Port Safety Evaluation from A Captain's Perspective: The Korean Experience

Abstract

There are many factors affecting navigational safety in ports, including weather, the characteristics of the channels and vessel types, etc. This paper aims to identify the factors influencing navigational safety in ports and to analyze the extent to which such factors affect the safety of ports from the perspective of ship captains through a real case study. A quantitative analysis is carried out using the data collected from 21 captains who have over 10 years experience in operating ships individually. The identified factors indicate risk implications in ports. A fuzzy analytical hierarchy process is used to evaluate the importance of the factors and to rank the safety levels of the targeted ports in Korea from a captain's perspective. Consequently, among Busan, Ulsan, Gwangyang, Incheon, and Mokpo, Busan is evaluated by captains as the safest port, while Mokpo is the most risky. The research also reveals that it is applicable to use domain expert knowledge when historical failure data is unavailable or difficult to access to evaluate port safety. The result shows great research significance in terms of providing relevant stakeholders, such as port authorities and shipping companies, with an insight into port safety performance and thus facilitating the development of the associated risk control measures.

Keywords: Port safety factors, Maritime transport, Fuzzy AHP, Safety evaluation, Maritime risk, Maritime safety, Expert knowledge

1. Introduction

Catastrophic maritime accidents still occur as demonstrated by the Costa Concordia accident despite great efforts to reduce their likelihood and consequences. Vessels are gradually increasing in size and speed, as well as being involved in higher traffic volumes, particularly in narrowing waters, such as ports (Liu et al., 2005). Consequently, marine accidents happen more likely in such waters causing extensive loss of lives, damage to vessels and cargo, and serious marine pollution. Regarding the marine pollution, Cho (2007) stated that the maritime accidents caused serious marine pollution over a large area of southern coastal water in Korea as well as damage to the fisheries.

The fact that Korea is surrounded by water has contributed to the development of its international trade. This has led to an increase of maritime traffic in ports and their associated narrow waters, which will affect port and maritime navigational safety. Evidence shows that among 882 marine accidents occurred from 2002 to 2008 in Korean waters, approximately one-fifth occurred in ports (Korea Coast Guard, 2008). It is therefore urgent to identify the factors influencing port safety and evaluate the navigational safety levels of Korean ports.

There are many factors that can cause the occurrence of the accidents in ports. Different stakeholders may have different concerns regarding such factors. This study mainly focuses on the captains' perception in order to identify the factors that can affect port navigational safety and analyze their influence using a fuzzy analytical hierarchy process (AHP). This paper applies a fuzzy AHP approach to overcome the difficulties involved in collecting historical data and quantifying experts' knowledge, experience, and conceptions. Pan (2008) stated that fuzzy AHP is a method capable of handling the inherent subjectivity and ambiguity involved in identifying perceptions in order to extract numbers. In this study, a questionnaire is designed and used to collect the required data from captains with more than

10 years experience in moving ships in Korean ports. To effectively collect the captains' judgments, linguistic terms are often be used. One realistic way to model linguistic terms is to use fuzzy set theory (Yang et al., 2011; 2012). In terms of the identification of major influencing factors, pairwise comparisons through an AHP approach are conducted to measure the importance of the influence factors (Promentilla, 2006). Combining fuzzy logic and AHP enables the evaluation of Korean port safety from a captain's perspective in a situation in which uncertainty in data is high.

In-depth interviews with experienced captains, together with a careful literature review, were carried out to identify the factors that affect port navigational safety in Korean ports. To evaluate the weights of the factors and the safety level of Korean ports, 21 experienced captains (who were carefully selected based on the navigational experience in Korean ports through Korean Maritime Pilot Association) provided their judgments via a designed questionnaire. Top five ports were selected in this study according to their traffic volume from 2000 to 2012. This paper is composed with five sections. A literature review on the issues of port safety and the safety factors relating to ports is presented in Section 2. Section 3 presents the methodology including the process of selecting port safety factors and the targeted ports, as well as the fuzzy AHP method. Section 4 describes an empirical study, including a questionnaire analysis, applying fuzzy AHP to the targeted ports, as well as a sensitivity analysis to validate the results. Finally, the conclusions and implications are given in Section 5.

2. Literature Review

There are no lack of studies conducted to reduce risks and extract the safety factors related to maritime traffic in ports. Fabiano et al. (2010) evaluated port safety in terms of the effect of containerization. Kaplan et al. (2000) examined the impact of fisheries' operations on safety at sea and the use of fishermen's opinions in the safety regulation and management process. Yip (2008) conducted a study on historical accidents in Hong Kong ports, and it was shown that port traffic risks follow a particular pattern and that collision is the most common accident when traffic is heavy. Hu et al. (2008) analyzed the risks related to the vessel traffic system at sea and developed a new method to establish safe ship operations.

Hazardous event evaluation was studied in terms of toxicity, reactivity, flammability, and the risk potential of handling chemicals by Rao and Raghavan (1996). All accidents in the Gulf of Finland were analyzed in terms of vessel and accident types, and the accident statistics were presented in the last 10 years (Kujala et al., 2009).

Jalonen et al. (2009) mentioned that factors in marine accidents include heavy storms, natural catastrophes, wind, current, etc., according to the marine accident database. These factors are external factors. An individual ship risk factor was shown using a fuzzy approach (Balmat et al., 2009), and ship capacity, ship history, and ship parameters (flag, year of construction, gross tonnage, number of companies, and duration of detention) were considered in the statistical risk evaluation. Also, Balmat et al. (2009) addressed the fact that weather conditions, such as wind speed, sea state, and visibility, were defined as a dynamic risk factor. Sage (2005) proposed the criteria used to monitor High Risk Vessels (HRVs) in coastal waters, and the criteria related to the ships, namely dynamic factors, such as the weather, sea, or traffic conditions, and the environmental sensitivity of the sea areas in which the ships are sailing.

Darbra and Casal (2004) suggested that the specific causes of accidents in seaports could be dividing into four types: (1) impacts (ship/land effects, ship/ship effects, general operations, heavy objects, rail accidents, high winds, and other causes), (2) mechanical errors (valve failures, flange coupling failures, metallurgy failures, hose failures, high winds, over pressure, and other causes), (3) human errors (general operation overfilling, maintenance, procedures, ship/land impacts, and other causes), and (4) external causes (high winds, sabotage, external fires, ship/land impacts, ship/ship impacts, and other causes).

Trbojevic and Carr (2000) presented specific hazards in port, and stated that *"Each specific hazard can be represented by one or several threats that have the potential to lead to an incident or top (initiating) event."* They listed eight general hazards: (1) impacts and collisions (vessel collisions, berthing impacts, and striking while at berth), (2) ship-related (flooding, loading/overloading, mooring failures, and anchoring failures), (3) navigation-related (navigation errors, pilotage errors, and vessels not under command), (4) maneuvering-related (fine maneuvering error and berthing/unberthing error), (5) fires/explosions (cargo tank fires/explosions, fires in accommodations, fires in the engine room, and other fires), (6) loss of containment (release of flammables and release of toxic materials), (7) pollution (crude oil spills and other cargo releases), and (8) environmental (extreme weather, winds exceeding port criteria, and strong currents).

The existing port accidents and port safety factor studies in the literature are mainly based on analysis of accident statistics in history (Christou, 1999; Darbra and Casal, 2004; Kujala, 2009; Jalonen and Salmi, 2009) and marine safety improvement factors (Hee et al., 1999; Trbojevic and Carr, 2002). Use of uncertainty modelling such as Bayesian network and evidential reasoning in risk assessment has been increasingly growing in recent years across different areas. In the maritime industries, use of Bayesian networks in risk studies is seen in (e.g. Hu et al., 2008; Yang et al, 2009a; Zhang et al., 2014), while evidential reasoning in Yang et al., 2009b; Yang et al., 2014). In various marine safety contexts, analytical methods have been developed to define risk factors and been documented in Yang et al. (2013). However, Bayesian networks require too much prior failure information when modelling casual relationships between risk factors. Evidential reasoning is mainly used to tackle the incompleteness in risk data. The preliminary investigation of Korean port safety analysis reveals that the interdependencies of the risk factors and incompleteness of subjective input data are insignificant. In other words, the combination of fuzzy logic and AHP is sufficiently capable of dealing with vagueness of expert evaluations and hierarchical structure presenting the risk factors relationship. In terms of the applications of fuzzy logics in risk research, Sii et al. (2001) and Lavasani et al., (2011) studied the safety assessment of maritime and offshore systems by using a fuzzy-logic-based approach, while Balmat et al. (2009) applied a fuzzy approach in maritime risk assessment. Fuzzy AHP concept was used to assess food safety risk in food supply chain management (Wang et al., 2012). Law et al. (2006) identified core safety management factors with respect to safety management systems (SMS) in the field of manufacturing enterprises using the analytic hierarchy process. Gürcanli and Müngen (2009) demonstrated useful parameters to assess workers' risk at a construction site using fuzzy sets. A fuzzy risk assessment was used to perform core hazard causes and types in the construction industry (Liu and Tsai, 2012). However, there is scant research in the existing literature investigating navigational safety in ports from a captain's perspective. The contribution of this study is to fill this research gap.

This study aims to present the factors affecting port safety from the perspective of captains and evaluate the navigational safety levels of five major Korean ports using the obtained factors. Fuzzy AHP presents an effective multiple-attribute decision making (MADM) tool that can accommodate both expert judgments and objective data and be used to evaluate port safety. It also has the advantages of easiness and visibility compared to other MADM and thus is selected for this investigation.

3. Methodology

3.1. Selection of port safety factors and ports to be investigated

This study consisted of four main steps, including the identification of influencing factors, selection of the ports being investigated, estimation of the factors' weights and evaluation of the ports' safety. The first step is to identify the critical factors influencing port safety from a captain's perspective. The safety factors were identified through the combination of literature reviews and in-depth interviews with domain experts. The in-depth interviews ensure that the factors which are important indicated by the relevant literature but not suitable to modeling the navigational safety in Korean ports, are eliminated. In order to identify and categorize the most relevant factors, a panel containing five navigationally experienced experts and a port authority was formed. The panel first selected five main factors from more than ten total factors (identified through the literature review) and then developed the sub-factors of each main one based on literature review and Korean port practices through a brainstorming process, as seen in Figure 1. The main factors and sub-factors were selected based on the following three questions.

Q1: Which factors can be eliminated from those selected in the literature review by considering the characteristics of Korean ports?

Q2: How do the remaining factors be grouped in accordance with their characteristics?

Q3: How should the grouped factors be presented in a hierarchy to facilitate the port safety evaluation?

The panel agreed to eliminate the factors of ship age, ship structure, natural catastrophes, and the close proximity of marine facilities through interactive discussions with respect to the characteristics of the accidents in history. Wind speed, wind direction, sea state, visibility, and current were categorized into a single main factor, ‘Weather/sea conditions’. Waterway was described as ‘Channel conditions’. Weather·sea condition and channel condition are classed as environmental factors. A traffic-related factor was specified as ‘Volume of traffic inside a port’. ‘Vessel size’ and ‘Vessel type’ were also included as the main factors. Fog, gale, wave height and tide were chosen as sub-factors of ‘Weather/sea conditions’. It is noteworthy that current was changed into tide because the Yellow Sea near the Korean peninsula has a large tidal range. Channel conditions were taken into account from the perspectives of depth, complexity, and width. For efficient evaluation, traffic volume was divided into heavy, average, and light. Vessel size was classified in an interval from 40,000 DWT to 100,000 DWT . Vessel type was divided according to the types of ships operating in Korean ports. In addition, the volume of traffic inside a port, ship size and ship type are classed as non-environmental factors.

Consequently, five main factors and 20 sub-factors are presented in Table 1.

[INSERT FIGURE 1]

Next, five Korean ports with large traffic volumes were chosen in order to evaluate their safety levels. These five ports were selected based on the volume of vessel traffic, including inbound and outbound traffic, in the Korean Republic from 2000 to 2012 (Table 2). As a result, Busan, Ulsan, Gwangyang, Incheon, and Mokpo were selected as the ports to be evaluated. Measuring the weights of the identified safety factors is the third step. The fourth step is to evaluate the selected ports using a fuzzy AHP approach. A sensitivity analysis is also carried out in the last step to test the feasibility of the method and the validity of the results.

[INSERT TABLE 1]

[INSERT TABLE 2]

3.2. Fuzzy AHP

Fuzzy AHP is a systematic approach to an alternative selection and justification problem that uses the concepts of fuzzy set theory and hierarchical structure analysis (Bozbura et al., 2007). It can specify preferences in the form of linguistic or numerical values that are related to the importance of each performance attribute (Güngör, 2009). In the fuzzy AHP method, the pair-wise comparisons in the judgment matrix are conducted using fuzzy mathematics and fuzzy aggregation operators. The process enables to calculate a sequence of weight vectors that can be used to select the main attributes. Decision makers may sometimes not be able to specify preferences between two factors using the nine-point scales in the traditional AHP (Güngör, 2009). In this study, Chang's (1996) extent analysis method was incorporated into the traditional AHP to form a new fuzzy AHP in order to address the ambiguous judgments by the experts in the data collection process.

The extent analysis method in handling fuzzy AHP for the synthetic extent value of the pairwise comparisons was introduced by Chang (1996) and he presented the vector of weight with each factor under a certain criteria. Usage of pairwise comparisons is an advantage of fuzzy AHP and it provides more precise information on the preferences of decision makers (Bozbura and Beskese, 2007). Similarly, Spires (1991) explained that decision makers are not required to clearly specify a measurement scale for each attribute. To measure imprecision in the pairwise comparisons between alternatives, triangular membership functions can be selected (Tang and Beynon, 2005). The steps in Chang's analysis approach are described as follows (Bozbura and Beskese, 2007).

X= $\{x_1, x_2, \cdots, x_n\}$ is an object set, and U=$\{u_1, u_2, \cdots, u_m\}$ is a goal set. Each object is taken and the extent analysis for each goal, g_i, is executed. Thus, m extent analysis values for each object can be obtained as follows:

$$M_{g_i}^{\ 1}, M_{g_i}^{\ 2}, \cdots, M_{g_i}^{\ m}, \quad i = 1, 2, \cdots, n \tag{1}$$

All the $M_{g_i}^{\ j}$ ($j = 1, 2, ..., m$) are comprised of parameters a, b, c of triangular fuzzy numbers (TFNs), where a and c are the lower and upper boundaries of the TFNs and c is the value of having the largest possible membership. TFNs are used due to their simplicity. According to Chang’s extent analysis, the steps are given as follows.

Step1: The fuzzy synthetic extent of the i^{th} object is defined as

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} \right]^{-1} \tag{2}$$

To calculate $\sum_{j=1}^{m} M_{g_i}^{j}$ execute the fuzzy addition operation of m extent analysis values for a specific matrix.

$$\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{j=1}^{m} a_{ij}, \sum_{j=1}^{m} b_{ij}, \sum_{j=1}^{m} c_{ij} \right), \ i = 1, 2, \cdots, n \tag{3}$$

To compute $\left[\sum_{i=1}^{n}\sum_{j=1}^{m}M_{g_i}^{j}\right]^{-1}$ execute the fuzzy addition operation of $M_{g_i}^{j}$ $(j=1,2,\cdots,m)$ values.

$$\sum_{i=1}^{n}\sum_{j=1}^{m}M_{g_i}^{j}=\left(\sum_{i=1}^{n}\sum_{j=1}^{m}a_{ij},\sum_{i=1}^{n}\sum_{j=1}^{m}b_{ij},\sum_{i=1}^{n}\sum_{j=1}^{m}c_{ij}\right) \quad (4)$$

The inverse of the vector in Equation (4) is calculated as follows.

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m}M_{g_i}^{j}\right]^{-1}=\left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m}c_{ij}},\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m}b_{ij}},\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m}a_{ij}}\right) \quad (5)$$

In step 2, fuzzy addition operation is applied to get the degree of possibility of $M_2=(a_2,b_2,c_2)\geq M_1=(a_1,b_1,c_1)$.When the fuzzy triangular numbers $M_1=(a_1,b_1,c_1)$ and $M_2=(a_2,b_2,c_2)$ are convex fuzzy number, the degree of possibility of $M_2=(a_2,b_2,c_2)\geq M_1=(a_1,b_1,c_1)$ is expressed as follows:

$$V(M_2\geq M_1)=hgt(M_1\cap M_2)=\mu_{M_2}(d)=\begin{cases}1, & if \quad b_2\geq b_1\\ 0, & if \quad a_1\geq c_2\\ \dfrac{a_1-c_2}{(b_2-c_2)-(b_1-a_1)}, & otherwise\end{cases} \quad (6)$$

As shown in Figure2, d is the ordinate of the highest intersection point D between μ_{M_1} and μ_{M_2}.

[INSERT FIGURE 2]

To compare M_1 and M_2, it is required the values both $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$.

In the third step, the degree of possibility that a convex fuzzy number M_i is greater than n convex fuzzy numbers (M_1, …, M_n), is as follows

$$P(M_i) = V(M_i \geq M_1, M_2, \cdots, M_n) =$$

$$V\left[M_i \geq M_1 \; and \; (M_i \geq M_2) \; and \; ... \; and \; (M_i \geq M_n)\right] = \min V(M_i \geq M_l) \tag{7}$$

$$l = 1,2,3,\cdots,n$$

Similarly, the weight vector is given by

$$W^{'} = (P(A_1), P(A_2), ..., P(A_n))^T \tag{8}$$

$A_i (i = 1,2,...,n)$ are n factors influencing port navigational safety in this study.

The normalized weight vectors are shown through the normalization of P, symbolized as $\overline{P}$ and W is a crisp number in the final step.

$$W = (\overline{P}(A_1), \overline{P}(A_2), ..., \overline{P}(A_n))^T \tag{9}$$

Triangular fuzzy conversion scales shown in Table 3 are used as the recommended grades.

The linguistic scale is converted into a fuzzy scale since it is impossible to perform mathematical calculations directly on linguistic values (Bozbura and Beskese, 2007). Experts have the flexibility to use different TFNs in order to fit various investigation contexts.

[INSERT TABLE 3]

3.3. Validation

Validation is needed to ascertain the reliability of the methodology and rationality of the results. If the evaluation process in the above methodology is logical, then a sensitivity analysis shout at least be in line with the following two axioms.

Axiom 1: A slight increase/decrease of the evaluation value of a port with respect to a particular factor should certainly result in an increase/decrease of the safety evaluation score for that port.

Axiom 2: The influence magnitude of the weight change of a particular factor on the output safety scores of the investigated ports will remain consistent with the distribution of the input evaluation scores of the ports against that factor.

4. Empirical analysis

4.1. Questionnaire analysis

The port safety factors hierarchy was first created based on the information in Table 1. It is shown in Figure 3. Each factor and sub-factor was obtained as described in Section 3.

[INSERT FIGURE 3]

Questionnaires were sent to captains who had experience with sailing in the five selected ports: Busan, Ulsan, Incheon, Gwangyang, and Mokpo. The questionnaires were distributed to 25 captains and the feedbacks from 21 captains were received and validated. The questionnaires were designed and analyzed with respect to the following three steps.

-Step 1: A weight evaluation of the five main factors, Weather/sea conditions, Channel conditions, Traffic volume, Vessel size, and Vessel type.

-Step 2:Weight evaluations of sub-factors with respect to their individual main factors.

-Step 3: Safety level evaluation of Busan, Ulsan, Gwangyang, Incheon, and Mokpo ports with respect to each sub-factor.

4.2. The result of the fuzzy AHP analysis

In this study, a questionnaire was developed using fuzzy triangular conversion scales, as shown in Table 3, in order to calculate the weights of the factors. For instance, the triangular fuzzy conversion scale for Weather/sea conditions and Channel conditions is calculated by averaging the evaluations of the 21 survey respondents. Consequently, the score for the crossing point of Weather/sea conditions and Channel conditions can be calculated as (1.11, 1.50, 1.94).

In a similar way, the pairwise comparison evaluations from the 21 captains can be obtained and presented in Table 4.

[INSERT TABLE 4]

From Table 4, the inverse value of the vector associated with Weather/Sea condition can be calculated using Equations (2) – (5) as follows.

$$S_i = \sum_{j=1}^{5} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{5} \sum_{j=1}^{5} M_{g_i}^{j} \right]^{-1} = (0.163, 0.253, 0.386)$$

Where $\sum_{j=1}^{5} M_{g_1}^{j}$ =(5.24, 6.58, 8.13) and

$\sum_{i=1}^{5} \sum_{j=1}^{5} M_{g_i}^{j}$ = ((21.0, 26.0, 32.2), respectively.

Similarly, the inverse values of the vectors of the five main factors can be obtained and presented in Table 5.

[INSERT TABLE 5]

The degree to which the weight of weather/sea condition (0.163, 0.253, 0.386) is greater than the one of channel condition (0.144, 0.224, 0.347) is calculated using Equation (6) as follows.

$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = 1.$ $if \quad b_1 \geq b_2$ (0.253>0.224)

V(Weather·sea condition)>V(Channel condition) : 1

$$V(M_2 \ge M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \frac{a_1 - c_2}{(b_2 - c_2) - (b_1 - a_1)},\ if\ \ b_1 < b_2 \text{ and } if\ \ a_1 < c_2$$

V(Weather·sea condition)<V(Channel condition): $\frac{(0.163 - 0.347)}{(0.224 - 0.347) - (0.253 - 0.163)} = 0.862$

The degree of the possibility associated with the other factors can be obtained by a similar procedure ~~as follows~~in Table 6. The value in the intersection represents the degree of the possibility that the factor in the vertical column is greater than the one in the horizontal row.

[INSERT TABLE 6]

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~~V(Weather·sea condition)> V(Traffic volume): 1~~

~~V(Weather·sea condition)< V(Traffic volume): 0.718~~

~~V(Weather·sea condition)> V(Vessel Size): 1~~

~~V(Weather·sea condition)< V(Vessel Size): 0.592~~

~~V(Weather·sea condition)> V(Vessel type): 1~~

~~V(Weather·sea condition)< V(Vessel type): 0.427~~

~~V(Channel condition)> V(Traffic volume): 1~~

~~V(Channel condition)< V(Traffic volume): 0.863~~

~~V(Channel condition)> V(Vessel Size): 1~~

~~V(Channel condition)< V(Vessel Size): 0.677~~

~~V(Channel condition)> V(Vessel type): 1~~

~~V(Channel condition)< V(Vessel type): 0.571~~

~~V(Traffic volume)> V(Vessel Size): 1~~

~~V(Traffic volume)< V(Vessel Size): 0.812~~

~~V(Traffic volume)> V(Vessel type): 1~~

~~V(Traffic volume)< V(Vessel type): 0.699~~

~~V(Vessel Size)> V(Vessel type): 1~~

~~V(Vessel Size)< V(Vessel type):0.884~~

The value of minimum degree of possibility in Equations (7) and (8) are calculated as follows.

$$
\begin{aligned}
&P(M_{Weatherseacondition}) = \\
&\min V\left[M_{Weatherseacondition} \geq M_{Channelcondition}\ and\ \ M_{Weatherseacondition} \geq M_{Trafficvolume}\ \ and\ .M_{Weatherseacondition} \geq M_{Vesselsize}\right] \\
&= \min(1,1,1) \\
&= 1
\end{aligned}
$$

In a similar way, the following is obtained.

Min(V (Channel condition) $\geq$ Vi)=0.862

Min(V(Traffic volume) $\geq$ Vi)=0.718

Min(V(Vessel Size) $\geq$ Vi)=0.529

Min(V(Vessel type) $\geq$ Vi)=0.427

Consequently, the non-normalised weights of the five factors are $W^{'} = (1, 0.862, 0.718, 0.529, 0.427)^T$

The normalized weights of the main factors are then obtained as follows and presented in Table ~~6~~7.

$$W = (\overline{P}(A_1), \overline{P}(A_2), ..., \overline{P}(A_n))^T$$

$$
\begin{aligned}
W = (&\frac{1}{(1+0.862+0.718+0.529+0.427)}, \frac{0.862}{(1+0.862+0.718+0.529+0.427)}), \frac{0.718}{(1+0.862+0.718+0.529+0.427)}, \\
&\frac{0.529}{(1+0.862+0.718+0.529+0.427)}, \frac{0.427}{(1+0.862+0.718+0.529+0.427)})
\end{aligned}
$$

W =(0.283, 0.244, 0.203, 0.150, 0.121)

[INSERT TABLE ~~6~~7]

The results in Table ~~6~~ 7 show that the factor of Weather/sea conditions was weighted as the highest important among all port safety factors. This suggests that captains are more influenced by the natural environment than by the other factors when they are sailing in Korean ports. Table ~~7~~ 8 shows that the weights of the sub-factors which were calculated in a similar way.

[INSERT TABLE ~~7~~8]

In Table ~~7~~8, it can be seen that fog is the most significant factor that affects Weather/sea conditions. A United States Coast Guard report (2010) stated that fog is the only major visibility restriction, which partially justifies that fog was evaluated as the key factor influencing port safety by the captains. Depth was ranked as the most important among the Channel conditions sub-factors Captains also perceived the heavy traffic volume to be more hazardous than the average or low. In terms of vessel size, the distribution of sub-factors' weights do not exactly follow the tendency of the vessel size. For instance, the most dangerous ship was evaluated to be more than 100,000 DWT, while the least goes to the category of 40,000 to 60,000 DWT.

Tankers are the most risky vessel type in terms of its effect on port safety, and the car carrier is the second most significant with respect to vessel type. This finding is in line with the work by Kujala et al. (2009), revealing that oil tankers, especially in the shallow waters, have a high risk of being involving in accidents. In other words, captains perceived fog, depth, heavy traffic volume, vessels more than 100,000 DWT in size, and tankers to be significant port safety sub-factors relating to different main factors. Similarly, using the fuzzy AHP approach, port safety with respect to each sub-factor was evaluated by pair-wise comparisons. As a result, the safety levels of the five selected ports were evaluated with respect to each sub-factor (Table ~~8~~9). Here the higher the value is, the better the port safety level.

[INSERT TABLE ~~8~~9]

Based on the safety evaluation value in Table ~~8~~9, the overall safety value for the five selected ports was calculated. The result shows that Busan is the safest port among the five ports. Busan has an ideal location and the islands located near the Busan port, named Yeong-do and Jo-do, play the role of a breakwater in the harbor front. Furthermore, the shape of the whole channel is a nearly straight line. Busan's overall safety is calculated as an illustrative example by using the sum of the multiplication of port safety evaluation values with respect to each sub-factor (Table ~~8~~9), the weight of each sub-factor (Table ~~7~~8) and the weight of each main factor (Table ~~6~~7). Port safety score of Busan equals 0.264.

The safety scores for the other ports were calculated in a similar way and presented in Table ~~9~~10.

[INSERT TABLE ~~9~~10]

Overall, Busan was evaluated as the safest port among the five Korean ports, followed by Ulsan, while Mokpo was the least safe.

4.3. Sensitivity analysis

A sensitivity analysis is undertaken to partially validate that the fuzzy AHP model is applicable to port safety evaluation and that the associated data is reliable. Ibrahim et al. (2011) stated that sensitivity analysis is needed in order to obtain an accurate result in the way that AHP with fuzzy theory is used to tackle the uncertainty. Sensitivity analysis involves using variations in the input values of the model to observe the change in the output value.

A sensitivity analysis was therefore conducted with respect to the two axioms in Section 3 First, it is found that a slight decrease in the safety input value of Busan with regard to a particular sub-factor (fog) resulted in a decrease in the output evaluation score of Busan, as shown in Table ~~10~~11. For example, if the input value of the sub-factor fog is reduced from 0.245 to 0.200, then the output safety evaluation value of Busan drops from 0.264 to 0.259. The safety value of Busan is seen clearly to decrease with the gradual decrease of the fog factor score, as seen in Table 10 and Figure 4. Similar testing process was carried out to test other sub-factors. All the result proves to be in a harmony with Axiom 1 in Section 3.

[INSERT TABLE ~~10~~11]

Regarding variations in the weight of the fog factor, when the weight of the fog factor is lower, the safety evaluation scores of the ports tend to decrease, as shown in Table ~~11~~12.

[INSERT TABLE ~~11~~12]

Busan was evaluated as the safest port in terms of fog. As shown in Figure 4, the slope indicates the degree of variation. The slope for Busan is 0.070 degrees, which is the most significant compared to the other ports. Busan shows the most sensitivity to the factor of fog. This keeps consistency with Axiom 2 in Section 3, thus partially validate the results

[INSERT FIGURE 4]

5. Conclusions

This study explores and explains the significant factors influencing port navigational safety through surveys of experienced captains. Port safety studies have so far mainly focused on historical and statistical analyses. This study describes port navigational safety factors and provides port safety analysis from a different viewpoint compared to existing relevant studies. Furthermore, five Korean ports, Busan, Ulsan, Incheon, Gwangyang, and Mokpo, were evaluated using the identified safety factors. To evaluate the safety factors and the five Korean ports, human perceptions using a linguistic scale were collected. The fuzzy AHP approach was used to evaluate the safety importance of the factors as well as the port safety values. Traditional risk analysis methods (e.g. quantitative risk analysis) are insufficient to deal with port safety evaluation, where failure data is often unavailable or incomplete. Consequently, fuzzy logic is often used to facilitate expert subjective evaluations based on linguistic terms. The AHP approach is combined with fuzzy logic in this study to reduce the bias introduced by the domain experts and improve the accuracy of their evaluation. It therefore provides port authorities/managers with a power decision support tool to enable safety research with uncertainty in input data and risk control in a rational way with reference to different risk factors. Although showing much attractiveness in port safety analysis, the proposed method based on a hierarchy of risk influencing factors cannot well deal with the cases in other sectors in which the risk influencing factors have a large amount of interdependencies. Further research on incorporation of established methods such as DEMATEL or development of a new standalone approach such as Bayesian reasoning needs to be investigated.

The identified port safety factors can contribute to the analysis of accidents in a port and can also assist in the development of safety guidelines. Consequently the result can set a benchmark for port authorities/managers to improve port navigational safety. It can also help captains to analyze the navigational safety of ports in a dynamic environment. For instance, if a over 100,000 DWT tanker approaching Mokpo or Gwangyang in a fog weather, passing through a shallow channel with heavy traffic, then the captain needs more safety attention (than the situation in which less risky factors are presented) to handle the high risk the vessel is being exposed. The research methods and findings can be tailored to explain the navigational safety of other ports and narrow waters in a wide context.

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