RISK ANALYSIS OF OFFSHORE TRANSPORTATION ACCIDENT IN ARCTIC WATERS

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SUMMARY

A methodology for risk analysis applicable to shipping in arctic waters is introduced. This methodology uses the Bowtie relationship to represent an accident causes and consequences. It is further used to quantify the probability of a ship accident and also the related accident consequences during navigation in arctic waters. Detailed fault trees for three possible ship accident scenarios in arctic transits are developed and represented as bowties. Factors related to cold and harsh conditions and their effects on grounding, foundering, and collision are considered as part of this study. To illustrate the application of the methodology, it is applied to a case of an oil-tanker navigating on the Northern Sea Route (NSR). The methodology is implemented in a Markov Chain Monte Carlo framework to assess the uncertainties arisen from historical data and expert judgments involved in the risk analysis.

1. INTRODUCTION

The size and number of ships has increased significantly over time (Toffoli et al., 2005). The quest for new energy sources in arctic regions has drawn attention to this area (Chance and Andreeva, 1995). The Northwest Passage and Northern Sea Route (NSR) are alternative trade routes with potential to shorten distances, reduce fuel consumption and lower emissions (Kitagawa, 2008). The environmental conditions of the region present challenges to mariners and the current ship technology and systems (Arctic Council, 2009). The cold temperatures, multi-year sea ice, ice ridges, pack ice, and severe climate are some of the features of this region (Kassens et al. 1994; Melling, 2002). For example, the thickness of ice varies seasonally in different areas. The central Arctic Ocean is almost permanently covered by ice, with a mean ice thickness of 3.4 m and standard deviation of 1.4 m (Bourke and Garrett, 1987). Although the effects of harsh and cold environmental conditions of arctic regions on human performance and control devices has been investigated (Noroozi et al., 2013), the work devoted to quantitative risk analysis of ship accidents in arctic transits is limited.

Accident statistics illustrates that number of serious ship accidents has decreased in the past few decades (Oltedal and Wadsworth, 2010). Regardless of this progress, about 500 serious accidents occur annually, 10% of which lead to fatalities (Fowler and Sorgard, 2000). The possibility of ship accident in this region is expected to increase as the number of arctic voyages increases (Borgerson, 2008).

Maritime traffic poses different risks to people, the environment, and assets (Youssef et al., 2014a). In the risk analysis of ship accidents, it is essential to obtain reasonable estimates for probabilities of accident scenarios and the associated consequences. The present study aims to develop a methodology based on Bow-tie (BT) diagram to represent different possible accident scenarios to quantify the risk of transit on arctic routes. The BT diagram, which is composed of a fault tree (FT) and an event tree (ET), represents the logical relationships between the causes and consequences of an accident. The probabilities of three possible accident scenarios on arctic routes are quantified using FTs. Then using the ET analysis, the possible consequences resulting from these accidents are determined and their probabilities are calculated. The methodology relies on expert judgments in the estimation of the probability distributions of primary events. Finally, to handle uncertainties arising from the distributions, the methodology is implemented in a Markov Chain Monte Carlo (MCMC) framework.

2. PROPOSED METHODOLOGY FOR SHIP ACCIDENT IN HARSH CONDITIONS

2.1 ACCIDENT PROBABILITY ANALYSIS: FAULT TREE MODELING

In risk analysis, it is necessary to have an estimation of an accident's probability to evaluate the risk of the accident (Youssef et al., 2014b). The basic probability may be obtained from historical data of previous reported accidents (Darbra and Casal, 2004), or from the application of probabilistic methods such as FT. FT presents a structured approach to investigate the probability of failure resulting from combinations of faults in a complex system (Tanaka et al. 1983). This logical and diagrammatic approach illustrates the minimum set of events that may cause the failure of a system. In FT technique, an undesired event (e.g., collision, foundering, and grounding) is defined and then decomposed to determine its environmental and operational basic events. The synthesis of the results is demonstrated with a graphical model presented by the logical AND-gates and OR-gates (Elliott, 1994).

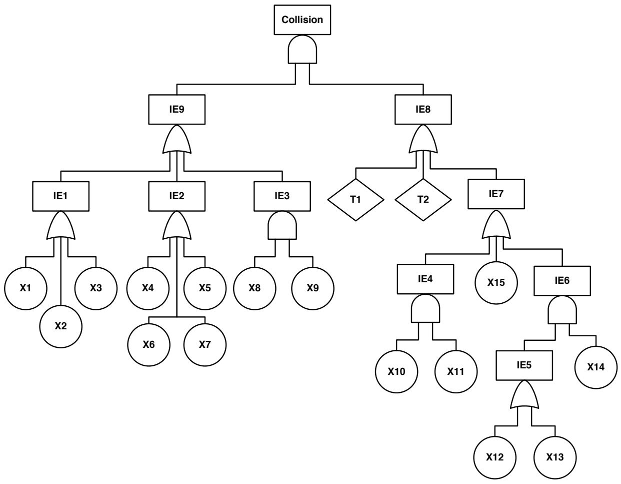

Figure 1. Fault tree of ship collision (events are explained in Table 1)

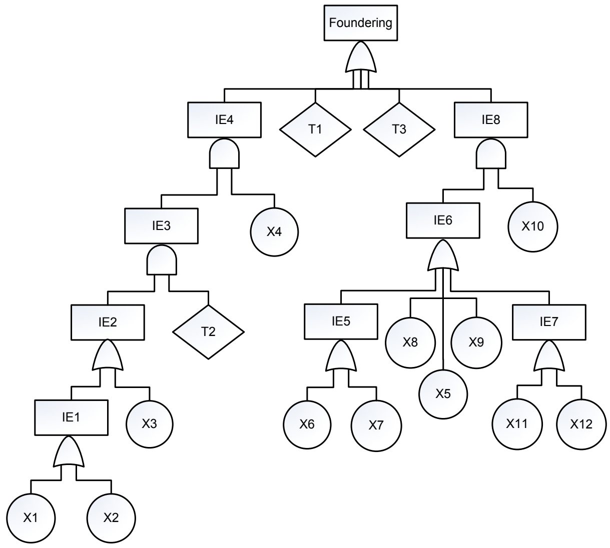

Figure 2. Fault tree of ship foundering (events are explained in Table 1)

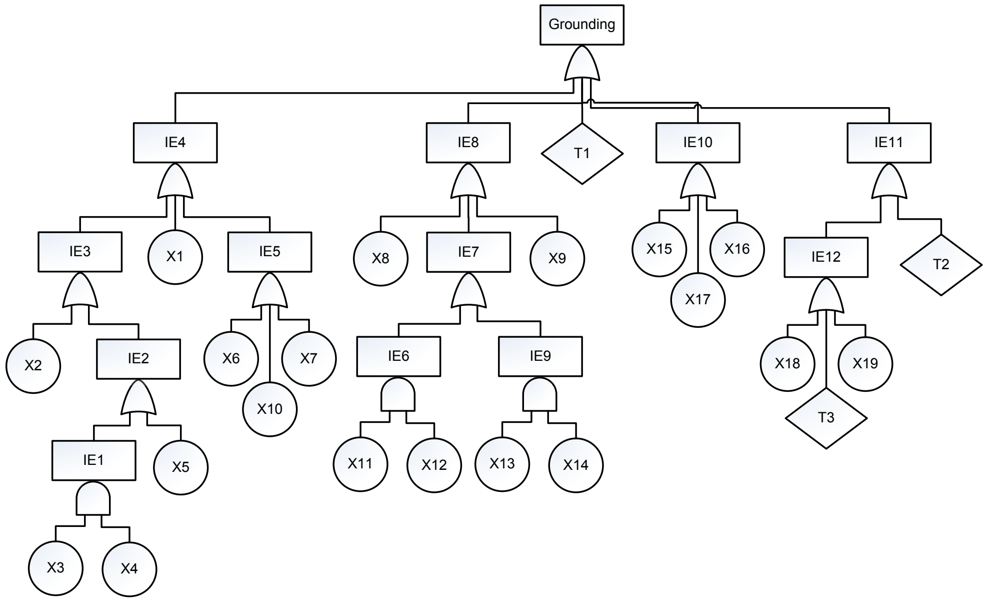

Figure 3. Fault tree of ship grounding (events are explained in Table 1)

Figures 1, 2, and 3 illustrate the relevant FTs for ship collision, foundering, and grounding accident scenarios, respectively. The FTs are developed according to previous literatures (e.g. Antao and Soares, 2006; Trucco et al. 2008) on ship accidents in normal environments and considering the particular characteristics of navigating in arctic environment using the expert opinions. Ship accidents are caused by a combination of accidental events and processes (Yang, Wang, and Li 2013). Human error and lack of visibility are recognized as main contributors to ship collisions (Macrae, 2009; Goerlandt and PenttiKujala, 2011). Fatigue, poor communication, faulty policies, practices and standards, poor knowledge of own ship systems and poor general technical knowledge are important human factor issues facing the marine industry (Talley, 2002; Dhillon, 2007).

In this study, the main focus is on the collision of a ship with arctic ice during arctic transits. One of the main reasons for ship collision with ice is detection failure, which, in turn, can be related to human error or failure of instrument used for detecting sea ice thickness and mass. In this study it is assumed that an icebreaker escorts a ship. The failure of the icebreaker to remove ice may lead to collision of a ship with ice. Finally, by increasing the arctic transit traffic in near future, the fault of other vessels can be considered as a possibility for collision scenarios.

2.2 ACCIDENT CONSEQUENCES ANALYSIS: EVENT TREE MODELING

An ET demonstrates a logical combination of possible event outcomes following by an initiating event (Huang, Chen and Wang, 2001). The progress of an accident is divided into discrete events, starting from an initiating event, and enumerates all the possible outcomes based on failure/success of sequential top events. The probability of each outcome is calculated by multiplying the failure/success probabilities along each path.

In ship collision analysis, different consequences depending on the ship type are identified. Considering an oil tanker in this study, the first possible outcome after collision is a breach in the vessel hull. The breach can consequently give rise to large spill of hydrocarbons in the sea, causing significant damage to the environment, costly remediation techniques, and economic loss (Dave and Ghaly, 2011; Goerlandt, Stahlberg, and Kujala, 2012). The release of hydrocarbons can be followed by fire and explosion, threatening the vessel and the crew. If the fire cannot be controlled and extinguished in a timely manner, it may escalate to a catastrophic accident, which may cause many fatalities and the loss of entire vessel (Dave and Ghaly, 2011). The probability of the consequences considered in event tree is estimated considering the expert judgment for a particular accident scenario. It should be noted that emergency responses and evacuation procedures are challenging in marine environments particularly in arctic waters, due to the impacts of cold, ice, and a harsh and often remote operating environment on response personnel and equipments (Verny and Grigentin, 2009). This may lead to more severe consequences in case of a ship collision on arctic routes, which should be considered in the consequence analysis.

2.3 RISK ANALYSIS: BOW-TIE MODELING

A BT diagram is a constructive risk assessment and management tool that combines a FT and an ET to demonstrate the relation between hazards, threats, controls, and consequences (Cockshott, 2005; Nordgard, 2008). The application of BT to risk analysis of chemical process facilities and offshore oil and gas industry has previously been discussed by researchers (Mokhtari et al., 2011; Khakzad et al. 2012). One of the advantages of the BT model is that all connections between an undesired event, safety barriers, and outcomes are fully recognized (Markowski and Kotynia, 2011). Therefore, it can be adopted as a tool to consider possible controls and safety barriers to prevent the occurrence of an undesired event and/or to mitigate the ensuing possible outcomes. BT diagram is centered on an undesired event with a FT on the left-hand side, addressing potential primary causes leading to the undesired event (ship collision in this study), and with an ET on the right-hand side, exploring the possible consequences resulting from the undesired event. Combining the FT of collision shown in Figure 1 and the ET depicted in Figure 4, the BT diagram for the ship collision can be developed as illustrated in Figure 5.

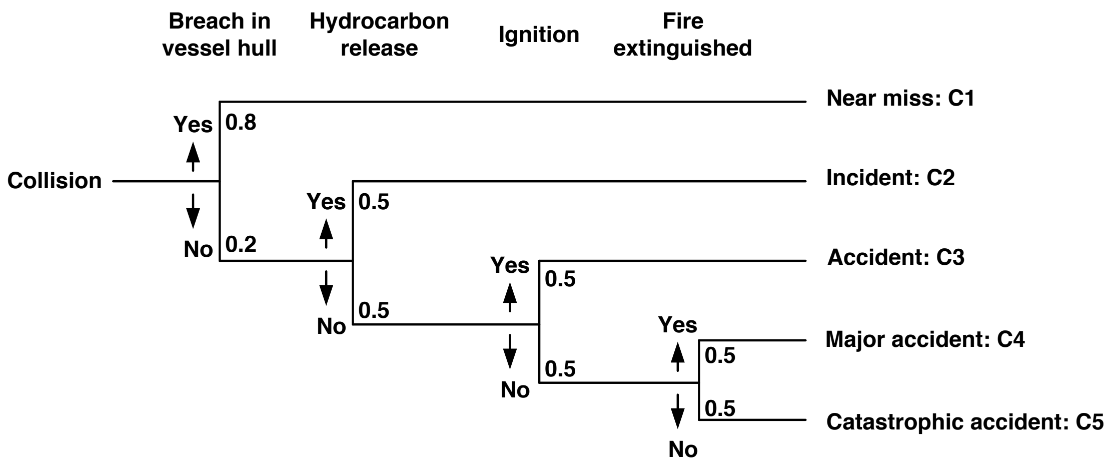

Figure 4. Event tree diagram for ship collision.

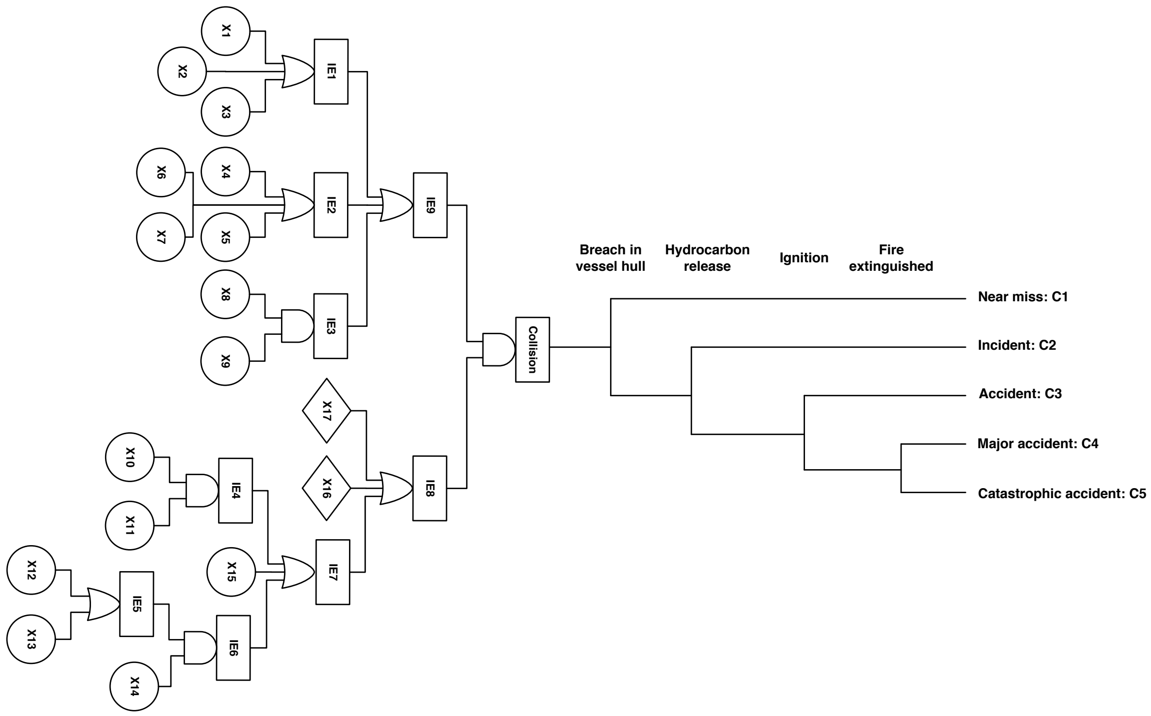

Figure 5. Bowtie diagram for ship collision.

2.4 HANDLING UNCERTAINTY IN RISK ANALYSIS

Information required for performing quantitative risk analysis can be achieved through historical data or expert judgment. The latter method is important, particularly, when the historical data to estimate the probabilities of events is missing or limited (Lindhe et al., 2009). However, expert knowledge is usually incomplete, inconsistent, vague, or imprecise, introducing sources of uncertainty to risk analysis (Goossens and Cooke, 1997; Mokhtari et al. 2011). Different approaches such as Monte Carlo simulation, evidence theory, and fuzzy sets have been adopted by researchers to model these uncertainties (Prassl, Peden, and Wong, 2005; Ferdous et al., 2009).

In this study, to model uncertainties in input data and propagate them through FT, a Markov Chain Monte Carlo (MCMC) simulation is used. MCMC methods (Geman and Geman, 1984) enable drawing samples from the joint posterior distribution of a set of parameters of interest. MCMC analysis has widely been used as a powerful tool for handling uncertainties (Rezaie et al., 2007; Smid et al., 2010; Khakzad et al., 2014).

To this end, the FT is implemented via OpenBUGS, a general-purpose software tool based on MCMC simulation (Lunn et al., 2009).

To apply the MCMC simulation, marginal probability distributions of the FT primary events can be determined using experts. In this study, a beta distribution is used for the natural events such as high wind, fog, and wave due to the flexibility of this distribution in modelling a wide variety of random events. Also, for events with unknown distributions such as radar failure or human error, a uniform distribution is applied. Finally, the normal distribution is adopted for two undeveloped events Chart error (T1) and Ice-breakers failure (T2) in the collision fault tree of Figure 1. For instance, the primary events High Speed (X2), Wave (X9), and Ice-breakers failure (T2) in Figure 1 can be modelled in OpenBUGS as:

```
Model {
X2 ~ dunif (0.001, 0.066)
X9 ~ dbeta (5.3, 1000)
T2 ~ dnorm (0.0073, 0.002)
}
```

where dunif, dbeta, and dnorm represent the uniform, beta, and normal distributions, respectively. After assigning the afore-mentioned probability distributions to the primary events, the probability distributions of the intermediate events and the top event can be derived based on logical gates of the FT. Furthermore, the mean value of each distribution along with the respective confidence interval can be calculated by the software. Having the probability distributions instead of single probability values facilitates the modelling of uncertainties more effectively.

3. APPLICATION OF THE METHODOLOGY

To illustrate the application of the proposed methodology, the probability of a ship collision navigating in the Northern Sea Route (NSR) is estimated. The NSR shortens the distance between a Northwest-European port and the Far East by approximately 40% in comparison with the Suez Canal for the similar purposes. As a result, the emissions into the air are decreased and the cost of transportation is reduced (Schoyen and Brathen, 2011). The growth of the NSR will also assist in the extraction of natural resources such as petroleum, natural gas and minerals in the regions along the route (Granberg, 1998). There are many challenges in using the NSR as a navigation route, such as the building costs of ice-classed ships and their non-regularity and slower speeds (Liu and Kronbak, 2010), navigation difficulties, greater risks due to the harsh and cold conditions along the route, as well as the release of pollutants that may affect the ecological balance in the region (Ranger 2008). This subsequently necessitates a comprehensive methodology to investigate the risk of navigation through the NSR, considering the effects of harsh and cold environments. Application of the methodology to quantitative risk analysis of a ship collision navigating on the NSR is presented in the following sections.

3.1 ACCIDENT SCENARIO ANALYSIS

The NSR crosses the Bering Sea into the Barents Sea from the north of Russia (Kitagawa 2001). The NSR in arctic region includes the Chukchi Sea, East Siberian Sea, Laptev Sea, Kara Sea, and Barents Sea from east to west. To analyze the risk of collision of an oil tanker along the NSR, various parameters such as the effects of wind, current, temperature, and ice along the route are considered. These parameters affect the ship's navigation as well as human performance in emergency situations. Although, the bathymetry of the seas, ice conditions, and meteorological parameters along the route have been investigated in more details by researchers (Pavlov et al., 1996; Budikova, 2009; Shibata et al., 2013), the work devoted to the effect of harsh and cold conditions along the NSR is limited. The severe climate of arctic regions along the NSR justifies the reason for re-evaluating the ship accident scenarios using the data obtained from this environment. This is also considered by experts in this study when defining the probabilities of the events.

Along the NSR, currents and sea ice exhibit high spatial and temporal variability. The only route from the Pacific to Arctic is the Chukchi Sea with a surface area of 6.20 E 05 km^2. The average depth of the Chukchi Sea is 80 m, and approximately 50% of the area is less than 50 m deep (Hunt et al., 2013). It is almost ice-covered from early December to mid-May; however, it is losing about 80% of its maximum winter extent during the summer. Air temperature is between -30^{o}C to -20^{o}C during winter, varying from west to east, and reaching to 2^{o}C to 5^{o}C in the summer (Mulherin, Sodhi, and Smallidge, 1994). The East Siberian Sea has an area of 8.95 E 05 with a mean depth of 52 m (Anderson et al. 2011). It is almost ice-covered during the winter season, and 50% of ice remains during summer as well. The winter mean temperature is -30^{o}C (Mulherin, Sodhi, and Smallidge, 1994). Overall, the average depth of Chukchi Sea and East Siberian Sea makes the whole coastal region along the eastern NSR relatively shallow for all marine operations (Arctic Council, 2009). However, the average depth of Laptev Sea is much deeper at 519 m depth, and it has an area of 6.50 E 05 km^2. The average wind speed over the sea is 5 m/s, and storms occur in the sea, three to four times monthly. Fog is frequent over the sea and the total humidity is between 95-98% (Fofonova, 2012). The Kara Sea has an area of 8.80 E 05 km^2 with a mean depth of 110 m (Galimov, et al., 2006). It has an average humidity of 85-95% recorded in summer. Air temperature varies seasonally between -28^{o}C and 5^{o}C in winter and summer seasons, respectively (Pavlov et al. 1996). Finally, the Barents Sea has a surface area of 1.40E 06 km^2 and the mean depth of 230 m (Sakshaug, 1997; Smedsrud et al., 2010). The climate conditions of Barents Sea are mostly affected by warmer Atlantic water with a temperature of 3-6^{o}C (Sakshaug and Slagstad, 1992; Adlandsvik and Loeng, 2007). During the summer seasons, the entire Barents Sea is ice-free (Sakshaung, 1997). This provides an opportunity for marine transportation and exploration of natural resource deposits.

There are variations between the values of different parameters such as temperature, wind, current, ice, and humidity along the NSR. However, to our knowledge, there is no particular parameter that can be used to clearly divide the NSR to different regions. Therefore, we divided the NSR based on the different seas along the route and used the boundaries between the seas. The five different seas along the route provide five different regions considered in this study.

The collision probability of an oil tanker in each individual region is calculated based on the generic FT in Figure 1. The probabilities of primary causes are adopted from previous literatures on ship accident modeling in normal conditions. In case these probabilities could not be found or there are specific to arctic environments, expert judgment to find out the probabilities is used. Three different experts are used to define the probability distributions of primary events in each region. Each expert has more than 10 years of industrial and research experiences on ship transportation and accident modeling. They are also familiar with cold and harsh environmental conditions of arctic regions. The final value of the probabilities for each event is the mean value of the corresponding distribution function. Finally, using the BT diagram, consequence analysis is performed for the worst case scenario, i.e., the region with the highest collision probability.

3.2 RESULTS AND DISCUSSIONS

The input data for BT analysis in each particular region is received from the experts. The mean values of these data for each region are presented in Table 2.

One of the frequent contributing factors to ship collision, based on the probabilities assigned by the expert judgments, is the effect of human factors on the detection failure. This is in agreement with previous research on offshore and maritime accidents, depicting that 80% or more of such accidents involve human error (Ruthblum et al., 2002). The cold temperature is another important factor that may affect the physical and cognitive performance of human activities. Cold temperature affects vigilance, reaction times, memory and recall, and strength (Enander, 1987; Hoffman, 2002; Noroozi et al., 2013). The collision of ship with pack ice and non-detected ice is another significant factor considered by the expert judgment to develop FTs. The existence of ice in arctic water is one of the main challenges for navigational purposes. The multiyear ice thickness can be greater than 3 m, and its presence on the NSR creates a dangerous environment for marine operations (Johannessen et al., 1997). Previous accidents such as the T/S 'Maxim Gorkiy' at in 1989, which, while navigating from Iceland to Spitsbergen, entered a field of drifting ice confirms the difference between the navigation in ice-covered waters and normal marine transportation (Jensen, 2007).

The results of the FT analysis illustrate the highest collision probability is in region 2 (the mean value of 4.61 E -03 with a 95% confidence interval as (1.01 E -03, 1.20 E -02)). The remote location, harsh environment, and the mostly unexplored physical oceanography (Munchow, Weingartner, and Cooper, 1999) are some of the characteristics of this region (East Siberian Sea) that create challenges for navigational purposes.

The final probability of the ship collision on the NSR is estimated by integrating the probabilities of collision in the all regions. The probability of collision on the NSR, according to the data received by expert judgments is calculated as 7.01 E -03. Having this probability value for the collision as the initiating event in the BT diagram, the probabilities of consequences are calculated as shown in Table 3. Likewise, the likelihood of catastrophic accident in NSR is 1.75 E -04. This confirms that the probability of a ship collision in NSR is higher than that of in temperate conditions (Fowler and Sorgard, 2000).

The possible safety measures to reduce the collision probability on the NSR and to mitigate the consequences are not considered in this study. However, the developed methodology can be used to investigate the possibility of preventing and mitigating ship collisions and the consequences.

4. CONCLUSION

A methodology was developed in this paper based on BT diagram, due to the need for reassessing ship accident scenarios in arctic transits. The methodology is aimed at helping decision makers and safety experts to estimate the probability of ship accidents and also to consider the factors that contribute the most to the overall accident probabilities. This provides a basis to decrease the risk of transportation in arctic routes.

Application of the proposed methodology to a ship accident scenario on the NSR confirms a higher probability for ship collision on this transit route. Due to significant variation of various parameters influencing a ship collision, the probability of accident is not similar within different regions along the route. It is demonstrated that the probability of an accident should be investigated in each individual region along the route to have an accurate estimation of the final accident probability. The total probability of ship collision on the NSR is calculated as 7.01 E -03, and the likelihood of a catastrophic accident is 1.75 E -04. This confirms a higher probability of collision on this transit route in comparison with that of temperate regions.

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6. REFERENCES

1. ADLANDSVIK, B., and LOENG, H. 2007. "*A study of the climatic system in the Barents Sea*." Polar Research 10(1): 45-49.
2. ANDERSON, L.G., BJORK, G., JUTTERSTROM, S., PIPKO, I., SHAKHOVA, N., SEMILETOV, I., and WAHLSTROM, I. 2011. "*East Siberian Sea, an Arctic region of very high biogeochemical activity*." Biogeosciences 8: 1745–1754.
3. ANTAO, P., and SOARES C.G. 2007. *Fault tree models of accident scenarios of RoPax vessels*. International Journal of Automation and computing 2: 107-116.
4. Arctic Council. 2009. *Arctic Marine Shipping Assessment*. Retrieved from: http://pame.is/images/stories/.
5. BORGERSON, S.G. 2008. "*Arctic meltdown: the economic and security implications of global warming*." Foreign Affairs 87(2): 63-77.
6. BOURKE, R.H., and GARRETT, R.P. 1987. *Sea ice thickness distribution in the Arctic Ocean*. Cold Regions Science and Technology 13: 259-280.
7. CHANCE, N.A., and ANDREEVA, E.N. 1995. "*Sustainability, equity, and natural resource development in Northwest Siberia and Arctic Alaska*." Human Ecology 23(2): 217-240.
8. COCKSHOTT, J.E. 2005. "*Probability Bowties: A Transparent Risk Management Tool*." Process Safety and Environmental Protection 83(4): 307-316.

9. DARBRA, R.M., and CASAL, J. 2004. "*Historical analysis of accidents in seaports*." Safety Science 42(2): 85-98.
10. DAVE, D., and GHALY, A.E. 2011. "*Remediation technologies for marine oil spills: a critical review and comparative analysis*." American Journal of Environmental Sciences 7(5): 423-440.
11. DHILLON, B.S. 2007. "*Human Reliability and Error in Transportation Systems*." Springer Series in Reliability Engineering XVI, 91-103.
12. ELLIOTT, M.S. 1994. "*Computer-assisted fault-tree construction using a knowledge-based approach*." IEEE Transactions on Reliability 43(1): 112-120.
13. ENANDER, A. 1987. "*Effects of moderate cold on performance of psychomotor and cognitive tasks*." Ergonomics 30(10), 1431-1445.
14. FERDOUS, R., KHAN, F., SADIQ, R., AMYOTTE, P. and VEITCH B. 2009. "*Handling data uncertainties in event tree analysis*." Process Safety and Environmental Protection 87(5): 283-292.
15. FIRESTONE, M., CRISP, P.F., BARRY, T., BENNETT, D., CHANG, S., CALLAHAN, M., BURKE, A., MICHAUD, J., OLSEN, M., CIRONE, P., BARNES, D., WOOD, W.P. and KNOTT, S.M., 1997. *Guiding principles for Monte Carlo analysis*. USEPA, Washington, DC.
16. FOFONOVA, V. 2012. "*The Laptev Sea inshore zone modeling with focus on the Lena Delta region*." Ph.D. Thesis Proposal, Alfred-Wegener-Institut, Jacobs University Bremen, Bremen, Germany.
17. FOWLER, T.G., and SORGARD, E. 2000. "*Modeling ship transportation risk*." Risk Analysis 20(2): 225-244.
18. GALIMOV, E.M., KODINA, L.A., STEPANETS, O.V. and KOROBEINIK, G.S. 2006. "*Biogeochemistry of the Russian Arctic. Kara Sea: Research Results under the SIRRO Project, 1995–2003*" Chemistry International 44(11): 1139-1191.
19. GEMAN, S., and GEMAN, D. 1984, "*Stochastic Relaxation, Gibbs Distributions, and the Bayesian Restoration of Images*." IEEE Transactions on Pattern Analysis and Machine Intelligence 6, 721–741.
20. GOERLANDT, F., and PENTTIKUJALA, P. 2011. "*Traffic simulation based ship collision probability modeling*." Reliability Engineering and System Safety 96: 91-107.
21. GOERLANDT, F., STAHLBERG, K., and KUJALA, P. 2012. "*Influence of impact scenario models on collision risk analysis*." Ocean Engineering 47: 74-87.
22. GOOSSENS, L.H.J., and COOKE, R.M. 1997. "*Application of some risk assessment techniques: formal expert judgment and accident sequence precursors*." Safety Science 26(1/2): 35-47.
23. GRANBERG, A.G., 1998. "*The northern sea route: trends and prospects of commercial use*." Ocean and Costal Management 41: 175-207.
24. HOFFMAN, R., 2002. *Human psychological performance in cold environments*. *Medical aspects of harsh environment*. Office of the Surgeon General United States Army, Falls Church, Virginia, USA.
25. HUANG, D., CHEN, T., and WANG, M.J.J. 2001. "*A fuzzy set approach for event tree analysis*", Fuzzy Sets and Systems 18: 153-165.
26. HUNT, G.L., BLANCHARD, A.L., BOVENG, P., DALPADADO, DRINKWATER, K.F., EISNER, L., HOPCROFT, R.R. et al. 2013. "*The Barents and Chukchi Seas: comparison of two Arctic shelf ecosystems*." Journal of Marine Systems 109-110: 43-68.
27. JENSEN, O., 2007. *The IMO guidelines for ships operating in arctic ice-covered waters*. Fridtj of Nansens Institutt, Lysaker, Norway.
28. JOHANNESSEN, O.M., SANDVEN, S., KLOSTER K, PETTERSSON, L.H., MELENTYEV, V.V., BOBYLEV, L.P., and KONDRATYEV, K.Y. 1997. "*Cover ERS-1/2 SAR monitoring of dangerous ice phenomena along the western part of Northern Sea Route*." International Journal of Remote Sensing 18:12: 2477-2481
29. KASSENS, H., HUBBERTEN, H.W., PRYAMIKOV, S.M., and STEIN, R. 1994. *Russian-German cooperation in the Siberian shelf seas: geo-system Laptev sea*. Ber. Polarforsch. 144, ISSN 01 76 – 5027.
30. KHAKZAD, N., KHAN, F., and AMYOTTE, P. 2012. *Dynamic risk analysis using bowtie approach*. Process Safety and Environmental Protection 104: 36-44.
31. KHAKZAD N., KHAN, F., and PALTRINIERI, N. 2014. *On the application of near accident data to risk analysis of major accidents*. Reliability Engineering & System Safety 126: 116-125.
32. KITAGAWA, H. 2001. *The Northern Sea Route: The shortest sea route linking East Asia and Europe*. Ship and Ocean Foundation, Tokyo, Japan.
33. KITAGAWA, H. 2008. "*Arctic routing: challenges and opportunities*." WMU Journal of Maritime Affairs 7(2): 485-503.
34. LINDHE, A., ROSEN, L., NORBERG, T., and BERGSTEDT, O. 2009. "*Fault tree analysis for integrated and probabilistic risk analysis of drinking water systems*." Water Research 43: 1641-1653.
35. LIU, M., and KRONBAK, J. 2010. "*The potential economic viability of using the Northern Sea Route (NSR) as an alternative*

route between Asia and Europe." Journal of Transport Geography 18(3): 434-444.

36. MACRAE, C. 2009. "*Human factors at sea: common patterns of error in groundings and collisions*." Maritime Policy and Management 36(1): 21-38.
37. MARKOWSKI, A.S., and KOTYNIA, A. 2011. "*Bowtie model in layer of protection analysis*." Process Safety and Environmental Protection 89: 205-213.
38. MELLING, H. 2002. "*Sea ice of the northern Canadian Arctic Archipelago*." Journal of Geophysical Research 107(C11): 2-1- 2-21.
39. METROPOLIS, N., ROSENBLUTH, A., ROSENBLUTH, M,. TELLER, A., and TELLER, E. 1953. "*Equations of State Calculations by Fast Computing Machines*." Journal of Chemical Physics 21 1087–1091.
40. MOKHTARI, K., REN, J., ROBERTS, C., and WANG, J. 2011. "*Application of a generic bowtie based risk analysis framework on risk management of sea ports and offshore terminals*." Journal of Hazardous Materials 192: 465-475.
41. MULHERIN, N., SODHI, D., and SMALLIDGE, E. 1994. *Northern Sea Route and icebreaking technology: an overview of current conditions*. US Army Corps of Engineer, Hanover, New Hampshire, US.
42. MUNCHOW, A., WEINGARTNER, T.J., and COOPER, L.W. 1999. "*The Summer hydrography and surface circulation of the East Siberian Shelf Sea*." Journal of Physical Oceanography 29: 2167-2182.
43. NORDGARD, D.E. 2008. *Quantitative risk assessment in distribution system maintenance management using bowtie modeling*. 16th Power Systems Computation Conference (PSCC), Glasgow, Scotland.
44. NOROOZI, A., ABBASSI, R., MACKINNON, S., KHAN, F., KHAKZAD, N. 2014. "*Effects of cold environments on human reliability assessment in offshore oil and gas facilities*." Human Factors, 56(5): 825-839.
45. OLTEDAL, H., and WADSWORTH, E. 2010. "*Risk perception in the Norwegian shipping industry and identification of influencing factors*". Maritime Policy and Management 37(6): 601-623.
46. PAVLOV, V.K., TIMOKHOV, L.A., BASKAKOV, G.A., KULAKOV, M.Y., KURAZHOV, V.K., PAVLOV, P.V., PIVOVAROV, S.V., and STANOVOY, V.V., 1996. *Hydrometeorological regime of Kara, Laptev, and East Siberian seas*. Federal Service of Russia for Hydrometeorology and Monitoring of the Environment, The Arctic and Antarctic Research Institute, St. Petersburg, Russia.
47. PRASSL, W.F., PEDEN, J.M. and WONG, K.W. 2005. "*A process-knowledge management approach for assessment and mitigation of drilling risks*." Journal of Petroleum Science and Engineering 49: 142–161.
48. RAGNER, C.L., 'Den norrasjovagen'. In Hallberg, Torsten (ed), Barents– ettgränslandi Norden. Stockholm, Arena Norden, 2008, pp. 114-127.
49. REZAEI, K., AMALNIK, M.S., GEREIE, A., OSTADI, B. and SHAKHSENIAEE, M.. 2007. "*Using extended Monte Carlo simulation method for the improvement of risk management: Consideration of relationships between uncertainties*." Applied Mathematics and Computation 190: 1492–1501.
50. ROTHBLUM, A., WHEAL, D., WITHINGTON, S., SHAPPELL, S.A., WIEGMANN, D.A., BOEHM, W., CHADERJIAN, M. 2002. *Improving Incident Investigation through Inclusion of Human Factors.* United States Department of Transportation - Publications & Papers. Paper 32.http://digitalcommons.unl.edu/usdot/32.
51. SAKSHAUG, E. 1997. "*Biomass and productivity distributions and their variability in the Barents Sea*." ICES Journal of Marine Science 54: 341–350.
52. SAKSHAUG, E., and SLAGSTAD, D. 1992. "*Sea ice and wind: Effects on primary productivity in the Barents Sea*." Atmosphere Ocean 30(4): 579-591.
53. SCHOYEN, H., and BRATHEN, S. 2011. "*The Northern Sea Route versus the Suez Canal: cases from bulk shipping*." Journal of Transport Geography 19(4): 977-983.
54. SHIBATA, H., IZUMIYAMA, K., TATEYAMA, K., ENOMOTO, H., and TAKAHASHI, S. 2013. "*Sea-ice coverage variability on the Northern Sea Routes, 1980-2011*." Annals of Glaciology 54(62): 139-148.
55. SMEDSRUD, L.H., INGVALDSEN, R., NILSEN, J.E.O., and SKAGSETH, O. 2010. "*Heat in the Barents Sea: transport, storage, and surface fluxes*." Ocean Science 6: 219-234.
56. SMID, J.H., VERLOO, D., BARKER, G.C., and HAVELAAR, A.H. 2010. "*Strengths and weaknesses of Monte Carlo simulation models and Bayesian belief networks in microbial risk assessment*." International Journal of Food Microbiology 139: S57-S63.
57. TALLEY, W.K. 2002. "*The safety of ferries: an accident injury perspective*". Maritime Policy and Management 29(3): 331-338.
58. TANAKA, H., FAN, L.T., LAI, F.S., and TOGUCHI, K. 1983. "*Fault-tree analysis by fuzzy probability*." IEEE Transactions on Reliability R-32(5): 453-457.
59. TOFFOLI, A., LEFEVRE, J.M., GREGERSEN, E.B., and MONBALIU, J. 2005. "*Towards the identification of warning criteria: Analysis of a ship accident database*." Applied Ocean Research 27(6): 281-291.

60. TRUCCO, P., CAGNO, E., RUGGERI, F., and GRANDE, O. 2008. *A Bayesian belief network modeling of organizational factors in risk analysis: a case study in maritime transportation*. Reliability Engineering and System Safety 93: 823-834.
61. VERNY, J., and GRIGENTIN, C. 2009. "*Container shipping on the Northern Sea Route*." International Journal of Production Economics 122(1): 107-117.
62. YANG, Z.L., WANG, J., and LI, K.X. 2013. "*Maritime safety analysis in retrospect*". Maritime Policy and Management 40(3): 261-277.
63. YOUSSEF, S.A.M., INCE, S.T., KIM, Y.S., PAIK, J.K., CHENG, F., and KIM, M.S. 2014. *Quantitative risk assessment for collisions involving double hull oil tankers*. International Journal of Maritime Engineering, 156(A2): 156-174.
64. YOUSSEF, S.A.M., KIM, Y.S., PAIK, J.K., CHENG, F., and KIM, M.S. 2014b. *Hazard identification and probabilistic scenario selection for ship-ship collision accidents*. International Journal of Maritime Engineering, 156(A1): 61-80.

APPENDICIES

Table 1. Events used in the fault trees of Figures 1 – 3

Collision		**Foundering**		**Grounding**	
Index	*Event*	*Index*	*Event*	*Index*	*Event*
X1	Human error	X1	Human error	X1	Loss of power
X2	High Speed	X2	Not tight enough	X2	Basic failure of the propeller
X3	Equipment error	X3	Structural failure	X3	Contaminated fuel in banker tanks
X4	Radar failure	X4	Inadequate pumping	X4	On-board fuel clean-up system fails
X5	Human factor	X5	Faulty design/assembly	X5	Engine fails to operate
X6	Environmental obstacles	X6	Human error	X6	Mechanical failure
X7	Fog	X7	Leaking	X7	Environmental constraints
X8	High wind	X8	Metal failure	X8	Human error
X9	Wave	X9	Communication	X9	Equipment error
X10	High wind	X10	Heavy weather	X10	Operational failure
X11	Pack ice	X11	Excessive wear	X11	High wind
X12	Equipment error	X12	Faulty design	X12	Wave
X13	Human factor	T1	Cargo shift	X13	High wind
X14	Ridge ice and iceberg	T2	Water line reaches door	X14	Pack ice
X15	Non-detected multi-layer ice	T3	Harsh weather effect	X15	Radar failure
T1	Fault of other vessels	IE1	Doors open	X16	Human failure
T2	Ice-breakers failure	IE2	Operating above water	X17	Environmental constrain
IE1	Navigation	IE3	Flooding	X18	Assistance not requested
IE2	Visibility	IE4	Flooding effect	X19	Assistance does not arrive
IE3	Wave effect	IE5	Storage of water, duct, oil	T1	Chart error
IE4	Pack ice effect	IE6	Machinery failure	T2	Ice-breakers failure
IE5	Detection failure	IE7	Component failure	T3	Unable to put ship on safe track
IE6	Ridge ice and iceberg effect	IE8	Mechanical effect	IE1	Fuel supply to engine is contaminated
IE7	Dangerous ice condition	TE	Foundering	IE2	Engine stops
IE8	Potential obstacles			IE3	Vessel losses propulsion
IE9	Environmental/operational effects			IE4	Fault of the vessel
TE	Collision			IE5	Anchor failure
				IE6	Wave effect
				IE7	Environmental effect
				IE8	Navigation
				IE9	Dangerous ice conditions
				IE10	Visibility
				IE11	Assistance failure
				IE12	Failure of tug
				TE	Grounding

Table 2. Mean value of probabilities for primary events received by expert judgment

Input events	Region 1	Region 2	Region 3	Region 4	Region 5
X1	1.3E-03	4.0E-03	1.3E-03	7.0E-04	3.0E-04
X2	7.0E-04	5.0E-03	7.0E-04	3.0E-04	1.0E-04
X3	5.3E-05	5.0E-04	3.0E-04	5.0E-05	1.0E-05
X4	1.0E-03	7.0E-03	1.0E-03	5.3E-04	1.0E-04
X5	1.3E-03	4.0E-03	1.3E-03	7.0E-04	1.0E-04
X6	1.0E-02	2.0E-01	1.0E-01	7.0E-02	2.0E-02
X7	5.0E-03	1.0E-02	5.0E-03	1.0E-03	5.0E-04
X8	1.7E-03	5.3E-03	1.7E-03	5.0E-04	1.0E-04
X9	2.3E-03	5.3E-03	1.0E-03	8.3E-04	1.0E-04
X10	1.7E-03	5.3E-03	1.0E-03	7.0E-04	1.0E-04
X11	5.3E-03	1.0E-02	3.7E-03	1.0E-03	1.0E-04
X12	3.0E-04	1.0E-03	7.0E-04	1.0E-04	5.0E-05
X13	1.0E-01	2.0E-01	1.0E-01	1.0E-01	5.0E-02
X14	1.0E-03	1.0E-02	5.0E-03	1.0E-03	5.0E-04
X15	5.7E-03	1.0E-02	5.0E-03	5.0E-04	1.0E-04
T1	1.0E-03	5.0E-03	1.0E-03	5.0E-04	1.0E-04
T2	5.7E-04	7.3E-03	5.3E-04	2.0E-04	1.3 E-05
Collision Probability	**7.93E-04**	**5.33E-03**	**7.52E-04**	**1.3E-04**	**1.13E-05**
Final collision probability in NSR					**7.01E-03**

Table 3. Risk analysis of ship collision in NSR

Index	Probabilities
C1	5.61E-03
C2	7.01E-04
C3	3.50E-04
C4	1.75E-04
C5	1.75E-04