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Risk factors analysis of Arctic maritime transportation system using structural equation modelling

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ABSTRACT
In recent years, commercial voyages in polar waters have become reality through the development of marine technology and the melt of Arctic sea ice. However, the Arctic marine Transportation system (AMTS) is a dynamic system that various influencing factors are involved, such as extend sea ice, low temperature, complex earth's magnetic fields, high sea state, poor visibility, heavy wind, insufficient communication equipment and rescue aids and so on. These hazards ask for enormous challenges to the safety management of AMTS. This paper analyses risk scenarios and associated risk factors, and present a preliminary model to express the interrelationships among the selected risk factors in the AMTS. First of all, risk factors are identified to the specific hazardous scenarios. For this, a typical voyage is chosen as a case study, and the interrelationships among the selected risk factors are discussed by structural equation model (SEM). Additionally, a preliminary SEM is proposed to guide the future studies on the risk analysis of the AMTS.

INTRODUCTION
The Arctic Ocean is seen as an important water area to shipping industry as well as economic development. There are two classic shipping routes in the Arctic Ocean, namely, Northeast Passage (NEP) and Northwest Passage (NWP), which are alternative routes connecting Europe with northeast Asian and North American respectively, in which NEP is a shorter shipping line compared with traditional Suez cannel (Schøyen, et al, 2011). Besides, ice breakers with higher grades can navigate directly over the North Pole in from Europe to north Asia and American.

Shipping enterprises and researchers in the coastal countries and regions around the Arctic Ocean have paid much attention to the development of AMTS. Several European ships like "Marilee" and "Palva" have crossed the ice-covered Arctic Ocean to a few ports in northeast Asian with reference to northern sea route (NSR) transit statistics. A Chinese merchant vessel "Yongsheng" has successfully conveyed iron bars from China to Rotterdam port via NEP (Zhao, 2014). With reference to the estimation in Zhang, et al. (2013), in 2030, natural gas and containers' freight transport from the Arctic regions to East Asian will rise to 10 and 17.43 million tonnage, respectively. Considering the huge demand of cargos transportation in Polar Regions, NEP has great potential to become a regular shipping route in the near future.

On account of the severe navigational conditions in the Arctic Ocean, the AMTS is seen as a dynamic system that various influencing factors are involved, such as extend sea ice, low temperature, earth's magnetic fields, high sea stage, poor visibility, heavy wind and so on. Compared with navigation in the open sea, polar voyages suffer some special events like icing and getting stuck in ice. International Maritime Organization (IMO) proposed a polar regulation to polar shipping (Maritime Safety Committee, 2014), in which potential navigational hazards, ship's design and the selection of rescue aids and communication equipment were interpreted. Nevertheless, there have very limited cases to explain how to identify, assess, and determinate the potential risk and associated vulnerability. Embracing a risk management view to AMTS, uncertainties as lacking of experiences in the ice-covered polar waters, bring enormous challenges to navigational risk assessment studies.

This paper intends to analyse hazardous scenarios and associated risk factors, and present a risk analysis model to express the interrelationships among the selected risk factors in the AMTS. First of all, several hazardous scenarios and associated risk factors are interpreted. After that, a risk analysis framework is developed on the basis of SEM. Furthermore, a typical voyage in the Arctic Ocean is chosen as a case study, and the interrelationships among the selected risk factors are discussed.

SCENARIOS AND RISK FACTORS ANALYSIS

Hazardous scenarios analysis

From a traditional point of view, ships may encounter various hazardous scenarios in maritime transportation, e.g., collision, grounding, contact, swell damage, wind damage, fire, explosion and some other scenarios (Zhang, et al., 2013). Standing on the view of navigation in the ice-covered waters, ships not only need to deal with those traditional hazardous scenarios as the open sea navigation, but also should have the abilities to encounter some alternative scenarios bring from the Arctic sea ice. For instance, ships may suffer risks of getting stuck in ice in Arctic Ocean voyage. If a ship encounters a heavy ice stream during a voyage, it would be difficult to withstand the ice conditions. In this situation, most ships would hardly navigate out of the ice-covered waters, or even lose its control. On the other hand, if a ships follows an ice breaker in a heavy ice conditions, the distance between ice breaker and the followed ship would have to be close enough so as to keep the route accessible, which may also lead to a collision accident between these two ships.

Risk factors analysis

Navigational hazardous scenarios may be influenced by various characteristics of environment conditions, human factors, other vessels, navigation aids as well as ship itself (Trucco, et al., 2008). To be specific, ships suffer extend sea ice, low temperature, remoteness, insufficient navigational aids, inadequate seamarks, extreme high latitude, and complex magnetic fields and so on, in the AMTS. The former risk influencing factors mainly belong to vessel, environment and management aspects. As there are only a few vessels passing through the Arctic Ocean, the impacts from other vessels can be considered as trivial until Arctic Ocean developing into a regular shipping line. Besides, because there are very limited crews with sufficient polar navigation experiences, it is difficult to support associated human factors analysis. In this study, three aspects of risk factors, namely, environment conditions, aids to navigation and ship conditions, are taken into consideration, and the risks from human errors are omitted.

The risk factors in the AMTS are collected and shown in Figure 1, and the selection of risk factors is conducted based on literatures review and extensive discussions with experts in this area. The AMTS risk is set in the top level in this study. The elements in level 2 are set to be environment conditions, aids to navigation and ship conditions. Each element in level 2 is investigated based on its associated factors given in level 3 and level 4. To be specific, from the aspect of environment conditions, both weather conditions and ice conditions are considered and set in level 3. As for elements in level 4 from weather conditions, wind speed has relations to ship operations about ship's navigation speed and associated angles controls; low temperature in the air may lead to freeze of cold air, which frosts deck as well as associated equipment on board; visibility is a variable to express impacts from fogs and aurora borealis in the voyage. As for elements from ice conditions in level 4, sea ice is a key attribute to ice navigation. Specifically, both ice concentration and ice thickness are significant attributes in terms of sea ice situations (Montewka, et al., 2013 & 2015). Besides, water temperature affects the formation of sea ice, which is also a significant risk factor in the AMTS. From the aspect of aids to navigation, the accuracy of magnetic compass is tremendously affected by the earth's magnetic fields, gyrocompass and GPS are also influenced by the complexity of electromagnetic field in high latitude regions, and these factors are set in level 4. Additionally, from the aspect of ship conditions, ship's ice class, navigational speed and engine power in the voyage are essential variables to reflect ships navigation conditions and set in level 4.

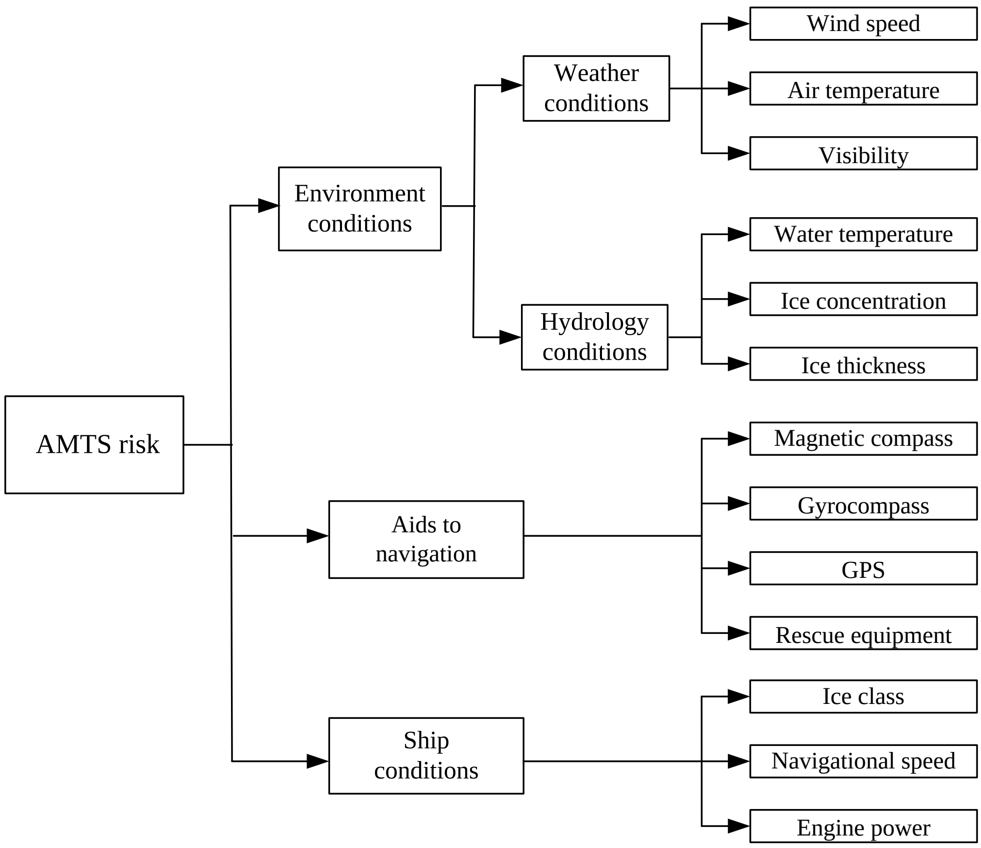

Figure 1. Risk factors in the AMTS

METHODOLOGY AND FRAMEWORK

Structural equation modeling

SEM is a multivariate analysis method that can be used to analyze causal relationships of variables in the social sciences (Wen, et al., 2014). Similar to the multiple-regression equation, SEM analyzes the structure of the selected characteristics as a serious of arithmetic equations (Cho, et al., 2009). Compared with other types of statistical methodologies, SEM has several advantages, such as the ability to estimate multiple and interrelated dependence relationships, the ability to represent unobserved concepts, and the ability to define a model explaining the entire set of relationships (Hair, et al., 2006). Because of these advantages, in recent years, SEM is gradually used in the structure analysis of complicated systems and some engineering fields so as to seek for complex relationships.

Generally, SEM consists of two parts, measurement equations and structural equations. The measurement part is a characterized model that measures exogenous variables with observed variables, which can be expressed as the following equations.

$$\begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_n \end{pmatrix} \xi + \begin{pmatrix} \delta_1 \\ \vdots \\ \delta_n \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{in(i)} \end{pmatrix} = \begin{pmatrix} \lambda_{i1} \\ \vdots \\ \lambda_{in(i)} \end{pmatrix} \eta_i + \begin{pmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_{in(i)} \end{pmatrix} \tag{2}$$

Where, ξ is a vector for exogenous variables, η_i is a vector for endogenous variables. Both exogenous and endogenous variables are latent variables, which are hardly measured and expressed directly. While, $(x_1, \dots, x_n)^T$ and $(y_{i1}, \dots, y_{ij}, \dots, y_{in(n)})^T$ are the observed indicators of ξ and η_i, respectively. $(\lambda_1, \dots, \lambda_n)^T$ is the coefficient vector relating $(x_1, \dots, x_n)^T$ to ξ, and $(\lambda_{i1}, \dots, \lambda_{ij}, \dots, \lambda_{in(i)})^T$ is the coefficient vector relating $(y_{i1}, \dots, y_{ij}, \dots, y_{in(n)})^T$ to η_i. Besides, δ and ε are error terms associated with the observed x or y variables.

The structural part is conducted by a characterized model, which is used to express the causal relationships between the endogenous and exogenous variables, as the following equation.

$$\eta_i = \begin{pmatrix} \lambda_{i1}' \\ \vdots \\ \lambda_{in(i)}' \end{pmatrix} \eta_i + \begin{pmatrix} \lambda_1' \\ \vdots \\ \lambda_n' \end{pmatrix} \xi + \zeta \tag{3}$$

Where, $(\lambda_{i1}', \dots, \lambda_{ij}', \dots, \lambda_{in(i)}')^T$ and $(\lambda_1', \dots, \lambda_n')^T$ are coefficient materials, and ζ is a vector used to express latent errors in the equations.

Continually, after acquiring the measurement and structural equations of concerned systems or variables, a SEM is constructed to express associated interrelationships among systems or variables. For the theme of risk analysis, variables in the SEM should be developed in accordance with multiple correlations among various risk factors.

Framework

Navigational risk assessment is widely used to prevent accidents and maintain the operations' efficiency during voyages. Although the existing methods are available for maritime transportation analysis, the formulation of risk assessment in the AMTS is a rather difficult task. In this paper, a framework is interpreted so as to support navigational risk analysis in the AMTS. In specific, the framework is divided into five steps illustrated in Figure 2.

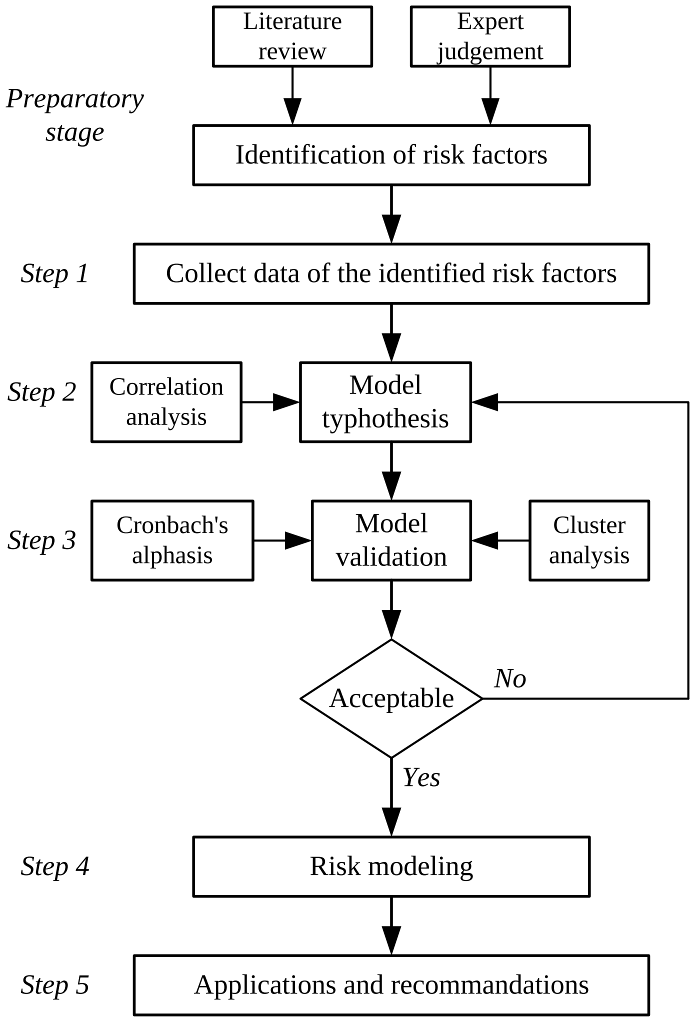

Figure 2. Research framework

Step 1: Data collection. Illustrate the research scope and boundaries, and collect relevant vessel's data in the AMTS according to the selected risk factors in the former section.

Step 2: Model hypothesis. Analyse correlation coefficients of the identified risk factors, and propose a hypothesized SEM to describe these interrelationships among associated risk factors.

Step 3: Model validation. As a preliminarily test, calculate data's reliability and construct validity to analyse the hypothesized model's accuracy and sensibility in terms of the ability to express interrelationships of risk factors.

Step 4: Risk modelling. On the basis of data testing, propose a modified hypothesized SEM model for risk analysis in the AMTS.

Step 5: Applications and recommendations. Discuss the proper applications of the proposed risk model, and present some recommendations for the AMTS.

CASE STUDY

This study focuses on navigational scenarios and the selected risk factors analysis in the AMTS. A merchant ship Yongsehng's polar voyage in the NEP is chosen as a case to conduct associated risk analysis.

Step 1: data collection

Both ship particular and navigational associated data in the Arctic Ocean voyage are required to conduct this case study. The basic information of this Yongsheng is listed in Table 1.

Table 1. Ship particular

Parameter (unit)	Ship 1
Name	Yongsheng
Flag (country)	Hong Kong & China
Type	General cargo
Ice class	Arc 4 (Russian ice class)
DWT (tonnage)	14357
Length (m)	159.985
Breadth (m)	23.70
Draught (m)	41.10
Operation power (kw)	7074

Yongsheng ship's navigational records during the NEP are used to carry out the risk analysis, and the duration was from Aug. 28 to Sep. 2, in 2013. Totally, 179 sets of data are obtained, including air temperature, relative speed of wind, visibility, water temperature, ice concentration, GPS, gyrocompass, magnetic compass, navigational speed and engine power in navigation. However, most of the Arctic sea ice belong to ice float in this voyage, the sea ice thickness remains still so it is not considered in the numerical analysis process.

Step 2: model hypothesis

All the sets of collected navigational record were used to estimate correlation coefficients among these selected risk factors. A statistic approach-Kendall's tau_b (Abdi, 2007) is used to measure the pair wise correlations coefficients between the selected risk factors. Due to the values of the Arctic sea ice thickness are not varying obvious in this summer voyage, and the associated equipment on board cannot express the variations of the ice thickness, its numerical analysis is therefore omitted in this step. Moreover, since this ship's ice class is constant, ice class factor is therefore taken out of consideration in the correlation analysis.

Table 2. Pare wise correlation coefficients between each risk factor

		Weather conditions			Hydrology conditions		Aids to navigation			Ship conditions	
		v_1	v_2	v_3	v_4	v_5	v_6	V_7	v_8	v_9	v_{10}
Weather conditions	Wind speed (v_1)	1.000	.179**	**-.042**	.355**	-.402**	-.219**	-.117*	-.134**	.083	.350**
	Air temperature (v_2)	.179**	1.000	**-.033**	.534**	-.290**	-.051	-.406**	-.470**	.142**	.512**
	Visibility (v_3)	**-.042**	**-.033**	**1.000**	**-.003**	**-.015**	**.095**	**.037**	**.061**	**-.018**	**-.019**
Hydrology conditions	Water temperature (v_4)	.355**	.534**	**-.003**	1.000	-.579**	-.358**	-.353**	-.384**	.335**	.702**
	Ice concentration (v_5)	-.402**	-.290**	**-.015**	-.579**	1.000	.214**	.222**	.243**	-.409**	-.633**
Aids to navigation	Magnetic compass (v_6)	-.219**	-.051	**.095**	-.358**	.214**	1.000	.390**	.311**	.025	-.208**
	Gyrocompass (v_7)	-.117*	-.406**	**.037**	-.353**	.222**	.390**	1.000	.883**	-.043	-.296**
	GPS (v_8)	-.134**	-.470**	**.061**	-.384**	.243**	.311**	.883**	1.000	-.018	-.322**
Ship conditions	navigational speed (v_9)	.083	.142**	**-.018**	.335**	-.409**	.025	-.043	-.018	1.000	.454**
	Engine power (v_{10})	.350**	.512**	**-.019**	.702**	-.633**	-.208**	-.296**	-.322**	.454**	1.000

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

From the Kendall's tau_b correlation coefficients results shown in Table 2, we find interrelationships among identified risk factors, as followed:

(1) majority of risk factors have significant correlations with the others except visibility, and the correlations between visibility variable and all the other variables are not significant;

(2) the variables from weather conditions have significant correlations with the variables from hydrology conditions, aids to navigation and ship conditions, for instance, correlation coefficient values between wind speed and water temperature, air temperature and water temperature, wind speed and ice concentration, air temperature and ice concentration, are 0.355, 0.534, -0.402, -0.290, respectively;

(3) the variables from hydrology conditions have significant correlations with the variables from aids to navigation and ship conditions;

(4) the variables from aids to navigation have significant correlations with the variables from ship conditions.

Based on the correlations analysis results of the selected risk factors, a hypothesized SEM for the risk factors in the AMTS is developed, as illustrated in Figure 3.

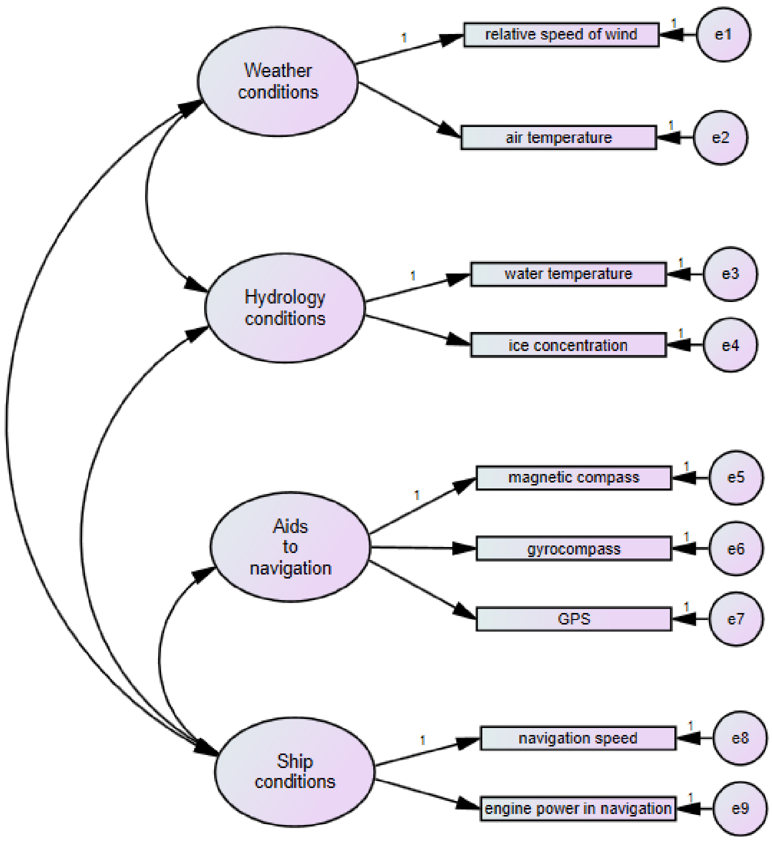

Figure 3. A hypothesized SEM for the risk factors in the AMTS

In this hypothesized SEM, weather conditions, hydrology conditions, aids to navigation, ship conditions are set as latent variables. To be specific, wind speed and air temperature factors are hypothesized as observed variables to express weather conditions; ice concentration and water temperature factors are hypothesized as observed variables to express hydrology conditions; magnetic compass, gyrocompass and GPS are hypothesized as observed variables to express aids to navigations; navigation speed and engine power are hypothesized as observed variables to express weather conditions. Furthermore, three risk factors (visibility, ice thickness and ship's ice class) identified in the section 2 are omitted in the hypothesized SEM. As for the visibility, the correlations between visibility and the other variables are insignificant. As for ice thickness and ice class variables, the variations of these data aren't obvious to support the associated numerical analysis.

Step 3: model validation

A. reliability analysis

Cronbach's alpha is used as an indicator to test the reliability of the hypothesized SEM (Wyrwich, et al., 1999). Generally, if calculation result of Cronbach's alpha is above 0.6, the internal consistency of tested variables is acceptable; and if calculation result of Cronbach's alpha is below 0.5, the associated consistency is unacceptable. The specific criteria of Cronbach's alpha and internal consistency results between the tested variables are shown in Table 3.

Table 3. Results of reliability test for the hypothesized model

Latent variable	Cronbach's alpha coefficient	Internal consistency
Weather conditions	0.353	Unacceptable (below 0.6)
Hydrology conditions	-2.816	Unacceptable (below 0.6)
Communication equipment	0.917	Excellent (above 0.9)
Ship conditions	0.962	Excellent (above 0.9)
Comprehensive	0.638	Acceptable (between 0.6 and 0.7)

According to the results in Table 3, the comprehensive consistency is acceptable and the associated Cronbach's alpha coefficient is 0.638; the internal consistencies of communication equipment and ship conditions are excellent, and their Cronbach's alpha coefficient is 0.917 and 0.962, respectively; the internal consistencies of weather conditions and hydrology conditions unacceptable with 0.353 and -2.816 Cronbach's alpha coefficient respectively. As the inter consistencies of weather conditions and hydrology conditions cannot pass the Cronbach's alpha test, the latent variables cannot support the observed variables of weather conditions and hydrology conditions in the hypothesized SEM.

B. cluster analysis

Then, cluster analysis of the associated observed variables are conducted so as to test the structure validity of the hypothesized SEM. Cluster analysis can be also used to investigate reasons for the unacceptable results of the reliability test.

Hierarchical cluster analysis is a common approach to do classify test (Rousseeuw, 1987). In specific, between-groups linkage method is used in this study to implement rescaled distance cluster analysis. The corresponding classification results are illustrated in Figure 4.

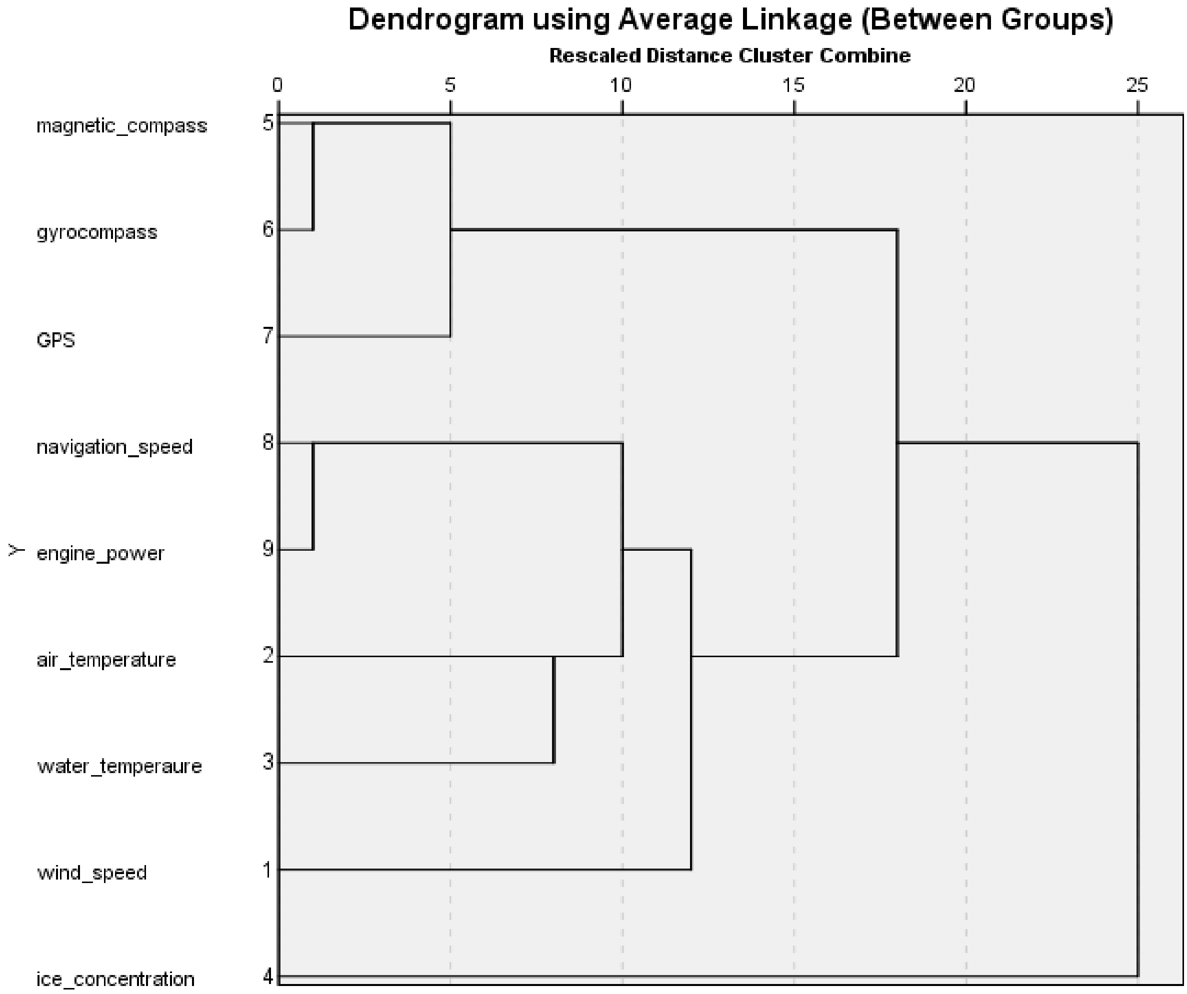

Figure 4. Classify of the observes variables in the hypothesized SEM

From cluster analysis results in Figure 4, the rescaled distance cluster combine among variables navigation aids and ship conditions are no more than 5, which means the classification of aids to navigation variables and ship conditions variables are acceptable; as rescales distance cluster combine among air temperature, water temperature and wind speed variables are no more than 13, these variables can be also classified into one cluster; as for ice concentration variables, it has a larger cluster distances with the other variables, it seems that this variable does not belong to any of the other clusters. Therefore, the hypothesis of the observed variables in weather and hydrology conditions latent variables need to be modified.

The results of reliability and cluster analysis show that: the hypothesis of aids to navigation and ship conditions associated variables are acceptable; water temperature and ice concentration variables have close relationship for their correlation coefficient is -0.579, but these two variables cannot be used to express the hydrology conditions observed variables neither in internal consistency nor cluster analysis results. Researchers should pay attention to interrelationships among hydrology conditions, such as ice concentration, ice thickness and water temperature. Only with the sufficient data of these variables, interrelationships of waters condition can be clearly demonstrated for the AMTS.

Step 4: risk modelling

According to the results of reliability and cluster analysis, a revised hypothesis SEM is proposed, as shown in Table 4 and Figure 5. As the rescaled distance cluster combine among weather temperature variables, air temperature and wind speed variables are no more than 13, the water temperature variables are modified to be the latent variable of weather conditions observed variable. Also the new weather conditions and comprehensive Cronbach's alpha coefficients are acceptable with values of 0.699 and 0.638 (shown in Table 5), has well validated the new hypothesized SEM.

Table 4. Variables in the hypothesized SEM

Latent variables	Observed variables
ice conditions ξ	Ice concentration x_1
	Water temperature x_2
Weather conditions η_1	Wind speed y_{11}
	Air temperature y_{12}
Aids to navigation η_2	Magnetic compass y_{21}
	Gyrocompass y_{22}
	GPS y_{23}
Ship conditions η_3	Navigation speed y_{31}
	Engine power in navigation y_{32}

Table 5. Results of reliability test for the modified hypothesized model

Latent variable	Cronbach's Alpha	Internal consistency
Weather conditions	0.699	Acceptable
Ice conditions	N/A	
Aids to navigations	0.917	Excellent
Ship conditions	0.962	Excellent
Comprehensive	0.638	Acceptable

Risk assessment of the AMTS can be conducted by using the algorithm of SEM. Due to the data deficiency in the aspect of ice conditions, this study presents a preliminary hypothesized SEM.

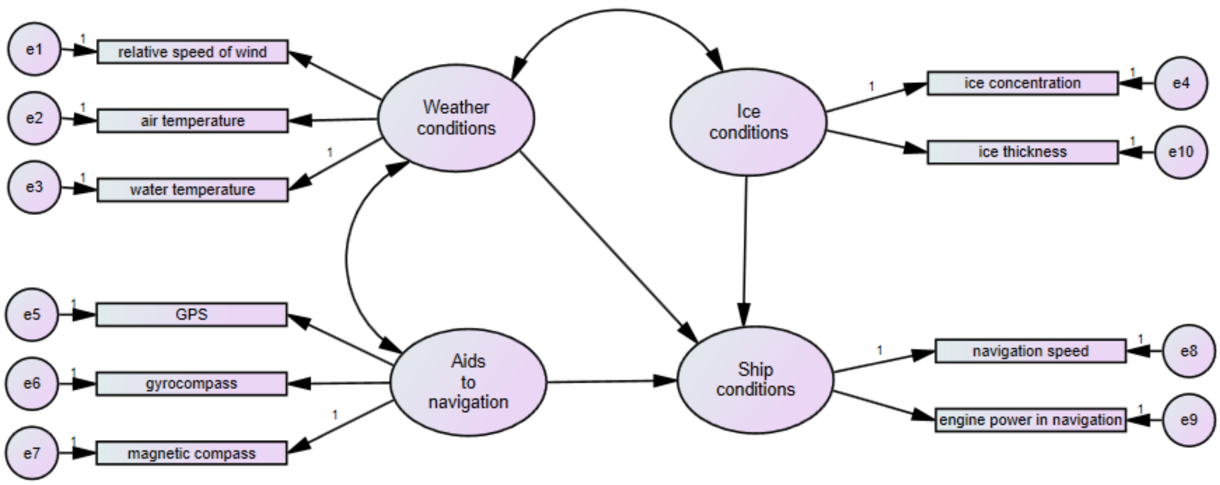

Figure 5. A modified hypothesized SEM

Step 5: applications and recommendations

The proposed research framework and the preliminary hypothesized SEM would provide insight knowledge and foundation for future navigational risk analysis research in the AMTS. Besides, the navigational condition complexity of AMTS is verified by the analysis results. To be specific, the identified environmental factors including air temperature, wind speed, water temperature and ice concentration have significant interrelationships between each other. However, according to the results of reliability and cluster analysis, the former three factors belong to a cluster to express weather conditions, and ice concentration factors belongs to an alternative cluster to express ice conditions according to the results of cluster analysis.

CONCLUSIONS

In the Arctic Ocean's severe and fast changing navigational conditions, navigation is an activity with high risks and uncertainties. SEM is an appropriate method to investigate interrelationships among some specific factors. Using this method, a preliminary hypothesized SEM is developed to explore the multiple interrelationships among the selected risk factors in the AMTS. Due to the data deficiency in ice conditions, this paper just interpreters the preliminary SEM for the identified risk factors. Future works will include model validation, risk estimation, and decision making in terms of navigational risk analysis in the AMTS.

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