Supporting the green concept by management and stakeholders, providing legal compliance, providing technical consultancy by experts, establishing an effective organizational structure, and establishing an effective internal and external communication network constitute the main framework of corporate criteria. It is an indispensable condition for institutions related to green technologies to first review their organizational structures. Economic feasibility is of strategic importance as green technologies will initially require high initial investment costs. Wrong decisions will cause irreversible dysfunctional investments and may cause irreparable losses in the short term. For this reason, the investment and operating costs of green shipyards and green ships, the income potential to be obtained, the rate of return on investment, the incentives of government or national/international institutions, and financial options are factors that should be considered. In terms of green technologies, technological transformation should be considered in a wide range. These are generally; focused on smart technologies such as automation and digitalization, sustainable energy efficiency, cyber security, supply chain management, quality control, maintenance-repair, data management, and virtual & augmented reality (VR & AR).

## Establishing Green Shipyards and Producing Green Ships

Shipyards are mostly second and third generation worldwide. For this reason, a labour-intensive workforce, qualified specialist personnel requirements, and production processes or delivery times are long compared to fourth and fifth-generation shipyards. In addition, the waste generation rates of the materials used in production are higher. In terms of energy efficiency, ontological energy management systems are required.

Transformation of the green shipyards aims to make existing shipyards more environmentally friendly and sustainable. This transformation includes a variety of different measures such as the use of solar panels, wind turbines and other renewable energy sources, as well as the implementation of recycling and waste management systems. The main objective of green shipyard transformation is to reduce environmental impacts in shipbuilding and maintenance and repair processes. Green shipyards using renewable energy sources decrease the dependence on fossil fuels, alleviate the emissions of GHGs, and prevent the damage caused by pollutants. Moreover, green shipyards can reduce their energy costs and increase their profitability. Thanks to the recycling and waste management systems of green shipyards, the need for raw materials decreases, productivity increases and costs decrease. In order to ensure international competition, first of all, there is a need for fourth or fifth-generation shipyards that can produce green ships in accordance with international standards. For this, the choice of shipyard location is of great importance. There is no distinctive difference regarding site selection between conventional shipyards and green ones. Since the creation of joint ventures, mergers, acquisitions, and alliances come to the fore in countries with competitive advantages, it is beneficial to consider these strategic processes. Fourth or fifth-generation green shipyards will be able to be used effectively, especially in producing small tonnage naval vessels. Since delivery time cannot be considered alone in shipbuilding processes, quality, and estimated budget must also be considered. Appropriate man-hour wages, labour, and raw material costs providing the minimum quality standards that IACS member classification societies can certify, and not exceeding the budget foreseen for the targeted profitability strongly reveal the importance of green shipyards and pave the way for gaining superiority in intense competition. Considering the difficulties in obtaining the necessary financing for the construction of a competitive shipyard, as ideals and real conditions will always be different, it is vital to prioritize government incentives for initial investments. Strengthening the reliability factors such as the guarantee of the state, letters of indemnity, and the legal infrastructure regarding the resolution of disputes in arbitration courts in case of defective commodity, assure the customer in international trade. Cooperation mechanisms should be established by taking into account the processes carried out by the countries that support green transformation and play a leading role in the world. Since the dependency on the manufacturers abroad, especially in terms of equipment, continues in conventional shipyards, cooperation mechanisms such as the *"Green Shipping Programme"* will reduce dependency on foreign countries. Thus, a result-oriented production model will be realized by distributing the risks in the transition to green technologies to the stakeholders.

## Methodology and Model of Meeting the Research Question

In order to determine the main criteria in the green transition of shipyards, which are the backbone of the maritime industry, it is necessary to consider the ecosystem in which green technologies are located. It is obligatory for shipyards to protect the environment on the one hand and to build ships equipped with green technologies for a sustainable clean environment in line with the requirements of shipowners within the framework of international legislation on the other. For this reason, the green transition of shipyards is not only to be an environmentally friendly shipyard but also to manufacture green ships that will meet IMO criteria. Therefore, determining and prioritizing the transition needs of workshops by considering ship production processes constitute the limits of the research. In this context, the research question is: ‘Do the prioritized main criteria provide reliable decision-making support?’ The methodology of the research and the model created in this context are shown in Figure 1.

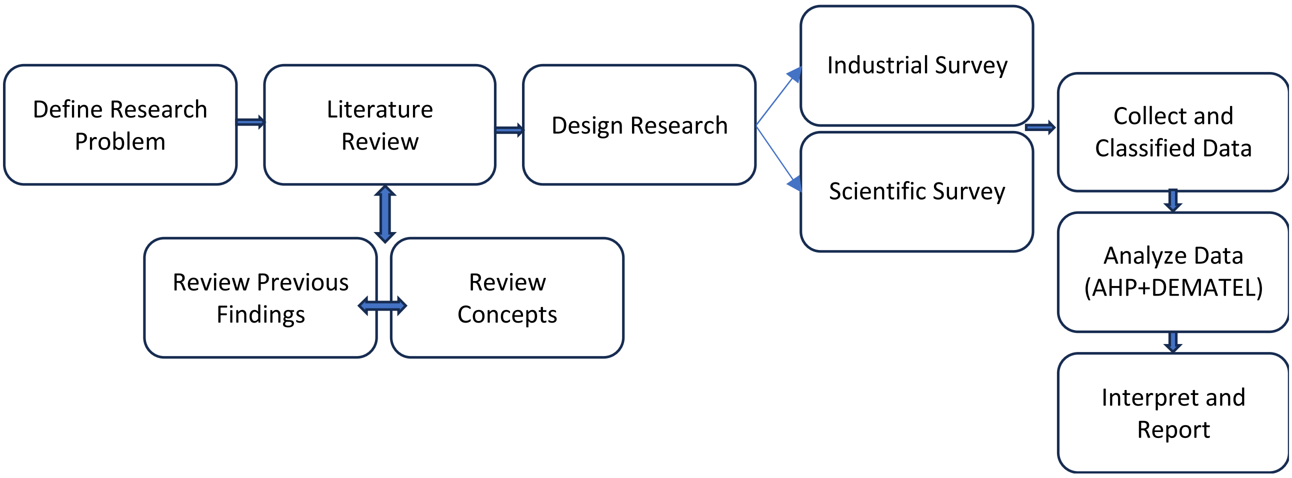


Fig. 1. The Methodology of Determining the Main Criteria for Green Transition.

At the stage of identifying the research problem, first of all, the current definitions regarding green standards were investigated and no standard accepted by IMO could be found. Regarding land and air systems, it has been observed that buildings and facilities have some environmental standards. Classification societies were examined, and it was seen that each of them developed different environmental standards. In the literature review, a green standard containing the entire ecosystem could not be found. In this part of the study, it was noticed that there is a gap that has not yet been clarified. It was understood at first glance that standards should be developed with a holistic approach that includes land, air, and sea systems for green transformation. It was decided to determine the main criteria to realize the green transformation of the maritime industry, with the main subject being green ships, and this decision determined the motivation and limits of the research. In order to design the research, industrial and scientific surveys were made, and interviews were made with field experts and shipyards that attach importance to green transformation. The literature focuses on specific areas that take into account IMO criteria rather than holistic approaches. In general, these have become widespread as individual studies in areas such as digitalization and optimization, identification of alternative fuels, energy efficiency, use of alternative energy sources, reduction of emissions, entropy management, exergy destruction, dual fuel main engines, biodiversity, occupational health and safety system (OHSAS), and prevention of environmental damage, and examining institutional reports helped to determine the limits of the research and gained a holistic view to the maritime industry. In the examination carried out in this context; It has been determined that regulation compliance, emission reduction, energy efficiency, digitalization and optimization, alternative fuels, ballast water treatment, renewable energy integration, noise and vibration reduction, port infrastructure, waste management are the issues that preoccupy the maritime industry the most. The Analytic Hierarchy Process (AHP) and The Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods were adopted as strategic decision support in determining the main criteria. With the AHP method, the weights of the main criteria were determined, and their consistency was tested by prioritizing among themselves.

***The Analytic Hierarchy Process (AHP)***

The Analytic Hierarchy Process (AHP) is a decision-making methodology developed by Thomas L. Saaty in the 1980s. Regarding AHP, ***formulae 1-6 and Saaty’s Scale as demonstrated in Table-3*** below are taken from the study called ***‘Practical Design Making: An Introduction to Analytic Hierarchy Process (AHO) Using Super Decision’*** (Mu and Rojas, 2017). It is a structured approach that helps individuals or groups make complex decisions by systematically evaluating and comparing criteria and alternatives. The AHP involves eight steps (see Figure 2) and, six equations (see 1-6). These steps are defining the decision problem, creating a hierarchy, performing pairwise comparisons, determining priorities, checking consistency, aggregating priorities, making sensitivity analysis, and taking a decision. To calculate the equalized and normalized weights, a pairwise comparison matrix (CM-A) was created as in equation-1. This matrix reflected the relative importance of each criterion. The matrix is normalized by dividing the sum of the rows corresponding to each cell by the number of criteria.

$$\text{CM}\ (A) = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \rightarrow a_{ij'} = \frac{a_{ij'}}{\sum_{i=1}^{n} a_{ij}} \rightarrow$$

$$A_1 = \begin{bmatrix} a_{11'} & a_{12'} & \cdots & a_{1n'} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1'} & a_{n2'} & \cdots & a_{nn'} \end{bmatrix} \quad \text{(Eq.1)}$$

After the comparison matrix is normalized, the eigenvector (w) is calculated using the following formula. This eigenvector represents the weights of each criterion. Each weight is normalized by dividing by the sum of all weights. The weights are equalized by multiplying each weight by a constant so that the sum of the weights equals one. Using these steps, equalized and normalized weights are calculated for each criterion that can be used to green transition in an AHP method. The equation-2 used for normalization is as follows;

$$A_1 = \begin{bmatrix} a_{11'} & a_{12'} & \cdots & a_{1n'} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1'} & a_{n2'} & \cdots & a_{nn'} \end{bmatrix} \rightarrow w_i = \frac{\sum_{i=1}^{n} a_{ij'}}{n} \rightarrow$$

$$w = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad \text{(Eq.2)}$$

where, n = # of criteria

Following the calculation of the eigenvector, the eigenvalue ($w'$) is calculated by multiplying the comparison matrix (A) with the eigenvector (w), as shown in the formula below.

CM (A) * Eigenvector (w) = Eigenvalue ($w'$)

$$A * w = w' = A_w = \begin{bmatrix} w_1{'} \\ w_2{'} \\ \vdots \\ w_{n'} \end{bmatrix} \quad \text{(Eq.3)}$$

One of the reasons for calculating the eigenvalue and eigenvector is to determine the lambda-max ($\lambda_{max}$) value so that consistency can be tested. ($\lambda_{max}$) can be calculated as the following formula;

$$\frac{\text{Eigenvalue } (w')}{\text{Eigenvector (w)}} = \lambda_{max}$$

$$\lambda_{max} = \frac{1}{n} * \left(\frac{w_1{'}}{w_1} + \frac{w_2{'}}{w_2} + \ldots\ldots\ldots + \frac{w_n{'}}{w_n}\right) \quad \text{(Eq.4)}$$

Consistency Index (CI) can be formulated as follows;

$$\text{Consistency Index (CI)} = \frac{\lambda_{max} - n}{n - 1} \quad \text{(Eq.5)}$$

where n = # of criteria

It is possible to calculate the Consistency Index and Random Index values and Consistency Ratio according to the formula below.

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}} \quad \text{(Eq.6)}$$

The Random Index values are included in the aforementioned formula, taking into account the number of requirements specified in Table 2.

Table 2. Random Index (RI) Values

| Number of Requirements | Random Index (RI) |
|---|---|
| 2 | 0,00 |
| 3 | 0,52 |
| 4 | 0,89 |
| 5 | 1,11 |
| 6 | 1,25 |
| 7 | 1,35 |
| 8 | 1,40 |
| 9 | 1,45 |
| 10 | 1,49 |

If CR < 0,10 → Consistent, if CR ≥ 0,10 → Inconsistent. For example, A is more important than B, if A is more important than C → Consistent, and B is more important than C, if C is more important than A → Inconsistent.

***The Decision-Making Trial and Evaluation Laboratory (DEMATEL) Technique***

DEMATEL Technique is a multi-criteria decision-making tool that has the ability to convert qualitative data into quantitative analysis. Regarding DEMATEL, ***formulae 7-10*** below are taken from the study called ***'World Problems Invitation to Think More in the Framework of DEMATEL'***. (Gabus and Fontela, 1972). The DEMATEL technique involves four steps. These are generating the direct relation matrix, normalizing the direct relation matrix (X), calculating the total relation matrix (T), and producing a causal diagram. The following equation is used to generate the direct relation matrix (A).

$$A = \frac{1}{n} \sum_{k=1}^{n} A_{ij}^{k} \quad \text{(Eq.7)}$$

The following equations are used to normalize the direct relation matrix (A).

$$X = k * A \quad \text{(Eq.8)}$$

$$k = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}} \quad \text{(Eq.9)}$$

where i,j = 1,2,…………n

The next step is calculating the total relation matrix (T) as in the following equation.

$$T = X\,(I - X)^{-1} \quad \ldots\ldots\ldots\ldots(10)$$

The last step is to draw a casual-effect diagram.

***Implementation of AHP and DEMATEL in a Case Study Regarding Green Transition***

In order to determine the weighting coefficients and priorities of the main criteria within the scope of the study, the AHP method was applied first. Main criteria articulated as decision variables were determined such as Regulation Compliance (RC), Emission Reduction (ER), Energy Efficiency (EE), Digitalization and Optimization (DAO), Alternative Fuels (AF), Ballast Water Treatment

(BWT), Renewable Energy Integration (REI), Noise and Vibration Reduction (NVR), Port Infrastructure (PI) and Waste Management (WM). The AHP method, which contains six formulae was applied in eight steps demonstrated in Figure 2.

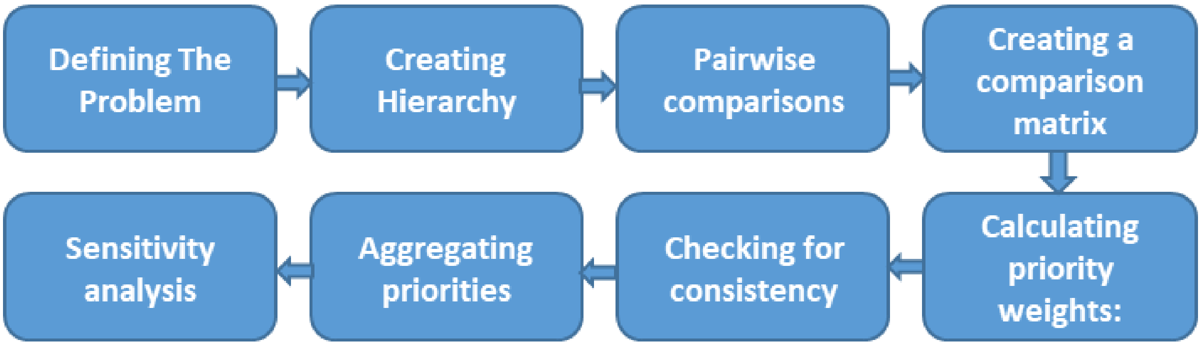


Fig. 2. The Eight Steps of The Analytic Hierarchy Process (*Source: Prepared by Author*)

Table 3: Saaty's Scale 1-9

| | Intensity of Importance | |
|---|---|---|
| SAATY Scale 1-9 | 1 | Equal Importance |
| | 3 | Moderate Importance |
| | 5 | Strong Importance |
| | 7 | Very Strong Importance |
| | 9 | Extreme Importance |
| | 2,4,6,8 | Intermediate Values |

Table 4: Normalized and Equalized Comparison Matrix.

| Decision Variables | EE | AF | ER | BWT | WM | NVR | DAO | REI | PI | RC |
|---|---|---|---|---|---|---|---|---|---|---|
| **Energy Efficiency (EE)** | 0.06 | 0.23 | 0.04 | 0.01 | 0.09 | 0.22 | 0.19 | 0.01 | 0.16 | 0.08 |
| **Alternative Fuels (AF)** | 0.01 | 0.05 | 0.02 | 0.22 | 0.13 | 0.09 | 0.02 | 0.13 | 0.12 | 0.08 |
| **Emission Reduction (ER)** | 0.17 | 0.32 | 0.13 | 0.22 | 0.13 | 0.16 | 0.19 | 0.13 | 0.12 | 0.08 |
| **Ballast Water Treatment (BWT)** | 0.17 | 0.01 | 0.03 | 0.04 | 0.09 | 0.09 | 0.19 | 0.01 | 0.12 | 0.06 |
| **Waste Management (WM)** | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.06 |
| **Noise & Vibration Reduction (NVR)** | 0.01 | 0.02 | 0.03 | 0.01 | 0.09 | 0.03 | 0.01 | 0.13 | 0.12 | 0.06 |
| **Digitalisation & Optimisation (DAO)** | 0.02 | 0.14 | 0.04 | 0.01 | 0.13 | 0.16 | 0.06 | 0.22 | 0.12 | 0.08 |
| **Renewable Energy Integration (REI)** | 0.28 | 0.02 | 0.04 | 0.13 | 0.09 | 0.01 | 0.01 | 0.04 | 0.07 | 0.06 |
| **Port Infrastructure (PI)** | 0.01 | 0.01 | 0.03 | 0.01 | 0.09 | 0.01 | 0.01 | 0.01 | 0.02 | 0.06 |
| **Regulation Compliance (RC)** | 0.28 | 0.23 | 0.63 | 0.31 | 0.13 | 0.22 | 0.31 | 0.30 | 0.16 | 0.40 |

Decision variables were collected in a matrix according to Saaty's 1-9 scale (Saaty, 1977) indicated in Table 3 according to the surveys conducted by field experts (15 Managers from Shipyards) and related institutions (10 Academician from Universities, 4 Expert from Classification Societies, 6 Engineers from Companies of Energy Solutions).

Analytical Hierarchy Process (AHP) can be used to evaluate and prioritize different options when converting conventional systems to green transitions of them. To create a hierarchy and make pairwise comparisons, it is necessary to equalize and normalize the cellular values of the matrix formed from the criteria obtained from field experts and sectoral data.

Pairwise comparison matrices are created between the criteria. The purpose of the pairwise comparison matrix is to determine the significance level between the criteria. The generated matrix is 10x10 in size. The comparison matrix is normalized and equalized as in Table 4.

The next step is calculating the priority vector. In this step, the importance level of each criterion is calculated according to the other criteria. The priority vector of the matrix is determined. The matrix size is obtained as 1x10 which is displayed as in Table-5. One of the reasons for calculating the eigenvalue and eigenvector is to determine the lambda-max (λmax) value so that consistency can be tested.

Table 5: Priority Vector of Comparison Matrix

| DECISION VARIABLES | EIGEN VECTOR | EIGEN VECTOR (%) | EIGEN VALUE | λmax |
|---|---|---|---|---|
| **Energy Efficiency** | 0.11 | 11.41% | 0.159579592 | 1.46696396 |
| **Alternative Fuels** | 0.09 | 9.43% | 0.123605514 | 1.42451677 |
| **Emission Reduction** | 0.16 | 16.27% | 0.256076757 | 1.57020953 |
| **Ballast Water Treatment** | 0.08 | 7.20% | 0.116959579 | 1.45065717 |
| **Waste Management** | 0.01 | 1.52% | 0.017504723 | 1.17954961 |
| **Noise and Vibration Reduction** | 0.05 | 5.45% | 0.064495684 | 1.28389823 |
| **Digitalisation and Optimisation** | 0.10 | 10.51% | 0.13949613 | 1.4348896 |
| **Renewable Energy Integration** | 0.08 | 5.52% | 0.117441896 | 1.55790591 |
| **Port Infrastructure** | 0.03 | 2.75% | 0.027863393 | 1.08427479 |
| **Regulation Compliance** | 0.30 | 29.94% | 0.430410768 | 1.44742051 |

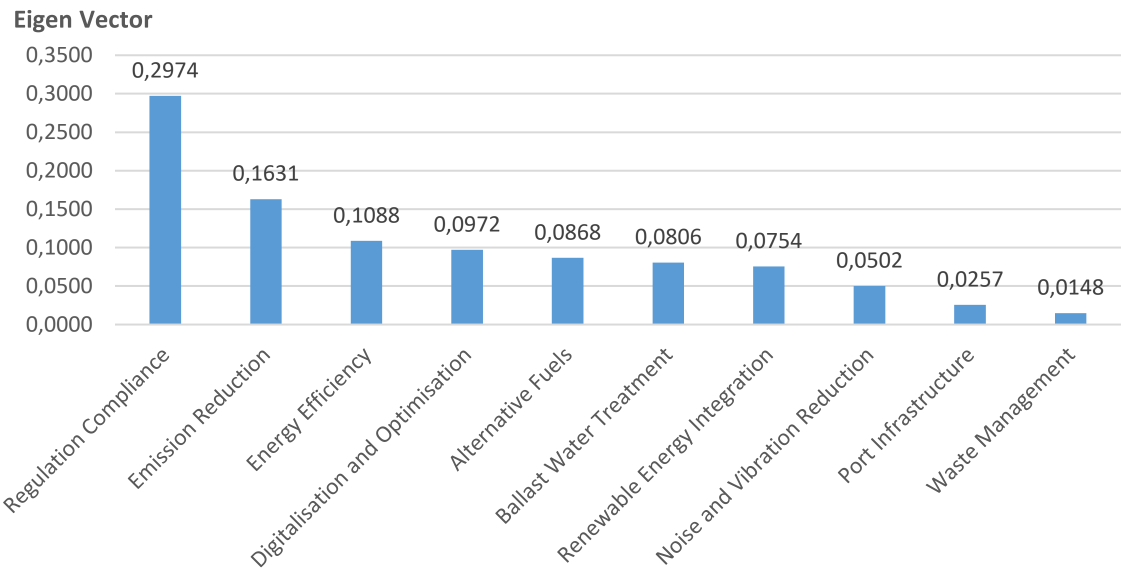


Fig. 3. Prioritised Criteria for Green Transition

Table 6: The Normalized Direct Relationship Matrix.

| Decision Variables | RC | ER | EE | DAO | TOTAL |
|---|---|---|---|---|---|
| **Regulation Compliance (RC)** | 0.00 | 0.17 | 0.33 | 0.50 | 6 |
| **Emission Reduction (ER)** | 0.17 | 0.00 | 0.17 | 0.33 | 4 |
| **Energy Efficiency (EE)** | 0.33 | 0.17 | 0.00 | 0.17 | 4 |
| **Digitalisation and Optimisation (DAO)** | 0.50 | 0.33 | 0.17 | 0.00 | 6 |

This eigenvector represents the weights of each criterion. Each weight is normalized by dividing by the sum of all weights. The weights are equalized by multiplying each weight by a constant so that the sum of the weights equals one. Following the calculation of the eigenvector, the eigenvalue (w') is calculated by multiplying the comparison matrix with the eigenvector. Thus, it is possible to calculate Consistency Index (CI) and Random Index (RI) values and Consistency Ratio (CR) using equations 5 and 6.

As a result, it is found that;

CI = -0,956663488, RI = 1,49, and CR = -0,642056032, since CR<0.10, the calculation is consistent. Equalized and normalized weights determined after each main criterion was compared were then calculated so that the sum of the weights of the criteria was equal to one. The weight coefficients determined were ordered from the largest to the smallest, and the prioritization of the criteria was ensured. Prioritized criteria are illustrated in Figure 3.

After prioritizing the criteria, the four with the highest weight were determined as the main criteria. These are regulation compliance, emission reduction, energy efficiency, and digitalization & optimization. Among other criteria, especially alternative fuels, are not insignificant. On the contrary, although there are criteria that should be considered, however, the impact rates are lower than the first four criteria. After this step, the cause-effect relationship of the four main criteria with the DEMATEL technique has been examined. DEMATEL technique aims to determine the relations between the criteria in the problem and their effects on each other. After the main criteria were determined, the Direct Relationship Matrix was created to determine the relationship between them. In the direct relationship matrix, the sums of the rows and columns were taken and the largest value at their intersection was found to be six. Each cell was divided into six and a normalized direct relationship matrix as in Table 6 was obtained.

Subsequently, the total relation matrix displayed in Table 7 was created. In the DEMATEL technique, the Total Relation Matrix (TRM) is a key output that helps in understanding the interrelationships between factors within a system. The TRM provides a comprehensive view of the driving and dependence powers of factors and their overall impact on each other. The TRM is a square matrix, where each row and column represent a factor within the system. The relationship between the related factors is represented by the intersection of a row and a column. Based on the values in the matrix, the TRM quantifies the driving and dependency powers of factors. A positive value in the TRM denotes a strong and direct correlation between the variables. It denotes a positive driving force behind or influence on the factor in the column for the factor in the row. A low score in the TRM denotes a strong negative correlation between the components. It indicates that the factor in the row negatively drives or affects the factor in the column. The size of the values gives a clue as to how strong the association is. Stronger influences or impacts between elements are indicated by higher absolute values, whether positive or negative. Based on the values in the matrix, the TRM quantifies the driving and dependency powers of factors. The TRM is typically used to compute the driving power (D) and dependency power (R). The D values show a factor's driving force, or how big of an influence it has on other factors. Stronger driving power is indicated by a higher D value. The R values, on the other hand, show how strongly a factor is influenced by other factors or their dependence power. A stronger reliance is indicated by a higher R-value.

Following the calculation of D and R values, the D+R and D-R values were determined for understanding the cause effectiveness of each criterion (see Table 8). The D and R values were also subtracted to provide the D-R values. The DEMATEL methodology should be used to examine and comprehend causal linkages. Identification of the driving and dependent forces of various components within a system, as well as those factors' interactions with one another, would be beneficial. The D value and the R-value are two crucial values that the approach delivers for each element. The driving strength of a factor is represented by the D Value (Causal Relationship), which shows how much it has an impact on other variables in the system.

Table 7: Total Relationship Matrix

| **Decision Variables** | **RC** | **ER** | **EE** | **DAO** | **D** |
|---|---|---|---|---|---|
| **Regulation Compliance (RC)** | 0.63078217 | 0.42977292 | 0.47687132 | 0.42388562 | 1.96131203 |
| **Emission Reduction (ER)** | 1.52481077 | 0.58957107 | 0.90075694 | 0.80067283 | 3.81581161 |
| **Energy Efficiency (EE)** | 1.35407906 | 0.73591253 | 0.58368377 | 0.62994113 | 3.30361648 |
| **Digitalisation and Optimisation (DAO)** | 1.53658537 | 0.68292683 | 0.85365854 | 0.53658537 | 3.6097561 |
| **R** | 5.04625736 | 2.43818335 | 2.81497056 | 2.39108495 | |

Table 8: Cause-Effect Tables Regarding D & R Values.

| **Decision Variables** | D | R | D+R | D-R | C-E |
|---|---|---|---|---|---|
| **Regulation Compliance** | 1.96131203 | 5.04625736 | 7.00756939 | -3.0849453 | **Effect** |
| **Emission Reduction** | 3.81581161 | 2.43818335 | 6.25399495 | 1.37762826 | **Cause** |
| **Energy Efficiency** | 3.30361648 | 2.81497056 | 6.11858705 | 0.48864592 | **Cause** |
| **Digitalisation and Optimisation** | 3.6097561 | 2.39108495 | 6.00084104 | 1.21867115 | **Cause** |

A low driving power and little influence on other factors are indicated by a D value that is near to 0. The component is favourably influencing other factors if the D value is positive, which denotes a positive driving power. The factor is pushing other variables adversely if the D value is negative, which denotes a negative driving power. The factors with the greatest driving power can be emphasized and a sorted list of factors based on their D values can be provided when reporting the D values. The R-Value (reliance) measures a factor's reliance power, or how much other components in the system have an impact on it. A stronger dependence is indicated by a higher R-value. When the R-value is close to 0, it is likely that the component has little dependence on and little impact from other variables. The factor is positively dependent on other factors if the R-value is positive, which denotes a positive dependence. The factor is said to be negatively dependent on other factors if the R-value is negative, which denotes a negative dependence. A cause-effect diagram was created after finding D and R values, as shown in Figure 4. A cause-effect diagram is used in the DEMATEL technique to visually express the causal linkages between various components in a system. It provides a thorough grasp of the dynamics of the system and aids in identifying the direct and indirect influences among the components. Nodes (representing factors) and arrows (indicating causal relationships) make up the cause-and-effect diagram. Each factor is represented by a node. The figure illustrates the components' direct and indirect relationships. The cause-and-effect diagram aids in determining the influence and reliance of the factors. It can be learned more about the dynamics of the system by analysing the cause-and-effect diagram. Understanding which variables significantly affect other variables, identifying the primary drivers and dependencies, and identifying any feedback loops or indirect impacts would be helpful. It is critical to take into account both the direction and intensity of the correlations between components when reading the cause-effect diagram in Figure 4. By emphasizing the important elements and their connections, it improves decision-making and analysis while providing a visual picture of the intricate interdependencies existing within the system. In Figure 4, D+R values range from 6.0 to 7.0, shown in blue. D-R values range from -3.1 to 1.4 and are shown in red.

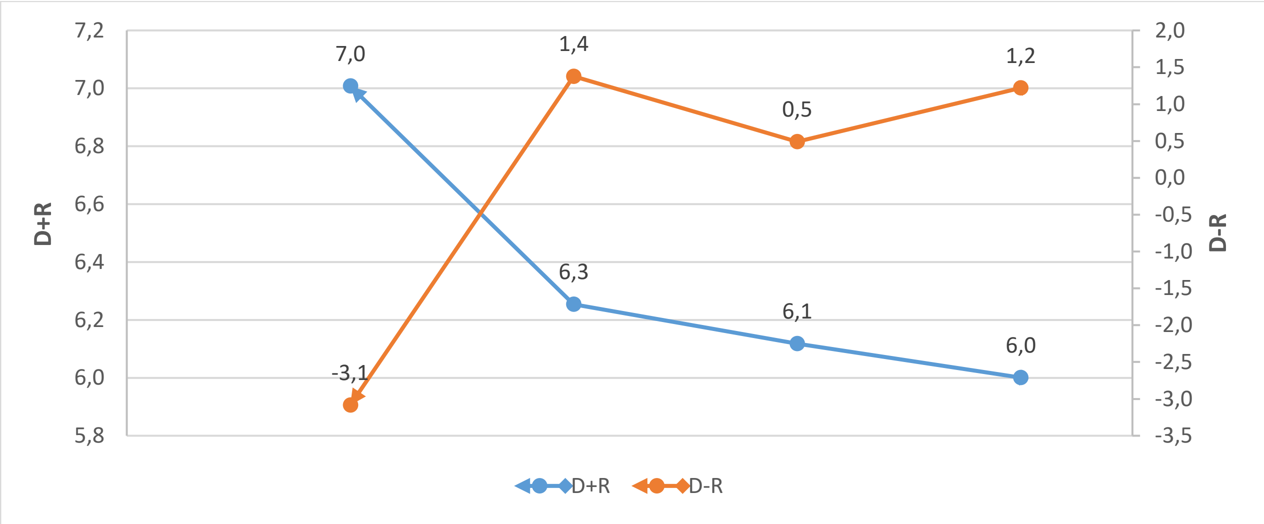


Fig. 4. Cause-Effect Diagram.

The specifications of merchant ships must adhere to IMO regulations in order to conduct maritime trade. Otherwise, states cannot trade outside their own cabotage transport lanes. In addition to IMO regulations, it is necessary to comply with the laws of port and flag states. To ensure this compliance, the certifications of the classification societies are needed. Although there are approximately 52 classification societies in the world, there are 12 classification societies in a high standard level that can become IACS members. Currently, RF's membership is suspended due to the RF-Ukraine war. Since the 11 states can meet the standards expected by the port states, which are important in terms of trade in the world, shipowners generally want to be certified by the classification societies suitable for the regions they want to maritime trade. Therefore, it is not surprising that the criterion of compliance with the regulations came to the fore in the study. The indispensable condition is compliance with regulations. Since IMO has recently increased its targets for 2050 and beyond, it is gradually moving towards a standard that protects the environment and exposes zero emissions. For this purpose, technology is developing towards reducing emissions. Regardless of the level of technology, ships that have been managed by power only up to now cannot achieve the realization of the green transition and meet new standards without having an ontological energy management system. Without energy efficiency, it will not be possible to meet IMO's goals. Unless there is a holistic energy management in ships, environmental standards will not be reached with conventional ship management. Since performing all these processes depends on digitalization and optimization, the eigen vectors of the other three criteria, except for the criteria of compliance with the determined regulations, were very close to each other. Therefore, the distinction between the DEMATEL technique and the main criteria could be determined by the cause-effect relationship. The criterion of regulation compliance has a negative D-R value suggesting that the dependence power of the factor is higher than its driving power. It means the factor is strongly influenced by other factors in the system and has a relatively weaker driving influence. However, the criterion of regulation compliance has also a positive D+R value suggesting that the factor has a net positive influence on the system. It means the factor has a significant driving power and is also influenced to some extent by other factors in the system. Other criteria have positive D+R and positive D+R. It means the factors have significant driving power and is also influenced to some extent by other factors in the system. Positive ER, EE, and DAO criteria has a positive value as seen in the D-R column respectively, and they have more influence and higher priority over each other. These criteria are in the position of sender or influencer. RC with a negative value in the D-R column is more affected by other criteria. This criterion is named as a buyer because it has a lower priority. D+R values of each criterion show its relationship with other criteria. RC, ER and EE, and DAO criteria in the D+R column are associated with each other. However, this relationship decreases in RC, ER, EE, and DAO respectively. In D-R, on the other hand, ER, DAO, and EE affect other criteria, respectively. The RC criterion, which has a negative value in the D-R column, is affected by all other criteria. As can be seen, RC, which has the highest weight in the AHP method, is affected by all other criteria, although it is seen as the lowest in prioritization in the DEMATEL method, and since no criteria that they are not compatible with the regulations, in reality, will be approved by the classification societies, it is recommended to use the DEMATEL technique together with other decision support methods. Likewise, the use of the DEMATEL technique in terms of evaluating the effects of the criteria determined according to the priority degrees and weight coefficients in the AHP was considered to be beneficial in terms of reaching meaningful results and making more accurate decisions. Subsequently, four main criteria with the highest weight among the ten criteria were selected.

## Discussion and Conclusion

As a result of the study carried out within the scope of the Green Transformation of the Maritime Sector in terms of Maritime Transportation Management Engineering, a total of ten criteria were determined and four of them were determined as the main criteria. According to the results obtained from the AHP method, the main criteria are Regulation Compliance (RC), Emission Reduction (ER), Energy Efficiency (EE), and

Digitalisation & Optimisation (DAO), respectively. However, the cause-effect relationship between the DEMATEL technique and the criteria has been revealed since no other criteria can be approved and certified by the classification society without meeting the RC criterion. Since the RC criterion plays an indispensable role, its degree of importance is high. Other criteria are ER, EE, and DAO respectively in prioritization. In addition, the order of priority of the remaining criteria is Alternative Fuels (AF), Ballast Water Treatment (BWT), Renewable Energy Integration (REI), Noise and Vibration Reduction (NVR), Port Infrastructure (PI) and Waste Management (WM). In the green transition phase, universities, maritime chambers of commerce and affiliated maritime companies, flag state and international regulation agencies, classification societies, banks, financial institutions, and insurance companies should enter into strong cooperation within an ecosystem. In addition, each institution should form working groups on green transition jointly with its counterpart institution in the international arena. None of the individual efforts will be economical or productive. It is considered that those who will carry out holistic studies for the green transition can achieve more beneficial results if they take into account the sub-criteria in addition to the main criteria determined by this study. As a result, this study is based on the fact that the AHP method and DEMATEL technique can provide decision support in terms of determining and prioritizing the main criteria constituting the first step of green transformation, which is a long marathon, and determining their effects on each other. In terms of the research question mentioned as ***'Do the prioritized main criteria provide reliable decision-making support?'***, the study covered the gaps targeted satisfactorily.

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