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# Application of the transdisciplinary shipyard energy management framework by employing a fuzzy multiple attribute group decision making technique toward a sustainable shipyard: case study for a Bangladeshi shipyard

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**Abstract**

Shipbuilding is an energy-intensive industrial sector that produces a significant amount of waste, pollution and air emissions. However, the International Maritime Organization concentrates only on reducing emissions during the operational phase. In order to completely phase out emissions from the shipping industry, a life-cycle approach must be taken. The study implemented the proposed transdisciplinary energy management framework in a Bangladeshi shipyard. The framework aims to support shipyard decision makers in making rational and optimized decisions to make shipyards sustainable, while maintaining good product quality and reducing relative cost. This is achieved by applying the Fuzzy Analytical Hierarchy Process and Fuzzy Order of Preference by Similarity to Ideal Solution methods to identify optimal solutions. In addition to making shipyards more sustainable, the framework can enhance both the business and socio-economic prospects of the shipyard and promote the reputation of the shipyard and improve its competitiveness and, in line with this, lead to the promotion of nationally determined contributions under the Paris Agreement for States. The implementation of the framework shows that the political and legal discipline, the social criteria and the implementation of ISO 14001 and cyber security were the most important criteria and options for the yard's decision makers.

**Keywords:** Air emissions, Decarbonization, Energy efficiency, Energy policy, Life cycle, Ship building, Shipping management, Trans-disciplinary

## Introduction

Although maritime transport, which accounts for 80% of freight transport, plays a crucial role in world trade and the economic growth of states (Vakili et al. 2021a, b, c), it has negative externalities, such as greenhouse gas emissions that cause climate change (Ritchie and Roser 2020) and air pollution that has a direct effect on human health (Kampa and Castanas 2008).

Addressing climate change is the top priority for humanity in this century, and the International Maritime Organization's (IMO) first strategy to reduce total annual greenhouse gas emissions by at least 50% from 2008 levels by 2050 (Vakili et al. 2020a, b; IMO 2020) shows that shipping is a priority. As shown in Fig. 1, the IMO has considered multidisciplinary technical, operational and economic measures to remove the barriers to reducing $CO_2$ emissions. The measures are divided into technical [energy efficiency design index (EEDI) and energy efficiency existing ship index (EEXI)], operational [enhanced ship energy efficiency management plan (ESEEMP)] and economic disciplines that are likely to be adopted for medium-term action in the future (Vakili et al. 2021a). However, to overcome the barriers to carbon reduction in industry, a systematic approach needs to be considered, moving from a multidisciplinary approach to a trans-disciplinary approach (Vakili et al. 2021b). This implies that the researcher must break the silos between disciplines and foster interaction and linkages between different active actors in different disciplines and build bridges between researchers from different disciplines with experts in other disciplines to create coherent interests, goals and approaches (Vakili et al. 2022a, b, c, d). Design, construction, operation and scrapping are important steps in the life cycle of a typical ship (Vakili et al. 2021a). In addition to air emissions during ship operation, there are emissions from ship production, maintenance and scrapping. Ships are designed and built according to IMO regulations (Mountaneas et al. 2015), but less attention is paid to controlling and reducing ship emissions during the construction, maintenance and dismantling periods, and regulations, studies and measures are focused on the operational cycle of ships (Vakili et al. 2022a). However, in order to achieve a zero emission industry, a life-cycle perspective needs to be developed by policy makers and within the framework of industry concepts (Vakili et al. 2021b). Shipbuilding is an energy-intensive and polluting industry. It contributes to 29% of carbon monoxide emissions during the life cycle of ships and 4–8% of carbon dioxide emissions during the life

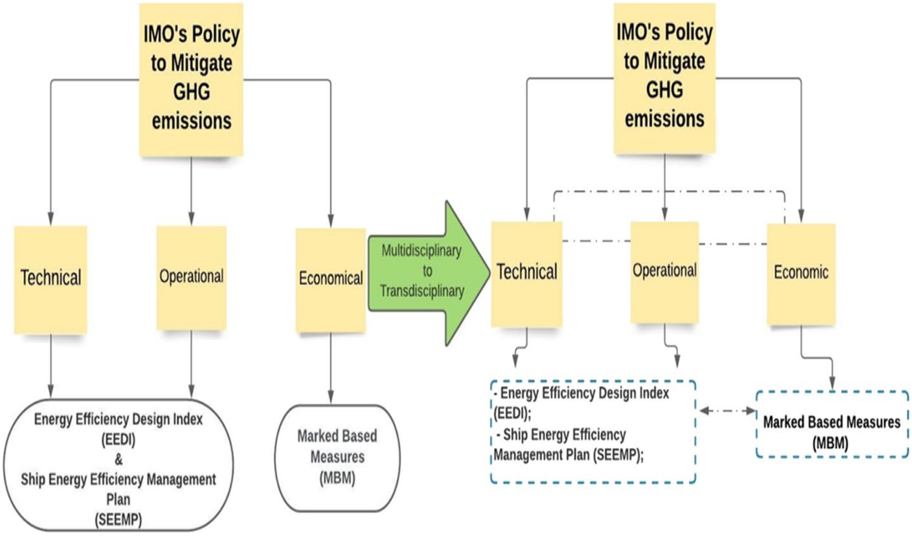

**Fig. 1** A transdisciplinary approach to mitigation of air emissions from shipping

cycle of ships (Vakili et al. 2022a, b, c, d). The latter is more than the contribution of ports to around 2–5% (Merk 2014) of ships' operational cycle $CO_2$ emissions.

The studies show that due to the transition of the operational phase of ships to the use of cleaner and carbon-free fuels, batteries and renewable energy, the contribution of the shipbuilding phase may even be greater than the operational phase (Vakili et al. 2022b), in some cases amounting to more than 50% of the cradle-to-grave carbon footprint (OSK Group 2022). As shown in Fig. 2 the maritime sector has measures such as EEDI, EEXI and ESEEMP to reduce GHG emissions in both the construction and operational phases of the ship life cycle. In addition, the Hong Kong Convention (Husan and Parisi 2020) focuses on the scrapping cycles, but the production phase is not covered by any international regulations (Vakili et al. 2021b).

Vakili et al. (2022a, b, c, d) classified shipyards into clean and green shipyards and conducted a strategic analysis from concept to case studies on shipbuilding towards zero emissions. The paper proves the environmental, economic and social benefits of the proposed framework through two case studies. In addition, Vakili et al. (2021a) developed a holistic, systematic and trans-disciplinary framework to identify shipbuilding priorities in a multi-criteria decision-making (MCDM) environment and Vakili et al. (2021b) developed a trans-disciplinary framework to overcome the barriers to energy efficiency in shipbuilding industry. The authors of the mentioned articles emphasized that in order to reduce the climate impact of shipyards and increase the sustainability of their context, a holistic, systematic and trans-disciplinary approach must be considered to identify the priorities of shipyard decision makers to improve energy efficiency and reduce air emissions based on the characteristics of the shipyard. The authors also recommend that further research through case studies of different types, sizes and geographical locations is crucial to validate the proposed framework and raise awareness among stakeholders and shipyard managers.

Considering the above, this study implements the framework proposed by Vakili et al. (2022a, b, c, d) in a Bangladeshi shipyard to design an energy management framework and an energy management system for the studied shipyard and aims to help the shipyard managers to manage the energy in the short, medium and long term and to reduce all types of air emissions from the energy sources in the studied shipyard based on the

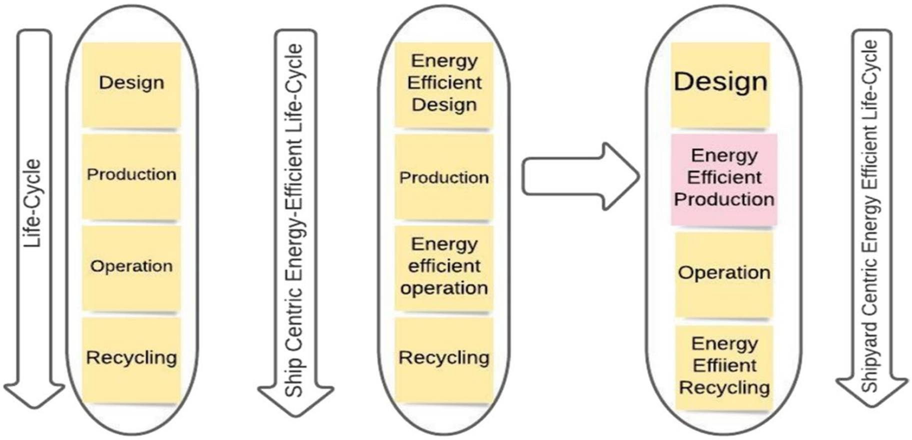

**Fig. 2** Stages of ship life cycle and energy management. *Source*: adapted from (Ölcer 2022)

priorities of the shipyard and help in moving towards a sustainable shipyard. By adopting and implementing the proposed framework, the shipyard can accelerate its transition to green technologies and achieve clean and emission-free production and promote sustainable shipping for a sustainable planet (Vakili et al. 2021b). In addition, the implementation of the framework can lead to the shipbuilding industry's emissions being considered within Bangladesh's Nationally Determined Contribution under the Paris Agreement, and as the proposed measures have been proven to reduce the impacts of climate change, it is expected to lead to economic, environmental and social benefits (Vakili et al. 2021a, 2022a, b, c, d).

This research should not only be of interest to shipyard owners and managers, international, regional and local policy makers and governments, but due to the generic aspects of the framework, it can also be tailored and applied to other shipyards of different geographical location, size and portfolio, as well as to other industries such as ports and shipping companies. In this context, "Concept of the proposed energy management framework" section presents the foundations and concepts of the proposed EnMF. In addition, the case study, i.e. Bangladeshi shipyard, is presented and the amount of material and energy and the contribution of different energy sources for one tonne of steel in building ship has been calculated in this section. The methodology and approach is described in "Research methodology" section, and "Results and recommendations" section presents the results and recommendations for the application of EnMF in the shipyard. Finally, conclusions are drawn in "Conclusions" section.

## Concept of the proposed energy management framework

### The concept of EnMF and its application

Energy is categorized in the sociotechnical system (Lachhab et al. 2017). This means that addressing energy issues must take into account not only the technology but also the related environment and social context. In order to improve energy consumption in shipyards, energy has been considered from the perspective of different stakeholders. This means that a systematic approach was considered to design the EnMF (Rossi et al. 2018) and that one-dimensional thinking was replaced by multidimensional thinking (Vakili et al. 2020a). In addition, the transdisciplinary principles were considered in the design of the framework to synthesize the energy efficiency improvement and air emissions reduction from different disciplines at shipyards (Vakili et al. 2022a, b, c, d).

Considering the above, the framework is formed by five complementary disciplines: human factor, technology and innovation, operations, policy and regulation, and economics. Each discipline can support and promote EnMF in different perspectives (see Fig. 3) (Vakili et al. 2021a, b, c) through the actions and tools embedded in each discipline. Although each discipline has its own tools and measures, the disciplines are interconnected, intertwined and interact with each other and some measures may even be common in different criteria (Vakili et al. 2022a). To help DMs in making rational decisions with complex criteria, multi-criteria decision making (MCDM) methods were proposed (Liesen et al. 2015; Strantzali and Aravossis 2016). The methods are helpful to rank and identify the best options to support decision support systems (DSS) and help decision makers to make more appropriate and optimized decisions in multi-criteria and fuzzy domains (Vakili et al. 2022a, b, c, d). Considering the Plan-Do-Check-Act

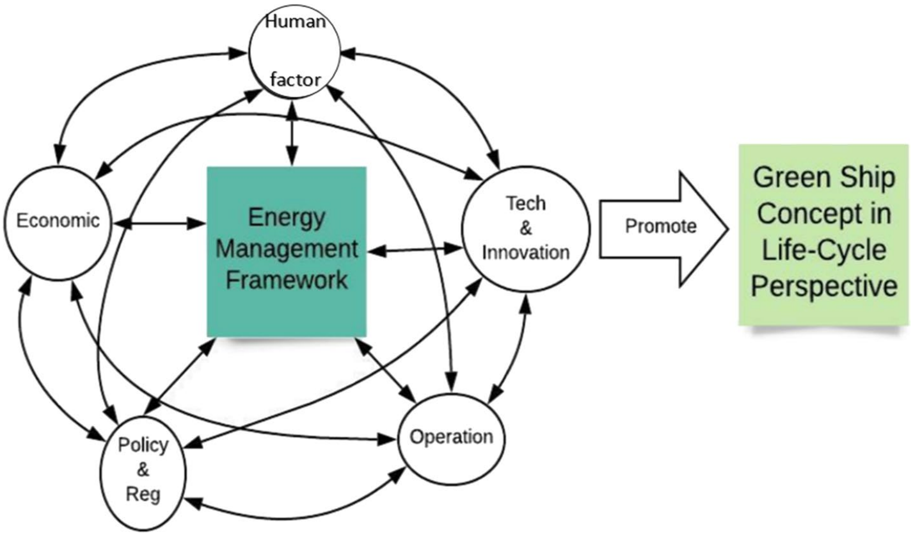

**Fig. 3** Energy management framework concept

(PDCA) cycle makes the framework a living document based on feedback and results of implementation. The feedback can help DMs to create and new benchmarks and highlights the actions required for further development (Oung 2016), leading to continuous improvement and adaptation of both EnMF and EnMS.

The proposed EnMF has been applied in various maritime industry sectors. Vakili et al. (2022a, b, c, d) explained in detail the concept of the study and provided initial results from the application of the framework to two different sizes and criterion-adapted shipyards. The framework was also adopted and used to identify the barriers to improving energy efficiency and reducing air emissions from a small Iranian shipyard. The study interviewed five of the yard's top managers who had the greatest influence on the final decision to invest in energy efficiency measures. The results showed that there was a significant imbalance between the importance of different disciplines and financial aspects and that limited access to capital was the main barrier for the studied shipyard, and that the lack of appropriate technology at the shipyard and investment risk were other important barriers for the shipyard in improving energy efficiency and reducing air emissions (Vakili et al. 2021b).

In another study, the proposed framework was also adopted for a large Turkish shipyard. The measures and tools for each discipline were studied and categorized. Due to the ownership of the shipyard (private sector), there were only three key directors on board who could make investment decisions on energy criteria. The results showed that the yard was more focused on its core business and that energy was not one of their priorities. Technology and innovation as well as safety and security were the most important disciplines for the shipyard and the shipyard was particularly attentive to replacing the old equipment with advanced digitalized technology and also electrification (Vakili et al. 2021a).

The implementation of the framework at a large Italian shipyard showed that the use of renewable energy and digitalisation are the main priorities for shipyard decision-makers when it comes to improving energy efficiency and reducing air emissions from their processes. A technical, economic and environmental feasibility study was carried out to deploy smart grids in the studied shipyard. Six different stand-alone and grid-connected modes were analysed. The analysis showed that the use of solar PV with a levelized energy cost of $0.053 per unit of energy was the most cost-effective smart grid for the shipyard. The study also found that market failures and high investment costs are the main barriers to renewable energy deployment in shipyards (Vakili et al. 2022b).

Flexibility is one of the most important features of the proposed framework. Vakili et al. (2022a) adopted the framework and the relative measures and tools for a large Iranian shipping company to identify the barriers to energy efficiency within the company and provide solutions to overcome the identified barriers to meet the initial targets of the IMO GHG strategy. The study proposed a diamond-shaped framework to identify barriers to energy efficiency to improve the energy efficiency of the ship's operation life cycle. The focus group consisted of five key decision makers in the shipping company. The results highlighted the importance of a holistic, systematic and transdisciplinary approach to improving energy efficiency in the maritime cluster and also emphasised the need to take into account the interrelationship and interaction of barriers for active stakeholders in the maritime industry in order to overcome barriers to energy efficiency.

Having regard to the above. The authors adopted the proposed framework for an IMO project "Improving the safety and energy efficiency of domestic passenger ships in the Philippines". The project aims to enhance the safety and energy efficiency of domestic passenger ferries in the Philippines and it is funded by the World Bank Group (WBG), the International Finance Corporation (IFC), the International Maritime Organization's (IMO), and Integrated Technical Cooperation Program (ITCP). To identify the barriers and also the priorities for decision makers in the Philippines' maritime sector, including maritime policy makers, port authorities, the Philippine Coast Guard as the port state, and shipping companies, the authors have used the proposed framework and identified the barriers to energy efficiency in domestic ferry services in the Philippines (WMU 2022).

## Case study

The nominated shipyard in Bangladesh is a private shipyard producing modern steel and aluminium vessels with a capacity to produce ten vessels of different types with a capacity of 15,000 DWT per year. After examining the procedures at the shipyard, the ship production has been divided into two processes, namely the production process and the support process. As shown in Fig. 4 and Table 1 each production and support process contains different elements and sub-processes. The production process is divided into material handling, surface treatment, metal working and equipment and quality control, each of which has sub-processes, and similarly the support process contains support services with associated sub-processes (Wahidi et al. 2021).

Based on the shipyard research, electricity, liquefied natural gas (LNG), carbon dioxide ($CO_2$), oxygen ($O_2$) and a mixture of oxygen and acetylene were identified as the main energy resources that had been used to meet the requirements of the ship production. The yard's database showed that the electricity consumption for ship production was 96 kWh per tonne of steel. For LNG, $CO_2$ and $O_2$ were 12 (kg per tonne

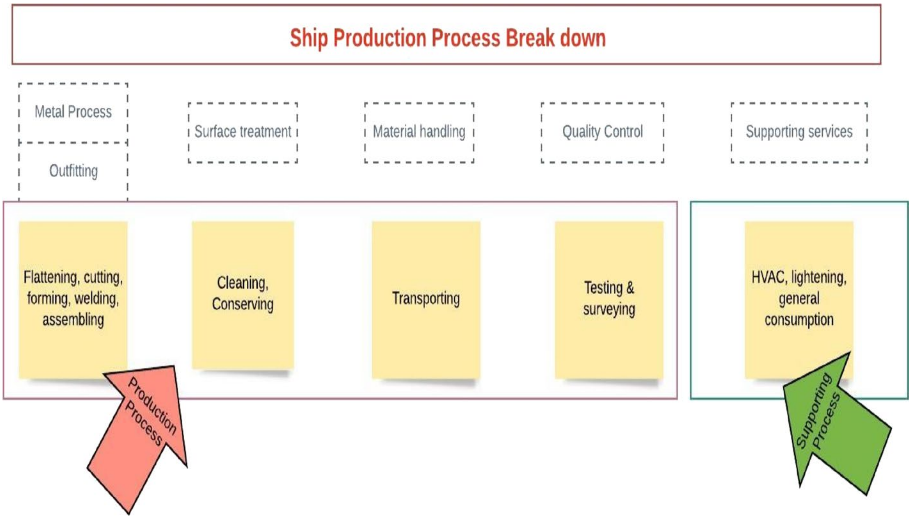

**Fig. 4** The typical ship production process in the shipyard

**Table 1** Ships' breakdown production (Wahidi et al. 2021)

| Main process | Sectors | Su-process |
|---|---|---|
| Production process | Material handling | This section handles the material needed between the sections and the most important sub-process is transport |
| | Surface treatment, | In this section, sub-processes such as cleaning and preservation are carried out |
| | Metal process and outfitting | In this section, sub-processes such as flattening, cutting, forming, welding and assembly are carried out |
| | Quality control | Testing and measurement is performed in this section |
| Supporting process | Supporting service | Heating, ventilation and air conditioning (HVAC), lighting and general energy and resource consumption are included in this section |

**Table 2** Consumables for per ship one ton steel

| Consumable | Quantity | Energy | MJ |
|---|---|---|---|
| Electrical power | 96 kWh/1 Ton net steel | 3.6 MJ/kWh | 345.60 |
| $O_2$ | 110 Cu. Met./1 Ton net steel | 5.04 MJ/Cu. Met | 554.40 |
| $CO_2$ | 35 kgs./1 Ton net steel | 10,204 MJ/Ton | 357.14 |
| LNG | 12 kgs./1 Ton net steel | 624.108 MJ/Ton | 624.10 |

of steel), 35 (kg per tonne of steel) and 110 (Cu. Met per tonne of steel) respectively. As shown in Table 2 the authors converted the energy sources consumed at the yard into electricity in order to evaluate the electricity required per tonne of steel in shipbuilding. According to the data provided by the yard, the consumables needed for the construction per tonne of steel are 522.56 kWh. Figure 5 shows the share of different energy sources in the ship production for the investigated yard. LNG had the highest contribution with a share of 33%, while $O_2$, $CO_2$ and electricity came in second to fourth place with contributions of 30%, 19% and 18% respectively.

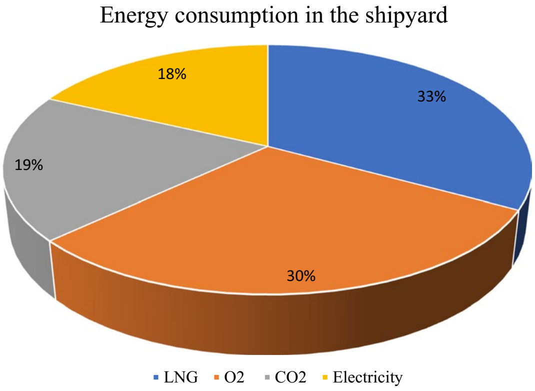

**Fig. 5** Consumed energy per ship one ton steel

**Table 3** Research methodology process step

| Step process | Actions |
|---|---|
| Step one | Select and adopt measures and tools for each discipline with reference to the authors' previous research (Vakili et al. 2022a, b, c, d) |
| Step two | Design a semi-structured questionnaire and conduct interviews with shipyard managers |
| Step three | Analysis of interviews and questionnaire using MCDM methods |

## Research methodology

In this study, mixed methods were used as the research strategy, which involves a combination of quantitative and qualitative research (Mackey and Bryfonski 2018). However, the qualitative method was prioritised over the quantitative method and the collection of both data was conducted simultaneously (Bryman 2016). In terms of the content of the analysis from the mixed method, triangulation, compensation, explanation and illustration are considered ways of combining quantitative and qualitative research (Bryman 2016).

While triangulation combinations (the qualitative interviews helped the author to check and correct the quantitative data) gave more validity to the data, the offset combination helped the author to compensate for the weaknesses of the data and benefit from the strengths of both methods (Hartley and Sturm 1997). The explanation combination refers to the prioritization of qualitative data that helped to better explain quantitative data and the qualitative data was used to illustrate quantitative results (Creswell 1999).

As shown in Table 3 the research consists of a three-step process:

The first step was to identify the options in each discipline and to design the energy management framework taking into account the investigated shipyard. As explained in the introduction, the aim of the study is to implement the framework proposed by the authors in their previous research. The authors refer to the proposed and developed framework in their previous research (Vakili et al. 2022a, b, c, d) and use the measures and tools provided in the study. However, the proposed measures and tools with considering the yard's geographical position, portfolio, and size were adopted for the studied yards.

The second step was designing the questionnaire. Based on the identified and adopted options, the semi-structured questionnaire was designed and the interviews were conducted with the yard managers.

Third step was analysis of interviews and questionnaire. Interdisciplinary and multi-criteria decision making (MCDM) methods were used to analyse the questionnaire.

### Selection of measures and tools to design and develop the energy management framework

With reference to the measures and tools listed in Vakili et al. (2022a, b, c, d), appropriate measures and tools were selected considering the size and portfolio of the shipyard and necessary adjustments were implemented to meet the requirements of the studied shipyard. As shown in Fig. 6, thirty two measures and tools in five main areas, namely human factor, policy and regulation, finance, technology and operations, were selected and used in the next step to design the questionnaire and design the energy management of the shipyard based on the priority areas.

### Design and conduct the semi-structured questionnaire/interview

The questionnaire sections were designed and developed on the basis of the first steps of the methodology and the selected measures and tools for each discipline. To validate the framework, interviews were conducted with decision-makers. The questionnaire consisted of six sections and was designed in a semistructured format (McIntosh and Morse 2015) considering the combination of qualitative and quantitative measures. The interviewees were asked to reflect on their ideas, experiences, causes, activities and more generally on how they perceive and act in terms of energy management in the shipyard. The proposed options within each discipline were achieved using the designed framework.

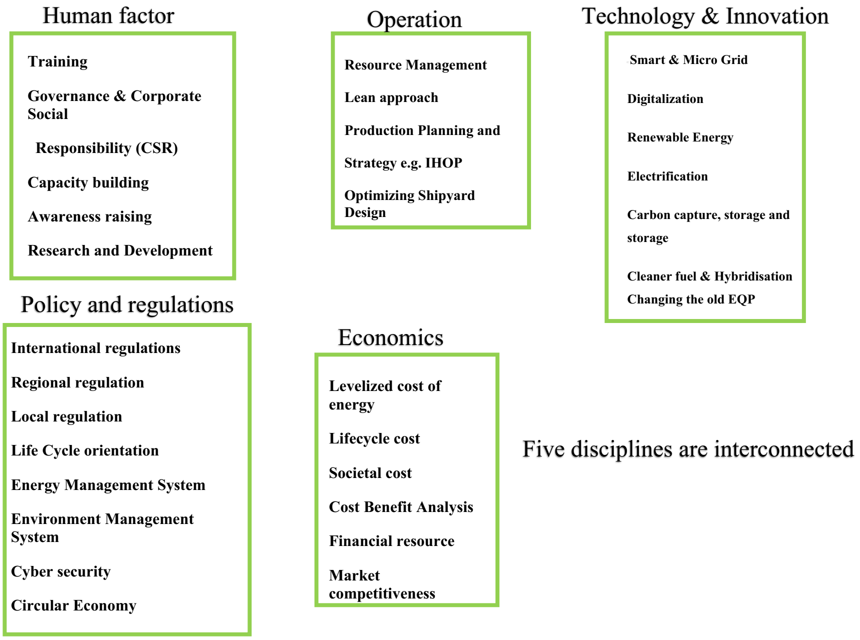

**Fig. 6** Selected measures and tools in five main criteria for the studied yard

**Table 4** Decision making members board

| Interview | Age | Sex | Background | Present position |
|---|---|---|---|---|
| No1 | 51 | Male | Mechanical engineer | Mechanical engineer |
| No 2 | 41 | Male | Electrical engineer | Deputy General Manager and Energy Manager |
| No 3 | 43 | Male | Mechanical engineer | Executive director |

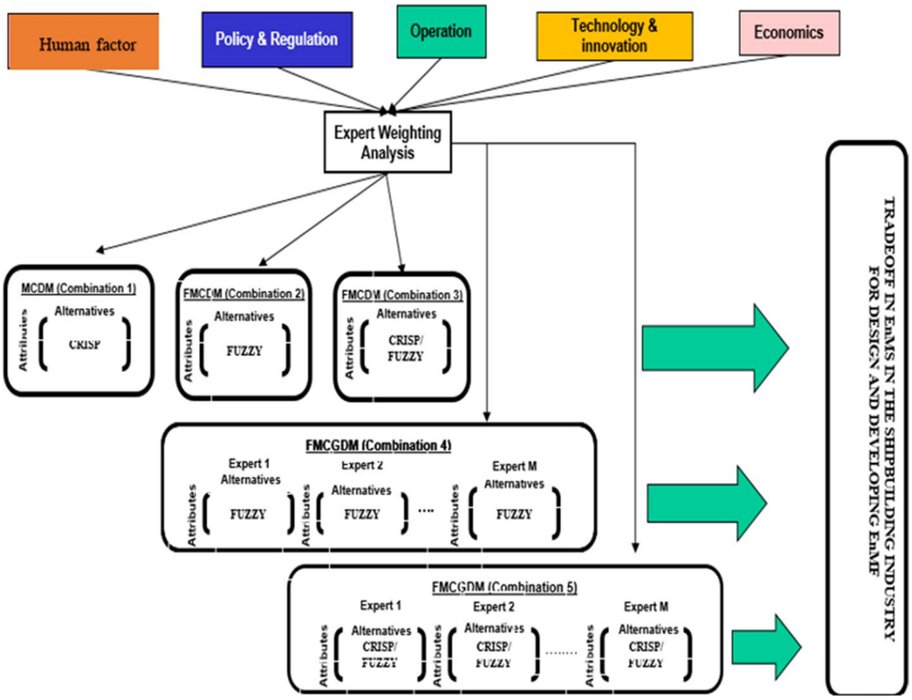

**Fig. 7** Proposed decision making framework for evaluating trade-off solutions. *Source*: Adapted from (Ölçer and Ballini 2015)

Table 4 shows age, sex, background, present position, and the current position of the interviewees who are the main decision makers in the shipyard. It can be seen that there is no woman among the key decision makers at the yard, which indicates the lack of gender equality in the yard's organizational structure. Furthermore, because the company was a private shipyard, only three key decision makers were presented as the final decision makers for all investments in the shipyard.

### Analysis the questionnaire by applying MCDM methods

The third step was the analysis of questionnaires and interviews. MCDM methods were used to analyse the questionnaire. In order to structure a process and create a strategic plan involving all decision makers, and to optimize the decision on a complex problem, an interdisciplinary approach in line with optimizing decision methods was considered and developed (Vakili et al. 2022a, b, c, d). The studies show that MCDM methods are popular and useful methods to support decision making in energy investments (Strantzali and Aravossis 2016). Figure 7 shows different decision methods for evaluating trade-offs between alternatives. Considering the above, the authors considered with respect to the type of data the fourth combination of Fuzzy Multiple Attribute Group Decision Making (FMAGDM) (includes FTOPSIS and FAHP) (Ölçer and Ballini 2015) to analyze the data and the interviews.

The application of fuzzy logic helps to assess the human mindset accurately and helps DMs to express their opinions when choosing between different options in a vivid way (Wang and Chen 2007). Any barriers to expressing DMs' opinions may lead to inaccurate judgments and increase uncertainty in the creation of pairwise comparison (Kuo et al. 2006), but the implementation of the fuzzy method gives DMs more confidence to make interval judgments rather than fixed-value judgments (Chan et al. 2019). In addition, the fuzzy method helps the authors to convert the linguistic format of data obtained from expert interviewees into quantity data.

#### *Fuzzy analytical hierarchy process (FAHP)*

Since the matrix for pairwise comparisons was uniform to avoid bias in the judgment of the knowledgeable group, the FAHP technique rather than the classical AHP method was used to determine the weights for each discipline and subcriterion in this study. In addition, the fuzzy method helped to deal with the imprecise information that can affect when deciding on DMs' preferences in the different variables (Kubler et al. 2016) and helped DMs at yards to eliminate uncertainties and give them more confidence to choose the best options with respect to the yard characteristics. Triangular Fuzzy Number (TFN) demonstrates by three numbers of $A = (a, b, c)$ are shown in Table 5 (Zadeh 1978; Wang et al. 2006).

FAHP method determines weights by creating a pairwise comparison matrix. Three senior managers and DMs at shipyards (see Table 4) were questioned to share their priorities among the main discipline and sub-criteria. As shown in Table 6, nine point scale was used for pairwise comparison of main disciplines and sub-criteria.

And to calculate weighting of attributes for the main disciplines and criteria equations in Table 7 have been used.

#### *Fuzzy TOPSIS*

In this study, FTOPSIS method was used to rank the alternatives in each criterion. Multiple attribute decision making is a common task in normal life. It is choosing the most prefered alternative among other alternatives. Due to complexity of the socio-economic environment of energy management within shipping industry is crucial that all aspects of the problem being taken into consideration by DMs (Faizi et al. 2020). In such a complex situation, the preference information provided by the DMs may be imprecises. In

**Table 5** Triangular fuzzy number (TFN) (Zadeh 1978; Wang et al. 2006)

| | | | |
|---|---|---|---|
| $\mu\,\mathrm{n}\,_{(A)}^{(X)}$ | 0 | $X < a$ | *a* has the lowest potential value of number of fuzzy number |
| | $\frac{X-a}{b-a}$ | $a \leq X \leq b$ | *b* has the higher potential value of number of fuzzy number |
| | $\frac{c-X}{c-b}$ | $b \leq X \leq c$ | *c* has the highest potential value of number of fuzzy number |
| | 0 | $X > c$ | *c* has the highest potential value of number of fuzzy number |

**Table 6** The linguistic scale of importance

| Linguistic scale | Triangular fuzzy numbers | Explanation |
|---|---|---|
| Equal importance | (1,1,1) | Two disciplines or sub-criteria has equal importance |
| Moderate importance | (2,3,4) | Experience and judgement moderately favour one discipline and sub- criteria over another |
| Strong importance | (4,5,6) | Experience and judgement strongly favour one discipline and sub- criteria over another |
| Very strong importance | (6,7,8) | One discipline and sub- criteria very strongly favoured over another one |
| Extremely strong importance | (9,9,9) | One discipline and sub- criteria extremely strong favoured over another one |

**Table 7** FAHP equations

| Number and description of the equationsc | Equation | |
|---|---|---|
| 1-Sum of a fuzzy number ⊕ | ñA ⊕ ñB = (*a* A + *a* B, *b* A + *b* B, *c* A + *c* B) | (1) |
| 2-Multiplication of a fuzzy number ⊗ | ñA ⊗ ñB = (*a* AX *a* B, *b* AX *b* B, *c* AX *c* B) | (2) |
| 3-Division of a fuzzy number Ø | ñA Ø ñB = (*a* A/*a* B, *b* A/*b* B, *c* A/*c* B) | (3) |
| 4-Subtraction of a fuzzy number Θ | ñA Θ ñB = (*a* A–*a* B, *b* A − *b* B, *c* A–*c* B) | (4) |
| 5-Reciprocal of a fuzzy number | Xñ a − 1 = (*a*, *b*, *c*) − 1 = (1/*c*, 1/*b*, 1/*a*) | (5) |
| 6-In this research, the geometric mean technique was employed to perform the data analysis to compute the fuzzy values (Coffey and Claudio 2021) | Ƒ = (ñi,1 ⊗ ñi,2 ⊗ … ñi,n) 1/n<br>= ((*a* i, 1X *a* i, 2 X *a* i, 3 … X *a* i, n) 1/n,<br>(*b* i, 1X *b* i, 2 X *b*, i3 … X *b* i, n) 1/n,<br>(*c* i, 1 X *c* i, 2 X *c* i, 3 … X *c* i, n) 1/n) | (6) |
| 7-wi = fuzzy weight of the *i* th event | $\mathrm{Wi} = \frac{Ƒi}{Ƒ1 \oplus Ƒ2 \ldots\ldots \oplus Ƒn}$ | (7) |
| 8-Ƒ*i* = geometric mean of the *i*th row | $\mathrm{DF\ Wi} = \frac{[(ci-ai)+(bi-ai)]}{3+ai}$ | (8) |
| 9-Difuzzified (DF) mean of the weights | Then $\mathrm{Wi} = \frac{DF\ Wi}{\sum DFWi}$ (A9) | (9) |

result, it is essential that DMs within shipyards utilise imprecise preference models in group setting to make the best and the most optimised decision.

In this study, Chen (2000) method, which is the extension of the TOPSIS of Hwang and Yoon, was used. The method used the fuzzy environment and developed a vertex procedure to calculate the distance between two triangular fuzzy number (Xu and Chen 2007). The method defines the closeness coefficient to determine the ranking order of all alternatives by calculating the distances to both the fuzzy positive-ideal solution (FPIS) and fuzzy negative-ideal solution (FNIS) simultaneously (Mu et al. 2021).

The TOPSIS to the fuzzy environment is an appropriate method for solving group decision-making problems. In this study, the weight of main disciplines and sub-criteria were calculated by the FAHP method (see "Fuzzy analytical hierarchy process (FAHP)" section). Additionally, the rating of qualitative or alternatives preference in each criterion was considered in the linguistic variables. The same variables were expressed in positive triangular fuzzy numbers as Table 6. By considering the different importance of each criterion, we can construct the weighted normalised fuzzy decision matrix as:

$\tilde{\mathrm{V}} = \left[\tilde{\mathrm{v}}_{\mathrm{ij}}\right]_{\mathrm{m}\times\mathrm{n}}, \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n$ (13), where $\tilde{\mathrm{v}}_{\mathrm{ij}} = \acute{\mathrm{r}}_{\mathrm{ij}}$ (·) $\mathrm{w}_{\mathrm{j}}$ ($\mathrm{w}_{\mathrm{j}}$ of the main disciplines and sub-criteria are calculate by FAHP method. Please refer to "Fuzzy analytical hierarchy process (FAHP)" section). Table 8 shows the the sequences and the

**Table 8** Sequences and equations to calculate fuzzy positive ideal solution and fuzzy negative ideal solution

| Sequence | Equations |
|---|---|
| Step 1: Distance from fuzzy positive ideal solution and fuzzy negative ideal solution | $d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_i^*)$<br>$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_i^*)$ (Zhang et al. 2021) (6)<br>$i = 1, 2, \ldots, m$ |
| Step 2: Calculating closeness coefficient of alternatives and ranking them | $CC_i = \frac{d_i^-}{d_i^* + d_i^-}$<br>$i = 1, 2, \ldots, m$ (Zhang et al. 2021) (7) |
| Step 3: Comaprison | Alternatives closer to fuzzy positive ideal solution and further from fuzzy negative ideal solutions are the best alternative and their closeness coefficient is nearer to 1 |

required equations to calculate fuzzy positive ideal solution and fuzzy negative ideal solution.

## Results and recommendations

### Results

The analysis of the interviewes and questionnaire identified the prorities of DMs in each discipline. To continue, by deploying FTOPSIS methods for each discipline, as well as FAHP method for main disciplines and sub-criteria, the interviews were analysed. In "Attribute weights in main and sub criteria" and "Top alternatives in Human factor criterion" sections, as the examples the calculation of main disciplines' weight (FAHP method) and ranking of human factor.

disciplines are presented, respectively. Other disciplines and sub-criteria weight were calculated based on the same methods.

#### *Attribute weights in main and sub criteria*

The results of the FAHP method for main disciplines are presented in this section. The study proposed the alternatives for improving energy efficiency within shipyards in five main disciplines. The priorities of focused group about each main discipline were asked during the interview and in the questionnaire. Based on the experts' linguistic answers and with refer to Table 6 to identify the related triangular fuzzy numbers (TFN), the pairwise comparison matrix was generated. Tables 9 and 10 show the TFNs and the pairwise comparison matrix.

The weight of each criterion could determined after developing the fuzzy pairwise comparison matrix. The fuzzy Geometric values were achieved based on Eq. (1) and (2). Table 11 and 12 show the geometric mean ($\tilde{r}$) and value of fuzzy weights ($W_i$) of disciplines.

In continue, fuzzy priority weights were defuzzed into the crispy weight by using Eq. (3). Table 13 shows the defuzzified mean value of weights of all disciplines.

Equation (4), was used to normalise the weight of all disciplines. Table 14 shows the normalized defuzzified weights of all disciplines and their ranking.

**Table 9** Transformed preference of DMs (main disciplines) towards criteria into TFNs

| **Main disciplines** | **DMs** | **Human factor** | **Technology and innovation** | **Operation** | **Policy and regulation** | **Economic** |
|---|---|---|---|---|---|---|
| Human factor | $DM_1$ | (1, 1, 1) | (6,7,8) | (1/9/,1/9,1/9) | (1/6,1/5,1/4) | (1/7,1/6,1/5) |
| | $DM_2$ | (1,1,1) | (1/6,1/5,1/4) | (1, 1, 1) | (1, 1, 1) | (1/6,1/5,1/4) |
| | $DM_3$ | (1, 1, 1) | (1/8, 1/7,1/6) | (1/6,1/5,1/4) | (1/8,1/7,1/6) | (1/6,1/5,1/4) |
| Technology and innovation | $DM_1$ | (1/8,1/7,1/6) | (1, 1, 1) | (9,9,9) | (1/7,1/6,1/5) | (1/6,1/5,1/4) |
| | $DM_2$ | (4,5,6) | (1, 1, 1) | (6,7,8) | (4,5,6) | (1/8, 1/7,1/6) |
| | $DM_3$ | (6,7,8) | (1, 1, 1) | (1/6,1/5,1/4) | (1/6,1/5,1/4) | (1/8, 1/7,1/6) |
| Operation | $DM_1$ | (9, 9, 9) | (1/9/1/9/1/9) | (1, 1, 1) | (1/6,1/5,1/4) | (1/9/1/9/1/9) |
| | $DM_2$ | (1, 1, 1) | (1/8,1/7,1/6) | (1, 1, 1) | (2,3,4) | (1/6,1/5,1/4) |
| | $DM_3$ | (4,5,6) | (4,5,6) | (1, 1, 1) | (1/6,1/5,1/4) | (1/8, 1/7,1/6) |
| Policy and regulation | $DM_1$ | (4,5,6) | (5,6,7) | (4,5,6) | (1,1,1) | (4,5,6) |
| | $DM_2$ | (1,1,1) | (1/6, 1/5, 1/4) | (1/4,1/3, 1/2) | (1,1,1) | (1/6, 1/5, 1/4) |
| | $DM_3$ | (6,7,8) | (4,5,6) | (4,5,6) | (1,1,1) | (1/6, 1/5, 1/4) |
| Economic | $DM_1$ | (5, 6, 7) | (4,5,6) | (9,9,9) | (1/6,1/5,1/4) | (1,1,1) |
| | $DM_2$ | (4,5,6) | (6,7,8) | (4,5,6) | (4,5,6) | (1,1,1) |
| | $DM_3$ | (4,5,6) | (6,7,8) | (6,7,8) | (6,7,8) | (1,1,1) |

**Table 10** Aggregated fuzzy comparison matrix of aspects

| **Criteria** | **Human factor** | **Tech and innovation** | **Operation** | **Policy and regulation** | **Economic** |
|---|---|---|---|---|---|
| Human factor | (1,1,1) | (0.125,2.447,8) | (0.111,0.437,1) | (0.125,0.447,1) | (0.142, 0.188, 0.25) |
| Tech and innovation | (0.125,4.047, 8) | (1, 1, 1) | (0.166, 5.4, 9) | (0.142, 1.788, 6) | (0.125, 0.161, 0.25) |
| Operation | (1,5,9) | (0.111. 1.751, 6) | (1, 1, 1) | (0.166,1.133, 4) | (0.111, 0.151, 0.25) |
| Policy and regulation | (1,4.333, 8) | (0.166, 3,733, 7) | (0.25, 3.433, 6) | (1,1,1) | (0.166, 1.8, 6) |
| Economic | (4,5.3332,7) | (6.333,8,4) | (4,7,9) | (4,5,6) | (1,1,1) |

**Table 11** Value of geometric mean (Ƒ) for all disciplines

| | |
|---|---|
| Human factor | (0.189,0.618, 1.149) |
| Tech and innovation | (0.205, 1.445, 2.551) |
| Operation | (0.289, 1.084, 2.221) |
| Policy and regulation | (0.369, 2.513, 4.58) |
| Economic | (3.031, 4.116, 4.967) |

**Table 12** Value of fuzzy weights ($w_i$) of disciplines

| | |
|---|---|
| Human factor | (0.012, 0.063, 0.281) |
| Tech and innovation | (0.013, 0.147, 0.624) |
| Operation | (0.018, 0.11, 0.543) |
| Policy and regulation | (0.023, 0.257, 1.12) |
| Economic | (0.196, 0.421, 1.215) |

**Table 13** Defuzzified mean value of weights of disciplines

| | |
|---|---|
| Human factor | 0.0169 |
| Tech and innovation | 0.0446 |
| Operation | 0.0305 |
| Policy and regulation | 0.0771 |
| Economic | 0.0704 |

**Table 14** Normalized defuzzified weights of disciplines

| Disciplines | Weights | Ranking |
|---|---|---|
| Human factor | 0.0765 | 5 |
| Tech and innovation | 0.1783 | 3 |
| Operation | 0.1473 | 4 |
| Policy and regulation | 0.3171 | 1 |
| Economic | 0.2807 | 2 |

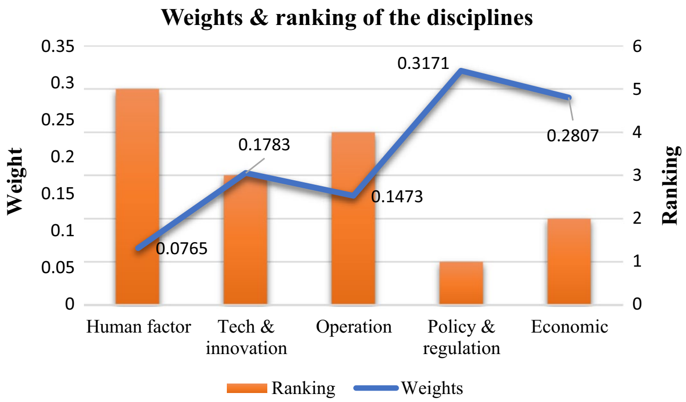

**Fig. 8** Weights and ranking of the disciplines

**Table 15** The sub criteria weights

| Sub-criteria | Weights | Rank |
|---|---|---|
| Cost | 0.189 | 3 |
| Air emission | 0.093 | 4 |
| Safety and security | 0.356 | 2 |
| Societal | 0.361 | 1 |

Figure 8 and the interpretation of Table 14 shows that the policy and regulation (0.3171) had the highest importance and economics (0.2807) was placed in the second rank. Technology and innovation (0.1783) and operation (0.1473) almost with the similar weights were placed in the third and fourth ranks, respectively. Finally, the human factor criterion (0.0765) had the least importance. As Table 15 shows the weights of sub-criteria, which were cost, air emission, safety and security and societal were calculated.

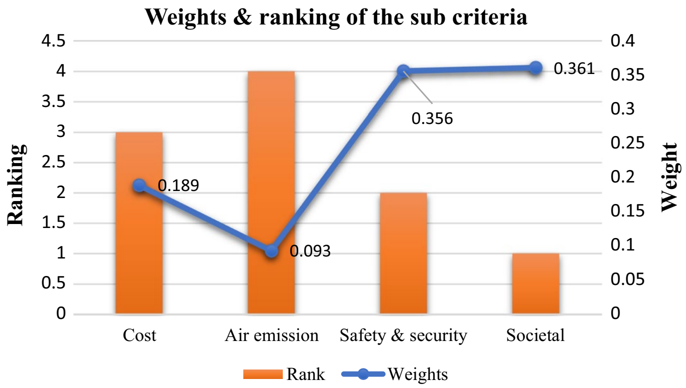

**Fig. 9** Weights and ranking of the sub criteria

Although the societal impact and safety and security had a relative weight, surprisingly, the societal (0.361) became the highest priority and the safety and security (0.356) criterion was in second place. Cost (0.189) and air emission (0.093) became the third and fourth priorities, respectively (Fig. 9). This means that the societal impact of the technology and measure has the highest importance, while safety and security is the second concern, and the cost of technology investment and its air emission reduction potential were the third and fourth priorities, respectively for DMs to improve energy efficiency and reduce air emissions from the shipyard's activities.

### *Top alternatives in human factor criterion*

As explained in "Fuzzy TOPSIS" section, FTOPSIS technique was used to determine the best alternatives in each criterion. In section two of the interview, focused group was asked about the importance of various alternatives, i.e., training, capacity building, corporate social responsibility (CSR), awareness raising and research and development (R&D) in the human factor criterion.

The interviewees provided their priorities about alternatives within four sub-categories: cost, air emission, safety and security, and societal in a linguistic format. With respect to the sub-criteria, which cost, air emission, and societal cost (non beneficial), and safety was the only beneficial sub-criterion. The linguistic evaluation was converted to TFN and the decision matrix developed. Tables 16 and 17 show the rating of the alternatives by three decision makers under the sub-criteria, and the fuzzy decision matrix, respectively.

In continuation by referring to the calculated weights of subcriteria in Table 15, the weighted normalised fuzzy decision matrix was developed (see Table 18).

In the next step, as Table 19 shows the distance of each alternative from FPIS and FNIS are claculted.

In the last step, according to the closeness coefficient, the ranking order of five alternatives was conducted. Table 20 shows the closeness coefficient of each alternative and their ranking.

As Table 20 and Fig. 10 reveal, training (0.6374), capacity building (0.59) and Corporate Social responsibility (CSR) (0.399) were placed in the top three ranks and awareness raising (0.3192), and R&D (0.122) were recognised as the fourth and fifth

**Table 16** Rating of the alternatives by three decision makers under the sub-criteria

| Sub-criteria | Alternatives | Decision-makers | | |
|---|---|---|---|---|
| | | $DM_1$ | $DM_2$ | $DM_3$ |
| Cost | Training | (4,5,6) | (6,7,8) | (4,5,6) |
| | Capacity building | (4,5,6) | (3,4,5) | (4,5,6) |
| | CSR | (1,1,1) | (6,7,8) | (4,5,6) |
| | Raising awareness | (2,3,4) | (6,7,8) | (2,3,4) |
| | R&D | (4,5,6) | (6,7,8) | (6,7,8) |
| Air emission | Training | (2,3,4) | (4,5,6) | (4,5,6) |
| | Capacity building | (2,3,4) | (4,5,6) | (4,5,6) |
| | CSR | (1,1,1) | (5,6,7) | (4,5,6) |
| | Raising awareness | (4,5,6) | (4,5,6) | (4,5,6) |
| | R&D | (4,5,6) | (4,5,6) | (4,5,6) |
| Safety and security | Training | (6,7,8) | (6,7,8) | (6,7,8) |
| | Capacity building | (4,5,6) | (4,5,6) | (4,5,6) |
| | CSR | (4,5,6) | (6,7,8) | (6,7,8) |
| | Raising awareness | (4,5,6) | (9,9,9) | (4,5,6) |
| | R&D | (2,3,4) | (6,7,8) | (4,5,6) |
| Societal | Training | (1,1,1) | (3,4,5) | (4,5,6) |
| | Capacity building | (1,1,1) | (3,4,5) | (4,5,6) |
| | CSR | (6,7,8) | (6,7,8) | (4,5,6) |
| | Raising awareness | (4,5,6) | (6,7,8) | (4,5,6) |
| | R&D | (4,5,6) | (6,7,8) | (4,5,6) |

**Table 17** Fuzzy decision matrix

| Attributes | Cost | Air emission | Safety | Societal |
|---|---|---|---|---|
| Training | (0.125, 0.176, 0.25) | (0.167, 0.231, 0.5) | (0.667, 0.778, 0.889) | (0.167, 0.3, 1) |
| Capacity building | (0.167, 0.214, 0.33) | (0.167, 0.231, 0.5) | (0.444, 0.556, 0.667) | (0.167, 0.3, 1) |
| CSR | (0.125, 0.231, 1) | (0.143, 0.25, 1) | (0.444, 0.704, 0.889) | (0.125, 0.158, 0.25) |
| Raising awarness | (0.125, 0.231, 0.5) | (0.167, 0.2, 0.25) | (0.444, 0.704, 1) | (0.125, 0.176, 0.25) |
| Research and development | (0.125, 0.158, 0.25) | (0.167, 0.2, 0,25) | (0.222, 0.556, 0.889) | (0.125, 0.176, 0.25) |

**Table 18** Weighted normalised fuzzy decision matrix

| Attributes | Cost | Air emission | Safety | Societal |
|---|---|---|---|---|
| Training | (0.024, 0.33, 0.047) | (0.016, 0.022, 0.048) | (0.235, 0.274, 0.313) | (0.06, 0.109, 0.363) |
| Capacity building | (0.031, 0.04, 0.063) | (0.016, 0.022, 0.048) | (0.157, 0.196, 0.235) | (0.06, 0.109, 0.363) |
| CSR | (0.024, 0.043, 0.188) | (0.014, 0.024, 0.096) | (0.157, 0.248, 0.313) | (0.045, 0.057, 0.091) |
| Raising awareness | (0.024, 0.043, 0.094) | (0.016, 0.019, 0.024) | (0.157, 0.248, 0.353) | (0.045, 0.064, 0.091) |
| Research and development | (0.024, 0.03, 0.047) | (0.016, 0.019, 0.024) | (0.078, 0.196, 0.313) | (0.045, 0.064, 0.091) |

top priorities, respectively. Training of personnel is an essential part of a shipyard's competence development and can improve energy efficiency within the shipyard. Surprisingly, R&D regarding the improvement of the energy sector was placed in the last priority. The DMs highlighted that they prefer to do research more on improve energy efficiency on the designed ship rather than improving energy efficiency within their

**Table 19** The distance measurement

| Alternatives | Fuzzy positive ideal solution (FPIS) | Fuzzy negative ideal solution (FNIS) |
|---|---|---|
| Training | 0.254919 | 0.448 |
| Capacity building | 0.302438 | 0.435 |
| CSR | 0.31632 | 0.211 |
| Raising awareness | 0.442526 | 0.207 |
| Research and development | 0.569551 | 0.079 |

**Table 20** Top Alternatives in the human factor criterion

| Alternatives | Closeness coefficient | Rank |
|---|---|---|
| A1 = Training | 0.6374 | 1 |
| A2 = Capaity building | 0.5900 | 2 |
| A3 = CSR | 0.3999 | 3 |
| A4 = Awareness raising | 0.3192 | 4 |
| A5 = R&D | 0.1220 | 5 |

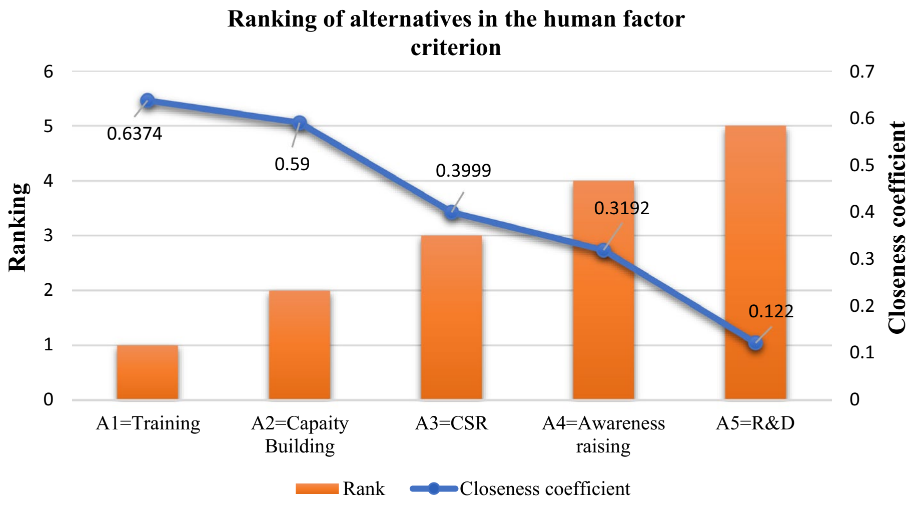

**Fig. 10** Ranking of alternatives in the human factor criterion

activities. The reason was highlighted due to availability of information from the technology providers as well as the trend of the market to have greener ships.

### *Ranking of alternatives in technology and innovation criterion*

In section three of the interview and questionnaire, i.e. technology and innovation criterion, various alternatives were suggested. The interviewees identified their priorities among the alternatives within four sub-categories in a linguistic format, and the data based on the FTOPSIS as described in "Top alternatives in Human factor criterion" section were analysed.

**Table 21** Top Alternatives in Technology and innovation criterion

| Alternatives | $C_i^*$ | Rank |
|---|---|---|
| B1 = Digitalization | 0.7579 | 2 |
| B2 = Micro and smart grid | 0.1156 | 7 |
| B3 = Renewable energy (RE) | 0.2092 | 5 |
| B4 = Carbon capture and storage (CCS) | 0.2474 | 4 |
| B5 = Alternative fuel | 0.1613 | 6 |
| B6 = Electrification | 0.3331 | 3 |
| B7 = Changing the old equipment | 0.8519 | 1 |

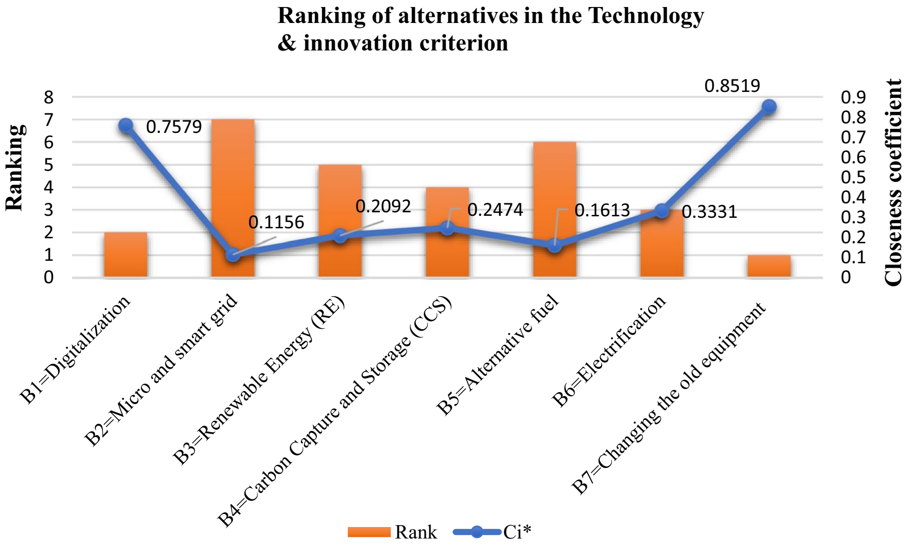

**Fig. 11** Ranking of alternatives in the technology and innovation criterion

As Table 21 and Fig. 11 show, the top three priorities in this criterion were changing the old equipment (0.8519), digitalization (0.7579) and electrification (0.3331), respectively. Carbon capture storage (CCS) (0.2474) was placed in fourth place. Although there was a great potential to harvest solar energy with respect to geographical position of the yard, renewable energy (RE) (0.2092) was ranked as the fifth priority. Alternative fuel (0.1613) and micro and smart grid (0.1156) were the last preferred alternatives, respectively. The ranking of the alternatives shows that the trend of changing equipment was toward digitalization and electrification. However, as the yard received national LNG and electricity at a reasonable price, there was no interest in using alternative fuels, renewables and micro- and smart grids, as they burden the yards with additional capital costs and the DMs were unsure whether they were efficient and effective.

### *Ranking of alternatives in operation criterion*

In section four of the interview, which is operation criterion, various alternatives were proposed. The interviewees identified their priorities about alternatives within four

**Table 22** Ranking of alternatives in operation criterion

| Alternatives | $C_i^*$ | Rank |
|---|---|---|
| C1 = Resource management (RMGM) | 0.7521 | 1 |
| C2 = Lean approach | 0.4439 | 3 |
| C3 = Optimizing the shipyard design | 0.4431 | 4 |
| C4 = Production planning strategy e.g. IHOP | 0.6554 | 2 |

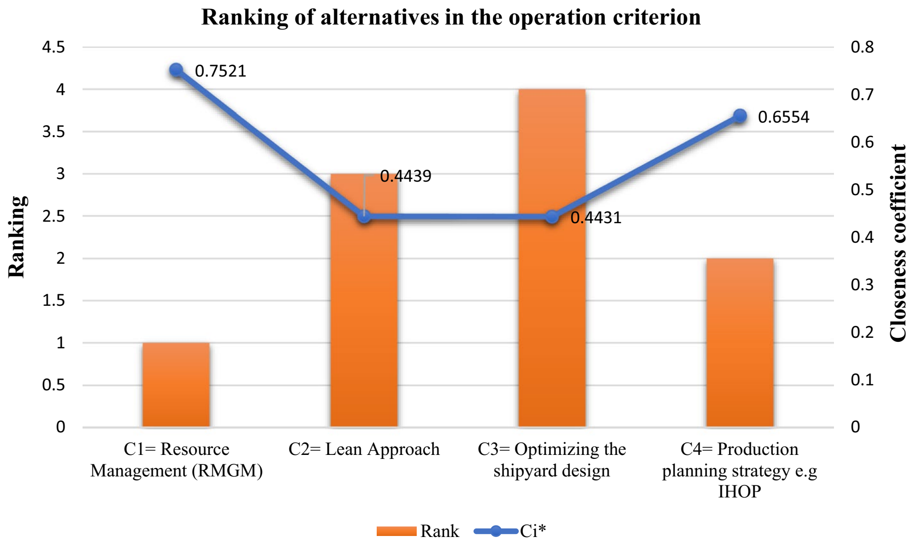

**Fig. 12** Ranking of alternatives in the operation criterion

sub-categories in a linguistic format, and the data based on the FTOPSIS as shown in "Top alternatives in Human factor criterion" section were analyzed.

As Table 22 and Fig. 12 show, RMGM (0.7521), production strategy plan, e.g. IHOP (0.6554) and lean approach (0.4439) were the top three priorities, and optimizing the shipyard design (0.4431) was the last option. The reason for choosing optimizing the shipyard design and lean approach as the previous priorities was due to the belief of DMs that the shipyard is well designed and a lean approach is considered in all activities. Moreover, for conducting such measures and applying the required changes, enormous capital cost and investment are necessary, and it can disrupt ship production (Vakili et al. 2021a), and can not be considered as a cost-effective measure.

### *Ranking of alternatives in policy and regulations criterion*

In section five of the interview (policy and regulation criterion) nine alternatives, were proposed. The interviewees identified their priorities among the alternatives within four sub-categories in a linguistic format, and the data based on the FTOPSIS were analysed.

Table 23 and Fig. 13 show that cybersecurity (0.0893) was placed in the first rank in the policy criterion. This was backed to the tendency among DMs to change the old equipment with modern and digitized equipment in shipyard. However, they

**Table 23** Ranking of alternatives in policy and regulation criterion

| Alternatives | $C_i^*$ | Rank |
|---|---|---|
| D1 = International regulation | 0.0329 | 7 |
| D2 = Regional regulation | 0.0387 | 6 |
| D3 = Local regulation | 0.0290 | 8 |
| D4 = Life cycle orientation | 0.0529 | 4 |
| D5 = ISO 50001 | 0.0712 | 3 |
| D6 = Cyber security | 0.0893 | 1 |
| D7 = ISO14001 | 0.0735 | 2 |
| D8 = Circular economy | 0.0474 | 5 |
| D9 = Voluntarily agreement | 0.0215 | 9 |

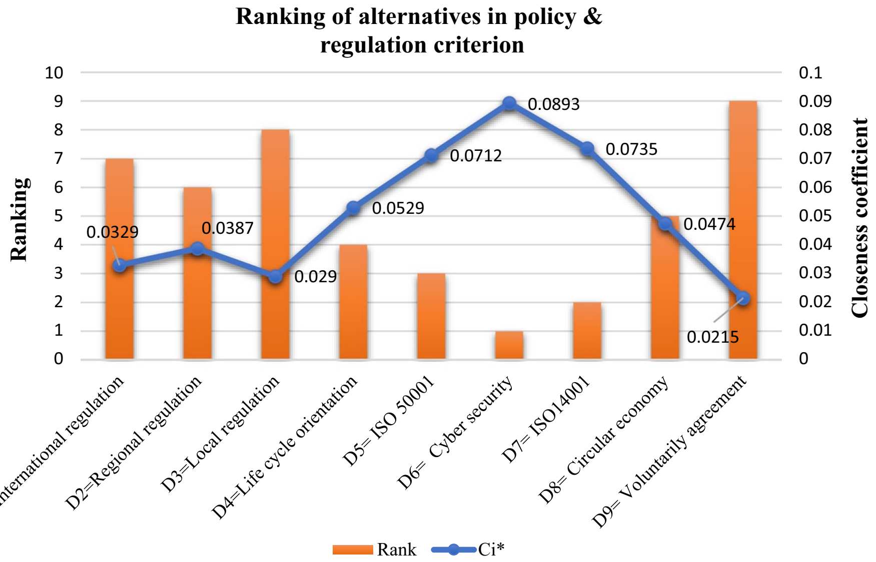

**Fig. 13** Ranking of alternatives in the policy and regulation criterion

had concern about cyber threat and had plans to raise awareness and conduct skill development for its staff in parallel with changing of old equipment and develop the related cybersecurity policy and management within their profile. The second and third top priorities were ISO 14001 (0.0735) and ISO 50001 (0.0712), respectively. The shipyard's DMs had more interst to implement ISO 14001 than ISO 50001. They believed that implementation of ISO14001 has an appropriate potential to mitigate the shipyard's environmentall negative impacts.

Life cycle orientation (0.0529) was placed in fourth priority and circular economy (0.0474) was ranked as the fifth priority for the yard's DMs. The shipyard's DMs believed that there is no point in considering the lifecycle perspective of the equipment, nor is there a great potential for the circular economy in the shipyard (only 5% of annual consumed steel that is not used is sold to steel factories). Although the International (0.0329), regional (0.0387) and local regulations (0.0290) had almost the same level of importance for DMs, the regional one was given higher priority in comparison with the international and local ones. Finally, the voluntary agreement

**Table 24** Ranking of alternatives in Economic criterion

| Alternatives | $C_i^*$ | Rank |
|---|---|---|
| E1 = Financial source | 0.5944 | 4 |
| E2 = Levelized cost of energy (LCOE) | 0.6875 | 2 |
| E3 = Life cycle cost (LCC) | 0.6459 | 3 |
| E4 = Societal cost | 0.3876 | 7 |
| E5 = Cost benefit analysis (CBA) | 0.6947 | 1 |
| E6 = Competitiveness | 0.4687 | 6 |
| E7 = Incentive regime | 0.4735 | 5 |

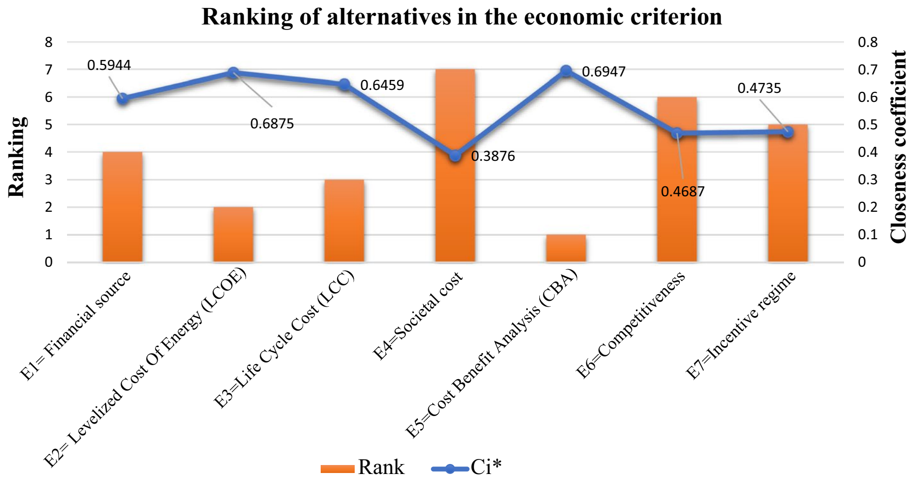

**Fig. 14** Ranking of alternatives in the economic criterion

(0.0215) was set in last priority in this criterion, which was due to lack of conducting such programs to improve energy efficiency at the country and regional level.

### *Ranking of alternatives in economic criterion*

As Table 24 and Fig. 14 show, in section six of the interview, seven alternatives of financial source were presented in the economic criterion. The interviewees provided their priorities about alternatives within four sub-categories in a linguistic format, and the data based on the fourth combination of FMAGDM were analyzed. The economic criterion had the highest priority for DMs. In choosing the economic indicator, cost–benefit analysis (CBA) (0.6947) was placed in the first place and LCOE (0.6875) and LCC (0.6459) were placed in the second and third top priorities, respectively.

In the measure options, financial source (0.5944) and incentive regime (0.4735) were ranked first and second, respectively; however, they were the fourth and fifth priorities in the economic criterion. The financial source concerning the interest can play a crucial role in providing the required capital for investment as long as determining the related risks of the investment, and incentive regimes can encourage and enthuse DMs to invest in energy efficiency measures. Regarding the incentive, the DMs prefer direct benefits from the project investment rather than dependency on other organizational and governmental bodies.

Competitiveness (0.4687) ranks third in top priorities of the economic measures and sixth in the economic criterion. Competitiveness depends significantly on the short, medium and long term strategies of the DMs at the shipyard about their position and role in the market. The low importance of competitiveness might show that the DMs believe in the large gap between the shipyard and the large East Asian or European shipyards or they believe that they have a safe position in the market in comparison with other existing shipyards of the same portfolio and size, both in the local and regional markets. The last alternative in the criterion was societal cost (0.3876). However, in sub-criteria societal impact had the highest weight among the others, which were cost, safety and security, technology and innovation, and air emission.

## Recommendations

The recommendations are based on the results of the analysis of the interviews and the contributions of the yard's DMs. In order to meet the Paris Agreement targets, it is necessary for nations to consider more ambitious targets, such as considering emissions from heavy industries like shipbuilding (Vakili et al. 2021a, b, c), and a holistic and systematic approach with cooperation between all active actors in the field is required (Vakili et al. 2022a, b, c, d). However, shipyards also face some barriers, such as regulatory compliance, competitive markets, economic growth, productivity levels and product quality, to improve energy efficiency and mitigate their negative environmental impacts (Vakili et al. 2021b).

As the studied shipyard did not have any startegies regarding energy and lifecycle emission within their portfolio, it is suggested that the shipyard design, develop and implement a holistic, systematic energy management framework and considere a short, medium and long strategy accordingly (Vakili et al. 2022a, b, c, d). Existing and implementing such a framework provides the required models, methods, measures and instruments to DMs for identifying the related energy efficiency barriers and guide to to overcome the identified barrieers and subsequently improve energy efficiency and mitigate air emissions within their context. Additionally, this approach can boost both business and socio-economic perspectives for the shipyard and plays a win-to-win deal (Thollander et al. 2020; Vakili et al. 2022a, b, c, d).

The framework as an innovative measure to fill the gap between the shipyard and the market competitors and can place the shipyard in a better position in the competitive market. In addition, the implementation of the framework can be considered as role model for other heavy industries to assist in in promoting Bangladeshi's NDC under the Paris Agreement. Furthermore, the implementation of the framework supports lifecycle green and sustainable productions in the maritime cluster (Vakili et al. 2021b). However, it is important that the dynamic and generic feature of the framework be taken into consideration and the appropriate monitoring and corrective actions such as updating the benchmark measures based on the portfolio, monitoring the progress of implementation, and introducing new technologies be taken place.

The second main recommendation for the shipyard is to consider a more balanced approach between the five disciplines. The policy and regulation (0.3171), was rated as the most important discipline, whereas the human factor was assigned a factor of 0.0765.

The importance of these two disciplines varies by a factor of around 4, which highlights a strong imbalance between the disciplines. It is required that DMs review their priorities and have a harmonised and multi-dimensional approach to manage energy aspects within the shipyards.

The third main recommendation for the shipyard is to consider and mitigate pollution and emissions to water, soil, and air. This can be accomplished by implementing the environmental management system (EMS) (ISO14001) and energy management system (EnMS) ISO 50001. Shipyards as an energy-intensive and material consumers has negative environmental impacts by introducung environmental pollutants to land, water, soil and air (Vakili et al. 2021a; Zhou et al. 2019). As the studied shipyard only considers its negative environmental impact throughout the Quality, Health, Safety and Environment (QHSE) department, it is suggested that EMS (ISO14001) (Mahzun et al. 2020) and EnMS (ISO 50001) (Chai and Yeo 2012) be compiled and applied in the shipyard. Implementation of the mentioned ISO standards can mitigate pollutants and reduce the shipyard's negative impacts on water, soil and land, as well as air. The mentioned actions will promote the yard's CSR as one of the most sustainable shipyards, and as it has exported to European countries, this policy will create a competitive advantage for the yard at a regional and global level.

The fourth main recommendation for the shipyard is to change the old equipment and machinery with new, modern and more efficient ones. Utilising more efficient technologies can increase energy productivity at shipyards and promote the quality of products (Vakili et al. 2021a). However, it needs finance which is the main barriers in improving energy efficiency at shipyards (Vakili et al. 2021b). Additionally, since the trends in chaging the equipment is toward digitalization, automation, and electrification the shipyard has to develop appropriate cyber security measures and policy to mitigate its vulnerability to cyber threat (Candell et al. 2020).

The fifth main recommendation for the shipyard is to consider the energy efficiency improvement in R&D projects of the shipyard. Although the shipyard has priorities other than energy within the R&D as well as training, it is recommended that the energy sector be considered accordingly. These factors play a crucial role in the development of the shipyard's competitiveness and to reduce the burden cost of personnel training, the courses can be classified to different levels and steps with providing higher priorities to staff who have more essential role to overcome energy efficiency barriers and improvement of energy efficiecny within the shipyard portfolio (Zhou et al. 2019).

The sixth main recommendation for the shipyard is to harvest RE to contribute in providing the shipyard's required energy. Utilising RE was not chosen as the priority of the yard's DMs. However, with respect to geographical position of the yard and due to the existing potential it is suggested to use the existing potential in utilising RE in the yard. Use solar and wind energy can be categorized within short and medium-term energy policy of the yard. Additionally, parallel investment in energy storage system can provide an opprtunity to desin and develop smart and microgrids in shipyard (Gomez et al., 2021). On the otherhand, investment in RE, can be considered as the long term energy strategy by providing the required fundamental infrastructure to produce cleaner fuel such as green hydrogen and gree methanol (Aspen and Sparrevik 2020) and promote the shipyard's position in the competitive market to a energy hub in the region (Vakili et al.

2022a, b, c, d). This vision not only provide economiyc growth of the yard, but also can be a role model for othe heavy industries to contribute in mitigatiuon of air emissions from their activies and placed in better position in coparision with other competitors in the market (Vakili et al. 2021d).

The seventh main recommendation for the shipyard is to promote the lean approach, resource management, and production planning strategy, as they have essential roles in reducing energy consumption at shipyards (Sharma and Gandhi 2017). It is suggested that periodic reviews and audits of the operational procedures within the shipyards be conducted. However, as the DMs indicated the importance of the economic disciplines, for any energy efficiency investment, a feasibility study with consideration of LCOE and CBA for all the provided recommendations must be conducted.

## Conclusions

To reach to a zero emission and green shipping industry, it is crucial to change the mindset into a broader vision and life-cycle perspective that strives to minimise and eliminate ships' emissions throughout the life cycle. Shipping industry starts its journey toward cleaner operational phase by using zero-carbon fuels, electricity and sail and solar power and it is predicted that the fraction of the operationl phase of ship's life-cycle will become less than their construction phase in future decades. However, shipyards have not been provided with a uniform, holistic, systematic, and transdisciplinary models, methods, measures and instruments to overcome to improvement of energy efficiency within their context. As a result, the IMO as the international shipping regulatory body needs to take a proactive, holistic, systematic and transdisciplinary approach as well as life-cycle vision in alignment with the engagement of all active actors in the mitigation of air emissions from the shipping industry.

By applying the proposed EnMF plan, the study proposed a measure for a short-, medium- and long-term energy strategy for the studied shipyard. The implementation of the framework can promote green ship aspects and promote sustainable shipping from a life cycle perspective. It is predicted that the implementation of the framework will lead to economic growth for the yard by increasing energy productivity and reducing the final cost of production, as well as reducing the negative environmental impact of the yard, promoting the reputation of the shipbuilding industry and improving the competitiveness of the yard.

The type and the fraction of the used energies in production of ships have been identified. Based on the case study, the consumables needed for the construction per tonne of steel are 522.56 kWh. LNG with 33% fraction (12 kg per one ton steel), had the highest contribution to ships production. $O_2$ was the second highest consumed energy. 35 kg of $O_2$ was needed per one tone of steel which is 30% of total required energy. $CO_2$ with 19% (110 $m^3$ per one-ton steel) and electricity with 18% (96 kWh per one tone of steel) were placed in the third and fourth places.

The second main conclusion is that we figured out that there is a lack of any holistic, systematic and transdisciplinary measures to support the shipyard's DMs in making rational and optimized decisions about energy sectors in the shipyard. The study provided a transdisciplinary approach and implement it with the consideration of five main disciplines and design the EnMF for the shipyard based on the priorities of DMs in each discipline. Conducting the framework within the shipyards indicated the priorities of DMs within five main disciplines and sub-criteria.

The third main conclusion from the analysis of interviews is that the policy and regulation discipline and the societal criterion were evaluated to be the most important of the five main disciplines and four sub-criteria, respectively. In the main disciplines, the policy and regulation criterion (0.3171), economic (0.2807), technology and innovation (0.1783), operation (0.1473) and the human factor criterion (0.0765) were ranked as top priorities, in this order of importance. The societal criterion (0.361) became the highest priority, while safety and security (0.356) placed in the second rank, and cost (0.189) and air emission (0.093) were the third and fourth priorities, respectively in the sub-criteria.

The fourth main conclusion from the analysis of interviews is that after analyzing the interviews and applying the FAHP and FTOPSIS methods, top alternatives in each discipline were identified The shipyard DMs by considering the ranking and alternatives can design, develop and implement short, medium and long term energy policies within the shipyards. However, they have to use the privilege of the PDCA cycle too maintain the dynamic aspects of the framework.

Furthermore, the implementation of the framework can be considered as a role model measure for Bangladeshi NDC in reduction of GHG emissions from heavy industries, as well as fulfil the relevant directives for green products and considering the environmental footprint from design, production and operation up to dismantling and recycling in the maritime cluster.

The authors would like to highlight the limitations of the study and the future research agenda as follows: The novelty of the study is that while there was a lack of awareness among shipyard managers about identifying the best solutions for carbon reduction, this study focused on designing and implementing the proposed EnMF to identify the managers' priorities with respect to the shipyard's characteristics for improving energy efficiency and reducing air emissions. In order to assess the applicability of the identified measures and calculate the real benefits, the barriers had to be identified and an individual feasibility study had to be carried out.

**Abbreviations**

| | |
|---|---|
| CBA | Cost benefit analysis |
| CCS | Carbon capture storage |
| CO2 | Carbon dioxide |
| CSR | Corporate social responsibility |
| DM | Decision making |
| DSS | Decision support systems |
| EEDI | Energy efficiency design index |
| EEXI | Energy efficiency existing ship index |
| EnMF | Energy management framework |
| EnMS | Energy management system |
| ESEEMP | Enhanced ship energy efficiency management plan |
| FAHP | Fuzzy analytical hierarchy process |
| FMAGDM | Fuzzy multiple attribute group decision making |
| FNIS | Fuzzy negative-ideal solution |
| FPIS | Fuzzy positive-ideal solution |
| FTOPSIS | Technique for order of preference by similarity to ideal solution |
| GHG | Greenhouse gas |
| HVAC | Heating, ventilation and air conditioning |
| IFC | International Finance Corporation |
| IHOP | Integrated hull construction, outfitting, and painting |
| IMO | International Maritime Organization |
| ITCP | Integrated Technical Cooperation Program |

| | |
|---|---|
| LCC | Life cycle cost |
| LCOE | Levelized cost of energy |
| LNG | Liquefied natural gas |
| MCDM | Multi criteria decision making |
| NDC | National determined contribution |
| O2 | Oxygen |
| PDCA | Plan Do Check Act |
| QHSE | Quality, Health, Safety and Environment |
| R & D | Research and development |
| RE | Renewable energy |
| RMGM | Resource management |
| TFN | Triangular fuzzy number |
| WBG | World Bank Group |

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