RISK ASSESSMENT OF ARCTIC NAVIGATION BY USING IMPROVED FUZZY-AHP APPROACH

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SUMMARY

In this study, navigational risk factors of the Arctic Ocean are defined and numerical weights of each risk are obtained by using Improved Fuzzy Analytical Hierarchy Process (IF-AHP) method after conducting expert consultations. The Northern Sea Route shortens the maritime distance approximately 7000 nautical miles comparing to the conventional Suez Canal route. Therefore, it takes a significant role of being economic and time advantage for global logistics. Its geographical position, presence of ice, heavy weather conditions, strong currents and winds are some risks for Arctic transportation. There always have the possibility of unpredictable catastrophes such as a collision, grounding, hull damage and etc. in this region. Reflections of such unwanted incidents might be very costly for economic, political, environmental and safety concerns. Due to there are limited academic studies regarding to analytical and systematical risk identification and determination of risk levels, this study contributes to complete this academic gap.

NOMENCLATURE

IF-AHP	Improved Fuzzy Analytical Hierarchy Process
NSIDC	National Snow and Ice Data Centre
EPPR	The Arctic Council's Emergency Prevention, Preparedness and Response
DAMA	Database for maritime accidents
FMA	Finnish Maritime Administration
AMSA	Arctic Maritime Shipping Assessment
IACS	The International Association of Classification Societies

1. INTRODUCTION

Risk analysis is composed of system description, hazard identification and risk assessment. Accordingly, risk analysis of Arctic Ocean is a function of (i) ice and weather conditions, geographical positions (ii) traffic patterns (iii) previous marine accidents (iv) traffic and ice class regulations as well as ice breaker assistance. Arctic routes provide some opportunities such as reduction of distance, time and oil consumption. Thus, Arctic navigation has been conducted intensively in summer seasons of the year, since 2009. According to National Snow and Ice Data Centre (NSIDC), on 17th of September, 2014, Arctic sea ice extent dropped to 5.02 million square kilometres (1.94 million square miles) which is the lowest extent of the year [1]. As a result of ice melt, traffic in the Arctic Ocean is increasing remarkably [2].

According to Ilulissat Declaration (2008), increased traffic in the Arctic region for all purposes (i.e. tourism, shipping and search and rescue etc.) increases the risk of accidents [3]. As reported by Lloyd's Marine Intelligence Unit Sea Searcher Database, Canadian Transportation Safety Board (Marine) and Canadian Hydraulics Centre - Arctic Ice Regime System Database there exist 293 marine incidents occurred in the Arctic region between 1995-2004 [4].

Since marine accidents are composed of constant and unsteady parameters, risk factors might trigger and involve different incidents. In order to clarify the primary reasons of each incident, determining the probable risks (root causes) plays a significant role. However, reports, summaries and relevant data of marine incidents are not solely enough to reveal the navigational risks. To overcome this shortcoming, experts are asked to discuss all probabilities considering all cases, and determine the probable risk factors as much as possible, which might occur in the future.

In this study, risk factors of ice navigation in the Arctic region are determined. The Arctic Council's Emergency Prevention, Preparedness and Response (EPPR) working group has noted that Arctic states do not generally collect and share Arctic marine activity data in any systematic manner, there exists no crisp data on the deep causes each unwanted incidents [5]. The aim of this study is to determine the numeric values of each risk levels by using IF-AHP approach. Several expert consultations are carried out for the intended problem. Risk factors have an intricate nature; therefore, inadequacy of the quantitative tendency, qualitative (fuzzy) approach is preferred to apply for the risk assessment based on subjective experience [6]

Database for maritime accidents (DAMA of Det Norske Veritas) of which is previously used by Finnish Maritime Administration (FMA) is re-assessed for constructing the hierarchical structural model of risk assessment for ice navigation in the Arctic Region [7,8]. The risks for Arctic navigation in the Arctic region are categorized in the Table 1.

Table 1. Risk Factors of Ice Navigation in the Arctic Region

B1 Risk factors outside the vessel
C01 Environmental conditions encountered such as fog, storms, compass anomalies, atmospheric effects and ice
C02 Drift of pack ice due to wind and surface currents and other ship-handling difficulties
C03 Colliding with floating obstacles (sharp corners of ice floes) or pressure to the vessel's hull, propellers, rudder
C04 Failure in establishment and maintenance of external aids to navigation
C05 Deficiencies in the reliability and detail of hydrographical and geographical information presented on polar navigation charts, coupled with a distinct lack of reliable bathymetry, current, and tidal data.
C06 Technical incapacitation of other vessels, icebreakers, tugs leads to some catastrophic outcomes
C07 Lack of operational efficiency and safety of other vessels.
C08 Technical equipment faults of external cargo loading / unloading or bunkering. Failures in quay, channel lock, or bridge structures
C09 Operational equipment faults in operation of cargo loading/unloading or bunkering. Operational faults in using port equipment or channel locks.
C10 Explosion or external conditions related to the oil drill.
C11 Ice restrictions which affect the vessel's movement and force to change of course and speed.
C12 Hazards of ice and snow accumulation on the superstructures.
B2 Risk factors related to structural design and arrangement of equipment locations
C13 Insufficiency of hull strength and horsepower of the vessel employed.
C14 Corrosion, welding for repair and for other works, which weaken the strength of the ship
C15 Risk of stability caused from construction failures of hull scantlings.
C16 Insufficient manoeuvring characteristics of vessel not specifically built for ice breaking or quick manoeuvring for rapid change of ice conditions.
17 Inappropriate designs of the engine room/ arrangements of the places of the equipment have caused a danger of leakage or fire.
C18 Inappropriate design of the engine room/ arrangement of the cargo space and store.
C19 Inappropriate design of the engine room/ arrangements of other space, not bridge
C20 Unusable design for maintenance, inspection, cleaning
C21 Other conditions (i.e. shell plating, frames, ice stringers, web frames, bow, stern, bilge keels) related to vessel construction or maintenance (i.e. rudder and steering arrangements, propeller, shafts and gears, miscellaneous machinery requirements)
B3 Risk factors related to technical faults in vessel equipment
C22 Technical fault in sophisticated electronic navigation equipment (such as radar, sonar, and the visible, infrared, and microwave radiation sensors on-board satellites)
C23 Technical fault in manoeuvring equipment (i.e. rudder and steering arrangements)
C24 Technical fault in propulsion machinery (i.e. propeller, shafts and gears,)
C25 Technical fault in auxiliary machinery (i.e. air compressors, cooling water system)
C26 Technical fault in berthing, (un) mooring, anchoring equipment / deck equipment
C27 Technical failures in remote and automatic control devices and emergency systems
C28 Cargo Handling Equipment technical faults
C29 Failures in safety devices /systems of redundant, inert gas and fire extinguish
C30 Technical errors in drilling equipment
C31 Other technical failures
B4 Issues related to the operation and placement of equipment on-board
C32 Useless design of the bridge, misplacement, removed or no devices
C33 Faulty, useless or illogical design or misplacement of controls
C34 Inappropriate placement of device for usage
C35 Ill-equipped, ill-suited, ill-adapted, improper and hard usage of device
C36 Faults in Ergonomics, design and operation of the device. Human-machine interface problems.
C37 Other factors related to the design / operation of the device. Man-machine interaction problems.
B5 Risks on cargo, fuel and related handling equipment
C38 Catching fire by itself of the cargo / fuel
C39 No or inadequate inert gas / fire or explosion prevention system
C40 Instability causes from the rules of faulty placement of cargo and imbalance causes from missing ballast etc.
C41 Poor cargo security
C42 Risks caused from liquid cargo leaks (barrels, containers, tanks, etc.)
C43 Leakages in cargo or fuel pipes/hoses
C44 Other factor related to cargo or fuel
B6 Communicational, organizational, operational instruction faults and routine failures
C45 Inadequate or deficiencies for following the general instructions
C46 Unfamiliarity of general methods of operation or insufficient practice
C47 missing or deficiencies for following the safety instructions
C48 Familiarity with safety instructions, but no implementation
C49 Safety instructions related to the welding are not performed.

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C50 Fire occurred during the welding process although safety precautions are taken.
C51 Tests and practices for lifesaving equipment not implemented
C52 No usage of equipment for protection.
C53 Poor knowledge of organization or instruction
C54 Rules for Inspection and maintenance not implemented
C55 No knowledge of stability or wrong calculations of stability.
C56 Leadership related and personal problems.
C57 Improper or insufficient look-out caused from manning. (i.e. missing helmsman)
C58 Directions of obligations or task area is not clear
C59 No or faulty bridge routines
C60 No implementation of bridge routines.
C61 No up to-date sea charts or publications.
C62 Coordination faults during the process of service / procedures with tugs, shore organization etc.
C63 Other risks related to organization, safety regulation, periodical tasks or communication
C64 Duty incompetency of training or certifications etc.

B7 Human factors, interpretation, awareness & assessment of situation, etc.

C65 Practical incompetency for duty such as experience, local knowledge of waters, usage of devices.
C66 Inappropriate design of task or operation such as cargo, night navigation, route planning, anchoring etc.
C67 Available warning mechanism is insufficiently developed and used.
C68 Alternative navigation systems are not used. Assessments of navigational lights, lighthouses etc. are wrongly or inadequate assessed
C69 The usage of available aids for navigation or publications is not sufficient.
C70 Failures of using the sea chart, Deficiencies regarding to positioning the own vessel
C71 Wrong of inadequate interpretation of other vessel's motions / intentions
C72 Wrong or inadequate interpretation of own vessel's motions (icebergs, current, wind etc.)
C73 Performing the task or operation under inconvenient and improper conditions
C74 Right side of the separation line is not used on the waterway, channel, track, crack, etc.
C75 Higher speed than expected.
C76 Sickness, fatigue, exhausting, overstrain etc.
C77 Falling asleep on the watch
C78 Usage of alcohol, drug or other intoxicating substance
C79 Other personnel related failures

2. LITERATURE REVIEW

There exist a vast amount of literature on various aspects of navigation in the Arctic region. A comprehensive review of previous research on this topic within Arctic shipping can be found in (Schøyen, 2011), (Ho, 2010) and (Verny, 2009) [9-11]. Economic aspects of Arctic transportation as well as its increase over the past decade were discussed in (Lasserre, 2014) and (Hong, 2012) [12-13]. These studies considered both Arctic routes and profitability. Existing navigation-oriented research on the Arctic region can broadly categorized into four groups: (1) Arctic shipping routes and profitability (2) environmental impacts and studies on Arctic meteorology and (3) Arctic politics (4) navigation. Previous research in these categories is briefly described below. The problem of economic viability of using the Northern Sea Route was studied in (Granberg, 1998), (Liu, 2010) and (Harsem, 2011) [14-16]. The same problem was considered in (Somanathan, 2009) under simulating the Northwest Passage by comparing the alternate routes in terms of predefined constraints, whereas (Lasserre, 2011) presents interest of shipping companies in developing activities in the Arctic [17-18]. Risk analysis of the marine accidents are highly studied in the literature. For instance, (Senol, 2015) studied chemical cargoes by using fault tree analysis for chemical tankers [19]. Root cause analysis of Arctic marine accidents are expressed in (Kum, 2015) [20]. However, the works of (Kujala, 2009) and (Jalonen, 2005) seem to be the only studies in the literature that consider the risk analysis of the ice navigation in the Baltic Sea from a navigator's point of view [21-22]. An overview of Arctic sea ice in global atmospheric circulation can be found in (Budikova, 2009) [23]. History of sea ice in the Arctic is given in (Polyak, 2010) and (Kellogg, 1995) [24-25]. A comparison of the past rates of climate changes in the Arctic region is given in (White, 2010), glacial history of Arctic is studied in (Jakobsson, 2013) [26-27]. (Yamanouchi, 2011) proposed some explanations on early 20th century warming in the Arctic whereas (Jakobbson, 2014) introduced a program to review the Arctic quaternary environmental change [28-29]. Models for snow depth and sea ice extent in the Arctic are proposed in Park (2013). (Ford, 2006) and (Doel, 2014) investigates vulnerability to climate change in the Arctic [30-32]. Studies of Arctic policy on the European Union is overviewed in (Wegge, 2011) and (Offerdal, 2008, 2009) [33-34]. For the USA politics, National strategy for the Arctic region (2013) is declared [35]. (Blank, 2011) and (Padrtová, 2012) are conducted strategic studies regarding to Russian politics [36-37]. Jensen (2010) compares the Norwegian and Russian policies by using the discourse analysis. Moreover, legal perspectives for the Arctic is studied in (Stokke, 2006) [38]. Regarding the icebreaking service, (Parsons, 2011) discussed the operational infrastructure and effectiveness of the icebreakers in the Arctic region [39]. (Kotovirta, 2009) studied route optimization ice covered waters [40]. In the presence of fuzziness, a novel process model is presented in (Sahin, 2014) [41]. On the other hand, Snider (2012) and (Buyssse, 2007) describe challenges of polar ship operations and handling ships in ice [42]. (Sahin, 2015)'s dissertation points out the marine accident analysis, risk assessment and route selection problem for ice-covered waters [43].

Satellite measurements and remote sensing technology regarding the both sea ice detection and ice navigation are studied in (Parkinson, 2008) and (Alexandrov, 2010) [44-45].

3. MATERIALS AND METHODS

3.1 IMPROVED FUZZY ANALYTICAL HIERARCHY PROCESS (IF-AHP) METHOD

IF-AHP transfers reciprocal judgment matrix into the fuzzy consistent judgment matrix. Also, normalized aggregation, square root and eigenvector methods involve the process.

The steps of IF-AHP are shown below [46, 47]:

For IF-AHP method, (0.1~ 0.9) scales are used. The scales and their meanings are given in the Table 2.

Table 2. Number scale: (0.1~ 0.9) and its meaning

a_{ij}	The significance of a_{ij}	a_{ji}
0.5	a_i is as important as a_j	0.5
0.6	a_i is slight precedence over a_j	0.4
0.7	a_i is obvious precedence over a_j	0.3
0.8	a_i is forceful precedence over a_j	0.2
0.9	a_i is extreme precedence over a_j	0.1

Step 1: Comparative judgment matrix is set up as $F=\left(a_{ij}\right)_{nxn}$. The elements of matrix $F(a_{ij},a_{ji})$ have these following properties: $0<a_{ij}<1, a_{ij}+a_{ji}=1, a_{ii}=0.5$

Step 2: Fuzzy complementary judgment matrix is established. It is listed as fuzzy consistent matrix: $F=(r_{ij})_{nxn}$, r_i is the sum of rows as $r_i=\sum_{j=1}^{n} r_{ij}$, r_j is the columns of judgment matrix F as $r_j=\sum_{i=1}^{n} r_{ij}$ and $i,j=1,2,...,n$

Step 3: Transformation formula $r_i=\frac{r_i-r_j}{2n}+0.5$ is used to solve the row sum $r_i=\sum_{j=1}^{n} f_{ij}$. The fuzzy consistent judgment matrix $R=(r_{ij})_{n\times n}$ is converted from fuzzy judgment matrix $F=(f_{ij})_{n\times n}$

Step 4: Rank aggregation method (eq.1) or Square root (eq.2) method is used to get the ordering vector.

$$W^{(0)}=(w_1, w_2, ... w_n)^T = \left(\frac{\sum_{j=1}^{n} e_{1j}}{\sum_{i=1}^{n}\sum_{j=1}^{n} e_{ij}}, \frac{\sum_{j=1}^{n} e_{2j}}{\sum_{i=1}^{n}\sum_{j=1}^{n} e_{ij}}, ... \frac{\sum_{j=1}^{n} e_{nj}}{\sum_{i=1}^{n}\sum_{j=1}^{n} e_{ij}} \right)^T \quad \text{(eq.1)}$$

$$W^{(0)}=(w_1, w_2, ... w_n)^T = \left(\frac{\sqrt[n]{\prod_{j=1}^{n} e_{1j}}}{\sum_{i=1}^{n}\sqrt[n]{\prod_{j=1}^{n} e_{ij}}}, \frac{\sqrt[n]{\prod_{j=1}^{n} e_{2j}}}{\sum_{i=1}^{n}\sqrt[n]{\prod_{j=1}^{n} e_{ij}}}, ... \frac{\sqrt[n]{\prod_{j=1}^{n} e_{nj}}}{\sum_{i=1}^{n}\sqrt[n]{\prod_{j=1}^{n} e_{ij}}} \right)^T \quad \text{(eq.2)}$$

Step 5: Transformation formula of $e_{ij}=\frac{r_{ij}}{r_{ji}}$ is used to obtain reciprocal matrix $E=(e_{ij})_{n\times n}$ that is transformed from the fuzzy complementary judgment matrix $R=(r_{ij})_{n\times n}$. High accuracy of the ranking vector is solved by $W^{(0)}$ which is regarded as V_0 of eigenvalue method.

For the Iterative initial value V_0, iteration formula $V_{k+1}=EV_k$ is used to find the eigenvector V_{k+1} and infinite norm $\|V_{k+1}\|_\infty$ of V_{k+1}. While $\|V_{k+1}\|_\infty - \|V_k\|_\infty$ less than ε, $V_{k+1}=\lambda_{max}$ which is the largest eigenvalue. Then V_{k+1} is normalized and become the form of

$$V_{k+1}=\left(\frac{V_{k+1,1}}{\sum_{i=1}^{n} V_{k+1,i}}, \frac{V_{k+1,2}}{\sum_{i=1}^{n} V_{k+1,i}}, ... \frac{V_{k+1,n}}{\sum_{i=1}^{n} V_{k+1,i}} \right)^T \quad \text{(eq.3)}$$

Step 6:

$V_k=\frac{V_{k+1}}{\|V_{k+1}\|_\infty}=\left(\frac{V_{k+1,1}}{\|V_{k+1}\|_\infty}, \frac{V_{k+1,2}}{\|V_{k+1}\|_\infty}, ... \frac{V_{k+1,n}}{\|V_{k+1}\|_\infty}\right)^T$ is taken and the ordering vector is $W^{(k)}=V_{i+1}$ and the calculation is completed. V_k becomes the new iterative initial value, which can be recalculated from the beginning.

3.2 APPLICATION FOR THE RISK ASSESSMENT OF ARCTIC NAVIGATION

Twenty anonymous field experts are asked for risk assessment of Arctic navigation. Experience and research areas of these experts are mainly focus on experimental and numerical investigation of the model ice failure process, efficiency of ships in ice and shape optimization, the influence of ice loads on the propulsion machinery, environmental risk assessments of shipping in ice covered waters, consequence assessment of accidental ship and ice impact, consequence assessment following design relevant service actions in ice, first principal-based approaches for the identification and evaluation of ice induced actions, risk-based design methods and risk mitigation measures for arctic ships, performance of ships in ice, arctic field logistics and Trans-Arctic shipping.

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After an expert consultation, judgment matrices are obtained and the evaluation results are analysed. Comparative judgement matrices and transformation of the complementary matrix into fuzzy consistent matrix are conducted. Then, complementary judgment matrix is transformed into the reciprocal matrix. Weight vector matrices are obtained. Then relative importance values are found.

The above mentioned steps are performed by using the MATLAB software. The sample codes are provided in the Appendix.

Priority judgment matrices based on the hierarchical structure model of risk assessment of ice navigation are shown below (Figure 1):

A-B judgment matrix:

$$\begin{bmatrix} 0.5 & 0.6 & 0.4 & 0.7 & 0.7 & 0.5 & 0.5 \\ 0.4 & 0.5 & 0.8 & 0.6 & 0.4 & 0.6 & 0.6 \\ 0.6 & 0.2 & 0.5 & 0.7 & 0.3 & 0.5 & 0.6 \\ 0.3 & 0.4 & 0.3 & 0.5 & 0.5 & 0.7 & 0.6 \\ 0.3 & 0.6 & 0.7 & 0.5 & 0.5 & 0.7 & 0.7 \\ 0.5 & 0.4 & 0.5 & 0.3 & 0.3 & 0.5 & 0.7 \\ 0.5 & 0.4 & 0.4 & 0.4 & 0.3 & 0.3 & 0.5 \end{bmatrix}$$

Fuzzy consistent judgment matrix $R_{ij} = (r_{ij})_{n\times n}$ is found as follows:

$$\begin{bmatrix} 0.5000 & 0.5000 & 0.5357 & 0.5429 & 0.4929 & 0.5500 & 0.5786 \\ 0.5000 & 0.5000 & 0.5357 & 0.5429 & 0.4929 & 0.5500 & 0.5786 \\ 0.4643 & 0.4643 & 0.5000 & 0.5071 & 0.4571 & 0.5143 & 0.5429 \\ 0.4571 & 0.4571 & 0.4929 & 0.5000 & 0.4500 & 0.5071 & 0.5357 \\ 0.5071 & 0.5071 & 0.5429 & 0.5500 & 0.5000 & 0.5571 & 0.5857 \\ 0.4500 & 0.4500 & 0.4857 & 0.4929 & 0.4429 & 0.5000 & 0.5286 \\ 0.4214 & 0.4214 & 0.4571 & 0.4643 & 0.4143 & 0.4714 & 0.5000 \end{bmatrix}$$

Normalized rank aggregation method is used and ordering vector is obtained as:

$$W^{(0)}=(0.1510, 0.1510, 0.1408, 0.1388, 0.1531, 0.1367, 0.1286)^T \quad \text{(eq.4)}$$

The reciprocal matrix $R_{ij} = (r_{ij})$ is given as:

$$\begin{bmatrix} 1.0000 & 1.0000 & 1.1538 & 1.1875 & 0.9718 & 1.2222 & 1.3729 \\ 1.0000 & 1.0000 & 1.1538 & 1.1875 & 0.9718 & 1.2222 & 1.3729 \\ 0.8667 & 0.8667 & 1.0290 & 0.8421 & 1.0588 & 1.0588 & 1.1875 \\ 0.8421 & 0.8421 & 0.9718 & 1.0000 & 0.8182 & 1.0290 & 1.1538 \\ 1.0290 & 1.0290 & 1.1875 & 1.2222 & 1.0000 & 1.2581 & 1.4138 \\ 0.8182 & 0.8182 & 0.9444 & 0.9718 & 0.7949 & 1.0000 & 1.1212 \\ 0.7284 & 0.7284 & 0.8421 & 0.8667 & 0.7073 & 0.8919 & 1.0000 \end{bmatrix}$$

For A-B judgment matrix, using the formulas in the second step to calculate the weight of the combination.

$$w=(0.1591,0.1591,0.1379,0.1340,0.1638,0.1302,0.1160) \quad \text{(eq.5)}$$

Similar steps are carried out for other risk criteria as follows:

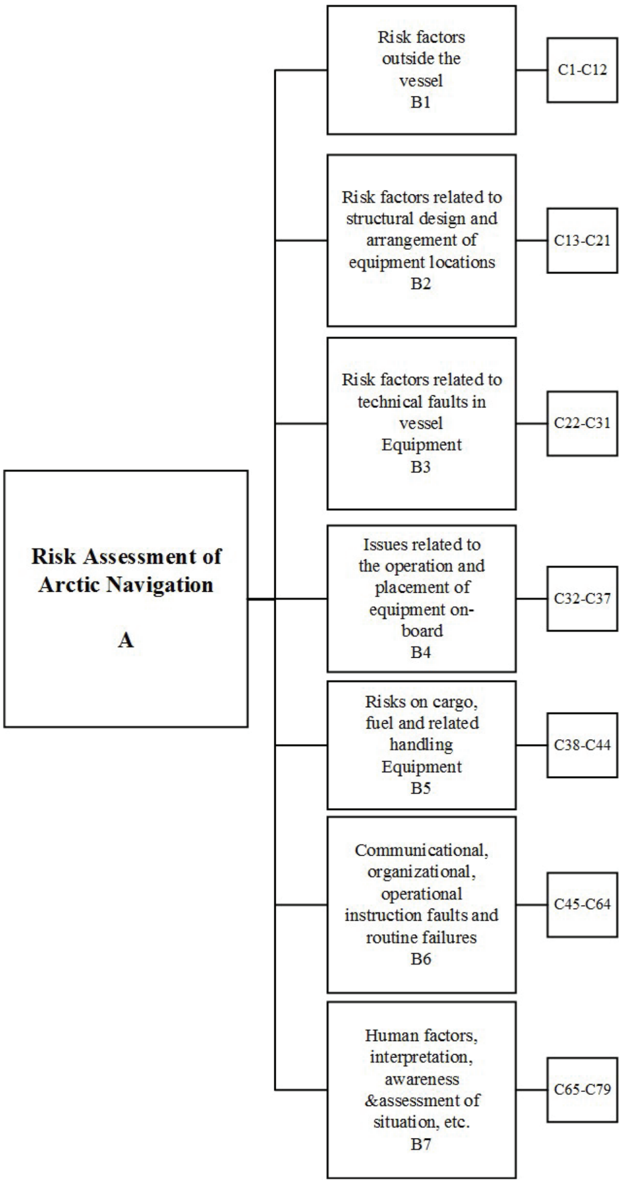

Figure 1 Structure of the Model for Risk Assessment of Arctic Navigation

B1-C judgment matrix:

$$\begin{bmatrix} 0.5 & 0.6 & 0.5 & 0.4 & 0.5 & 0.3 & 0.5 & 0.6 & 0.6 & 0.4 & 0.4 & 0.5 \\ 0.4 & 0.5 & 0.4 & 0.4 & 0.5 & 0.5 & 0.5 & 0.6 & 0.6 & 0.3 & 0.6 & 0.3 \\ 0.5 & 0.4 & 0.5 & 0.5 & 0.5 & 0.5 & 0.4 & 0.5 & 0.5 & 0.5 & 0.5 & 0.6 \\ 0.6 & 0.6 & 0.5 & 0.5 & 0.6 & 0.6 & 0.7 & 0.3 & 0.6 & 0.5 & 0.5 & 0.6 \\ 0.5 & 0.5 & 0.5 & 0.4 & 0.5 & 0.5 & 0.4 & 0.5 & 0.6 & 0.3 & 0.5 & 0.4 \\ 0.7 & 0.5 & 0.5 & 0.4 & 0.5 & 0.5 & 0.6 & 0.4 & 0.6 & 0.3 & 0.6 & 0.5 \\ 0.5 & 0.5 & 0.6 & 0.3 & 0.6 & 0.4 & 0.5 & 0.5 & 0.7 & 0.2 & 0.5 & 0.4 \\ 0.4 & 0.4 & 0.5 & 0.7 & 0.5 & 0.6 & 0.5 & 0.5 & 0.4 & 0.3 & 0.4 & 0.4 \\ 0.4 & 0.4 & 0.5 & 0.4 & 0.4 & 0.4 & 0.3 & 0.6 & 0.5 & 0.3 & 0.4 & 0.3 \\ 0.6 & 0.7 & 0.5 & 0.5 & 0.7 & 0.7 & 0.8 & 0.7 & 0.7 & 0.5 & 0.6 & 0.5 \\ 0.6 & 0.4 & 0.5 & 0.5 & 0.5 & 0.4 & 0.5 & 0.6 & 0.6 & 0.4 & 0.5 & 0.3 \\ 0.5 & 0.7 & 0.4 & 0.4 & 0.6 & 0.5 & 0.6 & 0.6 & 0.7 & 0.5 & 0.7 & 0.5 \end{bmatrix}$$

B2-C judgment matrix:

$$\begin{bmatrix} 0.5 & 0.4 & 0.4 & 0.6 & 0.5 & 0.5 & 0.5 & 0.4 & 0.4 \\ 0.6 & 0.5 & 0.4 & 0.6 & 0.6 & 0.5 & 0.7 & 0.5 & 0.5 \\ 0.6 & 0.6 & 0.5 & 0.4 & 0.5 & 0.5 & 0.6 & 0.5 & 0.4 \\ 0.4 & 0.4 & 0.6 & 0.5 & 0.3 & 0.5 & 0.4 & 0.4 & 0.6 \\ 0.5 & 0.4 & 0.5 & 0.7 & 0.5 & 0.6 & 0.2 & 0.4 & 0.4 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.4 & 0.5 & 0.4 & 0.6 & 0.4 \\ 0.5 & 0.3 & 0.4 & 0.6 & 0.8 & 0.6 & 0.5 & 0.5 & 0.4 \\ 0.6 & 0.5 & 0.5 & 0.6 & 0.6 & 0.4 & 0.5 & 0.5 & 0.2 \\ 0.6 & 0.5 & 0.6 & 0.4 & 0.6 & 0.6 & 0.6 & 0.8 & 0.5 \end{bmatrix}$$

B4-C judgment matrix:

$$\begin{bmatrix} 0.5 & 0.5 & 0.3 & 0.6 & 0.4 & 0.4 \\ 0.5 & 0.5 & 0.4 & 0.3 & 0.4 & 0.3 \\ 0.7 & 0.6 & 0.5 & 0.4 & 0.4 & 0.3 \\ 0.4 & 0.7 & 0.6 & 0.5 & 0.5 & 0.5 \\ 0.6 & 0.6 & 0.6 & 0.5 & 0.5 & 0.5 \\ 0.6 & 0.7 & 0.7 & 0.5 & 0.5 & 0.5 \end{bmatrix}$$

B3-C judgment matrix:

$$\begin{bmatrix} 0.5 & 0.3 & 0.5 & 0.6 & 0.6 & 0.5 & 0.7 & 0.7 & 0.6 & 0.6 \\ 0.7 & 0.5 & 0.7 & 0.7 & 0.4 & 0.4 & 0.5 & 0.6 & 0.4 & 0.5 \\ 0.5 & 0.3 & 0.5 & 0.5 & 0.5 & 0.4 & 0.4 & 0.4 & 0.5 & 0.4 \\ 0.4 & 0.3 & 0.5 & 0.5 & 0.4 & 0.4 & 0.4 & 0.6 & 0.5 & 0.5 \\ 0.4 & 0.6 & 0.5 & 0.6 & 0.5 & 0.5 & 0.5 & 0.6 & 0.6 & 0.5 \\ 0.5 & 0.6 & 0.6 & 0.6 & 0.5 & 0.5 & 0.6 & 0.4 & 0.4 & 0.4 \\ 0.3 & 0.5 & 0.6 & 0.6 & 0.5 & 0.4 & 0.5 & 0.7 & 0.6 & 0.4 \\ 0.3 & 0.4 & 0.6 & 0.4 & 0.4 & 0.6 & 0.3 & 0.5 & 0.4 & 0.5 \\ 0.4 & 0.6 & 0.5 & 0.5 & 0.4 & 0.6 & 0.4 & 0.6 & 0.5 & 0.5 \\ 0.4 & 0.5 & 0.6 & 0.5 & 0.5 & 0.6 & 0.6 & 0.5 & 0.5 & 0.5 \end{bmatrix}$$

B5-C judgment matrix:

$$\begin{bmatrix} 0.5 & 0.4 & 0.4 & 0.4 & 0.5 & 0.4 & 0.3 \\ 0.6 & 0.5 & 0.3 & 0.4 & 0.4 & 0.3 & 0.3 \\ 0.6 & 0.7 & 0.5 & 0.4 & 0.4 & 0.3 & 0.4 \\ 0.6 & 0.6 & 0.6 & 0.5 & 0.4 & 0.4 & 0.3 \\ 0.5 & 0.6 & 0.6 & 0.6 & 0.5 & 0.3 & 0.5 \\ 0.6 & 0.7 & 0.7 & 0.6 & 0.7 & 0.5 & 0.5 \\ 0.7 & 0.7 & 0.6 & 0.7 & 0.5 & 0.5 & 0.5 \end{bmatrix}$$

B6-C judgment matrix:

$$\begin{bmatrix} 0.5 & 0.6 & 0.4 & 0.4 & 0.4 & 0.5 & 0.4 & 0.5 & 0.6 & 0.6 & 0.6 & 0.4 & 0.7 & 0.7 & 0.4 & 0.6 & 0.5 & 0.6 & 0.7 \\ 0.4 & 0.5 & 0.7 & 0.4 & 0.6 & 0.6 & 0.6 & 0.6 & 0.6 & 0.6 & 0.6 & 0.7 & 0.7 & 0.4 & 0.4 & 0.4 & 0.4 & 0.3 & 0.3 \\ 0.6 & 0.3 & 0.5 & 0.4 & 0.4 & 0.4 & 0.3 & 0.4 & 0.3 & 0.4 & 0.7 & 0.6 & 0.6 & 0.5 & 0.4 & 0.4 & 0.6 & 0.6 & 0.6 \\ 0.6 & 0.6 & 0.6 & 0.5 & 0.5 & 0.6 & 0.6 & 0.7 & 0.7 & 0.5 & 0.5 & 0.5 & 0.6 & 0.7 & 0.5 & 0.5 & 0.6 & 0.7 & 0.7 \\ 0.6 & 0.4 & 0.6 & 0.5 & 0.5 & 0.7 & 0.6 & 0.6 & 0.6 & 0.5 & 0.5 & 0.6 & 0.6 & 0.6 & 0.6 & 0.5 & 0.6 & 0.7 & 0.6 \\ 0.5 & 0.4 & 0.6 & 0.4 & 0.3 & 0.5 & 0.7 & 0.6 & 0.7 & 0.7 & 0.5 & 0.6 & 0.6 & 0.6 & 0.6 & 0.5 & 0.7 & 0.5 & 0.5 \\ 0.6 & 0.4 & 0.7 & 0.4 & 0.4 & 0.3 & 0.5 & 0.6 & 0.6 & 0.5 & 0.6 & 0.4 & 0.7 & 0.6 & 0.5 & 0.5 & 0.6 & 0.5 & 0.6 \\ 0.5 & 0.4 & 0.6 & 0.3 & 0.4 & 0.4 & 0.4 & 0.5 & 0.3 & 0.4 & 0.3 & 0.4 & 0.3 & 0.4 & 0.5 & 0.5 & 0.6 & 0.5 & 0.7 \\ 0.4 & 0.4 & 0.7 & 0.3 & 0.4 & 0.3 & 0.4 & 0.7 & 0.5 & 0.5 & 0.6 & 0.5 & 0.7 & 0.7 & 0.7 & 0.6 & 0.4 & 0.5 & 0.4 \\ 0.4 & 0.4 & 0.6 & 0.4 & 0.5 & 0.3 & 0.5 & 0.6 & 0.5 & 0.5 & 0.4 & 0.4 & 0.4 & 0.3 & 0.3 & 0.7 & 0.7 & 0.6 & 0.4 \\ 0.4 & 0.4 & 0.3 & 0.4 & 0.5 & 0.5 & 0.4 & 0.7 & 0.4 & 0.6 & 0.5 & 0.5 & 0.8 & 0.6 & 0.6 & 0.5 & 0.6 & 0.6 & 0.5 \\ 0.6 & 0.3 & 0.4 & 0.4 & 0.4 & 0.4 & 0.6 & 0.6 & 0.5 & 0.6 & 0.5 & 0.5 & 0.6 & 0.6 & 0.5 & 0.7 & 0.6 & 0.7 & 0.6 \\ 0.3 & 0.3 & 0.4 & 0.4 & 0.4 & 0.4 & 0.3 & 0.7 & 0.3 & 0.6 & 0.2 & 0.4 & 0.5 & 0.7 & 0.7 & 0.4 & 0.7 & 0.4 & 0.5 \\ 0.3 & 0.6 & 0.5 & 0.3 & 0.4 & 0.4 & 0.4 & 0.6 & 0.3 & 0.7 & 0.4 & 0.4 & 0.3 & 0.5 & 0.6 & 0.6 & 0.4 & 0.5 & 0.7 \\ 0.6 & 0.6 & 0.6 & 0.5 & 0.4 & 0.4 & 0.5 & 0.5 & 0.3 & 0.7 & 0.4 & 0.5 & 0.3 & 0.4 & 0.5 & 0.6 & 0.6 & 0.7 & 0.7 \\ 0.4 & 0.6 & 0.6 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.4 & 0.3 & 0.5 & 0.3 & 0.6 & 0.4 & 0.4 & 0.5 & 0.7 & 0.7 & 0.7 \\ 0.5 & 0.6 & 0.4 & 0.4 & 0.4 & 0.3 & 0.4 & 0.4 & 0.6 & 0.3 & 0.4 & 0.4 & 0.3 & 0.6 & 0.4 & 0.3 & 0.5 & 0.6 & 0.5 \\ 0.4 & 0.7 & 0.4 & 0.3 & 0.3 & 0.5 & 0.5 & 0.5 & 0.5 & 0.4 & 0.4 & 0.3 & 0.6 & 0.5 & 0.3 & 0.3 & 0.4 & 0.5 & 0.6 \\ 0.3 & 0.7 & 0.4 & 0.3 & 0.4 & 0.5 & 0.4 & 0.3 & 0.6 & 0.6 & 0.5 & 0.4 & 0.5 & 0.3 & 0.3 & 0.3 & 0.5 & 0.4 & 0.5 \end{bmatrix}$$

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B7-C judgment matrix:

$$\begin{bmatrix}
0.5 & 0.6 & 0.7 & 0.7 & 0.4 & 0.6 & 0.6 & 0.4 & 0.5 & 0.5 & 0.4 & 0.6 & 0.7 & 0.6 & 0.6 & 0.6 \\
0.4 & 0.5 & 0.6 & 0.7 & 0.7 & 0.6 & 0.6 & 0.7 & 0.6 & 0.6 & 0.6 & 0.5 & 0.6 & 0.6 & 0.6 & 0.5 \\
0.3 & 0.4 & 0.5 & 0.7 & 0.6 & 0.6 & 0.6 & 0.7 & 0.7 & 0.6 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 \\
0.3 & 0.3 & 0.3 & 0.5 & 0.6 & 0.7 & 0.6 & 0.7 & 0.6 & 0.6 & 0.7 & 0.6 & 0.7 & 0.7 & 0.7 & 0.6 \\
0.6 & 0.3 & 0.4 & 0.4 & 0.5 & 0.4 & 0.5 & 0.4 & 0.6 & 0.5 & 0.6 & 0.4 & 0.4 & 0.4 & 0.4 & 0.4 \\
0.4 & 0.4 & 0.4 & 0.3 & 0.6 & 0.5 & 0.4 & 0.4 & 0.4 & 0.3 & 0.4 & 0.4 & 0.3 & 0.3 & 0.3 & 0.4 \\
0.4 & 0.4 & 0.4 & 0.4 & 0.5 & 0.6 & 0.5 & 0.4 & 0.4 & 0.4 & 0.3 & 0.5 & 0.5 & 0.4 & 0.4 & 0.4 \\
0.6 & 0.3 & 0.3 & 0.3 & 0.6 & 0.6 & 0.6 & 0.5 & 0.6 & 0.6 & 0.5 & 0.7 & 0.5 & 0.5 & 0.4 & 0.5 \\
0.5 & 0.4 & 0.3 & 0.4 & 0.4 & 0.6 & 0.6 & 0.4 & 0.5 & 0.3 & 0.5 & 0.4 & 0.4 & 0.6 & 0.6 & 0.3 \\
0.5 & 0.4 & 0.4 & 0.4 & 0.5 & 0.7 & 0.6 & 0.4 & 0.7 & 0.5 & 0.4 & 0.6 & 0.4 & 0.4 & 0.4 & 0.6 \\
0.6 & 0.4 & 0.3 & 0.3 & 0.4 & 0.6 & 0.7 & 0.5 & 0.5 & 0.6 & 0.5 & 0.5 & 0.5 & 0.4 & 0.5 & 0.4 \\
0.4 & 0.5 & 0.3 & 0.4 & 0.6 & 0.6 & 0.5 & 0.3 & 0.6 & 0.4 & 0.5 & 0.5 & 0.4 & 0.5 & 0.6 & 0.5 \\
0.3 & 0.4 & 0.3 & 0.3 & 0.6 & 0.7 & 0.5 & 0.5 & 0.6 & 0.6 & 0.5 & 0.6 & 0.5 & 0.5 & 0.5 & 0.5 \\
0.4 & 0.4 & 0.3 & 0.3 & 0.6 & 0.7 & 0.6 & 0.6 & 0.4 & 0.6 & 0.6 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \\
0.4 & 0.4 & 0.3 & 0.3 & 0.6 & 0.7 & 0.6 & 0.6 & 0.4 & 0.6 & 0.5 & 0.4 & 0.5 & 0.5 & 0.5 & 0.4 \\
0.4 & 0.5 & 0.3 & 0.4 & 0.6 & 0.6 & 0.6 & 0.5 & 0.7 & 0.4 & 0.6 & 0.5 & 0.5 & 0.5 & 0.6 & 0.5
\end{bmatrix}$$

B1-C, B2-C, B3-C, B4-C, B5-C, B6-C, and B7-C are found as respectively:

$$w^{(2)}=(0.0803, 0.0777, 0.0817, 0.0918, 0.0777, 0.0845, 0.0790, 0.0777, 0.0691, 0.1069, 0.0803, 0.0934) \quad \text{(eq.6)}$$

$$w^{(2)}=(0.1036, 0.1211, 0.1133, 0.1013, 0.1036, 0.1060, 0.1133, 0.1083, 0.1295) \quad \text{(eq.7)}$$

$$w^{(2)}=(0.1124, 0.1080, 0.0884, 0.0902, 0.1059, 0.1017, 0.1017, 0.0884, 0.0997, 0.1038) \quad \text{(eq.8)}$$

$$w^{(2)}=(0.1496, 0.1352, 0.1599, 0.1768, 0.1829, 0.1956) \quad \text{(eq.9)}$$

$$w^{(3)}=(0.1187, 0.1153, 0.1332, 0.1371, 0.1452, 0.1778, 0.1727) \quad \text{(eq.10)}$$

$$w^{(2)}=(0.0559, 0.0542, 0.0498, 0.0628, 0.0609, 0.0583, 0.0553, 0.0467, 0.0536, 0.0493, 0.0542, 0.0559, 0.0477, 0.0493, 0.0542, 0.0531, 0.0462, 0.0467, 0.0458) \quad \text{(eq.11)}$$

$$w^{(2)}=(0.0703, 0.0739, 0.0788, 0.0721, 0.0561, 0.0494, 0.0540, 0.0628, 0.0561, 0.0612, 0.0597, 0.0590, 0.0612, 0.0620, 0.0597, 0.0636) \quad \text{(eq.12)}$$

4. RESULTS

The results of the calculations indicate that fuzzy consistency judgment matrix is modified from the priority judgment matrix. Consistency condition is satisfied and iteration times are reduced. Convergence speed is improved under the accuracy condition of 0.0001. In the B layer, the risk factors have the weights as follows: w= (0.1591, 0.1591, 0.1379, 0.1340, 0.1638, 0.1302, 0.1160). Risk Factors outside the vessel is 0.1591, Risk factors related to structural design and arrangement of equipment locations is 0.1591, Risk factors related to technical faults in vessel equipment is 0.1379, Risks based on the usage and arrangements of the equipment on-board for operation process is 0.1340, Risks on cargo, fuel and related handling equipment is 0.1638, communicational, organizational, operation instruction faults and routine failures is 0.1302 and Human factors, interpretation, awareness assessment of situation, etc. is 0.1160. Thus, they are in such sequence as risks on cargo, fuel and related handling equipment, Risk Factors outside the vessel and Risk factors related to structural design and arrangement of equipment locations with the same risk level, Risk factors related to technical faults in vessel equipment, Risks based on the usage and arrangements of the equipment on-board for operation process, Communicational, organizational, operational instruction faults and routine failures, Human factors, interpretation, awareness assessment of situation, etc.

The result is observed consistent; three standard degree method is used to establish the priority judgment matrix. Marine accident statistical data agree well with this study. For C layer, Explosion or external conditions related to the oil drill (C10-0.1069), Other conditions (i.e. shell plating, frames, ice stringers, web frames, bow, stern, bilge keels) related to vessel construction or maintenance (i.e. rudder and steering arrangements, propeller, shafts and gears, miscellaneous machinery requirements) (C21-0.1295), Technical fault in sophisticated electronic navigation equipment (such as radar, sonar, and the visible, infrared, and microwave radiation sensors on-board satellites) (C22-0.1124), Faults in ergonomics, design and operation of the device, Human-machine interface problems (C37-0.1956), Leakages in cargo or fuel pipes/hoses (C44-0.1778), Familiarity with safety instructions, but no implementation (C48-0.0628), Inappropriate design of task or operation such as cargo, night navigation, route planning, anchoring etc.(C66-0.0788) have more heavily weight. These results indicate that more regulations or enforcement for the current codes are required to eliminate the risks. For instance, the result of C22 proves the significance of polar class, The International Association of Classification Societies (IACS) published a set of Unified Requirements for Polar Class Ships which is not mandatory [48]. Arctic Maritime Shipping Assessment (AMSA) has suggested qualifications and training for crew and ice navigators as need for the example of C66. In a conclusion, the results can accurately present the levels of the risks under their domain. This provides the theoretic basis for representatives, ship-owners and navigators on the focus on managing the ice navigation operations safely in the Arctic Region.

All vessels in ice-covered waters should be equipped adequately. Especially characteristics of pipelines and hoses are required to be strong enough and elastic in order to stand for probable minimum temperatures. Polar class vessels should be revised based the risks given in this study. Marine threat monitoring systems and forecast models for potential obstacles should be developed for ice-covered waters. By considering the risks of cargo, fuel and related handling equipment and B2-9 new design vessels should be constructed. Only polar class ships, based on IACS Unified Requirements for Polar Class Ships, should operate in polar waters or another similar alternative standard. Satellite integrated alternative route selection problems should be dealt with in a dynamic environment including weather conditions. Probabilistic models considering the future traffic congestion should be studied for analysing the probable marine accidents. Infrastructure problems such as inadequate numbers of icebreakers, etc. should be solved. New vessel traffic services are required for ice-covered waters. A new chapter based on ice navigation might be added to COLREGs. For further studies, risk management tools for the Polar Regions including Arctic region can be generated by considering the results of this thesis. Fault Tree Analysis for the other ice-navigation-related failures such as icing, stuck in ice, machinery failures and similar accidents are the research gaps to be developed for the Polar Regions including Arctic. Finally, optimization of route selection problem in ice-covered waters can be generated in a dynamic environment.

5. CONCLUSIONS

Comparing to the conventional Suez Canal route, newly opened routes in the Arctic region grab their attention of logistics firms and oil/gas companies with its shorter distance, less travel time and oil consumption and provision of new markets. Accordingly, marine traffic (especially number of tankers) increases in this region. A risk analysis is an emerging necessity in order to become aware of the risks and consider the numerical risk levels. A novel aspect of our research is that the risk levels of ice navigation in the Arctic region are determined by implementing improved fuzzy AHP approach, which is more convenient than the conventional AHP models with its consistency check. The relevant data is derived from the expert consultations and the algorithm is run through the MATLAB software. The main purpose of this study is to provide awareness of the risks with numerical probabilistic levels in order to understand taking corresponding measures to avoid such probable future unwanted events. The field experts agree the results that indicate there is a big consensus between the practical situation and the found risk levels.

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7. APPENDIX

MATLAB SOURCE CODE

```
function ifahp
clear ; clc ;
e=0.0001
Max=20
F=[]
N= size( F )
r=sum(F')
for i=1:N(1)
   for j=1:N(2)
R(i , j)=(r(i)-r(j))/(2*N(1))+0.5
end
end
E = R./R'
U=sum(R') / sum(sum(R) )
V(: ,1)=U'/max( abs (U) )
for i=1:Max
V(: , i+1)=E*V(: , i )
V(:,i+1)=V(:,i+1)/max(abs(V(:,i+1)))
if max( abs (V(: , i+1)-V( : , i ))) <e
k=i
W=V(: , i +1)./sum(V(: , i +1))
break
else
end
end
end
```

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