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Evaluation of shipyard selection criteria for shipowners using a fuzzy technique

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There are various stages to the process of acquiring a vessel. First, a decision must be made on what vessel is needed. Next, an appropriate shipyard is selected; this decision is very significant, as it will determine the workmanship quality and delivery date of the vessel to be manufactured. From the point of view of a shipowner, receiving the vessel on time and manufactured to specification is crucial. From the point of view of the shipyard, it is vital to take as many orders as possible; therefore, one of the highest priorities of shipyards is to be the first choice for as many shipowners as possible in order to increase their requirement for steel fabrication and consequently their profits. In this study, the shipyard selection criteria for shipowners are presented and the degree of importance of each criterion is determined using a fuzzy analytic hierarchy process (AHP) technique. The aim of the study is to provide shipyards with information about the perspective of shipowners with regard to the shipyard selection process, thus allowing shipyards to strengthen their weaknesses and increase the number of shipowners which choose them to manufacture their ships.

Introduction

Operations in the maritime industry involve a large number of interrelated partners, with each performing manufacturing or distribution activities, thus forming a 'maritime supply chain' (Chryssolouris et al. 2004). The shipowner and shipyard are the main components of this chain; both are involved with repair operations and new vessel building activities.

The new vessel building process is a critical issue for shipowners, as they want to obtain vessels constructed in accordance with precise specifications which are tailored to their requirements. Furthermore, it is important thing for shipowners to obtain their new vessels as quickly as possible; the sooner the vessel is constructed, the earlier the vessel is put into operation and the quicker it begins to earn money, bringing in a return on investment for both the shipowner and shipyard.

A modern ship is a very complex facility, combining various types of equipment, technologies, and disciplines; the capital invested in a new merchant ship is massive (Xie et al. 2008). Therefore, the selection of an appropriate shipyard which can fabricate the vessel in accordance with the specifications and requirements of the shipowner in a relatively quick turnaround time is crucial.

After the decision about the type of vessel required has been made, the next step is to prepare the documents, including vessel specifications and drawings, which precisely detail the vessel. These documents will be submitted to various shipyards, which will return proposals in terms of what they can provide and how soon the ship can be completed. At this point, it is absolutely crucial to select the most appropriate shipyard. When selecting a shipyard, the shipowner needs to consider various parameters. If the selected shipyard is not appropriate then the vessel fabrication may be affected in a negative way, such as late delivery or poor workmanship, resulting in a loss of some of the return on the massive investment in the ship.

In the literature, there are few works which examine shipyard selection criteria for new vessel construction. Celik, Kahraman et al. (2009) studied the shipyard selection criteria for docking facilities of shipyards by using multiple-criteria fuzzy axiomatic design (FAD). For this study, 11 shipyards situated in Turkey were chosen as examples and by determining the weights of the criteria, the most suitable shipyards for docking facilities were presented in terms of which ones meet these criteria the best. Ozyigit (2006) presented the shipyard selection criteria for shipbuilding and recommended that they could be employed in the process of shipyard selection.

The Canadian government wanted to commission the construct ion of a number of large vessels and five Canadian shipyards were short listed. These shipyards were evaluated according to some performance criteria such as the shipyard's current status and contracts, the cost to Canada for improvements, the shipyard's financial status, the offered price, etc. (Public Works and Government Services Canada 2014).

In this study, the criteria which need to be considered by shipowners were identified and the impact of these criteria on the process of selecting an appropriate shipyard

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were determined. For this, the methodology of the fuzzy analytic hierarchy process (AHP) implemented by Buckley (1985) was employed. Fuzzy AHPs have been applied across a range of fields, including construction (Hsieh et al. 2004; Jaskowski et al. 2010), education (Goksu 2008; Celik, Kandakoglu, & Er 2009), human resources (Chou et al. 2012), location selection (Bilisik et al. 2014), marine engineering (Miri Lavasani et al. 2011; Wang & Chin 2011; Celik & Kandakoglu 2012; Yanar & Tozan 2012), the automotive industry (Nepal et al. 2010; Badizadeh & Khanmohammadi 2011; Bilgen & Sen 2012; Ghadimi et al. 2012; Rathi et al. 2015), supplier selection (Chan et al. 2008; Kilincci & Onal 2011; Yucenur et al. 2011; Shaw et al. 2012; Rezaei et al. 2014) and technology management (Erensal et al. 2006). A comprehensive description of the methodology is expounded in the next section. The aim of the study is to provide knowledge for shipyards about the point of view of shipowners when selecting a shipyard. In this way, shipyards may be able to strengthen their weaknesses and thus become the first choice of more shipowners.

Methodology

The thoughts of decision-makers and experts about an issue can be clearly described with fuzzy logic. A fuzzy AHP is presented for the purpose of resolving the lack of manifesting human perception and thought of the AHP developed by Thomas Saaty (Tayal et al. 2009). In the literature, many fuzzy AHP methods are proposed by different authors. In this study, Buckley's (1985) fuzzy AHP method is implemented. The steps followed in the study are explained below.

Step 1: definition of the criteria

Decision-makers and/or experts establish the qualifying criteria for shipyard selection.

Step 2: definition of the linguistic terms

The linguistic scale and fuzzy numbers used in the study are appointed from the literature.

Step 3: the collection of expert opinions

Expert assessments on the degree of importance of each criteri on were amassed with the aid of a survey (see Appendix 1). Equation (1) shows the fuzzy decision matrix.

$$\tilde{E}^k = \begin{pmatrix} \tilde{e}^k_{11} & \cdots & \tilde{e}^k_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{e}^k_{n1} & \cdots & \tilde{e}^k_{nn} \end{pmatrix}, \tag{1}$$

$$\tilde{e}^k_{ij} = \begin{cases} \text{If the criterion in the row is more important than the criterion in the column} & \begin{cases} \text{Row demon. im.} \\ \text{Row very str. im.} \\ \text{Row str. im.} \\ \text{Row mod. im.} \end{cases} \\ \text{If the criterion in the row is of the same importance as the criterion in the column} & \{\text{Row-column eq.} \\ \text{If the criterion in the column is more important than the criterion in the row} & \begin{cases} \text{Column mod. im.} \\ \text{Column str. im.} \\ \text{Column very str. im.} \\ \text{Column demon. im.} \end{cases} \end{cases} \tag{2}$$

where $\tilde{E}^k$ is a fuzzy decision matrix given by the kth expert for the degree of importance of each criteri on, $k = 1, \ldots, p$, p is number of experts, $\tilde{e}^k_{ij}$ is the fuzzy comparison value of criterion i to criterion j according to the kth expert, $i, j = 1, \ldots, n$ and n is the number of compared criteria. The abbreviations in Equation (2) are as follows: 'demon' is short for 'demonstratively', 'eq' is short for 'equally', 'im' is short for 'important', 'Mod' is short for 'moderate' and 'str' is short for 'strongly'. An example of expanding these abbreviations is as follows: *Row demon. im.* is short for 'the criterion in the row is demonstratively more important than the criterion in the column' (for the full versions of all the statements, see Appendix 1).

Step 4: the transformation of the data into triangular fuzzy numbers

The linguistic evaluations must be converted into triangular fuzzy numbers (TFNs), as mathematical operations cannot be performed on verbal expressions. A fuzzy set is represented by a membership function, $\mu_{\tilde{y}}(x)$, which defines the membership degree of the elements in the range [0, 1] (Zadeh 1965). The description of a TFN is given in Equation (3):

$$\mu_{\tilde{y}}(x) = \begin{cases} \text{if} & y_l \le x \le y_m, & (x - y_l)/(y_m - y_l) \\ \text{if} & y_m \le x \le y_u, & (y_u - x)/(y_u - y_m) \\ \text{if} & x > y_u \text{ or } x < y_l, & 0 \end{cases} \tag{3}$$

where $\mu_{\tilde{y}}(x)$ is a membership function, y_l is the lower boundary, y_u is the upper boundaryand y_m is the mean value. For an example of a TFN, see Figure 1.

Let $\tilde{y} = (y_l, y_m, y_u)$ and $\tilde{z} = (z_l, z_m, z_u)$ be two triangular fuzzy numbers; the algebraic operations are summarized below (Chen & Hwang 1992):

$$\tilde{y} \oplus \tilde{z} = (y_l + z_l, \ y_m + z_m, \ y_u + z_u), \tag{4}$$

$$\tilde{y} \ominus \tilde{z} = (y_l - z_u, \ y_m - z_m, \ y_u + z_l), \tag{5}$$

$$\tilde{y} \otimes \tilde{z} = (y_l \times z_l, \ y_m \times z_m, \ y_u \times z_u), \ \tilde{y} > 0, \ \tilde{z} > 0, \tag{6}$$

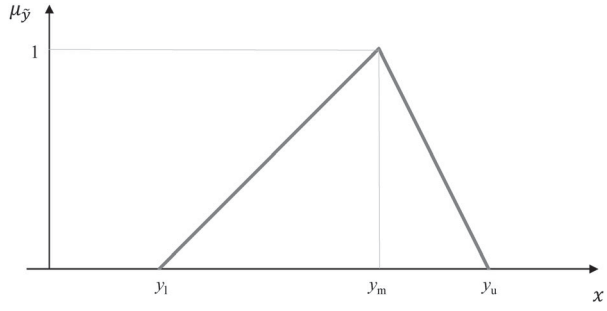


Figure 1. $\tilde{y} = (y_l,\ y_m,\ y_u)$ TFN.

$$\tilde{y} \oslash \tilde{z} = (y_l \div z_u,\ y_m \div z_m,\ y_u \div z_l),\ \ \tilde{y} > 0,\ \ \tilde{z} > 0, \tag{7}$$

$$\tilde{y}^{-1} = (1 \div y_u,\ 1 \div y_m,\ 1 \div y_l). \tag{8}$$

A positive fuzzy number, $\tilde{y}$, is defined as $\mu_{\tilde{y}}(x) = 0,\ \ \forall x < 0$ (Zimmermann 2001).

Step 5: aggregation of the experts' preferences

In the case of there being more than one expert opinion collected during the assessment stage, an aggregation process is needed to combine the experts' preferences. The geometric mean method is used to obtain an aggregated pairwise comparison matrix (Hsieh et al. 2004).

$$\tilde{E}^a = \begin{pmatrix} \tilde{e}^a_{11} & \cdots & \tilde{e}^a_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{e}^a_{n1} & \cdots & \tilde{e}^a_{nn} \end{pmatrix}, \tag{9}$$

$$\tilde{e}^a_{ij} = (\tilde{e}^1_{ij} \otimes \tilde{e}^2_{ij} \otimes \ldots \otimes \tilde{e}^p_{ij})^{1/p}, \tag{10}$$

where $\tilde{E}^a$ is an aggregated pairwise comparison matrix for the degree of importance of each criterion , $\tilde{e}^a_{ij}$ is the aggregated fuzzy comparison value of criterion i to criterion j, p is the number of experts, $i, j = 1, \ldots, n$ and n is the number of compared criteria.

Step 6: calculation of the criteria weights

In presented study, Buckley's (1985) fuzzy AHP is applied to calculate the fuzzy weights. The method is summarized below (Celik, Kandakoglu, & Er 2009):

After the aggregated pairwise comparison matrix, $\tilde{E}^a$, is obtained, the fuzzy weight matrix is calculated by Buckley's (1985) method as follows:

$$\tilde{r}_i = (\tilde{e}^a_{i1} \otimes \tilde{e}^a_{i2} \otimes \ldots \otimes \tilde{e}^a_{in})^{1/n}, \tag{11}$$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \ldots \oplus \tilde{r}_n)^{-1}, \tag{12}$$

where $\tilde{r}_i$ is the geometric mean of the fuzzy comparison value of criterion i to each criterion, $\tilde{w}_i$ is the fuzzy weight of the ith criterion, $i = 1, \ldots, n$ and n is the number of compared criteria.

Step 7: the defuzzification and normalization procedure for the fuzzy weights

In order to convert the fuzzy weights into crisp values, the centroid method, which generates a crisp value based on the centre of the gravity, is applied:

$$w_i^{c,\mathrm{sc}} = \frac{w_l + w_m + w_u}{3}, \tag{13}$$

where $w_i^{c,\mathrm{sc}}$ is the crisp weight of the ith main or sub-criterion, w_l is the lower boundary, w_u is the upper boundaryand w_m is the mean value of the fuzzy weight of the ith criterion.

The crisp values should be normalized to obtain much more comprehensible results as follows (Ding 2011):

$$(w_N)_i^c = \frac{w_i^c}{\sum_{i=1}^{b} w_i^c}, \tag{14}$$

where$(w_N)_i^c$ is the normalized crisp weight of the ith main criterion, $w_i^c$is the crisp weight of the ith main criterion calculated by Equation (13)and b is the number of main criteria.

For sub-criteria, the following equation is used:

$$(w_N)_i^{\mathrm{sc}} = \frac{w_i^{\mathrm{sc}}}{\sum_{i=1}^{g} w_i^{\mathrm{sc}}}, \tag{15}$$

where $(w_N)_i^{\mathrm{sc}}$ is the normalized crisp weight of the ith sub-criterion, w_i^{sc} is the crisp weight of the ith sub-criterion calculated by Equation (13)and g is the number of sub-criteria under the germane main criterion.

Step 8: calculation of the relative criteria weights

In order to compare sub-criteria among themselves, relative crisp weights are calculated as follows:

$$(w_R)_i^{\mathrm{sc}} = (w_N)^c \times (w_N)_i^{\mathrm{sc}}, \tag{16}$$

where $(w_R)_i^{\mathrm{sc}}$is the relative crisp weight of the ith sub-criterion, $(w_N)^c$ is the normalized crisp weight of the main criterion which includes the germane sub-criterion, $(w_N)_i^{\mathrm{sc}}$ is the normalized crisp weight of the ith sub-criterion, $i = 1, \ldots, g$and g is the number of sub-criteria under the germane main criterion. Due to the fact that number of sub-criteria under each main criterion is not equal, an equalization process is recommended in order to obtain a realistic comparison:

$$(w_E)_i^{\mathrm{sc}} = (w_R)_i^{\mathrm{sc}} \times \frac{g}{t}, \tag{17}$$

where $(w_E)_i^{\mathrm{sc}}$ is the equalized crisp weight of the ith sub-criterion, g is the number of sub-criteria under the germane main criteria and t is the total number of sub-criteria. After

this, a normalization is applied:

$$(w_E^N)_i^{sc} = \frac{(w_E)_i^{sc}}{\sum_{i=1}^{t}(w_E)_i^{sc}}, \quad (18)$$

where $(w_E^N)_i^{sc}$ is the equalized and normalized crisp weight of the *i*th sub-criterion and *t* is the total number of all sub-criteria.

Application

In this study, the preferences of four experts who have experience with shipbuilding were collected.

Step 1: definition of the criteria

The model constructed in this study consists of five main criteria: *financial conditions*, *managerial conditions*, *technical competence*, *experience* and *work safety policy*. These main criteria also include a considerable number of sub-criteria (Table 1 and Figure 2).

Step 2: definition of the linguistic terms

The linguistic terms used in the study and their equivalent fuzzy numbers are given in Table 2 (Erensal et al. 2006).

Step 3: the collection of expert preferences

The expert preferences on the degree of importance of each criterion were collected using a questionnaire. To illustrate the collected data, the preferences of Expert 1 for the degree of importance of each main criterion are presented in Table 3.

Table 1. The definitions of the sub-criteria used in the shipyard selection process.

Sub-criteria	Definition
Bid price (F1)	What is the price quoted by the shipyard?
Payment conditions (F2)	What are the payment dates and instalments?
Claiming extra payment for revisions (F3)	Will the shipyard request extra payments from the ship owner for all revisions?
Institutional structure (M1)	Does the shipyard have the departments needed for shipbuilding and does it have a well-organized structure?
Financial status (M2)	What is the current balance sheet of the shipyard?
Current workload (M3)	How many existing projects does the shipyard currently have?
Physical facilities provided to shipowner's staff (M4)	Does the shipyard provide offices, office furniture and equipment, Internet access, etc. for the ship owner's staff?
Jurisdiction of shipowner's staff (M5)	Can the shipowner's staff give input and exercise influence during the ship building process?
Number of shipowner's staff members permitted (M6)	How many of the shipowner's staff members can enter the shipyard for inspecting the ship?
Conflict resolution procedures (M7)	How does shipyard approach conflict resolution during the fabrication process (e.g., arbitration or court)?
Use of information technology (M8)	Does the shipyard employ the use of information technology such as enterprise resource planning (ERP)?
Number of engineers (T1)	How many engineers does the shipyard have?
Number of foremen (T2)	How many foremen does the shipyard have?
Number of workers (T3)	How many workers does the shipyard have?
Quality control policy (T4)	Does the shipyard have quality control system certifications?
Technological infrastructure (T5)	What are the features and quantities of the equipment and machinery in the shipyard?
Delivery on time (T6)	What is the performance on past projects in terms of delivering on time?
Delivery date (T7)	When will the shipyard deliver the commissioned vessel?
Capacity of slipway (T8)	What are the dimensions of the slipways located in the shipyard?
Lifting capacity of cranes (T9)	How much can the cranes lift (maximum load in t)?
Covered area (T10)	Are the fabrication work centres covered?
Compliance with specification changes (T11)	If the shipowner needs to make modifications to the specification during the fabrication process, will the shipyard facilitate or obstruct the changes?
Quality of similar ships built (T12)	What is the nature of the quality and performance of the vessels fabricated by the shipyard in the past?
Number of similar ships built (E1)	How many vessels similar to the vessel commissioned by the shipowner has the shipyard fabricated in the past?
Tonnage of biggest ship built (E2)	What is the tonnage of the largest ship fabricated by the shipyard to date?
Age of shipyard (E3)	How long has the shipyard been operating?
Presence of work safety staff (S1)	Does the shipyard have occupational safety staff?
Work safety education (S2)	Are safety training activities periodically performed?
Use of protective equipment (S3)	Do employees regularly use individual protective equipment?
Reliability of using protective equipment (S4)	Does the protective equipment adhere to current regulations?
Number of severe accidents (S5)	How many severe work accidents have occurred in the past?

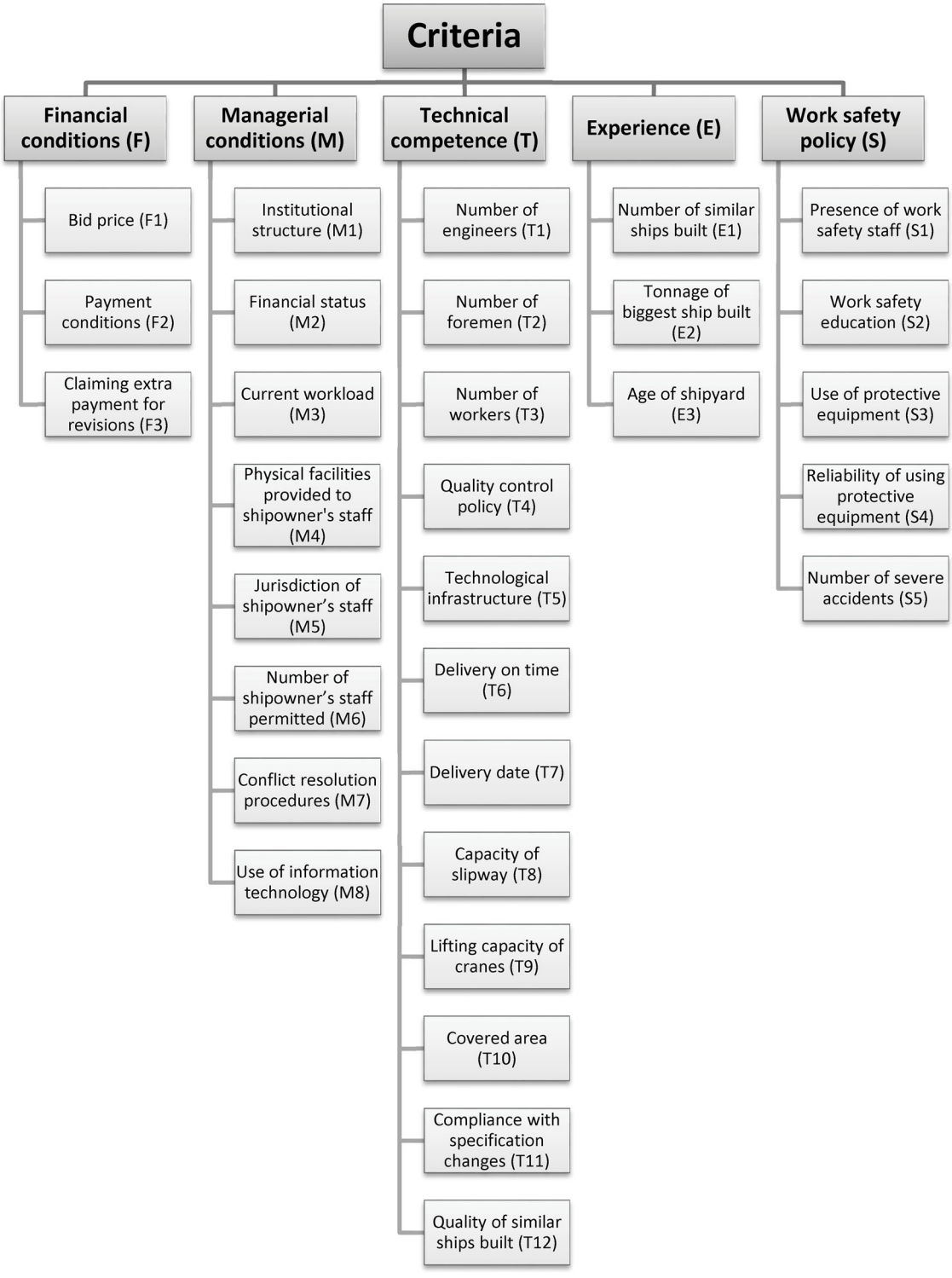


Figure 2. All main and sub-criteria used in the study.

Step 4: the transformation of the data into TFNs

In this paper, the linguistic scale given in Table 2 was used for pairwise comparisons. The linguistic terms were converted into TFNs by using this scale. For instance, *column very str. im.* in Table 3 was converted to (1/9,1/7, 1/5). In the same way, *row very str. im.* was converted to (5,7,9).

Table 2. Linguistic terms used to evaluate the criteria and sub-criteria.

Equally important	(1,1,1)
Moderately more important	(1,3,5)
Strongly more important	(3,5,7)
Very strongly more important	(5,7,9)
Demonstrativelymore important	(7,9,11)

Step 5: aggregation of the experts' preferences

There are four experts in the evaluation procedure and it is accepted that each specialist has the same authorization for the final decision. The aggregated fuzzy decision matrices were calculated by Equations (9) and (10) and are given in Tables 4–9. As an example, aggregation for pairwise comparisons of the *financial conditions* and *managerial conditions* criteria is calculated below:

$$\begin{aligned}\tilde{e}_{12}^{a} &= (\tilde{e}_{12}^{1} \otimes \tilde{e}_{12}^{2} \otimes \tilde{e}_{12}^{3} \otimes \tilde{e}_{12}^{4})^{1/4} \\ &= \left(\left(\frac{1}{9}, \frac{1}{7}, \frac{1}{5}\right) \otimes (7,9,11) \otimes (5,7,9) \otimes (5,7,9)\right)^{1/4} \\ &= \left(\left(\frac{1}{9} \times 7 \times 5 \times 5\right)^{1/4}, \left(\frac{1}{7} \times 9 \times 7 \times 7\right)^{1/4}, \right. \\ &\quad \left. \left(\frac{1}{5} \times 11 \times 7 \times 7\right)^{1/4}\right) \\ &= (2.1, 2.817, 3.654).\end{aligned}$$

Step 6: calculation of the criteria weights

The fuzzy weights of the criteria calculated by Buckley's (1985) Fuzzy AHP according to Equations (11) and (12) are given in Table 10. As an example, the fuzzy weight of the *financial conditions* criterion was calculated as follows:

$$\begin{aligned}\tilde{r}_1 &= (\tilde{e}_{11}^{a} \otimes \tilde{e}_{12}^{a} \otimes \tilde{e}_{13}^{a} \otimes \tilde{e}_{14}^{a} \otimes \tilde{e}_{15}^{a})^{1/5} \\ &= ((1.000, 1.000, 1.000) \otimes (2.100, 2.817, 3.654) \\ &\quad \otimes (0.411, 0.669, 1.136) \otimes (0.508, 0.699, 1.088) \\ &\quad \otimes (0.669, 1.316, 2.236))^{1/5} \\ &= (0.782, 1.116, 1.588); \\ \tilde{r}_2 &= (\tilde{e}_{21}^{a} \otimes \tilde{e}_{22}^{a} \otimes \tilde{e}_{23}^{a} \otimes \tilde{e}_{24}^{a} \otimes \tilde{e}_{25}^{a})^{1/5} \\ &= ((0.274, 0.355, 0.476) \otimes (1.000, 1.000, 1.000) \\ &\quad \otimes (0.378, 0.553, 1.000) \otimes (0.253, 0.340, 0.577) \\ &\quad \otimes (0.589, 0.863, 1.627))^{1/5} \\ &= (0.434, 0.565, 0.851); \\ \tilde{r}_3 &= (\tilde{e}_{31}^{a} \otimes \tilde{e}_{32}^{a} \otimes \tilde{e}_{33}^{a} \otimes \tilde{e}_{34}^{a} \otimes \tilde{e}_{35}^{a})^{1/5} \\ &= ((0.880, 1.495, 2.432) \otimes (1.000, 1.809, 2.646) \\ &\quad \otimes (1.000, 1.000, 1.000) \otimes (0.669, 0.939, 1.732) \\ &\quad \otimes (0.880, 1.495, 2.432))^{1/5} \\ &= (0.877, 1.306, 1.935); \\ \tilde{r}_4 &= (\tilde{e}_{41}^{a} \otimes \tilde{e}_{42}^{a} \otimes \tilde{e}_{43}^{a} \otimes \tilde{e}_{44}^{a} \otimes \tilde{e}_{45}^{a})^{1/5}\end{aligned}$$

Table 3. Pairwise comparison for the main criteria.

	Financial conditions (F)	Managerial conditions (M)	Technical competence (T)	Experience (E)	Work safety policy (S)
F	–	Column very str. im.	Column mod. im.	Row-column eq.	Row mod. im.
M	Row very str. im.	–	Row very str im.	Row-column eq.	Row str. im.
T	Row mod . im.	Column very str. im.	–	Column mod. im.	Row str. im.
E	Row-column eq.	Row-column eq.	Row mod. im.	–	Row-column eq.
S	Column mod. im.	Column str. im.	Column str. im.	Row-column eq.	–

Table 4. Aggregated pairwise comparisons for the main criteria.

	Financial conditions (F)	Managerial conditions (M)	Technical competence (T)	Experience (E)	Work safety policy (S)
F	(1.000,1.000,1.000)	(2.100,2.817,3.654)	(0.411,0.669,1.136)	(0.508,0.699,1.088)	(0.669,1.316,2.236)
M	(0.274,0.355,0.476)	(1.000,1.000,1.000)	(0.378,0.553,1.000)	(0.253,0.340,0.577)	(0.589,0.863,1.627)
T	(0.880,1.495,2.432)	(1.000,1.809,2.646)	(1.000,1.000,1.000)	(0.669,0.939,1.732)	(0.880,1.495,2.432)
E	(0.919,1.432,1.968)	(1.732,2.943,3.956)	(0.577,1.065,1.495)	(1.000,1.000,1.000)	(0.669,1.000,1.495)
S	(0.447,0.760,1.495)	(0.615,1.158,1.699)	(0.411,0.669,1.136)	(0.669,1.000,1.495)	(1.000,1.000,1.000)

Table 5. Aggregated pairwise comparisons for the *financial conditions* sub-criteria.

	Bid price (F1)	Payment conditions (F2)	Claiming extra payment for revisions (F3)
F1	(1.000,1.000,1.000)	(0.669,0.939,1.732)	(0.615,1.524,2.541)
F2	(0.577,1.065,1.495)	(1.000,1.000,1.000)	(1.592,2.432,3.482)
F3	(0.394,0.656,1.627)	(0.287,0.411,0.628)	(1.000,1.000,1.000)

Table 6. Aggregated pairwise comparisons for the *managerial conditions* sub-criteria.

	Institutional structure (M1)	Financial status (M2)	Current workload (M3)	Physical facilities provided to shipowner's staff (M4)
M1	(1.000,1.000,1.000)	(0.760,1.136,1.884)	(0.508,0.919,1.627)	(1.401,2.236,3.270)
M2	(0.531,0.880,1.316)	(1.000,1.000,1.000)	(1.291,1.627,2.006)	(2.590,4.787,6.853)
M3	(0.615,1.088,1.968)	(0.498,0.615,0.775)	(1.000,1.000,1.000)	(0.577,1.000,1.732)
M4	(0.306,0.447,0.714)	(0.146,0.209,0.386)	(0.577,1.000,1.732)	(1.000,1.000,1.000)
M5	(0.483,0.656,1.000)	(0.155,0.227,0.439)	(1.210,2.141,3.201)	(0.809,1.316,1.848)
M6	(0.275,0.508,1.136)	(0.275,0.508,1.136)	(0.589,1.136,2.432)	(0.378,0.447,0.577)
M7	(1.000,1.524,2.069)	(0.669,1.158,2.069)	(1.088,1.732,2.723)	(1.000,1.524,2.069)
M8	(0.809,1.000,1.236)	(0.159,0.237,0.508)	(0.447,0.577,1.000)	(0.226,0.293,0.467)
	Jurisdiction of shipowner's staff (M5)	Number of shipowner's staff permitted (M6)	Conflict resolution procedures (M7)	Use of information technology (M8)
M1	(1.000,1.524,2.069)	(0.880,1.968,3.637)	(0.483,0.656,1.000)	(0.809,1.000,1.236)
M2	(2.280,4.401,6.435)	(0.880,1.968,3.637)	(0.483,0.863,1.495)	(1.968,4.213,6.300)
M3	(0.312,0.467,0.827)	(0.411,0.880,1.699)	(0.367,0.577,0.919)	(1.000,1.732,2.236)
M4	(0.541,0.760,1.236)	(1.732,2.236,2.646)	(0.483,0.656,1.000)	(2.141,3.409,4.430)
M5	(1.000,1.000,1.000)	(1.732,2.943,3.956)	(0.549,0.714,1.065)	(0.809,1.236,2.141)
M6	(0.253,0.340,0.577)	(1.000,1.000,1.000)	(0.226,0.293,0.467)	(0.809,1.316,1.848)
M7	(0.939,1.401,1.821)	(2.141,3.409,4.430)	(1.000,1.000,1.000)	(0.939,1.316,2.109)
M8	(0.467,0.809,1.236)	(0.541,0.760,1.236)	(0.474,0.760,1.065)	(1.000,1.000,1.000)

Table 7. Aggregated pairwise comparisons for the *technical competence* sub-criteria.

	Number of engineers (T1)	Number of foremen (T2)	Number of workers (T3)	Quality control policy (T4)	Technological infrastructure (T5)	Delivery on time (T6)
T1	(1.000,1.000,1.000)	(1.158,1.699,2.646)	(0.483,0.656,1.000)	(0.273,0.386,0.577)	(0.541,0.760,1.236)	(0.257,0.355,0.508)
T2	(0.378,0.589,0.863)	(1.000,1.000,1.000)	(1.081,1.848,2.590)	(0.273,0.386,0.577)	(0.208,0.340,0.531)	(0.195,0.312,0.467)
T3	(1.000,1.524,2.069)	(0.386,0.541,0.925)	(1.000,1.000,1.000)	(0.232,0.394,0.656)	(0.253,0.447,0.863)	(0.195,0.312,0.467)
T4	(1.732,2.590,3.661)	(1.732,2.590,3.661)	(1.524,2.541,4.304)	(1.000,1.000,1.000)	(1.732,2.236,2.646)	(0.212,0.270,0.411)
T5	(0.809,1.316,1.848)	(1.884,2.943,4.818)	(1.158,2.236,3.956)	(0.378,0.447,0.577)	(1.000,1.000,1.000)	(0.279,0.403,0.669)
T6	(1.968,2.817,3.899)	(2.141,3.201,5.131)	(2.141,3.201,5.131)	(2.432,3.708,4.717)	(1.495,2.480,3.584)	(1.000,1.000,1.000)
T7	(1.627,2.141,3.154)	(1.627,2.817,4.717)	(1.627,2.817,4.717)	(1.404,1.732,2.109)	(1.627,2.141,3.154)	(1.236,1.592,1.981)
T8	(1.968,2.817,3.899)	(2.432,3.708,4.717)	(2.432,3.708,4.717)	(0.541,1.000,1.848)	(0.541,0.760,1.236)	(0.444,0.760,1.136)
T9	(1.968,3.201,4.213)	(1.968,4.213,6.300)	(1.968,4.213,6.300)	(0.615,0.827,1.316)	(0.615,0.880,1.136)	(0.208,0.258,0.355)
T10	(0.615,1.158,1.699)	(1.000,1.732,2.236)	(0.615,1.158,1.699)	(0.386,0.467,0.669)	(0.447,0.577,1.000)	(0.195,0.237,0.312)
T11	(0.809,1.000,1.236)	(1.000,1.236,1.732)	(1.316,1.848,2.817)	(0.386,0.467,0.669)	(0.589,0.863,1.627)	(0.483,0.656,1.000)
T12	(0.669,1.732,3.344)	(0.669,1.732,3.344)	(0.880,1.968,3.637)	(0.669,0.760,1.000)	(0.669,0.760,1.000)	(0.549,0.577,0.615)
	Delivery date (T7)	Capacity of slipway (T8)	Lifting capacity of cranes (T9)	Covered area (T10)	Compliance with specification changes (T11)	Quality of similar ships built (T12)
T1	(0.317,0.467,0.615)	(0.257,0.355,0.508)	(0.237,0.312,0.508)	(0.589,0.863,1.627)	(0.809,1.000,1.236)	(0.299,0.577,1.495)
T2	(0.212,0.355,0.615)	(0.212,0.270,0.411)	(0.159,0.237,0.508)	(0.447,0.577,1.000)	(0.577,0.809,1.000)	(0.299,0.577,1.495)
T3	(0.212,0.355,0.615)	(0.212,0.270,0.411)	(0.159,0.237,0.508)	(0.589,0.863,1.627)	(0.355,0.541,0.760)	(0.275,0.508,1.136)
T4	(0.474,0.577,0.712)	(0.541,1.000,1.848)	(0.760,1.210,1.627)	(1.495,2.141,2.590)	(1.495,2.141,2.590)	(1.000,1.316,1.495)
T5	(0.317,0.467,0.615)	(0.809,1.316,1.848)	(0.880,1.136,1.627)	(1.000,1.732,2.236)	(0.615,1.158,1.699)	(1.000,1.316,1.495)
T6	(0.505,0.628,0.809)	(0.880,1.316,2.251)	(2.817,3.873,4.818)	(3.201,4.213,5.131)	(1.000,1.524,2.069)	(1.627,1.732,1.821)
T7	(1.000,1.000,1.000)	(5.207,7.297,9.344)	(3.482,4.486,5.395)	(4.583,6.708,8.775)	(2.646,3.948,4.960)	(2.646,3.000,3.317)
T8	(0.107,0.137,0.192)	(1.000,1.000,1.000)	(1.000,1.316,1.495)	(1.316,2.590,3.637)	(0.411,0.669,1.136)	(0.447,0.760,1.495)
T9	(0.185,0.223,0.287)	(0.669,0.760,1.000)	(1.000,1.000,1.000)	(1.316,1.968,2.432)	(0.669,1.000,1.495)	(0.589,1.136,2.432)
T10	(0.114,0.149,0.218)	(0.275,0.386,0.760)	(0.411,0.508,0.760)	(1.000,1.000,1.000)	(0.355,0.411,0.508)	(0.411,0.508,0.760)
T11	(0.202,0.253,0.378)	(0.880,1.495,2.432)	(0.669,1.000,1.495)	(1.968,2.432,2.817)	(1.000,1.000,1.000)	(0.411,0.508,0.760)
T12	(0.302,0.333,0.378)	(0.669,1.316,2.236)	(0.411,0.880,1.699)	(1.316,1.968,2.432)	(1.316,1.968,2.432)	(1.000,1.000,1.000)

Table 8. Aggregated pairwise comparisons for the *experience* sub-criteria.

	Number of similar ships built (E1)	Tonnage of biggest ship built (E2)	Age of shipyard (E3)
E1	(1.000,1.000,1.000)	(4.787,6.853,8.887)	(1.065,1.495,2.010)
E2	(0.113,0.146,0.209)	(1.000,1.000,1.000)	(1.316,1.968,2.432)
E3	(0.497,0.669,0.939)	(0.411,0.508,0.760)	(1.000,1.000,1.000)

Table 9. Aggregated pairwise comparisons for the *work safety policy* sub-criteria.

	Presence of work safety staff (S1)	Work safety education (S2)	Use of protective equipment (S3)	Reliability of using protective equipment (S4)	Number of severe accidents (S5)
S1	(1.000,1.000,1.000)	(0.367,0.577,0.919)	(0.159,0.237,0.508)	(0.411,0.508,0.760)	(0.253,0.340,0.577)
S2	(1.088,1.732,2.723)	(1.000,1.000,1.000)	(1.000,1.236,1.732)	(1.495,2.141,2.590)	(1.495,2.010,3.000)
S3	(1.968,4.213,6.300)	(0.577,0.809,1.000)	(1.000,1.000,1.000)	(2.236,2.646,3.000)	(1.495,2.010,3.000)
S4	(1.316,1.968,2.432)	(0.386,0.467,0.669)	(0.333,0.378,0.447)	(1.000,1.000,1.000)	(1.375,1.769,2.280)
S5	(1.732,2.943,3.956)	(0.333,0.497,0.669)	(0.333,0.497,0.669)	(0.439,0.565,0.727)	(1.000,1.000,1.000)

$$
\begin{aligned}
&= ((0.919, 1.432, 1.968) \otimes (1.732, 2.943, 3.956) \\
&\quad \otimes (0.577, 1.065, 1.495) \otimes (1.000, 1.000, 1.000) \\
&\quad \otimes (0.669, 1.000, 1.495))^{1/5} \\
&= (0.907, 1.350, 1.771); \\
\tilde{r}_5 &= (\tilde{e}^a_{51} \otimes \tilde{e}^a_{52} \otimes \tilde{e}^a_{53} \otimes \tilde{e}^a_{54} \otimes \tilde{e}^a_{55})^{1/5} \\
&= ((0.447, 0.760, 1.495) \otimes (0.615, 1.158, 1.699) \\
&\quad \otimes (0.411, 0.669, 1.136) \otimes (0.669, 1.000, 1.495) \\
&\quad \otimes (1.000, 1.000, 1.000))^{1/5} \\
&= (0.597, 0.899, 1.340); \\
\tilde{w}_1 &= \tilde{r}_1 \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \tilde{r}_3 \oplus \tilde{r}_4 \oplus \tilde{r}_5)^{-1} \\
&= (0.782, 1.116, 1.588) \otimes ((0.782, 1.116, 1.588) \\
&\quad \oplus (0.434, 0.565, 0.851) \oplus (0.877, 1.306, 1.935) \\
&\quad \oplus (0.907, 1.350, 1.771) \oplus (0.597, 0.899, 1.340))^{-1} \\
&= (0.105, 0.213, 0.441).
\end{aligned}
$$

The subscripts are defined as follows: 1 = *financial conditions*, 2 = *managerial conditions*, 3 = *technical competence*, 4 = *experience* and 5 = *work safety policy*.

Step 7: the defuzzification and normalization procedure for the fuzzy weights

Firstly, the fuzzy weights were def uzzified to obtain crisp weights using Equation (13). After this, normalized crisp criteria weights were calculated according to Equations (14) and (15). The normalized crisp weights are given in Table 10. As an example, the defuzzification and normalization of the main criteria are as follows (with the subscripts defined as in the previous step:

$$
\begin{aligned}
w_1^c &= \frac{(0.105 + 0.213 + 0.441)}{3} = 0.253; \\
w_2^c &= \frac{(0.058 + 0.108 + 0.237)}{3} = 0.134; \\
w_3^c &= \frac{(0.117 + 0.249 + 0.538)}{3} = 0.301, \\
w_4^c &= \frac{(0.121 + 0.258 + 0.492)}{3} = 0.290; \\
w_5^c &= \frac{(0.080 + 0172 + 0.372)}{3} = 0.208; \\
(w_N)_i^c &= \frac{w_i^c}{\sum_{i=1}^{5} w_i^c}; \\
\sum_{i=1}^{5} w_i^c &= 0.253 + 0.134 + 0.301 + 0.290 + 0.208 = 1.186; \\
(w_N)_1^c &= \frac{0.253}{1.186} = 0.213; \\
(w_N)_2^c &= \frac{0.134}{1.186} = 0.113; \\
(w_N)_3^c &= \frac{0.301}{1.186} = 0.254; \\
(w_N)_4^c &= \frac{0.290}{1.186} = 0.245; \\
(w_N)_5^c &= \frac{0.208}{1.186} = 0.175.
\end{aligned}
$$

Step 8: calculation of the relative criteria weights

The relative crisp weights were calculated using Equation (16), and the equalized and normalized crisp weights were calculated using Equations (17) and (18) (Table 10). As an example, the equalized and normalized crisp weight of the sub-criterion *bid price* is calculated below:

$$
\begin{aligned}
(w_R)_1^{sc} &= (w_N)^c \times (w_N)_1^{sc} = 0.213 \times 0.364 = 0.078; \\
&\vdots
\end{aligned}
$$

Table 10. The degrees of importance of all main and sub-criteria.

Main and sub-criteria	Fuzzy weights	Normalized crisp weights	Relative crisp weights	Equalized and normalized weights
Financial conditions (F)	**(0.105,0.213,0.441)**	**0.213**		
Bid price (F1)	(0.170,0.358,0.745)	0.364	0.078	0.038
Payment conditions (F2)	(0.222,0.436,0.788)	0.414	0.088	0.043
Claiming extra payment for revisions (F3)	(0.110,0.205,0.458)	0.221	0.047	0.023
Managerial conditions (M)	**(0.058,0.108,0.237)**	**0.113**		
Institutional structure (M1)	(0.064,0.140,0.307)	0.140	0.016	0.020
Financial status (M2)	(0.092,0.226,0.490)	0.221	0.025	0.032
Current workload (M3)	(0.043,0.098,0.224)	0.100	0.011	0.015
Physical facilities provided to shipowner's staff (M4)	(0.050,0.102,0.222)	0.102	0.012	0.015
Jurisdiction of shipowner's staff (M5)	(0.055,0.117,0.258)	0.118	0.013	0.017
Number of shipowner's staff permitted (M6)	(0.032,0.070,0.172)	0.075	0.008	0.011
Conflict resolution procedures (M7)	(0.082,0.176,0.369)	0.172	0.019	0.025
Use of information technology (M8)	(0.035,0.070,0.159)	0.072	0.008	0.011
Technical competence (T)	**(0.117,0.249,0.538)**	**0.254**		
Number of engineers (T1)	(0.023,0.044,0.095)	0.047	0.012	0.023
Number of foremen (T2)	(0.018,0.036,0.081)	0.039	0.010	0.019
Number of workers (T3)	(0.017,0.036,0.083)	0.039	0.010	0.019
Quality control policy (T4)	(0.050,0.099,0.186)	0.096	0.024	0.047
Technological infrastructure (T5)	(0.038,0.079,0.154)	0.078	0.020	0.038
Delivery on time (T6)	(0.081,0.155,0.291)	0.152	0.038	0.074
Delivery date (T7)	(0.108,0.204,0.378)	0.199	0.050	0.098
Capacity of slipway (T8)	(0.040,0.083,0.168)	0.084	0.021	0.041
Lifting capacity of cranes (T9)	(0.039,0.081,0.160)	0.081	0.020	0.040
Covered area (T10)	(0.021,0.040,0.081)	0.041	0.010	0.020
Compliance with specification changes (T11)	(0.036,0.065,0.130)	0.066	0.017	0.033
Quality of similar ships built (T12)	(0.036,0.079,0.159)	0.079	0.020	0.039
Experience (E)	**(0.121,0.258,0.492)**	**0.245**		
Number of similar ships built (E1)	(0.400,0.615,0.921)	0.610	0.149	0.072
Tonnage of biggest ship built (E2)	(0.123,0.187,0.281)	0.186	0.046	0.022
Age of shipyard (E3)	(0.137,0.198,0.315)	0.204	0.050	0.024
Work safety policy (S)	**(0.080,0.172,0.372)**	**0.175**		
Presence of work safety staff (S1)	(0.050,0.085,0.173)	0.094	0.016	0.013
Work safety education (S2)	(0.166,0.280,0.487)	0.284	0.050	0.040
Use of protective equipment (S3)	(0.182,0.321,0.532)	0.314	0.055	0.044
Reliability of using protective equipment (S4)	(0.104,0.163,0.262)	0.161	0.028	0.023
Number of severe accidents (S5)	(0.085,0.151,0.249)	0.147	0.026	0.021

$$(w_R)^{\text{sc}}_{31} = (w_N)^c \times (w_N)^{\text{sc}}_{31} = 0.175 \times 0.147 = 0.026;$$

$$(w_E)^{\text{sc}}_1 = (w_R)^{\text{sc}}_1 \times \frac{g}{t} = 0.078 \times \frac{3}{31} = 0.008;$$

$$\vdots$$

$$(w_E)^{\text{sc}}_{31} = (w_R)^{\text{sc}}_{31} \times \frac{g}{t} = 0.026 \times \frac{5}{31} = 0.004;$$

$$\sum_{i=1}^{31} (w_E)^{\text{sc}}_i = 0.200;$$

$$(w^N_E)^{\text{sc}}_1 = \frac{(w_E)^{\text{sc}}_1}{\sum_{i=1}^{31}(w_E)^{\text{sc}}_1} = \frac{(w_R)^{\text{sc}}_1 \times (g/t)}{\sum_{i=1}^{31}(w_E)^{\text{sc}}_1} = \frac{0.078 \times \frac{3}{31}}{0.200} = 0.038.$$

In the above calculations, $g = 3$ because *bid price* comes under the main criterion *financial conditions* and there are a total of 3 sub-criteria under this criterion, and $t = 31$ because there are 31 sub-criteria in total across all main criteria.

Discussion

According to the calculated weights using Buckley's (1985) fuzzy AHP, criteria are compared in this chapter. Figure 3 shows the weights of the main criteria which

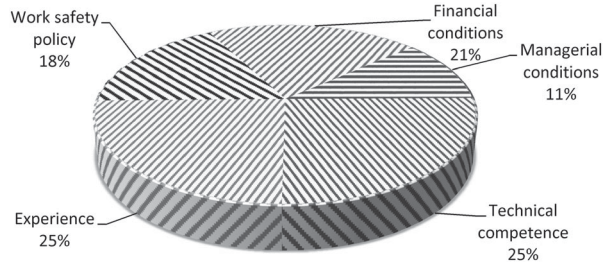


Figure 3. The degrees of importance for the main criteria.

play a role in shipyard selection. *Technical competence* and *experience* have a weight of 25% among all the criteria, so they are most considered by shipowners when selecting the shipyard, followed by *financial conditions*.

Figure 4 displays the sub-criteria of *financial conditions*. As can be seen, *payment conditions* is the most

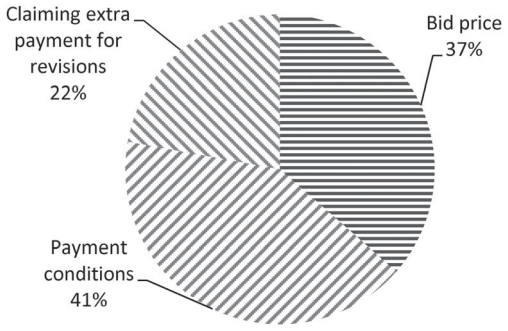


Figure 4. The degrees of importance for the *financial conditions* sub-criteria.

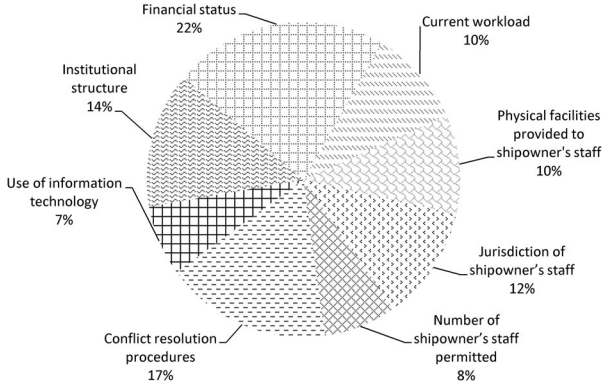


Figure 5. The degrees of importance for the *managerial conditions* sub-criteria.

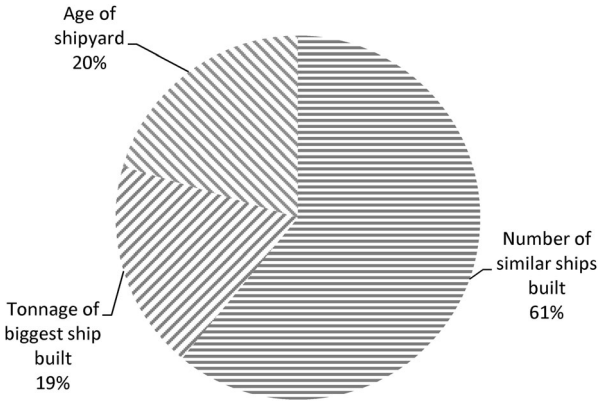


Figure 7. The degrees of importance for the *experience* sub-criteria.

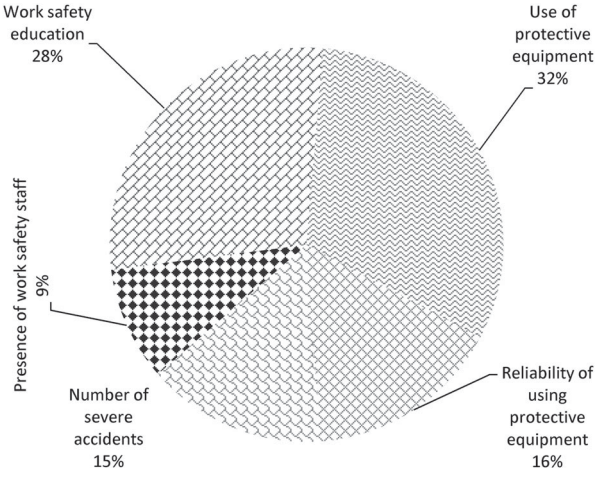


Figure 8. The degrees of importance for the *work safety policy* sub-criteria.

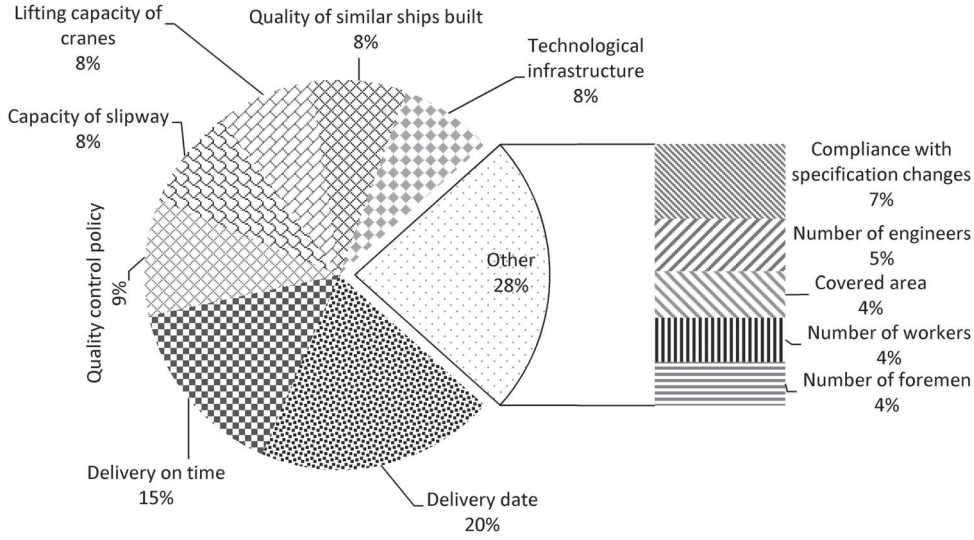


Figure 6. The degrees of importance for the *technical competence* sub-criteria.

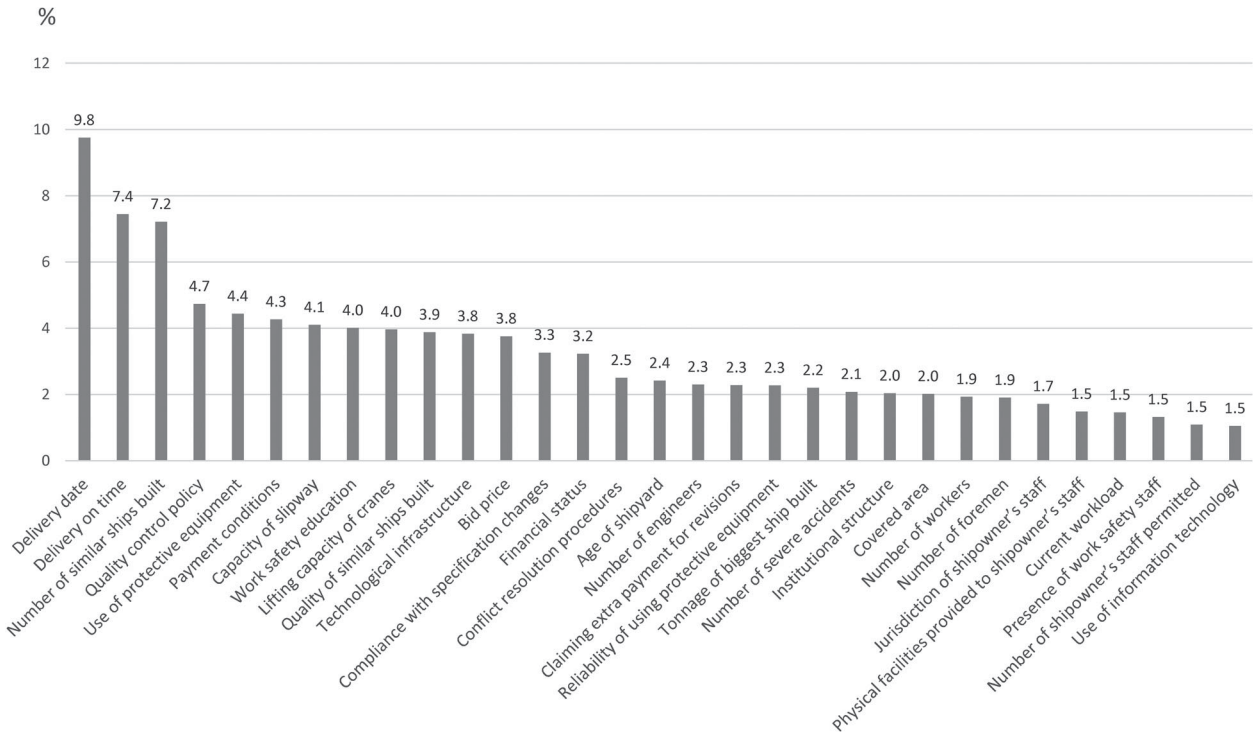


Figure 9. The degrees of importance for all sub-criteria.

significant sub-criteria since it has a weight of 41% in *financial conditions*.

Figure 5 depicts the sub-criteria of *managerial conditions* and it can be seen that *financial status* and *conflict resolution procedures* have more weights than the others. Therefore, in terms of *managerial conditions*, these two sub-criteria have more influence on shipowners in the decision-making process.

Figure 6 shows the sub-criteria of *technical competence*. In this criterion, it is the *delivery date* and *delivery on time* which are most important to the shipowner.

Figure 7 displays the sub-criteria of *experience*. Accordingly, the sub-criterion of *number of similar ships built* has a weight of 61%. Therefore, the most important factor is the shipyard's experience in constructing vessels similar to the one that the shipowner requires.

Figure 8, which examines the sub-criteria of *work safety policy*, shows that the sub-criteria of *use of protective equipment* and *work safety education* are considered by the shipowner in the shipyard selection process.

Figure 9 depicts the weights of each sub-criterion among all sub-criteria. For instance, *delivery date* has a weight of around 10% across all sub-criteria, while *delivery on time* and *number of similar ships built* follow with a weight of around 7%. In this way, the weights of all the sub-criteria and their degrees of importance in the shipyard selection process can be seen in Figure 9.

Conclusion

Taking into consideration the main criteria, *technical competence* and *experience* are the most significant for shipowners by a weight of around 25%. Examining the sub-criteria, the most important factors for the shipowner are *delivery date*, *delivery on time*, *number of similar ships built*, *quality control policy* and *use of protective equipment*, which have percentages of 9.8%, 7.4%, 7.2%, 4.7% and 4.4%, respectively.

Shipyard management can now consider the viewpoints of shipowners and the most crucial factors to their decision-making process when determining which shipyard to select, and then modify their performance and presentation accordingly. By strengthening any of the most important areas which may currently be weak, they are likely to increase the number of orders they receive from shipowners.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1

The survey was prepared in Microsoft Excel. Experts evaluated the degree of importance of each criterion by making pairwise comparisons. Figure 10 depicts a portion of the survey. White coloured cells were filled based on the following procedure.

The decision-maker chooses the degree of importance of the selection criterion by comparing it with the other criteria for shipyard selection. If the criterion in the row is judged as being more important than the criterion the in column then one of the options below is selected in order to determine 'how important the criterion is':

- Row demon. im. (the criterion in the row is demonstratively more important than the criterion in the column);
- Row very str. im. (the criterion in the row is very strongly more important than the criterion in the column);
- Row str. im. (the criterion in the row is strongly more important than the criterion in the column);
- Row mod. im. (the criterion in the row is moderately more important than the criterion in the column).

If the criterion in the column is judged as being more important than the criterion in the row then one of the options below is selected in order to determine 'how important the criterion is':

- Column mod. im. (the criterion in the column is moderately more important than the criterion in the row);
- Column str. im. (the criterion in the column is strongly more important than the criterion in the row);

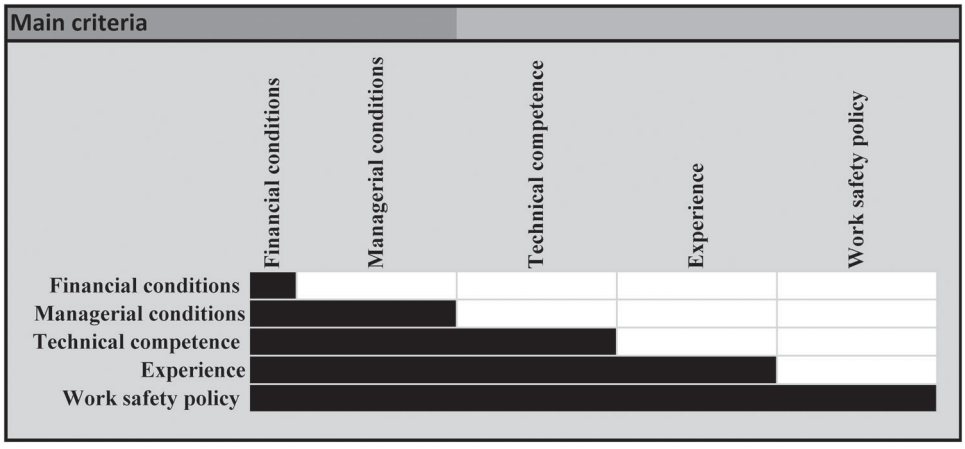


Figure 10. A portion of the survey.

- Column very str. im. (the criterion in the column is very strongly more important than the criterion in the row);
- Column demon. im. (the criterion in the column is demonstratively more important than the criterion in the row).

If the criterion in the row is judged as being equally important as the criterion in the column then the option below is selected in order to determine 'how important the criterion is':

- Row-column eq. (the criterion in the row is equally important to the criterion in the column).