

Article

Identification of Shipyard Priorities in a Multi-Criteria Decision-Making Environment through a Transdisciplinary Energy Management Framework: A Real Case Study for a Turkish Shipyard

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Abstract: Ship building, as an energy-intensive sector, produces significant amounts of air emissions, including greenhouse gases. Most research in greenhouse gas reductions from shipping concentrates on the reduction in emissions during the operational phase. However, as emissions during ship operation are reduced, the construction and dismantling phases of ships are becoming increasingly important in the assessment of the life-cycle impact of ships. In this study, priorities for a Turkish shipyard to become energy efficient were identified by means of a semi-structured questionnaire and an interview. This was undertaken using Fuzzy Multi-Criteria Decision-Making methods, including the Fuzzy Analytical Hierarchy Process and Fuzzy Order of Preference by Similarity to Ideal Solution, which are part of a proposed systematic and transdisciplinary Energy Management Framework and System. By applying Multi-Criteria Decision-Making methods, this framework supports the shipyard's decision makers to make rational and optimized decisions regarding energy sectors within their activities. Applying the framework has significant potential to help achieve good product quality while reducing costs and environmental impacts, and can thereby enhance the sustainability of shipping. Moreover, the framework can boost both business and socio-economic perspectives for the shipyard, and improve its reputation and competitiveness, in alignment with achieving the Nationally Determined Contributions of States under the Paris Agreement.

Keywords: air emissions; decision making; Energy Management Framework; energy policy; life cycle; shipbuilding; transdisciplinary; sustainable production; sustainable shipping



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1. Introduction

Shipping, by transferring commodities and passengers, accounts for the carriage of 80% of global trade by volume and 70% by value [1], and thus plays a crucial role in global trade and nations' economic growth. Although it is the most fuel-efficient means of transportation, it has negative externalities that impact the environment [2], such as marine litter, oil spillage, sewage, underwater noise pollution, and transportation of invasive species. One of the most important and challenging issues is air pollution, which consists of both greenhouse gas (GHG) emissions that cause global warming [3] and air pollutants, which have a direct effect on human health [4,5].

The life cycle of a ship consists of the design, construction, operation, and scrapping phases. The IMO, which regulates international shipping, seeks to control and reduce air emissions from shipping by adopting and enforcing stringent environmental regulations in the design and operational phases of ships. However, in addition to air emissions from ship operation, emissions are also generated from the production, maintenance, and scrapping of ships, which have received less attention in terms of controlling and reducing air emissions. If there is a real interest and willingness to reduce emissions from the

shipping industry, a holistic and broader vision must be taken into account and mitigation measures must be implemented throughout the life cycle of the ship.

A shipyard is an industrial production facility where certain inputs are used to design, develop, build, repair, or dismantle a ship. Shipbuilding involves many industrial processes, such as cutting, surface treatment, bending, welding, blasting, painting and coating, and fiberglass production [6]. A significant quantity of pollutants and waste is emitted during these processes, which can have a negative impact on both the environment and human health. Shipbuilding is an energy-intensive industry, producing significant amounts of carbon dioxide (4% of ships' life cycle emissions, i.e., more than the ports' contribution, which is about 2% [7] of ships' life cycle carbon dioxide emissions), and air pollutants such as carbon monoxide (29% of ships' life cycle emissions [8]), SO_x, and NO_x, which leave a footprint on the environment [9]. This provides an important first indication of the scale of greenhouse gas and air pollutant emissions from shipyards as part of the ship life cycle. However, emissions are likely to be sensitive to the types of ships on which work is carried out and to the working practices used. Moreover, as the shipping industry moves to carbon-free fuels, such as electricity, sail, and solar power, the share of shipyard activities in the life cycle of a ship is expected to be larger than the operational phase in the coming decades. As an example, a previous study showed that if a car ferry is powered by batteries using electricity from the Norwegian grid, the shipbuilding phase has a greater life-cycle climate impact than the operational phase [10]. This justifies more extensive research in this area. Despite the Hong Kong Convention on the safe recycling of ships [11], no comprehensive and effective energy efficiency provisions exist, either for the recycling phase or for the shipbuilding phases. However, consideration of appropriate measures in shipyards can help to minimize GHG emissions and the risks of air pollutants on people and the environment. In addition, it can promote resource savings and improve economic and social benefits.

With this in mind, this study focused the management of energy in the short, medium, and long term, in addition to the reduction in air emissions resulting from energy use in shipyards. To address these issues, the study aimed to provide a holistic, systematic, and transdisciplinary energy management framework (EnMF) to the shipyards' senior decision makers (DMs) as a focused group¹. The purpose was to help them make rational decisions and optimize their decisions in an uncertain environment to improve energy efficiency and reduce air emissions within their portfolio, which is not related to the operational phase of the ships, such as the ships' main engine. The proposed framework enhances the decision support system (DSS) within the context of the shipbuilding industry. In this study, we used the techniques of Fuzzy Order of Preference by Similarity to Ideal Solution (FTOPSIS) and Fuzzy Analytic Hierarchy Process (FAHP), which are applied extensively in different clusters [12] and are popular for creating frameworks in the energy sector [13]. The use of these methods helps managers to compare different options with regards to different criteria and rank them according to their preferences.

The framework serves as a micro-level niche for the shipbuilding industry and, due to its flexible and generic characteristics, it can be adapted and applied to other shipyards and other industries. To demonstrate the validity of the framework, a case study was conducted in a private Turkish shipyard. Adopting the framework proposed in this paper will promote the concept of green shipping in the context of the ship life cycle and support sustainable shipping for a sustainable planet. In addition, it has the potential to contribute to countries' NDCs under the Paris Agreement and the EU Green Deal by supporting zero-carbon footprint products and decarbonization in the maritime transport sector. The work should be of interest to shipyard owners and managers, offshore managers, international, regional, and local policy makers, and governments. In this context, Section 2 provides an overview of the EnMF and its elements, in addition to the specific characteristics of the shipyards included in the case study. The methodology and approach are described in Section 3, and Section 4 presents the results and recommendations for the application of the EnMF in the shipyard. Finally, conclusions are drawn in Section 5.

2. Literature Review

2.1. Why EnMF in Shipyards?

To improve energy efficiency and overcome barriers and gaps, all industrial companies need to have a long-term energy strategy and implement it through an energy management program [14,15]. It is becoming increasingly clear that only a holistic and integrated approach covering all sectors can improve energy efficiency and reduce air emissions from shipbuilding. In addition, to achieve a reduction in CO₂ emissions from the shipping industry, the life-cycle perspective to reduce air emissions must be taken into account [9].

The EnMF determines the procedures required in a long-term strategy regarding energy production, consumption, and conservation within shipyards, whereas the Energy Management System (EnMS) contains measures and tools that may be used for implementing the procedures to achieve the goals of the strategy [16]. The framework provides shipyard managers with an opportunity to make satisfactory and straightforward decisions in complicated situations. However, to support the EnMF in shipyards, the related EnMS must be appropriately adopted by the shipyard organizations. The framework, by considering a holistic and the transdisciplinary approach, strives to break the silos and provide depth (extent of knowledge), breadth (number of knowledge criteria), and synthesis (integration of various knowledge perspectives to a developed and uniform type of knowledge and experience) [17] to optimize the performance of the DSS.

Employing the framework leads to mitigation of industrial air pollutants and GHG emissions from shipyards. In addition, by considering the life-cycle analysis of the procedures within shipyards, the framework supports a zero-emission industry, green products, and mitigation of emissions throughout the life cycle of ships to support the aim of the European Green Deal to be a climate-neutral continent by 2050 [18]. To reach this ambitious goal, the development, implementation, and compliance with EnMF within shipyards can be part of an industrial policy. This is also in agreement with recent developments in policy, such as the EU Green Deal regarding decarbonization of transportation. Additionally, applying the EnMS leads to the improvement of energy efficiency and air quality, and the reduction in emissions within the shipyards, which makes it a cost-effective measure concerning the Emission Trading System (ETS). Furthermore, shifting to green technologies and using renewable sources of energy to provide the necessary power to shipyards is a sustainable investment that fosters job creation, promotes innovation, and supports the EU's innovative companies, while assisting in the transition process and the exports of the EU Green Deal.

Because there is no "one-size-fits-all" approach to improving energy efficiency [19], the framework can be adapted based on the shipyards' portfolio and DMS' priorities. In addition, trade-offs can be made between issues to tailor the framework to any other size and type of shipyard. The final EnMF and EnMS for each shipyard can be designed and developed by comparing the present case and alternatives concerning the defined criteria.

Designing, developing, and implementing such a holistic framework will raise the awareness of policymakers to adopt policies by considering energy management to enhance energy efficiency potential [20] and create a movement to meet the zero-emission goal in the life cycle of ships. The development and implementation of the framework not only promotes the yard's position in terms of economic competitiveness in the market and improves the economic benefits both from a business (reduced energy costs and improved industrial capacity in ETS) and a socio-economic (external costs) perspective, but also creates a potential for capacity building so that yards can train staff in other interested shipyards and even in other sectors of the industry.

2.2. Concept of EnMF

Figure 1, prepared by the authors, shows EnMF and EnMS and their specific components. The EnMF comprises five disciplines, and promotes the development of the green ship concept from a life-cycle perspective [9]. A systematic approach was used to design the framework. This means that to solve the problem, we examined energy from other

stakeholders’ perspectives and replaced single-dimension thinking with multi-dimensional thinking [21]. Because energy is categorized in the socio-technical system [22], it is essential to consider a technological solution within the related surrounding and social context. Accordingly, the framework is based on five complementary pillars of the human factors of technology and innovation, operation, policy and regulation, and economics, each of which contains various measures and tools to support and promote the EnMF. Additionally, the EnMF is a transdisciplinary framework, and a variety of perspectives, methods, and models can be used to synthesize the improvement of energy efficiency in shipyards. Although each pillar has its own tools and measures, the pillars are interlinked, intertwined, and interact with each other, and some measures may even be common in different criteria. The detailed measurements and tools of each discipline are shown in Table 1 and Figure 1.

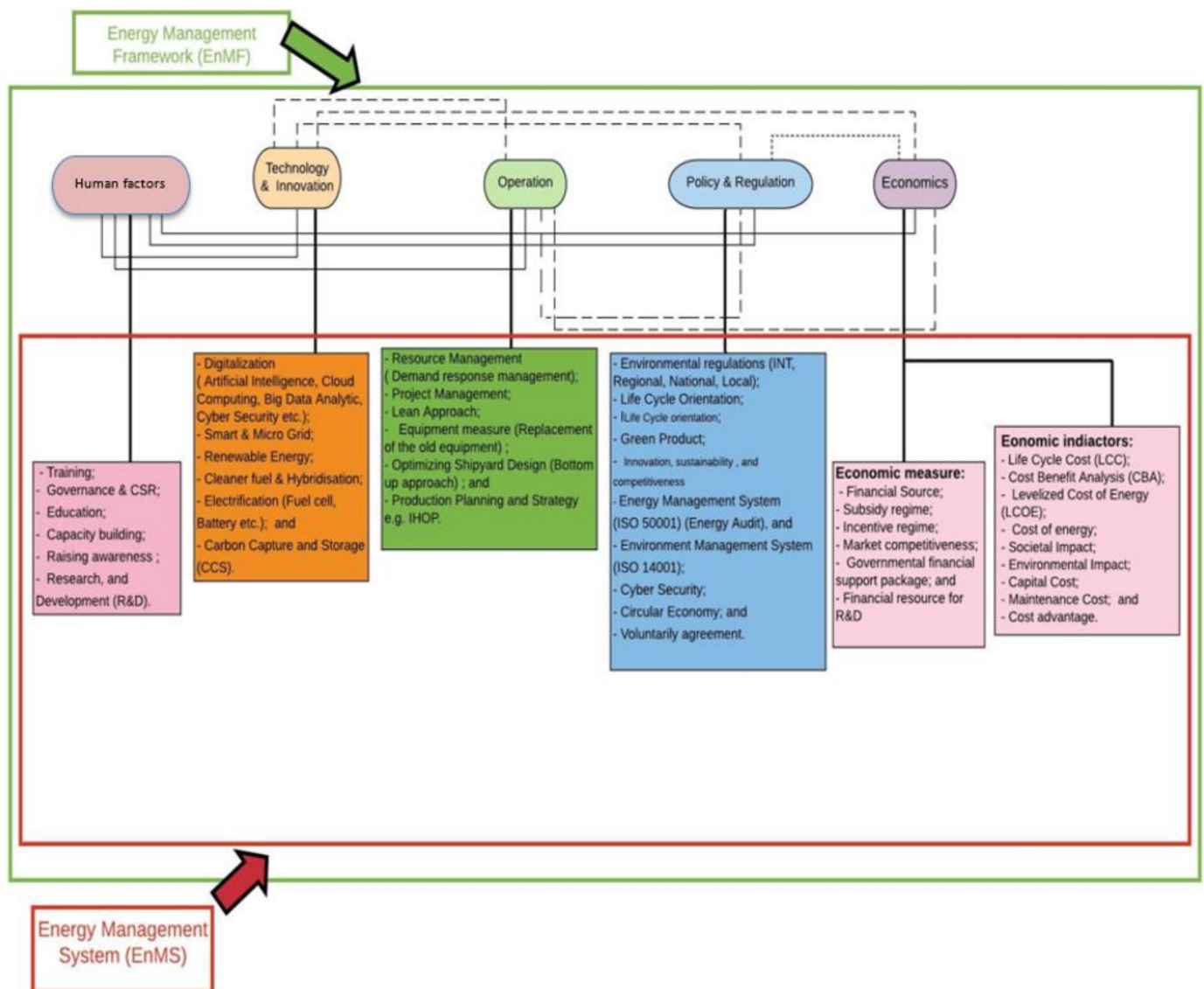


Figure 1. EnMF and EnMS in shipyards.

Table 1. Disciplines and related measures and tools. References [23–65].

Disciplines	Measures and Tools	References
Human factors	Training	[23,24]
	Governance & Corporate Social Responsibility (CSR)	[25]
	Access to skill worker	[26]
	Capacity building	[27]
	Awareness raising	[28]
	Research and Development (R&D)	[29]
Technology and innovation	Smart & micro grid	[30]
	Digitalization (4th Industrial revolution)	[31,32]
	Renewable energy	[33,34]
	Electrification (Battery, Fuel cell)	[35]
	Carbon Capture and Storage (CCS).	[36]
	Cleaner fuel & hybridization (Natural gas, H2, methanol etc.)	[37]
	Changing the old equipment	[38]
Digital twin	[39]	
Operation	Resource management (Demand response management)	[40]
	Lean approach	[41–43]
	Production planning and strategy	[44]
	Optimizing shipyard design	[45]
Policy and regulations	Environmental regulations (international, regional, national, and local)	[46]
	Life cycle orientation	[47]
	Green policy	[48]
	Innovation, sustainability, and competitiveness	[49]
	Energy Management System (ISO 50001)	[50,51]
	Environment Management System (ISO 14001)	[52]
	Cyber security	[53]
	Circular economy	[54]
	Voluntarily agreement.	[55]
	Sustainable policy	[56]
Stakeholder policy	[57]	
Economics	Financial resource	[56]
	Market competitiveness	[58]
	Incentives regime	[59]
	Subsidy regime	[60]
	Governmental financial support package	[61]
	Financial resource for R&D	[62]
	Capital cost	[63]
	Wages of skilled labor	[64]
Pooled funds	[65]	

PDCA Cycle within the Framework

Shipbuilding is an energy-intensive industry² [58,66,67], and it is therefore important that energy savings are considered in the context of strategic management in order to continuously optimize energy consumption. However, in order to optimize energy consumption, the framework must be kept up to date and the PDCA (Plan-Do-Check-Act) function must be taken into account within the framework. By applying the PDCA cycle, the framework is continuously updated on the basis of feedback and implementation results. Managers can therefore set new benchmarks and requirements to ensure continuous improvement [68]. Figure 2 illustrates the sequences of the PDCA cycle that make the framework a living document. These characteristics of the framework lead to continuous improvement and adaptation.

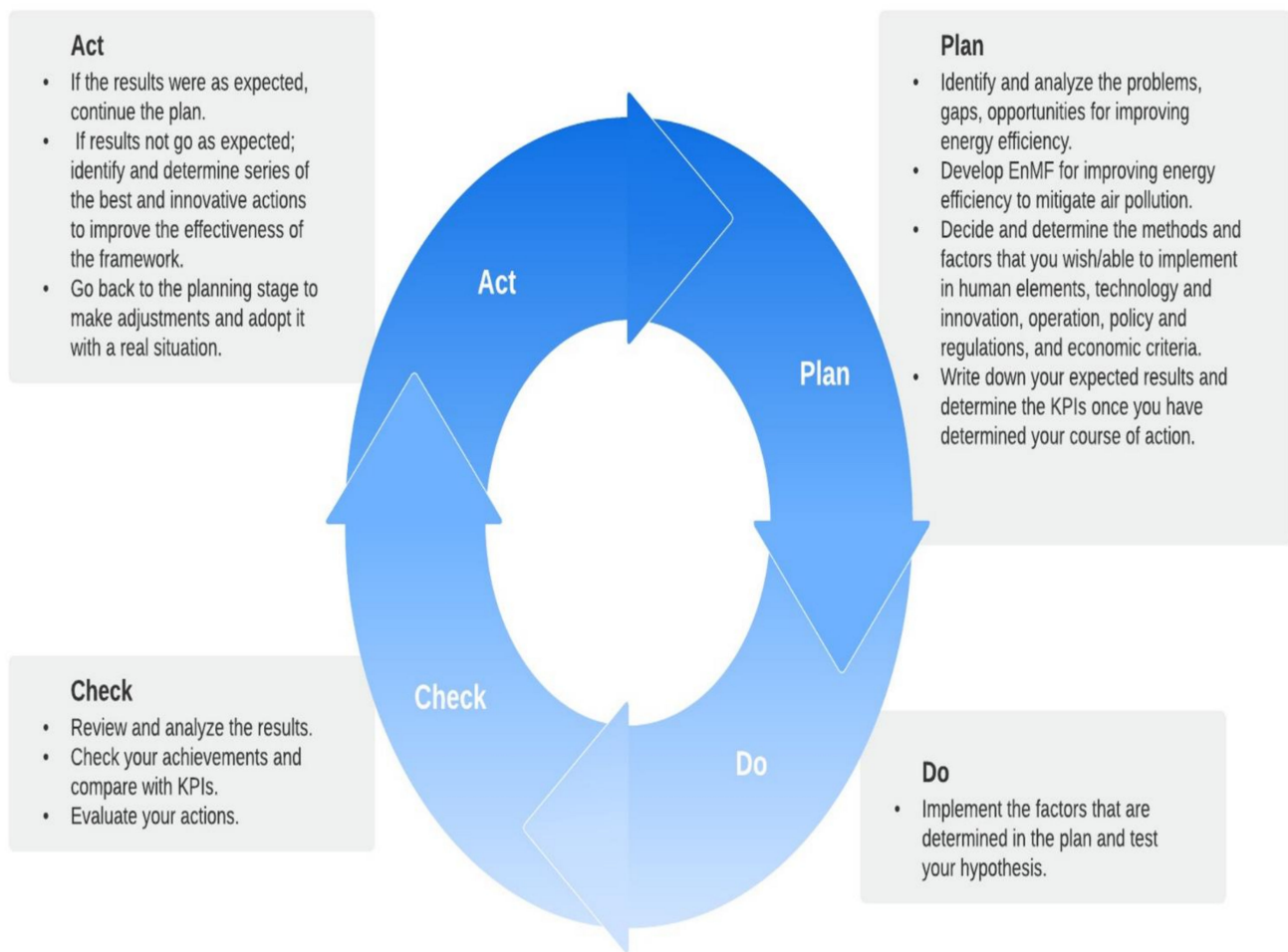


Figure 2. Plan, Do, Check, and Act (PDCA) cycle.

2.3. Case Study

2.3.1. Turkey's Concept in Shipbuilding

Shipbuilding has a long history and background in Turkey. Turkey holds a strong position in a variety of manufacturing sectors, such as clothing, motor vehicles, steel, and shipbuilding. In 2019, the shipbuilding sector contributed 0.6% of total Turkish exports, which was equivalent to USD 1.02 billion [69]. Turkey has a modern shipbuilding industry, which is quality certified and has export capacity. The shipyards in Turkey can build different types of offshore and ocean-going ships, specialized types of vessels, yachts, mega-yachts, and sailing boats, in addition to carrying out extensive repair and conversion works [70]. According to the Clarkson Shipping Intelligence Network (2021) [71], Turkey is regularly placed in the top ten countries based on its deadweight (dwt) production, and in the top five countries by the number of ships. The country's order book amounted to 141 vessels with around 494 k.CGT as at August 2021.

2.3.2. The Studied Shipyard

For the reason of confidentiality, the authors are not able to share the name of studied shipyard. To identify the size of the shipyard, the European Union (EU) definition was taken into consideration. Shipyards with more than 250 employees are categorized as big shipyards. Based on the EU definition, the studied shipyard was categorized as a private big size shipyard. The shipyard extended its operation into the three categories of ship repair and conversion; shipbuilding; and offshore and oil gas projects and infrastructure. The shipyard is highly active in building the required infrastructure for offshore projects and sub-sea activities. Additionally, the shipyard builds the specialized type of offshore

vessels, such as jack-up barges, pipe/cable laying vessels, DP vessels, PSV, and FPSO. The shipyard has the vision to be the best in class and the preferred partner on a global basis for demanding projects in the steel fabrication industry, marine and offshore vessel building, marine conversion projects, and marine vessel repair and maintenance. Additionally, the shipyard has been awarded ISO 9001 (quality management systems), ISO 14001 (Environmental Management), and ISO 45001 (Occupational Health and Safety Management Systems) certificates.

3. Research Methodology

As shown in Figure 3, the research consisted of a three-step process:

- First, a systematic literature review was conducted to identify EnMF alternatives and designs in all five main disciplines, i.e., human factors, technology and innovation, policy and regulation, operations, and economics.
- In the second stage, a semi-structured questionnaire was designed to identify the priorities of the shipyards. Based on the identified alternatives, the questionnaire was designed and the interview was conducted with the shipyard’s highest manager.
- The third step was the analysis of the interview and the questionnaire to identify the priority of the yard’s DMs, the ranking of the options within each discipline, and an overall final ranking.

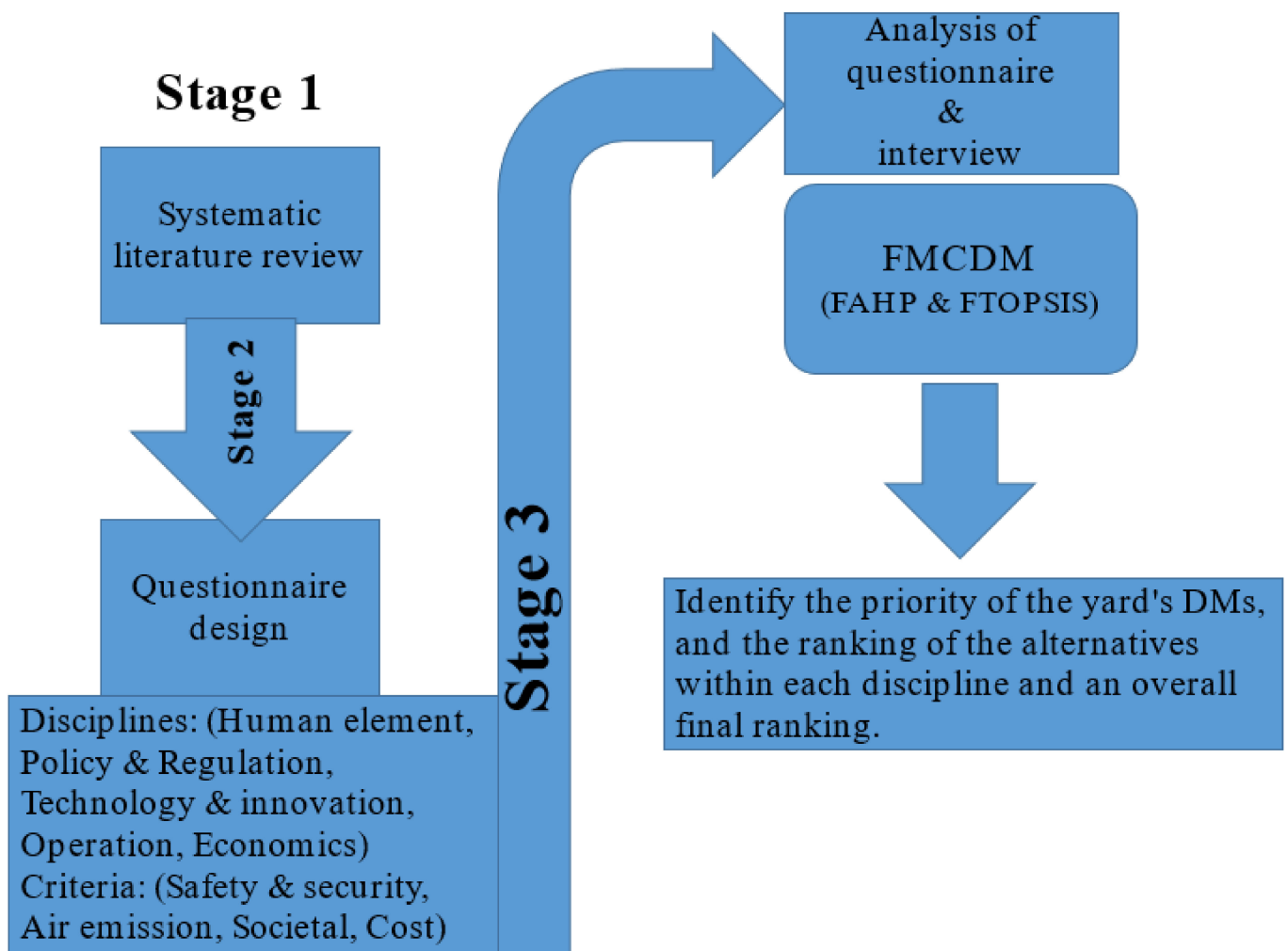


Figure 3. The structure and flow of analysis of the study.

During the interview and the study, the authors discovered that the topic is not concrete and that there are ambiguities and an uncertain environment in the shipyard. In an uncertain environment, characterized by a lack of information and inconsistency, DMs generally fail to make appropriate decisions and define their preferences. MCDM can help DMs to understand problems and choose the best option in an ambiguous environment among different alternatives by considering and evaluating different attributes. The FAHP method is one of the techniques used to deal with ambiguous information, which can affect DMs' preferences for different variables [72,73]. FTOPSIS is another MCDM method that is used for ranking of alternatives. By identifying the problems and applying their priorities for each attribute, DMs can evaluate the alternatives, identify preferences, and finally rank and choose the best alternatives among the others. MCDM methods are very popular for solving energy supply problems because these problems involve multiple and often conflicting criteria [13]. As an example, 41% of the studies of renewable energy investment decision making used one, or a combination, of AHP (analytical hierarchy process), multiple criteria, TOPSIS, and fuzzy methods [74].

Taking the above into consideration, given the nature of the study, transdisciplinary and MCDM methods were chosen to analyze the questionnaire. In the first step (of the third stage), the FAHP method was used to determine the weights of the main disciplines (human factors, technology and innovation, policy and regulation, operations, and economics) and the weights of the criteria (cost, safety and security, air emissions, and social issues) based on the DM's priorities. In the second step (of the third stage), the interviewee was asked about his preferences regarding the choice of the proposed alternatives within each discipline (in a linguistic format). Fuzzy Multiple Criteria Decision Making (FMCDM) [75,76], which employs FTOPSIS, was used to rank the alternatives within each discipline. Finally, the top three options from each main discipline were selected and, by applying the assigned weight for the main disciplines, the top options were ranked based on the yard's priorities in the case study.

3.1. Systematic Literature Review

In this study, a systematic literature review was conducted on energy management in shipyards. Due to the limited literature review on energy management in shipyards, the authors aimed to transfer and tailor knowledge and experience from other industrial sectors into shipyards. Based on the literature review, the most important and related options, whose potential to improve energy efficiency and reduce air emissions has been proven, were identified for each discipline.

The literature was identified by searching for keywords in the following databases: Scopus, Science Direct, Google Scholar, Research Gate, and EBSCO. The following specific keywords and combinations thereof were used: "GHG emissions", "air pollution", "air emissions", "energy management", "energy intensive industry", "energy efficiency", "shipping", "shipbuilding", "ship repair", "green shipyard", "port", "green production", "life cycle assessment", "MCDM", "interdisciplinary", "transdisciplinary", "sustainable shipping", "alternative energy", "renewable energy", "environmental protection", "decision making", "socio-technology", "human factors", "economics" and "policy and legislation".

In this research, a total of 663 articles were obtained without duplicates. After the initial screening of titles, conclusions, abstracts, and keywords, 522 articles were excluded because they did not address, or help to improve, energy management in shipbuilding. In the second round, 141 papers were fully analyzed. In addition, 16 papers were included by backward snowball analysis. Thirty-three papers were excluded because they did not contribute explicitly to the development of energy management in the shipbuilding industry. A total of 124 documents were obtained and 89 of these (period 2004–2021) were used for the article.

3.2. Design and Conduct the Semi-Structured Questionnaire/Interview

Based on the literature review and the identified alternatives, the questionnaire's sections were designed and developed. The questionnaire consisted of eight sections and was designed in a semi-structured format. The questions consisted of a combination of qualitative and quantitative measures, allowing respondents to provide both in-depth responses, in addition to numerical evaluations of the various aspects of their awareness and the use of the alternatives. Because the questionnaire was designed in a semi-structured format, it provided the interviewee with the opportunities to explain more about his concerns and actions regarding the topic [77,78].

To validate the framework, an interview was conducted with one of the top managers and key decision makers for the Turkish yard. The interviewee was asked to reflect on his ideas, experiences, and activities, and more generally on how the yard perceives and acts in terms of energy management. Although there were only three key DMs in the shipyard, the interview was conducted with the manager who had the highest weight in the final decision-making process, because the other managers were busy and unwilling to participate in the interview. The authors note that this may affect the accuracy of the results and that if the priorities of all DMs were taken into account, the results may have been more accurate.

3.3. A Transdisciplinary Approach to Analysis of the Questionnaire/Interviews

The EnMF is a multi-sectoral framework consisting of the contribution of different agents based on fuzzy logic. The framework helps the DMs to make better and well-justified decisions when confronted with a complicated situation [79]. To structure a process and generate a strategic plan with the participation of all of those involved, and to optimize the decisions made for a complex problem, a transdisciplinary approach aligned with optimizing decision methods must be considered and developed [14].

The third part of the study was the analysis of the questionnaire and interview. This included transdisciplinary and MCDM approaches to identify the priorities for the DM³ in each discipline and to identify the interlinked alternatives. In sections one and two of the questionnaire, using the FAHP method, the weights of the main disciplines and the criteria were assigned based on the DM priorities. From sections three to seven, the preferences of the DM in choosing the proposed alternatives in each discipline concerning the introduced criteria were questioned in the linguistic format. The data were analyzed and, by applying the FTOPSIS within the FMCDM [75] (combination 2, please see Figure 4), the alternatives in each main discipline were ranked. The reason for using combination 2 was that only one DM's preferences were covered in this study. By increasing the number of DMs, combination 4 can be applied. Moreover, the framework has flexible properties and depending on the type of data (crisp or linguistic) and the number of DMs, any combinations (1–5) in Figure 4 can be applied in the framework. In the final stage (section eight), by choosing the top three best alternatives from each main discipline and applying the assigned weight for the main disciplines and the FTOPSIS method, the top alternatives were based on the interviewee's determined priorities.

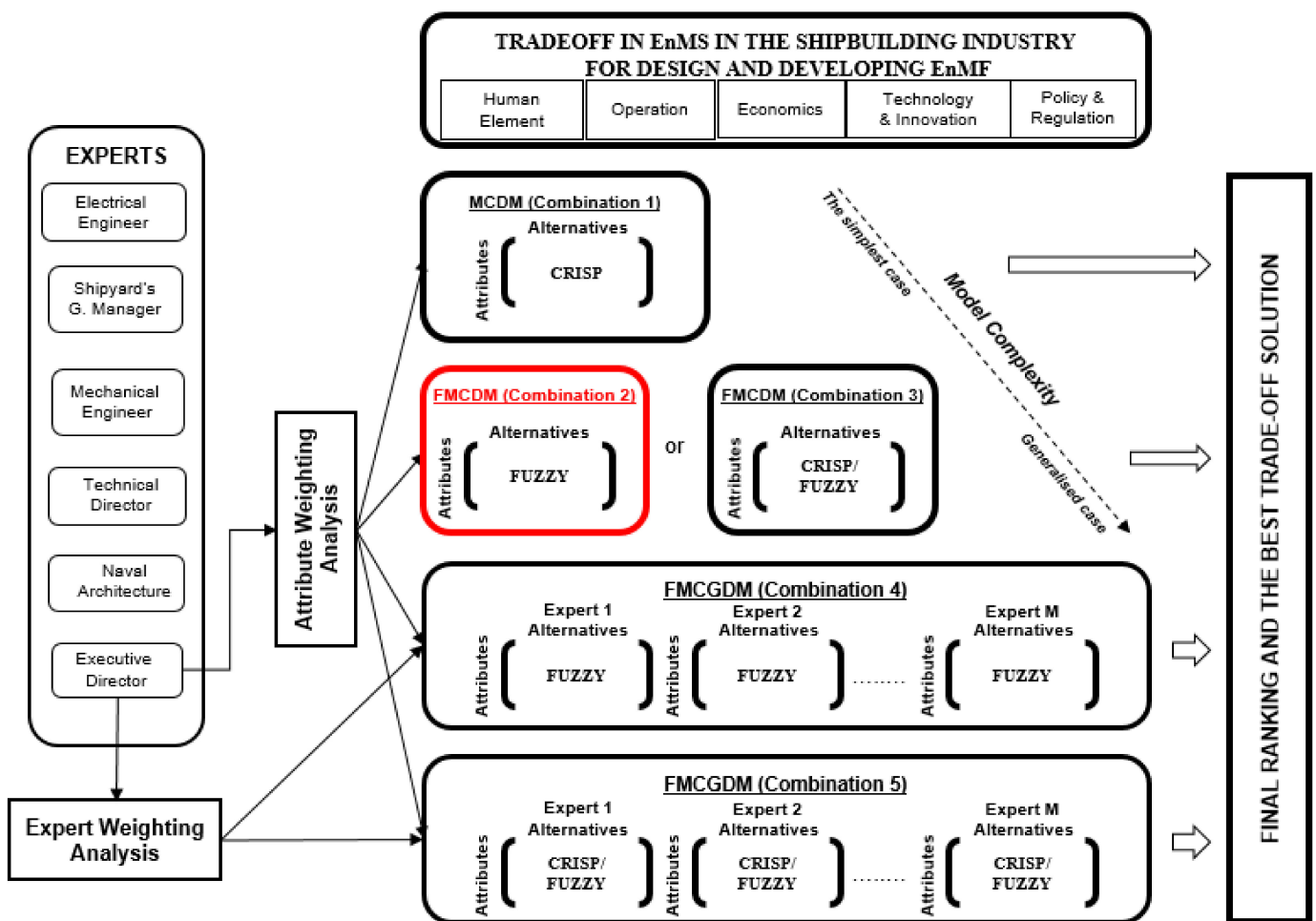


Figure 4. Generalized decision-making framework for evaluating trade-off solutions. Source: Adapted from [76].

3.3.1. Fuzzy Analytical Hierarchy Process (FAHP)

As described in Section 3.3, the FAHP method was used to determine the weighting of attributes for the main disciplines and criteria. AHP is a tool that can be used to analyze different types of issues in different disciplines, such as social, political, economic, and technological problems [75], in addition for both qualitative and quantitative analysis, and can transfer information (derived from experience) to decision making [80]. Some literature argues that the traditional AHP method still cannot accurately reflect the human mind-set [81] and express the DM’s opinion in a comparison of alternatives [82], and that it uses an unbalanced scale for judgments and cannot overcome uncertainty and the imprecise pairwise comparisons process [83]. To address all these limitations, the FAHP method was developed. The FAHP method gives the DM more confidence to provide interval assessments instead of fixed value assessments [84].

Triangular fuzzy numbers (TFN) are represented by three numbers $A = (a, b, c)$; where a , b , and c are the lowest potential value, higher potential value, and the highest potential value of fuzzy number \tilde{n} respectively. A as a triangular fuzzy number, where $a \leq b \leq c$, has the following function [85]:

$$\mu_n^{(X)} = \begin{cases} 0 & X < a \\ \frac{X-a}{b-a} & a \leq X \leq b \\ \frac{c-X}{c-b} & b \leq X \leq c \\ 0 & X > c \end{cases}$$

The arithmetic operations between two fuzzy numbers are as follows.
 Sum of a fuzzy number \oplus :

$$\tilde{n}A \oplus \tilde{n}B = (aA + aB, bA + bB, cA + cB) \tag{1}$$

Multiplication of a fuzzy number \otimes :

$$\tilde{n}A \otimes \tilde{n}B = (aA \times aB, bA \times bB, cA \times cB) \tag{2}$$

Division of a fuzzy number \oslash :

$$\tilde{n}A \oslash \tilde{n}B = (aA/aB, bA/bB, cA/cB) \tag{3}$$

Subtraction of a fuzzy number \ominus :

$$\tilde{n}A \ominus \tilde{n}B = (aA - aB, bA - bB, cA - cB) \tag{4}$$

Reciprocal of a fuzzy number:

$$\tilde{n}a^{-1} = (a, b, c)^{-1} = (1/c, 1/b, 1/a) \tag{5}$$

In this study, the geometric mean technique [86] was used for the analysis of the data to calculate the fuzzy weights.

$$\begin{aligned} \mathcal{F} &= (\tilde{n}i,1 \otimes \tilde{n}i,2 \otimes \dots \otimes \tilde{n}i,n)^{1/n} \\ &= \left((a_{i,1} \times a_{i,2} \times a_{i,3} \dots \times a_{i,n})^{1/n}, \right. \\ &\quad \left. (b_{i,1} \times b_{i,2} \times b_{i,3} \dots \times b_{i,n})^{1/n}, \right. \end{aligned} \tag{6}$$

$$\left. (c_{i,1} \times c_{i,2} \times c_{i,3} \dots \times c_{i,n})^{1/n} \right) \tag{7}$$

$$\omega_i = \frac{\mathcal{F}_i}{\mathcal{F}_1 \oplus \mathcal{F}_2 \oplus \dots \oplus \mathcal{F}_n}$$

where \mathcal{F}_i = geometric mean of the i th row, and ω_i = fuzzy weight of the i th event.

After determining the fuzzy weights for disciplines and criteria, the geometric mean method [87] was used to obtain the defuzzified (DF) mean of the weights:

$$DF \omega_i = \frac{[(ci - ai) + (bi - ai)]}{3 + ai} \tag{8}$$

$$\text{Then } W_i = \frac{DF \omega_i}{\sum DF \omega_i} \tag{9}$$

3.3.2. Fuzzy TOPSIS

Energy management at the shipyard is undertaken in a highly complex socio-economic environment. In order to make rational decisions about energy, it is important that all factors are considered. However, in a complex context, preference options may not be accurate and rational. Therefore, it is important that DMs are supported by the DSS. This support can be provided by designing and implementing conceptual frameworks for group decision making to help DMs make and optimize rational decisions [88].

In this study, the importance of the main disciplines and criteria was calculated using the FAHP method (see Section 3.3.1), and the FTOPSIS method was used to determine the distance between two triangular fuzzy numbers. The FTOPSIS approach is a suitable method for solving group decision-making problems [79]. To rank all alternatives, the method simultaneously determines the distances to both the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS) [89].

Assuming that each discipline has K options, the weight of each criterion and the rating of the options with respect to each criterion can be calculated as follows:

$$\bar{v}_{ij} = \frac{1}{K} \left[\bar{v}_{ij}^1 (+) \bar{v}_{ij}^2 (+) \dots (+) \bar{v}_{ij}^K \right] \tag{10}$$

$$\omega_j = \frac{1}{K} \left[\omega_j^1 (+) \omega_j^2 (+) \dots (+) \omega_j^K \right] \tag{11}$$

where \bar{v}_{ij}^K and ω_j^K are the rating and the importance weight of the Kth decision maker (the ω_j^K , the weight for the main disciplines and criteria, were achieved from Section 3.3.1 utilizing the FAHP method). Thus, a fuzzy multi-criteria group decision-making problem can be shown as follows:

Alternatives	Criteria (Attributes)				
	C1	C2	....	....	Cm
A1	\bar{v}_{11}	\bar{v}_{12}	....	....	\bar{v}_{1m}
A2	\bar{v}_{21}	\bar{v}_{22}	....	....	\bar{v}_{2m}
....
....
An	\bar{v}_{n1}	....	....	....	\bar{v}_{nm}
ω	ω_1	ω_2	....	....	ω_n

where \bar{v}_{ij} , \forall_{ij} and ω_j , $j = 1, 2, \dots, n$ are linguistic variables, which can be described by triangular fuzzy numbers, $\bar{v}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, and $\omega_j = (\omega_{j1}, \omega_{j2}, \omega_{j3})$. The linear scale transformation was used to convert the different criteria into a comparable scale. The normalized fuzzy decision matrix \hat{R} was therefore obtained by the following:

$$\hat{R} = \hat{r}_{ijm \times n}, \tag{12}$$

where B and C are the sets of benefit criteria and cost criteria, respectively, and

$$\hat{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right), j \in B;$$

$$\hat{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right), j \in C;$$

$$c_j^* = \text{Max } c_{ij} \text{ if } j \in B;$$

$$a_j^- = \text{Min } a_{ij} \text{ if } j \in C.$$

By taking into account the different importance of each criterion, the authors constructed the weighted normalized fuzzy decision matrix in the following manner:

$$\tilde{V} = [\tilde{v}_{ij}]_{m \times n}, i = 1, 2, \dots, m, j = 1, 2, \dots, n \tag{13}$$

where $\tilde{v}_{ij} = \hat{r}_{ij} (\cdot) \omega_j$.

The fuzzy positive ideal solution (FPIS, A^*) and fuzzy negative ideal solution (FNIS, A^-) are: $A^* = (\tilde{v}^*1, \tilde{v}^*2, \dots, \tilde{v}^*n)$, and $A^- = (\tilde{v}^-1, \tilde{v}^-2, \dots, \tilde{v}^-n)$, where, $\tilde{v}^*j = (1,1,1)$ and $\tilde{v}^-j = (0,0,0)$, $j = 1, 2, \dots, n$.

The distance of alternatives from FPIS and FNIS are calculated as follows:

$$d_i^* = \sum_{j=1}^n d(v_{ij}, v^*i) \quad i = 1, 2, \dots, m \tag{14}$$

$$d_i^- = \sum_{j=1}^n d(v_{ij}, v^-j) \quad i = 1, 2, \dots, m \tag{15}$$

The closeness coefficient of each alternative to determine the ranking order of alternatives is calculated by:

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-}, \quad i = 1, 2, \dots, m \tag{16}$$

In summary, we can determine the best option by taking into account its near coefficient number. The option that was closer to FPIS and further from FNIS was the option that had a CC_i close to 1. Figure 5 shows the hierarchical decision-making framework for selecting options to improve energy efficiency and reduce the footprint of air emissions at shipyards.

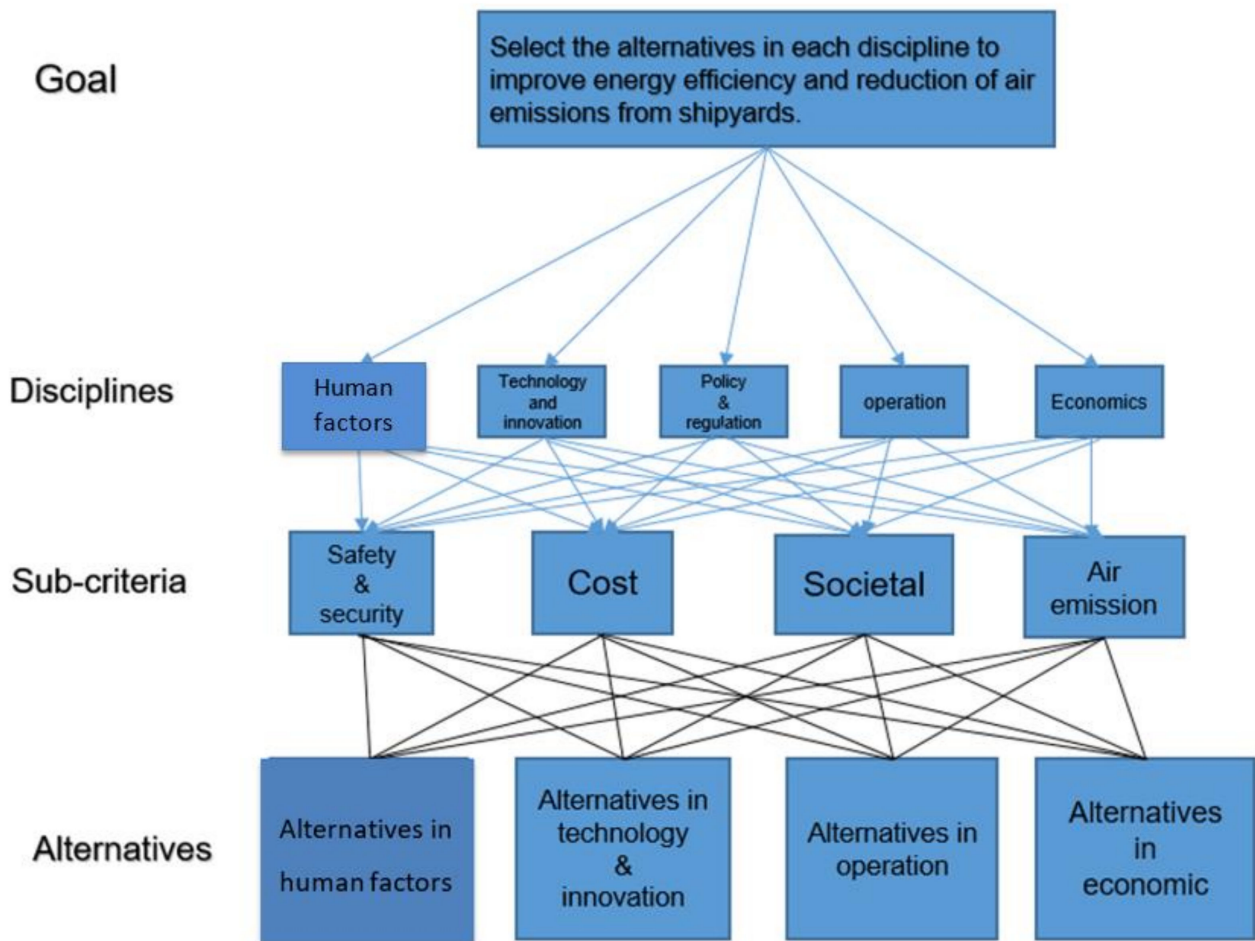


Figure 5. The hierarchical decision framework for selecting options to improve energy efficiency and reduce air emissions from shipyards.

4. Results and Recommendation

4.1. Results

Analysis of the questionnaire identified the priorities made by the DM when selecting alternatives within each discipline. The authors analyzed the questionnaire data by applying two methods of FMCDM, namely FAHP and FTOPSIS. The FAHP method was used to determine the weighting of attributes for disciplines and criteria. Equations (1)–(9) (Section 3.3.1) were used to calculate the attribute weights in Section 4.1.1. By applying the weight of each criterion (obtained in Section 4.1.1) and using the FTOPSIS method (Equations (10)–(15) in Section 3.3.2), the alternatives in each discipline were ranked, as shown in Sections 4.1.2–4.1.6 Finally, the top three options from each discipline were se-

lected and, after applying the attribute weight for each discipline and using the FTOPSIS method (Equations (10)–(15)), the top alternatives were ranked (see Section 4.1.7).

4.1.1. Attribute Weights in Disciplines and Criteria

In section one, the interviewee provided the linguistic phrases identifying the relative importance among the disciplines. Table 2 shows the weights that contributed to the main criteria. For determining the weight of the disciplines, Equations (1)–(9) in Section 3.3.1 were used.

Table 2. The discipline weights.

Disciplines	Weights	Rank
Human factors	0.13	4
Technology and innovation	0.42	1
Operation	0.08	5
Policy and regulation	0.19	2
Economics	0.18	3

The results revealed that in the DM board of the shipyard, the technology and innovation criterion (0.42) had the highest importance, and policy and regulation (0.19) was ranked second. Economic (0.18) and human (0.13) factors, with a minor difference in the weights, were ranked third and fourth, respectively, and the operation criterion (0.08) had the least importance.

The authors also concluded that there was a significant imbalance between the importance of the disciplines. Technology and innovation was about two-fold more important than the second-most important discipline, policy and regulation (0.19). In addition, technology and innovation was about five-fold more important than the last ranked discipline, operations (0.08). Although the third-most important discipline (economics (0.18)) was very close to policy and regulation (0.19), the importance of the economics discipline was about two-fold higher than the fifth-most important discipline (operations 0.08).

As shown in Table 3, the weights for the criteria, i.e., cost, air emissions, safety and security, and social and environmental aspects, were determined on the basis of the DM’s preferences. In selecting options, the authors explained to the DM that when introducing a technology or measures to improve energy efficiency and reduce air emissions, four criteria must be considered: safety and security, cost, societal factors, and the potential of the technology to reduce air emissions. The DM was asked which criterion was the most important to him when choosing a technology or implementing a measure.

Table 3. The sub-criteria weights.

Sub Criteria	Weights	Rank
Cost	0.05	4
Air emission	0.10	3
Safety and security	0.50	1
Societal	0.35	2

Safety and security (0.50) was given the highest priority and the societal criterion (0.35) came second. Air emissions (0.10) and costs (0.05) came third and fourth, respectively. This means that if the DM wants to choose a measure and a tool to improve energy efficiency and reduce air emissions from shipyard operations, the safety aspects of the measures have the highest importance, the societal impacts are second, and, interestingly, the potential to reduce air emissions and the costs of technology and investments have the third and fourth priorities, respectively.

As with the importance of the main disciplines, there was a significant imbalance between the importance of the criteria. For example, the weight of the first option (safety

and security (0.50)) was ten-fold greater than the last priority (cost (0.05)). In addition, the weight of the social criterion (0.35) was 3.5-fold greater than the third priority (air emissions (0.10)). However, the difference between the weight of the last two options, i.e., air emissions and cost, was smaller than the difference between the other criteria. Additionally, air emissions were ranked third. This shows that the potential of the technology to reduce air pollution was third when choosing a technology. Because the threat to the safety and security of the yard can affect the yard's production and has a negative impact on the yard's business objectives, the director was more concerned about the impact of the technologies and measures on the safety and security of the personnel, which he placed first, and in third place he ranked their potential to reduce air emissions. This shows that the yard's managers were more focused on the core business than on environmental protection. This implies that the strategies set by the yard were more business strategies, and that energy and air emission reductions were not the main concern of the managers. Energy targets were at lower levels of the yard's strategy. The sensitivity analysis also shows that the weighting of the criteria has a significant impact on the ranking of the alternatives within each discipline, and that the weighting of the disciplines has a significant impact on the final ranking. If the weights are changed, the ranking of the priorities within the yard will change. For example, if the weight for operation is increased to 0.21 and the weight for technology and innovation is decreased to 0.29, the operation discipline will move from the least popular ranking to the second most popular. Although technology and innovation still remain in first place, the priorities of policy and regulation, economics, and human factors decrease to third, fourth, and fifth, respectively. In the final ranking, electrification (from the discipline of technology and innovation), is moved from the third highest priority to the sixth highest priority, and resource management is moved from the 12th highest priority to the third highest priority.

4.1.2. Top Alternatives in Human Factors Criterion

The human factors play a crucial role in promoting the efficiency and effectiveness [23] of any industry. The role of the human factors in decarbonization should not be underestimated. Any actions related to energy transitions depend on the human factor.

In section two of the interview, participants were asked about the importance of various alternatives in the discipline (see Table 4). The DM provided their priorities about alternatives within four sub-categories: cost, air emissions, safety and security, and societal factors, in a linguistic format. Table 4 shows that training (0.55) and capacity building (0.51) placed first and second, respectively. However, the three alternatives of CSR, R&D, and access to skilled workers (0.49) ranked in the third position, and awareness-raising (0.42) was recognized as the fourth highest priority. Staff training is an important part of a shipyard's commitment to improving energy efficiency and can have a significant impact [32]. Surprisingly, R&D to improve the energy sector was considered the third priority. This is due to the existence and availability of information from the equipment manufacturer. This convinced the DM to consider other priorities, such as ship design and improving the operational efficiency of ships in the R&D area, which is linked to the yard's core business perspective. In addition, it is highlighted that energy in the context of shipyard operations is not the most important issue for the DMs.

4.1.3. Ranking of Alternatives in the Technology and Innovation Criterion

Technology has a crucial role in achieving climate policy objectives [15]. In section three of the interview, various alternatives (see Table 5) were suggested in the technology and innovation criterion. Implementing industry 4.0 (I_4) technology promotes the yard's energy and general productivity, and reduces machine downtime through remote monitoring and prediction of required maintenance. In addition, automation leads to increasing productivity [31]. Using developed software, engineers can view 3D models that show how machines do their jobs, thus making shipbuilding faster and safer, and reducing the cost [32]. Micro grids enable shipyard DMs to have more energy sources

in their energy supply chain and to place greater reliance on RE energy sources [30]. In addition, alternative fuels such as methanol, hydrogen, and ammonia play an important role in the decarbonization of industries [37].

Table 4. Ranking of alternatives in human factor criteria.

Alternatives	Ci*	Rank
Training	0.55	1
Capacity building	0.51	2
Corporate Social Responsibility (CSR)	0.49	3
Raise awareness	0.42	6
R&D	0.49	3
Access to skilled workers	0.49	3

Table 5. Top alternatives in the technology and innovation criterion.

Alternatives	Ci*	Rank
Digitalization	0.37	5
Micro grid	0.39	4
Renewable energy	0.28	6
Carbon Capture and Storage (CCS)	0.28	6
Alternative fuel	0.63	1
Electrification	0.40	3
Changing the old EQP	0.63	1
Digital twin	0.41	2

As shown in Table 5, the top three priorities in this criterion were replacement of old equipment (0.63), alternative fuels (0.63), digital twin (0.41), and electrification (0.40). Micro grids (0.39) came in fourth place, followed by digitalization (0.37) as the fifth priority. The yard has a plan to use cleaner alternative fuels in its operations and will invest more in the necessary infrastructure and technology. Renewable energy (RE) and CCS (0.28) were ranked as the sixth highest priority. However, there is significant potential to use solar energy to provide energy for the yard’s buildings, such as offices and warehouses. The ranking of the alternatives showed that the trend for changing equipment is towards an advanced level of digitalization (digital twin) and electrification, and it is expected that the contribution of electricity to the final production cost (ships and offshore infrastructure) will soon increase. It is important to stress that the transition to digitalization had started in the shipyard and that it had not become a top priority (fifth priority) in the discipline. However, the yard had plans to move to an advanced level of digitization by introducing digital twinning technology in its concept.

4.1.4. Ranking of Alternatives in Operation Criterion

Shipbuilding is a complex project and consists of different, complicated processes. However, appropriate operations accelerate decarbonization, resource management prevents overhead costs and delays [44], and project management identifies project risks and promotes productivity in shipbuilding projects [42]. Additionally, an appropriate shipyard design facilitates operations and improves efficiency [45], and the implementation of the lean system accelerates the shipyard’s reduction in carbon emissions [42,43]. Managing the operational cost is one of the main challenges in shipyards. Appropriate planning can improve the efficiency and effectiveness of operations in shipyards and assists in the reduction in shipyards’ carbon footprint [43]. Moreover, promoting operational measures in shipyards leads to a reduction in labor costs and production time, which are the main elements in the improvement of shipyards’ productivity [41].

In section four of the interview, various alternatives, i.e., Resource Management (RMGM), the lean approach, optimizing the shipyard design, and the production planning strategy, were proposed in the operation criterion. The DM identified the yard’s priorities

from alternatives within four categories in a linguistic format, and the authors, by applying the FMCDM, analyzed the achieved data. As shown in Table 6, optimal shipyard design (0.88) had the highest priority for the DM in the shipyard, whereas RMGM (0.31), the production strategy plan (0.19), and the lean strategy (0.01) were ranked second, third, and fourth respectively.

Table 6. Ranking of alternatives in operation criterion.

Alternatives	Ci*	Rank
Resource Management (RMGM)	0.31	2
Lean approach	0.01	4
Optimizing the shipyard design	0.88	1
Production planning strategy	0.19	3

The DM stressed that in the new phase of the yard’s expansion, the shipyard insists on an appropriate yard design (the first ranked alternative), which is an important measure of the yard’s productivity [45]. Although the DM considered that they follow the concept of the lean methodology correctly in their operations, it is important to improve the RMGM and production planning strategy within the framework of their concept.

4.1.5. Ranking of Alternatives in Policy and Regulations Criterion

The IMO focuses on the operational phase of the ship’s life cycle, but reducing carbon emissions in the shipping industry requires a broader vision. In the transition to zero carbon development in shipbuilding, it is important to adopt and implement policies and regulations. The shipbuilding industry, in cooperation with other stakeholders, aims to minimize its negative environmental impact. However, the adoption and implementation of appropriate international and regional environmental policies and legislation is crucial to accelerate the reduction in carbon emissions in shipbuilding.

In the fifth section of the interview (the policy and regulation criterion), twelve options were proposed (see Table 7). The manager identified the yard’s priorities for the options within four criteria in a linguistic format, and the authors analyzed the data obtained using FMCDM methods.

Table 7. Ranking of alternatives in policy and regulation criterion.

Alternatives	Ci*	Rank
International regulation	0.49	3
Regional regulation	0.49	3
Local regulation	0.49	3
Life-cycle orientation	0.49	3
ISO 50001	0.37	6
Cyber security	0.51	2
ISO 14001	0.55	1
Circular economy	0.51	2
Voluntarily agreement	0.38	5
Green policy	0.44	4
Sustainable policy	0.51	2
Stakeholder policy	0.36	7

As shown in Table 7, ISO 14001 (0.55) was prioritized in the policy criterion. These results show that the framework is valid, because the yard has already implemented ISO 14001 to reduce its negative environmental impact. The interviewee vividly expressed that the implementation of ISO 14001 helps them to manage energy within their concept and they do not consider implementing ISO 50001 (the sixth highest priority (0.37)), because this would mean unnecessary additional costs for the shipyard.

Cyber security, the circular economy, and Sustainable Policy (0.51) were the second highest priorities. This proves the conceptual link between different disciplines and elements of the framework. The yard has already gone digital and has a plan to replace the remaining old equipment (the highest priority in the technology and innovation discipline) with modern and digital equipment, and to introduce digital twinning technologies (the second highest priority technology in the technology and innovation discipline) within its conceptual framework. Interestingly, the analysis showed that shipyard managers were rationally concerned about the vulnerability to cyber-attacks [53], and they listed cybersecurity policy as the second highest priority in the regulatory section. In addition, the analysis showed that the shipyard is committed to expanding the circular economy, as they have already implemented this policy at the shipyard.

The third highest priority was implementation of (international, regional, and local) regulations and life-cycle orientation (0.49). International, regional, and local regulations were equally important for the yard. Due to the location of the yard and its membership in the European Community Shipyard Association (ECSA), it must comply with European rules and regulations in addition to local regulations (Turkish government) [70]. In addition, in order to maintain and promote their position in the competitive market, the shipyard had a strategic plan to comply with all necessary regulations. In view of the above, the shipyard aimed to implement the life-cycle and environmental policy (0.44) (fourth highest priority) in its concept, in order to meet the EU Green Deal targets [18].

4.1.6. Ranking of Alternatives in Economics Criterion

Energy is categorized within the socio-technical system. This means that to manage energy within any sector the surroundings must be taken into consideration [15]. The economy plays a crucial role to solve the problems related to energy in the shipbuilding industry [63]. To meet the energy targets, the shipyard's DMs must consider both environmental and economic factors within their agenda. To boost the economic aspects and reduce the shipyard's negative environmental impacts, cost-effective energy efficiency and decarbonizing measures within the shipyards' energy supply chain system must be implemented [16]. As Table 8 shows, in section six of the interview, nine alternatives were presented. Surprisingly, the four alternatives of market competitiveness, wages of skilled labor, pooled funds, and financial resources (0.55) were placed as the top priorities. The second highest priority was financial support from the government (0.52). The interviewee pointed out that the yard prefers to receive government financial support directly. They believe that government financial support helps the yard to invest in energy efficiency improvements according to their priorities. It was stressed that the creation of common funds in cooperation with other shipyards not only supports the shipyards during periods of financial crises and recessions, but can also promote the shipyards' position in the competitive market. In view of the above, yards prefer government subsidies (0.47), such as tax subsidies and energy cost subsidies, to incentives (0.32—fourth highest priority). In addition, the interviewee pointed out that the high wages paid to skilled labor in Turkey is one of the main problems for the shipyard management.

Providing sources of finance and capital costs (0.47, third highest priority) was another priority for managers. This was the reason why the shipyard aimed to comply with (international, regional, and local) regulations such as life-cycle orientation and green policy [45,46] (third and fourth highest priorities in terms of regulation and policy). This places the shipyard in a better position in negotiations with banks to obtain financial support, with an appropriate risk to invest in energy efficiency measures [63].

Table 8. Ranking of alternatives economic criterion.

Alternatives	CI*	Rank
Financial source	0.47	3
Capital cost	0.47	3
Subsidy regime	0.47	3
Incentive regime	0.32	4
Market competitiveness	0.55	1
Wages of skilled labor	0.55	1
Pooled funds	0.55	1
Governmental financial support	0.52	2
Financial resource for R&D	0.55	1

4.1.7. Ranking of Best Alternatives

As a continuation of the analysis, the top three options from each primary discipline were selected. Due to the similarity of some options, C_i^* , more than three options from some disciplines were placed in the final ranking. The total number of alternatives selected was 21. The assigned weights were applied to the primary disciplines (see Table 2), and the top options were ranked accordingly using the FTOPSIS method to look at the linguistic responses of the DM in different parts of the interview. Equations (10)–(15) (Section 3.3.2) were used to analyze the data in this section.

Table 9 shows the ranking of the top options for EnMF. The main criteria have a significant impact on the ranking of the top options. Technological options, namely alternative fuels, replacement of old equipment (0.86), digital twinning (0.71), and electrification (0.69), were ranked as the highest options among the others. This is supported by the high importance of the technology discipline (0.42), which was 2.2-fold higher than the second highest priority (policy and legislation (0.19)).

Due to the close importance of policy and regulation (0.19) and economics (0.18), the options in these two disciplines were ranked very closely and their C_i^* were categorized in the channels 0.22 and 0.3. Due to the higher importance of the policy and regulation discipline (0.01 more than the economics discipline), its options, i.e., ISO 14001 (0.3), cyber security, the circular economy, and sustainable policy (0.29), were placed in fourth and fifth place, respectively. The fact that ISO 14001 was considered the third highest priority was due to the local regulation that enforced the implementation of ISO 14001 in the shipyard [70]. In addition, cybersecurity was ranked fifth in the final ranking because managers were concerned about the potential and consequences of cyber-attacks. The yard’s concern about the cyber-attack was due to the measures taken in the transition to digitalization. In addition, the yard extended and accelerated this development by introducing new and modern technologies such as the digital twin (second priority).

The economic options, such as wages for skilled workers, pooled funds, and financial resources for R&D, had similar C_i^* (0.25) and were ranked sixth. However, the government financial (0.22) option was ranked seventh. Shipyard managers preferred government financial support, and they believed that if they received such support they could invest more in R&D to improve energy efficiency in the shipyard. In addition, they were interested in creating joint funds in cooperation with other yards in the region. They believed that such an innovative approach may promote their position in the competitive market and support them during economic and financial crises. Another concern for the shipyard was the high wages paid to skilled workers in Turkey [69], which are higher in Turkey compared to some other competitor countries. The interviewee argued that timely payment of staff salaries during an economic recession, and particularly during the COVID-19 pandemic, is a major challenge for the shipyard managers.

Table 9. Highest ranked alternatives.

Disciplines	Alternatives	Ci*	Ranking
Human factors	Training	0.20	8
	Capacity building	0.19	10
	CSR	0.19	9
	R&D	0.19	9
	Access to skill worker	0.193	9
Technology and innovation	Alternative fuel	0.86	1
	Electrification	0.69	3
	Changing the old equipment	0.86	1
	Digital twin	0.71	2
Operation	Resource MGM	0.02	12
	Optimum system design	0.04	11
	Production planning strategy	0.18	13
Regulations and Policy	Cyber security	0.29	5
	Circular economy	0.29	5
	ISO 14001	0.30	4
	Sustainable policy	0.29	5
Economic	Market competitiveness	0.25	6
	Wages of skilled labor	0.25	6
	Pooled funds	0.25	6
	Governmental financial support	0.22	7
	Financial resource R & D	0.25	6

The human factor (0.13) was the fourth highest priority within the disciplines. The options within this discipline were ranked in the 0.19 and 0.2 channels. Education (0.20) was the most popular option among the others within the discipline and was ranked as the eighth highest priority overall. CSR, R&D, and access to skilled labor (0.19) was the ninth highest priority. The lowest ranked discipline (0.08) was operations, and consequently the proposed options were ranked as the 11th, 12th, and 13th highest priorities. The fact that the operation options were ranked as the last priority was due to the fact that they had the lowest weighting compared to the other main criteria.

4.2. Recommendations

According to the Paris Agreement, it is not only nations but also individuals and industries that are responsible for reducing GHG emissions, and shipyards are no exception. Therefore, governments need to take shipyard emissions into account in their national development plans. Meeting international, regional, national, and local regulatory requirements, maintaining and improving economic growth and welfare to support sustainable development, and improving efficiency and productivity are the main challenges in shipbuilding [40].

The managers of the shipyard had a core-business view. This means that the defined strategies of the shipyard were more aligned with business strategies, and energy and air emissions mitigation were not the main concerns of managers. The energy goals were present in the lower levels of the shipyard’s strategy. It is recommended to the managers that they consider energy in the higher levels of the shipyard’s strategy.

The shipyard does not have an energy plan or an energy strategy. It is recommended to the DMs that the shipyard designs, develops, and implements an EnMF [16]. Considering short-, medium-, and long-term energy strategies can promote the position of the EnMF within the shipyard’s portfolio [14].

The proposed framework is an innovative measure to promote the shipyard’s competitiveness in the market [16]. It was applied in the shipyard and based on the preferences of the shipyard DM, top alternatives to improve energy efficiency within the shipyard were identified. As seen in the studied shipyard, there was a lack of a uniform and holistic

approach for energy planning to provide required models, methods, measures, and instruments for DMs. Thus, it is recommended that the shipyard managers design and develop short-, medium-, and long-term energy strategies. Implementation of the proposed EnMF as a systematic, holistic, and transdisciplinary measure can cover all aspects of energy and mitigation of air emissions [15] in the shipyard. Additionally, the framework can boost both business and socio-economic perspectives for the shipyard and can result in a win–win outcome.

Developing, implementing, and monitoring such innovative measures can help in promoting the NDC of Turkey under the Paris Agreement and promote green and sustainable production (from design, production, and operation up to dismantling and recycling) in the maritime cluster [14]. It is crucial that DMs consider the dynamic aspects of the framework and monitor the progress of implementation, and act to promote and update the benchmark measures based on the portfolio, condition, and new technologies.

The analysis showed that there was a significant imbalance between the five disciplines. Technology and innovation was considered the most important discipline with a factor of 0.42, whereas the operation discipline received a factor of 0.08. The importance of these two disciplines varied by a factor of 5, indicating a strong imbalance between the disciplines. This imbalance may lead to a loss of opportunities to improve energy efficiency within the yard. It is recommended that the managers of the yard in question take a broader view of the energy criteria in their portfolio and make use of the various opportunities to improve energy efficiency and reduce air emissions.

Implementing ISO 14001 and the circular economy in the shipyard is a major step toward reducing the negative environmental impacts of the shipyard. However, it is suggested to the DMs that, for better energy management, the shipyard managers implement ISO 50001. Although the implementation of ISO 50001 may impose additional costs on the shipyard, due to its benefits such as reduction in energy cost and increase in energy productivity, the payback period is short [50,51]. Additionally, the implementation of ISO 50001 will also lead to a reduction in air emissions at the yards, providing a better and more standardized workplace for employees. The Port of Antwerp is a good example, at which the implementation of ISO 50001 was able to reduce internal CO₂ emissions by 10% (compared to the 2016 level) [90]. This will promote the CSR [25] of the shipyard and help place the yard in a better position in the competitive market for negotiation with other stakeholders, such as financial organizations and banks [63].

The challenge to maintain a high product quality and increase energy productivity can be reduced by improving energy efficiency [16]. It is recommended to the managers to replace old equipment and machinery with new and more efficient examples. However, this requires investment in energy-efficient technologies and the replacement of old equipment with modern and digitized equipment. As the shipyard has already started toward digitalization and has a plan for accelerating the transition, it is highly recommended to the shipyard's manager that, to reduce the shipyard's vulnerability against cyberattacks, cybersecurity measures be implemented in the shipyard. This needs investment in raising awareness, training of the personnel, and providing the required infrastructures and software [53].

Although the shipyard has other priorities in R&D and training departments, it is highly recommended to the managers that the energy aspects are considered within the agendas of both departments. Because the training of the personnel to improve energy efficiency may impose an additional cost burden to the shipyard, it can be conducted in various steps by considering the priorities of staff, such as top managers, who have essential impacts on the energy issues [15].

It is recommended to the managers that the shipyard harvests RE and increases the share of RE in the energy sector of the yard. Investment in RE assists the yard in the transition toward the EU's Green Deal goals, creates job opportunities, and supports innovation and EU's innovative companies [18]. Although using RE has not been considered within the top priorities of the shipyard, it is highly recommended to the managers to consider

harvesting solar and wind energy within the shipyard’s medium- and long-term energy policy. Because using alternative fuels was chosen as one of the best alternatives by the DM, in addition to increasing energy productivity and reducing negative environmental impacts, investments in RE can be used as the fundamental infrastructure for the long-term energy strategy of the shipyard to produce green hydrogen or methanol as alternative fuels. Additionally, through the development of an energy storage system in alignment with RE, smart and micro grids can be developed accordingly [30].

It is suggested to the shipyard managers to conduct a periodic energy audit and review of their energy strategy [14]. However, before investing in any energy-efficient projects, a feasibility study having consideration of various economic analyses must be conducted.

5. Conclusions

A holistic, systematic, and transdisciplinary approach is necessary to achieve zero emissions over the life cycle of the maritime industry. This study used a mixture of two different FMCDM techniques, i.e., FAHP and FTOPSIS, to identify the priorities of shipyard managers (DMs) in improving the energy efficiency in shipyards and reducing air emissions in the shipbuilding portfolio. This study proposed a transdisciplinary EnMF that enables shipyard managers to make rational decisions and optimize their decisions to improve energy efficiency in their context. The results of the framework can strengthen the DSS in the shipbuilding industry. By taking into account the ranking of alternatives, shipyard DMs can design, develop, and implement energy policies in the short, medium, and long term. However, DMs must use the PDCA cycle and the dynamic aspects of the framework, monitor progress in implementation, and act to promote and update the benchmark measures based on the portfolio, circumstances, and new technologies. This article is addressed to researchers, policy makers, and DMs concerned and/or involved in the shipbuilding industry. This paper can raise awareness among DMs in maritime clusters and promote a holistic, systematic, transdisciplinary, and life-cycle approach to reduce the air emissions of the shipping industry.

The framework was applied to a large private Turkish shipyard, which was used as a case study. To assess the yard’s priorities, 39 alternatives, whose potential to improve energy efficiency and reduce air emissions has been proven, were identified within five disciplines: human factors, operations, policy and regulation, technology and innovation, and economics. The alternatives were ranked according to the priorities and preferences of the yard’s top management. Table 10 shows the results of the implementation of the framework for the case of the shipyard.

Table 10. The results of the implementation of the framework for the case of the studied shipyard.

No	Results
1	The shipyard is focusing more on its core business and energy is not one of their top priorities.
2	The yard is not supported by any holistic, systematic, and transdisciplinary perspective to make rational and optimized decisions on its energy sectors.
3	“Technology and innovation” and “safety and security” were the most important disciplines and criteria respectively. It was found that there was a significant imbalance between the importance of the disciplines and the criteria. The ranking of the disciplines was as follows: technology and innovation (0.42), policy and regulation (0.19), economics (0.18), the human factors criterion (0.13) and operations (0.08). “Safety and security” criterion (0.50) and the “societal” criterion (0.35) were the highest ranked criteria, whereas there was a large gap between them, with air emissions (0.10) and costs (0.05) as the third and fourth criteria, respectively.
4	The trend for changing equipment is linked to advanced digitalization and electrification, and it is expected that the contribution of electricity to the final production cost will increase in future.
5	The managers of the shipyard prefer ISO 14001 rather than ISO 50001 for managing the energy within their portfolio.
6	After using the FAHP and FTOPSIS methods, the best alternatives in each discipline were identified. By selecting the three best options from each discipline and applying the weight of the disciplines, the selected alternatives were ranked. The weight of the disciplines had a significant impact on the final ranking.
7	The development, implementation, and monitoring of such innovative measures can also contribute to the promotion of Turkey’s NDC under the Paris Agreement for shipyards.

The authors would like to draw attention to the specific limitations that can be addressed in future studies:

- The sample of shipyards may be selected from several countries with different economic and geographical areas. The results may obviously differ in each case study.
- The types of alternatives in each discipline may vary from those proposed in the current study.
- Choosing different alternatives, disciplines, and criteria may change the ranking of alternatives.
- Although there were only three main DMs in the case study, the interview was conducted with only one decision maker with the highest weight. This may affect the accuracy of the results. If all DMs' priorities are taken into account, the results will be more accurate.
- Before investing in energy-efficiency projects, a feasibility study must be carried out, taking into account various economic analyses.

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Notes

- 1 Typically, there are no more than two or three decision makers involved in making strategic decisions in the energy management of a shipyard.
- 2 A study in India showed that the total energy required from fabrication to hull berths for 1 Ton net of ship steel work is 2.73 Gigajoules [59].
- 3 Depending on the type of data (explicit or linguistic) and the number of DMs, other MCDM techniques can be used. The number of respondents may also vary depending on many factors, such as ownership and the organizational form of the yard. There are usually no more than three decision makers involved in making strategic choices regarding the strengths of a yard.

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