INTEGRATED ACCIDENT MODEL FOR MARINE CONVOY TRAFFIC IN ICE-COVERED WATERS

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SUMMARY

Independent safe navigation in ice-covered water is difficult. Icebreaker assistance is required for sailing through ice-covered waters. This poses an additional risk of collision. The study proposes a modified Human Factor Analysis and Classification (HFACS) framework to identify and classify contributing risk factors during a convoy. HFACS integration with Nagel-Schrekenberg (NaSch) model considers an operator's behaviour and links it with the occurrence of various risk factors. The study finds significant influence in risk from small changes in two new factors, viz., crew reduction and crew overload. For example, based on the sensitivity analysis, it is determined that about a 17% contribution of crew reduction and about a 24% of contribution of crew overload increase the contribution of risk taking by an amount of approximately 93% in the overall risk of accidents. The accident probabilities obtained here will be helpful in decision making concerning safe operations during a convoy.

NOMENCLATURE

AIS	Automatic Identification System
BN	Bayesian Network
CA	Cellular Automata
f	Flow
FI	Fast Ice
HFACS	Human Factor Analysis and Classification System
HFACS-Grounding	Human Factor Analysis and Classification System for grounding
HFACS-MA	Human Factor Analysis and Classification System for maritime accidents
HFACS-MCTAI	Human Factor Analysis and Classification-Marine Convoy Traffic and Accidents in Ice-covered waters
HFACS-RR	Human Factor Analysis and Classification for railway investigation
HFACS-SIBCI	Human Factor Analysis and Classification System-Ship-Icebreaker Collision in Ice-covered waters
IAM	Integrated Accident Model
IF	Ice Floe
IR	Ice Ridge
L	Length of cell
NI	New Ice
NaSch	Nagel-Schrekenberg model
NSR	Northern Sea Route
T_e	Number of iterations
ρ	Global density
$J(\rho)$	Global Flow
v_{max}	Maximum velocity
$p_{deceleration}$	Deceleration probability
$\rho_{critical\ density}$	Critical density
v	Mean Velocity
VTS	Vessel Traffic Service

1. INTRODUCTION

Icebreaker assistance is used extensively to support shipping in ice-covered waters, including icebreaker escort of single or several ships (Zhang *et al.*, 2019). Such operations are useful for reducing the risk of vessel-ice damage during ice navigation. If the distance between the ships and the icebreaker is not maintained appropriately, collision accidents could occur between the icebreaker and a leading ship, and between the assisted ships during a convoy. Valdez Banda (2017) showed that 48% of accidents in the Baltic Sea and 55% of accidents in the Northern Sea Route (NSR) have occurred under the same icebreaker assistance conditions.

Khan *et al.* (2019) studied the dynamics of the traffic flow in navigable channels. The authors proposed an updated Nagel-Schrekenberg (NaSch) model to estimate the critical densities of the convoys to avoid sudden traffic jams and collisions during a convoy in Arctic waterways. They tested the model on the Vilkitskii strait and combined it with a Bayesian Network (BN) model to estimate the ship-ship and ship-icebreaker collision probability during a convoy. Goerlandt *et al.* (2017) investigated the escort and convoy operations using Automatic Identification System (AIS) and sea ice data. They also investigated the escort and convoy speeds with respect to the prevailing ice conditions in the Gulf of Finland. The authors focused on the relationship between the domain size of the ship and the existing ice conditions in the Gulf. Ship domain is a safe distance between ships in a convoy, while ships are required to maintain a safe zone between each other and between the icebreaker and the leading ship of a convoy (Khan *et al.*, 2019).

Human errors are often recognized as a main cause of accidents (Chen and Chou, 2012; Rothblum, 2000; Khan *et al.*, 2018; Islam *et al.*, 2016, 2020). According to the statistics, human error contributes 84-88% in tanker accidents, 79% in towing vessel groundings, and 89-96% in collisions (Transportation Safety Board of Canada, 1993). Islam *et al.* (2018, 2017) applied human error assessment during maintenance operations of marine systems. Similar to aviation accidents (Wiegmann and Shappell, 2003), HFACS is also used in various marine investigations, including HFACS-MA, HFACS-Grounding, HFACS-SIBCI (Chen and Chou, 2012; Mazaheri *et al.*, 2015; Zhang *et al.*, 2019, 2018) as well as railway accident investigations (Reinach and Viale, 2006; Baysari *et al.*, 2008). An HFACS framework is specifically developed to define the relevant active and latent failures in Reason's swiss cheese model (Wiegmann and Shappell, 2003). Initially, it contains four layers of risk levels: (1) unsafe acts, (2) precondition for unsafe acts, (3) unsafe supervision, and (4) organizational factors, together with 19 classifications. Reinach and Viale (2006) proposed a fifth layer called the *external factors.* The authors believed that the economy, law, and policy should also be considered during the identification of accident risk factors. Later, other authors also used the five-layer HFACS model in their studies to identify the risk factors, such as HFACS-Ground (Mazaheri *et al.*, 2015) and HFACS-SIBCI (Zhang *et al.*, 2019, 2018). The layers in HFACS model are hierarchical: each layer is dependent on the previous one and factors are believed to make progress from active to latent conditions as they progress up the hierarchy from unsafe acts to external influences.

The present study has proposed a five-layer Human Factor Analysis and Classification System-Marine Convoy Traffic and Accident in Ice-covered waters (HFACS-MCTAI) model with 21 classifications. Changes have been proposed in preconditions for unsafe acts, unsafe supervision, organizational factors, and external factors, on the basis of which accident risk factors can be identified and classified. The cause-consequence relationship between risk factors has been developed to estimate the accident probabilities of unsafe acts, preconditions of unsafe acts, unsafe supervision, organizational factors, and external factors during a convoy navigation. The updated NaSch model (Khan *et al.*, 2019) is used to estimate the critical density of the convoy traffic in order to avoid traffic jams and collisions in ice-covered waters. Next, the updated NaSch and HFACS-MCTAI models are integrated in a BN and form a model called the Integrated Accident Model (IAM) for Marine Convoy Traffic in Ice-covered Waters. This integrated model extends the concept of an operator's behaviour during a convoy by adding the knowledge of various risk factors that are identified and classified through the proposed HFACS-MCTAI model. Further, the model is also extended to observe the effects of unsafe acts, preconditions for unsafe acts, unsafe supervision, organizational factors, and the external factors on critical density, maximum velocity, deceleration probability and a sudden traffic jam during a convoy in ice-covered waters. Also, the model estimates the accident probabilities of collision between two ships, ship-ice collision, and collision between an icebreaker and the leading ship in a convoy. The proposed methodology is applied to a case study that involves convoying through the St. Lawrence Seaway. The remainder of the paper is structured as follows: section 2 presents the methodology, section 3 presents the results and discussions, and section 4 discusses the conclusions of the study.

2. THE FRAMEWORK TO DEVELOP INTEGRATED ACCIDENT MODEL

Figure 1 presents the general framework of the proposed collision risk model. In the following sections, the main components of the proposed framework are discussed in detail.

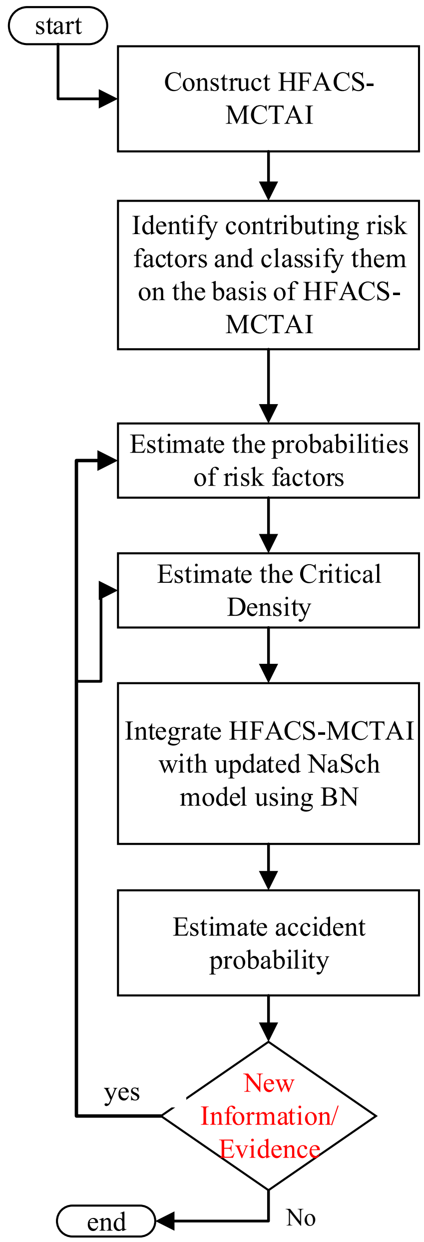

Figure 1: Generic framework for Marine Convoy Traffic Accidents in ice-covered waters

2.1 HFACS-MARINE CONVOY TRAFFIC AND ACCIDENTS IN ICE-COVERED WATERS (HFACS-MCTAI) MODEL

This section presents the HFACS-MCTAI model adapted from Wiegmann and Shappell (2003). The proposed model has five layers of accident risk levels: (1) unsafe acts of the operators, (2) preconditions for unsafe acts, (3) unsafe supervision, (4) organizational factors, and (5) external factors. The risk levels have 21 classification categories (see Figure 2). Some changes have been made in the second, third, fourth, and fifth layer of the proposed HFACS-MCTAI model. The changes are briefly discussed as follows:

i. The classification category, technical faults (Khan *et al.*, 2018) has been introduced to the second layer of the proposed HFACS-MCTAI model.

ii. Two classification categories, inadequate planning regarding operations in ice, and failure to recognize a hazard during a convoy have been introduced to the third layer of the proposed HFACS-MCTAI model, instead of planned inappropriate operations, and failure to correct problem of the original HFACS model.

iii. We replace the classification category organizational climate with safety culture in the fourth layer of the proposed HFACS-MCTAI model. organizational climate can be viewed as the overall working environment within the organization, while safety culture actually refers to unspoken rules, values, attitudes, beliefs and customs of an organazation (Wiegmann and Shappell, 2003). Precisely, culture is stable and permanant while, climate is dependent and fluctuates in response to change in local variables (Yule, 2003).

iv. The classification category economic pressures instead of social factors has been introduced to the fifth layer of the proposed HFACS-MCTAI model.

The proposed model identifies and classifies various accident risk factors that can affect a marine convoy in ice-covered waters. Risk factors have been used to develop the proposed model are obtained by studying various accident literatures (Rothblum, 2000; Khan *et al.*, 2019; Khan *et al.*, 2018; Zhang *et al.*, 2018; Chen and Chou, 2012; Mazaheri *et al.*, 2015; Sahin and Kum, 2015; Zhang *et al.*, 2019; National Research Council, 1990; Danial *et al.*, 2018; Danial *et al.*, 2019a; b; c; Reinach and Viale, 2006; Yule, 2003). Sections 2.1(a) to

2.1 (a) Unsafe Acts of Operators

Unsafe acts of operators can be classified into two categories: errors and violations (Reason, 1990). Errors are generally characterized as mental or physical activities of individuals/employees that fail to achieve the desired outcome. Violations, on the other hand, are deliberate acts that disregard the rules and regulations regarding safety (Wiegmann and Shappell, 2003). Rasmussen (1982) and Reason (1990) classified errors into decision-based, skill based, and *perceptual* errors, while violations are classified into routine violations and exceptional violations (see Figure 2). Decision-based errors are due to the intentional behaviour or actions of an individual that are inadequate or inappropriate in a given situation (Mazaheri *et al.*, 2015; Wiegmann and Shappell, 2003). Skill-based errors are technical errors that are caused due to improper implementation procedures, inadequate training or low job competency. Perceptual errors result from misunderstandings or misjudgments (Zhang *et al.*, 2019). Routine violations are due to frequently ignored rules and instructions, while, exceptional violations occur due to violations of operating procedures. Such violations stem from the inexperience or lack of discipline of operators (Zhang *et al.*, 2019; Mazaheri *et al.*, 2015).

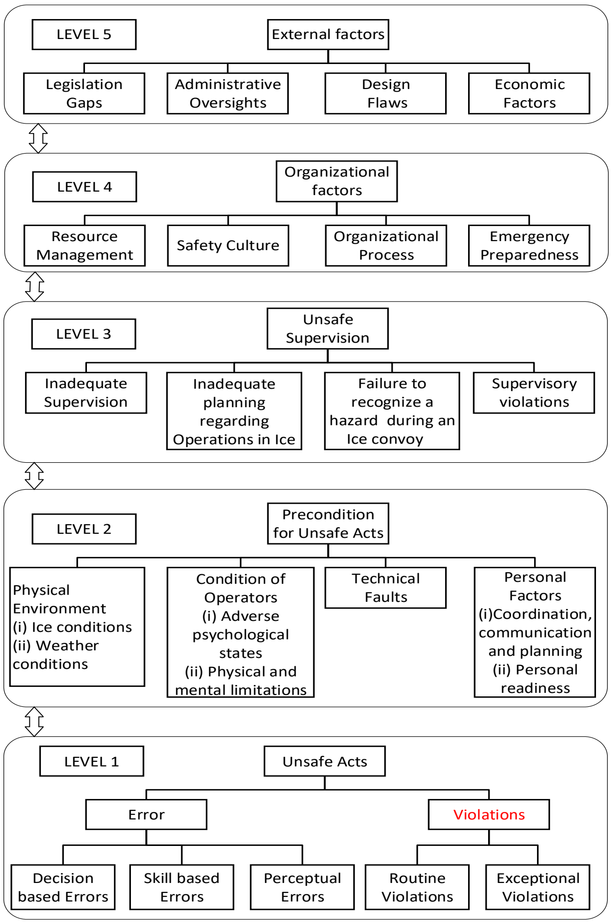

Figure 2: HFACS-MCTAI model

2.1 (b) Preconditions for Unsafe Acts

Wiegmann and Shappell (2003) concluded that approximately 80% of all aviation accidents are due to unsafe acts. The authors also found that the main cause of unsafe acts in aviation accidents is the preconditions for unsafe acts. These preconditions include the environment, condition of operators and personal factors. The same factors are also analyzed as the main causes for unsafe acts in marine accidents (Zhang *et al.*, 2019; Mazaheri *et al.*, 2015; Chen and Chou, 2012).

Physical environments, such as harsh weather, can cause unsafe conditions. However, in the proposed HFACS-MCTAI model, we have included ice in the physical environment. Severe states of ice (Khan *et al.*, 2018) can cause a major precondition for unsafe acts in maritime accidents. The condition of operators, such as an adverse psychological and physical state due to lack of sleep, and fatigue, can cause a major precondition for unsafe acts in aviation (Wiegmann and Shappell, 2003) as well as in marine accidents (Zhang *et al.*, 2019; Mazaheri *et al.*, 2015; Chen and Chou, 2012). Personal factors, such as inadequate communication, coordination, planning and inadequate judgment, which are considered as factors of poor personal readiness, can also play an important role in the precondition for unsafe acts.

The newly introduced classification category, i.e., technical faults, has been proposed as an addition to preconditions for unsafe acts. Technical faults such as mechanical and navigational failures or poor maintenance can cause mental and physical fatigue in the crew (Rothblum, 2000) which can act as major preconditions for unsafe acts in marine accidents.

2.1 (c) Unsafe supervision

Unsafe supervision includes inadequate supervision, which is defined as failure to provide proper guidance and training appropriate to the given situation. It also includes failure to identify and control risks during operations (Zhang *et al.*, 2019; Mazaheri *et al.*, 2015). The newly introduced classification categories: (1) inadequate planning regarding operations in ice, and (2) failure to recognize a hazard during a convoy, involve inappropriate planning and disregard for the possible risks associated with ice. The fourth classification category of unsafe supervision, i.e., *supervisory violations*, occurs when the supervisor intentionally disregards instructions, guidance, rules, or operating instructions by breaking speed and distance rules (Zhang *et al.*, 2019; Mazaheri *et al.*, 2015) that are established according to the given ice conditions.

2.1(d) Organizational Factors

Wiegmann and Shappell (2003) highlighted the fact that most of the time organizational errors go unnoticed by the safety professionals. They explained that latent failures most often revolve around issues related to resource management, organizational climate, and operational processes.

Zhang *et al.* (2019) in their study also introduced an emergency process to the organizational factors. The proposed HFACS-MCTAI model introduced the class safety culture in place of organizational climate to organizational factors. Resource management and organizational processes remained the same, while emergency preparedness is adopted from Zhang *et al.* (2019).

Resource management involves the allocation and maintenance of organizational assets, such as human resources, monetary assets, equipment and facilities (Wiegmann and Shappell, 2003). Wrongly distributed resources often lead to a safety hazard (Zhang *et al.*, 2019). The newly introduced classification category safety culture introduces the broad concept of organizational environments related to appropriate training of crew, using vessels of appropriate ice strength in a convoy, appropriate decisions, proper maintenance, appropriate scheduling, management practices and policies that fecilitate proper risk control options. Any of the these factors which fall outside the acceptable range of values can result in a severe safety breach. Organizational processes involve organizational operations and systems that may adversely affect individuals, supervisory or organizational performances (Zhang *et al.*, 2019; Mazaheri *et al.*, 2015). Emergency preparedness is an integral factor of the organizational factors in the proposed HFACS-MCTAI model. It involves emergency response training (Danial *et al.*, 2018; Danial *et al.*, 2019a) of crews and ensures the presence of life jackets, lifeboats, alarms, and visual aids related to emergencies (Danial *et al.*, 2019c; b). The lack of emergency preparedness can cause a severe safety hazard during operations in ice-covered waters.

2.1(e) External factors

Reinach and Viale (2006), proposed an HFACS-RR model in which the authors introduced the fifth layer, external factors to the original model. The authors believed that the identification of accident risk factors should also consider the economy and law policies as supplements in the HFACS (Zhang *et al.*, 2019).

(Zhang *et al.*, 2019) introduced legislation gaps, administrative oversights, and design flaws to the fifth layer in their model HFACS-SIBCI. The authors explain that legislation gaps involve differences between international and national navigation regulations and policies related to navigation in ice-covered waters. These gaps affect operations under icebreaker escort that may cause poor management or unsafe acts of operators. Administrative oversights involve the negligence of duties by the shipping companies and ship officers. The authors also mentioned design flaws of ships that are usually related to the flawed ability of icebreakers and their assisted ships during icebreaker escorts.

The newly introduced classification category of economic pressures to the layer external factors in the model plays an important role in maritime accidents because tight economic pressures on shipping companies can increase the probability of risk-taking, for instance, making tight schedules which leads taking risks (Rothblum, 2000). These economic pressures can have a direct impact on unsafe acts of operators.

2.2 IDENTIFICATION AND CLASSIFICATION OF ACCIDENT RISK FACTORS IN THE HFACS-MCTAI MODEL

In the present section, we first identify accident risk factors for the marine convoy traffic in ice-covered waters on the basis of the five-layer HFACS-MCTAI model (Figure 2) proposed in section 2.1. Later, we classify risk factors on the basis of 21 classification categories of the proposed HFACS-MCTAI as errors, violations, technical faults, and so on (see Table 1).

2.2 (a) Identification and Classification of Accident Risk Factors

Table 1 shows the identified risk factor with respective description and classification according to the HFACS-MCTAI model. Risk factors in the proposed study have been classified according to the description of 21 classification categories of the proposed HFACS-MCTAI. These classification categories are described in section 2.1. Seven risk factors are identified as unsafe acts of operators (Zhang *et al.*, 2019; Khan *et al.*, 2018; Rothblum, 2000; National Research Council, 1990). Fifteen risk factors are identified as preconditions of unsafe acts (Khan *et al.*, 2018, 2014; Rothblum, 2000). Five risk factors are identified as unsafe supervision (Khan *et al.*, 2019; Zhang *et al.*, 2019), five are identified as organizational factors (National Research Council, 1990; Zhang *et al.*, 2019), and three risk factors are identified as external factors (Rothblum, 2000) respectively (see Table 1).

2.3 DEVELOPMENT OF THE CAUSE-CONSEQUENCE RELATIONSHIP AMONG THE ACCIDENT RISK FACTORS

This section explains how the risk factors considered in the HFACS-MCTAI model per layer contribute to a consequence or effect. A BN model (Figure 3) for unsafe acts considers the relevant risk factors as input nodes and estimates the probability of occurrence of unsafe acts as a function of the risk factors. Similarly, BN models for precondition of unsafe acts, unsafe supervision, organizational factors, and external factors have been constructed and presented in Figures 4-7 respectively. Interested readers should consult (Khan *et al.*, 2019; Zhang *et al.*, 2019; Khan *et al.*, 2018; Chen and Chou, 2012; Mazaheri *et al.*, 2015; Sahin and Kum, 2015; Rothblum, 2000; National Research Council, 1990; Khan *et al.*, 2014; Islam *et al.*, 2018a) to understand the relationships among the risk factors considered in the BNs. Some of the prior probabilities have been taken from earlier studies (Khan *et al.*, 2019; Khan *et al.*, 2014; Rothblum, 2000). The software package GiNIe 2.2 (BayesFusion, 2018) is used for the construction of the BNs.

Table 1: Classification of accident risk factors during a convoy in ice-covered waters.

RL	Risk Factors	Classification
Unsafe acts	Judgment failures	PEr
	Inadequate decisions	DEr
	Negligence	EV
	Loss of situational awareness	Per
	Inadequate general technical knowledge	SEr
	Improper lookouts	EV
	Deficiency of crew Attention	SEr
Preconditions for unsafe acts	Extremely low temperatures	PE, W
	Fog	PE, W
	Darkness	PE, W
	Poor Visibility	PE, W
	Blowing Snow	PE, W
	Ice	PE, ice
	Types of ice	PE, ice
	Ice concentration	PE, ice
	Ice strength	PE, ice
	Ice drift	PE, ice
	ICC	PF, CC
	Poor maintenance	TF
	Mechanical failures	TF
	Navigational failures	TF
	Fatigue	APOS
Unsafe supervision	Failure to maintain safe speed	F1
	Failure keep ships at safe distance	IPI
	Failure keep IB,LS at safe distance	IPI
	Failure continue safe ice operation	ISp
	Inadequate route selection	ISp
Organizational factors	Management practices	SC
	Crew reduction	RM
	Crew overloaded	RM
	Lack of training	SC
	Maintenance	SC
	Schedules	SC
	Risk Taking	SC
	Lack of emergency preparedness	EP
External factors	Economic pressures	EF
	Faulty policies and standards	AO
	Design flaws	DF

RL=Risk level, PE=Physical environment, PF=Personal factors, CC=coordination and communication, IB=Icebreaker, EV= exceptional violations, DEr =decision-based errors, SEr =skill based errors, PEr =Perceptual errors, TF=technical faults, APOS=Adverse psychological operator's states, F1= Failure to recognize a hazard during a convoy, IPI = inadequate planning regarding operations in ice, ISp = inadequate supervision, SC= safety culture, RM=resource management, EP=emergency preparedness, W=weather, AO=administrative oversight, DF=design flaws, ICC=Inadequate communication and coordination, LS=leading ship.

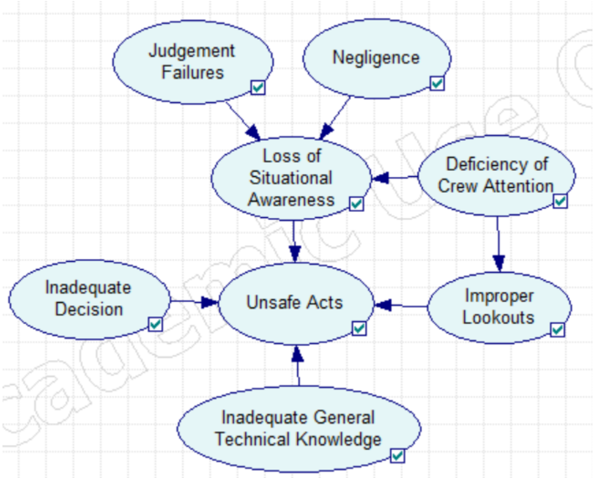

Figure 3: Cause-Consequence relationship among the risk factors for *Unsafe Acts*

2.4 ESTIMATION OF ACCIDENT PROBABILITIES DURING A CONVOY IN ICE-COVERED WATERS – WINTER NAVIGATION OF THE MARINE CONVOY TRAFFIC ON THE ST. LAWRENCE SEAWAY

The St. Lawrence Seaway (Figure 8) allows vessels to travel from the Atlantic Ocean to the great lakes of North America. The seaway named Saint Lawrence River, flows from Lake Ontario to the Gulf of St. Lawrence, Atlantic ocean. The river is officially extended from Montreal, Quebec to Lake Erie. The navigation season on the river extends from late March to late December. Ice begins to form in the river during the first half of December between Montreal and Quebec city. The combination of river currents and winds produces new ice to grow and spread along the south shore of the river. Ice in the region, typically grows to 20 to 60 centimeters in winters, while ridging, rafting, and hammocking can significantly increase these thicknesses. Ice floes in the region are thick and large (up to eight km or more), they are uneven and discolored and are easy to identify. Masters are advised to avoid them, as they are the major hazards to navigation in the region (Canadian Coast Guard, 2012).

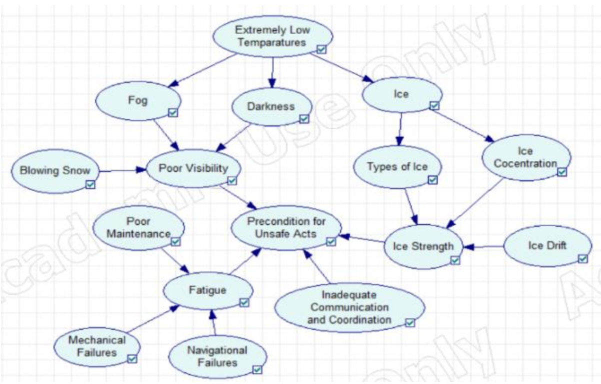

Figure 4: Cause-Consequence relationship among the risk factors for *Precondition for Unsafe Acts*

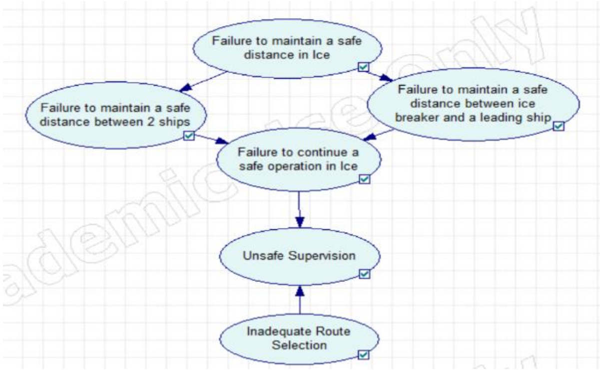

Figure 5: Cause-Consequence relationship among the risk factors for *Unsafe Supervision*

The shipping channels are mostly congested by ice in winter, this is due to the ice removed from the banks to which it is attached (Canadian Coast Guard, 2012). For such reasons, the icebreaker assistance operation is sometimes necessary to continue maneuvers on the river.

Here we assume that an icebreaker assistance convoy operation is comprised of five vessels (oil tankers and bulk carriers) transiting the St. Lawrence Seaway. First, we estimate the accident probabilities of unsafe acts, preconditions of unsafe acts, unsafe supervision, organizational factors, and external factors that are earlier identified and classified on the basis of the proposed HFACS-MCTAI (see section 2.1), and then calculate the critical density of the traffic flow in the channel (see Tables 2 and 3, and Figures 9 and 10).

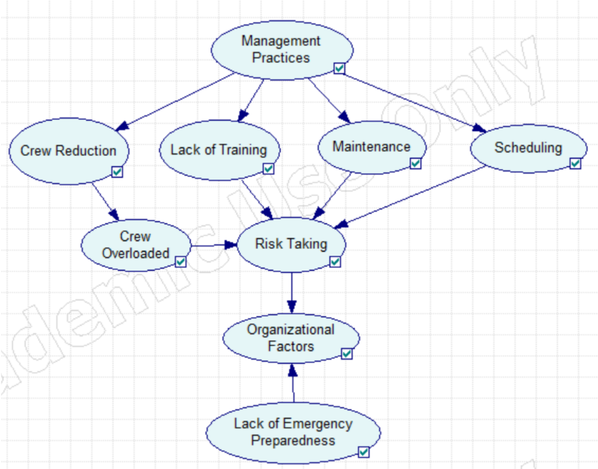

Figure 6: Cause-Consequence relationship among the risk factors for *Organizational Factors*

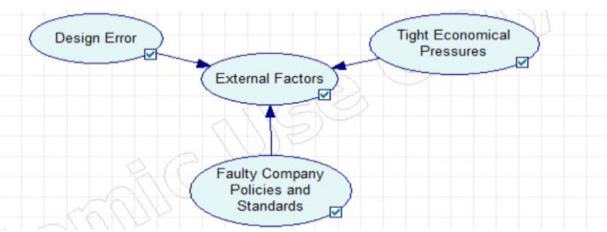

Figure 7: Cause-Consequence relationship among the risk factors for *External Factors*

2.4 (a) Probability Estimation

Table 2 shows the estimated accident probabilities of unsafe acts, preconditions for unsafe acts, unsafe supervision, organizational factors, and external factors for marine convoy traffic on the St. Lawrence Seaway that have been calculated from Figures 3 to 7. Since, in the present study, we have attempted to model human errors and the quantification of human errors in maritime risk assessment perspective is relatively difficult. For such reason, some of the prior values of human errors that have been used in the study are based on assumptions, while some have been taken from the earlier studies (Khan *et al*., 2019; Khan *et al.*, 2018, 2014; Rothblum, 2000). Therefore, the magnitude of the estimated posterior probabilities presented in Table 2 are significantly variable. In the BN of unsafe acts, all risk factors are Boolean variables that take values from the set {Yes, No}.

Table 2: Estimated accident probabilities of marine convoy traffic on the St. Lawrence Seaway

Risk Factors	**Estimated Probabilities**
Unsafe Acts	0.10
Preconditions for Unsafe Acts	0.11
Unsafe Supervision	0.02
Organizational Factors	0.01
External Factors	0.07
Ship-ice Collision	0.02
Collision between two ships	0.04
Collision between an icebreaker and the leading ship of a convoy	0.04

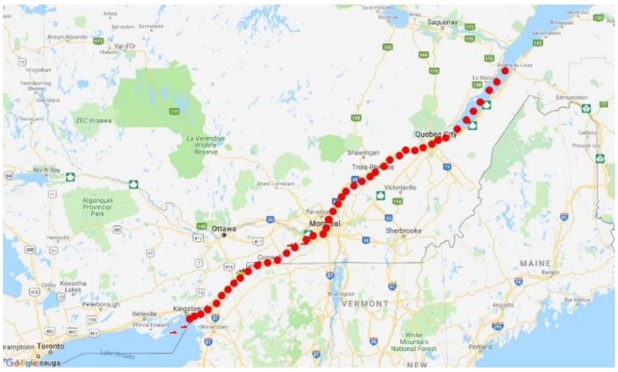

Figure 8: St. Lawrence Seaway (Source: Google maps)

In the BN for preconditions of unsafe acts, the node *ice strength* takes values from the set {High, Medium, Low}, the node types of *ice* takes values from the set {New Ice (NI), Fast Ice (FI), Ice Floes (IF), Ice Ridge (IR)}, however, the remaining nodes are all Boolean. BN for unsafe supervision contains all Boolean nodes, and takes values from the set {Yes, No}. The node *Management Practices* in the BN for organizational factors takes values from the set {Inappropriate, Appropriate}, the node *Maintenance* takes values from the set {Proper, Improper}, the node *Scheduling* takes values from the set {Tight, Relaxing}, and the node *Organizational factors* takes values from the set {Present, Absent}. The remaining nodes take values from the set {Yes, No}. The node *External Factors* in the BN of External Factors takes values from the set {Present, Absent}, while, all other nodes of the BN are Boolean, taking values from the set {Yes, No}.

2.4 (b) Critical Density Estimation

The present section adopts the Cellular Automata (CA) technique called the Nagel and Schreckenberg (NaSch) model (1992) for critical density estimation. NaSch model is one of the most widely used cellular automata theory based traffic model. This model is selected in the present study due to its relevance to simulate covey traffic scenarios.

The primary purpose of using NaSch model is to (a) estimate the critical density of the convoy traffic to avoid sudden traffic jams and collisions in ice-covered waters, (b) simulate scenarios of safe distance between two ships of the convoy and between the leading ship of a convoy and icebreaker, and (c) to integrate HFACS-MCTAI which helps to study the effects of unsafe acts, preconditions for unsafe acts, unsafe supervision, organizational factors, and external factors on critical density, deceleration probability, the maximum velocity of the system and the sudden traffic jam during a convoy in ice-covered waters. The NaSch model, with a little updating in the rules, can also be used for maritime traffic flow (Khan *et al*., 2019; Qi *et al*., 2017).

Table 3: Estimation of critical densities $\rho_{critical\ densities}$ of marine convoy traffic on the St. Lawrence Seaway with respect to the varied maximum velocities v_{max} and deceleration probabilities $p_{deceleration}$.

Maximum Velocity (v_{max}) (ship/timestep)	**Deceleration Probability $p_{deceleration}$**	**$\rho_{critical\ density}$ (ship/site)**
3	0.01	0.25
3	0.10	0.22
3	0.30	0.18
5	0.02	0.18
5	0.24	0.12
5	0.30	0.10

This section presents the $\rho_{critical\ density}$ estimation of a marine convoy traffic flow on the St. Lawrence Seaway using an updated NaSch model (Khan *et al*., 2019). For such a purpose, we take a shipping channel in the St.

Lawrence Seaway of the length of 45,120m and divide it into 200 equal cells (i.e. L =200 cells); each cell has L = 225.6m. We use 200 iterations, i.e., T_e = 200, where each T_e is approximately 1 sec (an approximation of the response time of a ship operator). Values of v_{max} have been selected randomly as 3 and 5, and values of $p_{deceleration}$ have been selected randomly from the range 0.01-0.30. The reason for doing so is to see the behavior of the flow at random values of v_{max} and $p_{deceleration}$ in the system. The results of the simulation (Figure 9) show that the $\rho_{critical\ density}$ of the flow decreases with the increasing values of v_{max} and $p_{deceleration}$ respectively (see the values of $\rho_{critical\ density}$ with respect to v_{max} and $p_{deceleration}$ in Table 3). Increasing v_{max} and $p_{deceleration}$ cause the maximum flow and mean velocity of the system to collapse at lower densities, leading to sudden traffic jams and possible collision accidents in the region. In Figure 9, the value pointed to by the arrows are the estimated critical densities of the marine convoy traffic on the St. Lawrence Seaway.

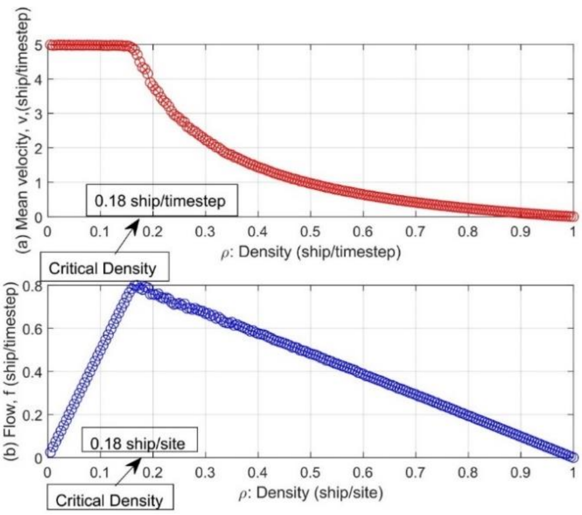

Figure 9: Simulation results of marine convoy traffic on the St. Lawrence Seaway using updated NaSch model with $p_{deceleration} = 0.02$, $v_{max} = 5$, $L = 200$, and $T_e = 200$ (a) Mean velocity, v vs Density, ρ, (b) A fundamental density-flow diagram.

2.5 INTEGRATED ACCIDENT MODEL (IAM) FOR MARINE CONVOY TRAFFIC IN ICE-COVERED WATERS

Since $p_{deceleration}$ is a stochastic component introduced in the NaSch model by the process of randomization, it induces a non-deterministic motion of vehicles due to operators' behavior (Nagel and Schreckenberg, 1992). Khan *et al.* (2019) proposed the updated version of the NaSch model in which, including the process of randomization, all the rules of road traffic are updated with respect to the marine convoy traffic in ice-covered waters. Here we integrate the HFACS-MCTAI model with the updated NaSch model. The model is also extended to observe the effects of the risk levels reported in Table 1 on v_{max}, $p_{deceleration}$, $\rho_{critical\ density}$, and sudden traffic jam during a convoy in ice-covered waters. The model estimates the accident probabilities of collision between two ships, ship-ice collision and collision between an icebreaker and the leading ship in a convoy. The integration takes place through Bayesian Network (Figure 10). The resulting model is called the Integrated Accident Model (IAM) for Marine Convoy Traffic in Ice-covered Waters.

The nodes in the model are Boolean. The nodes $p_{deceleration}$, v_{max}, and $\rho_{critical\ density}$ take values from the set {High, Low}, while the nodes sudden traffic jam, collision between two ships, ship-ice collision, and collision between an icebreaker and the leading ship in a convoy take values from the set {Yes, No}respectively.

3. RESULTS AND DISCUSSION

The hypothetical case study illustrates that precondition of unsafe acts plays the most frequent role in the accidents during a convoy on the St. Lawrence Seaway, while unsafe acts stands second, followed by external factors, unsafe supervision, and organizational factors (Table 2). The results agree with the results of (Zhang *et al.*, 2019). Table 3 presents the values estimated through the updated NaSch model for the critical density of a marine convoy on the St.

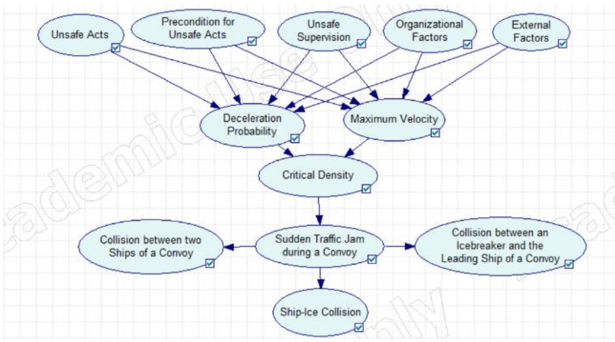

Figure 10: The IAM model.

Lawrence Seaway. The accident probabilities of ship-ice collision, collision between two ships in a convoy, and collision between an icebreaker and the leading ship of a convoy, that are computed by using the IAM model are also given in Table 2.

3.1 SENSITIVITY ANALYSIS

Sensitivity analysis is performed to determine the percentage contribution of accident risk factors for those listed in the risk levels of unsafe acts, precondition of unsafe acts, unsafe supervision, organizational factors, and external factors (see Tables 4 to 8). This section also shows the failure probabilities of unsafe acts, precondition for unsafe acts, unsafe supervision, organizational factors, external factors, deceleration probability, maximum velocity, critical density, sudden traffic jam, and their contribution percentage to the accident probabilities in a convoy on the St. Lawrence Seaway (see Table 9).

Table 4 shows that inadequate general technical knowledge, inadequate decision, improper lookouts, and deficiency of crew attention have the greatest impact on unsafe acts of operators. Table 5 shows that ice concentration, extreme low temperatures, ice, fatigue, blowing snow, ice drift, darkness, fog, and inadequate communication influence the preconditions for unsafe acts during a convoy. However, 25% contribution each of poor maintenance, mechanical failures, and navigational failures can cause fatigue during a convoy.

Table 4: Percentage of contribution of the risk factors on unsafe acts of operators during a convoy on the St. Lawrence Seaway.

Ranking	Risk factors	Effect of the risk factors on unsafe acts (Percentage value of contribution of sensitivity analysis)
1	Inadequate general technical knowledge	27.0
2	Inadequate decisions	26.6
3	Improper lookouts	24.4
4	Deficiency of crew attention	14.1
5	Judgment failure	7.40
6	Negligence	7.30
7	Loss of situational awareness	3.30

Table 5: Percentage of contribution of the risk factors on precondition for unsafe acts during a convoy on the St. Lawrence Seaway.

Ranking	Risk factors	Effect of the risk factors on precondition for unsafe acts (Percent contribution sensitivity analysis)
1	Ice concentration	25.6
2	Extremely low temperatures	23.6
3	Ice	22.5
4	Fatigue	21.3
5	Blowing snow	14.7
6	Ice drift	14.6
7	Darkness	14.0
8	Fog	13.9
9	Inadequate communication and coordination	11.2
10	Poor maintenance, mechanical failure, navigational failure	5.50
11	Ice strength	3.70

Table 6 shows that inadequate route selection, failure to continue a safe operation in ice, and failure to maintain a safe distance in ice have played the greatest role in unsafe supervision during a convoy. Table 7 shows that lack of emergency preparedness and risk taking have diminished the role of organizational factors during a convoy, while around 27% contribution of management practices, 24% contribution of crew overloaded, 22% contribution of lack of training, maintenance and scheduling and about 17% contribution of crew reduction in risk taking make the situation worse during the convoying. Table 8 shows that design error, faulty company policies and standards, and tight economic pressures have a major impact on *External Factors* during a convoy on the St. Lawrence Seaway.

Table 6: Percentage of contribution of the risk factors on unsafe supervision during a convoy on the St. Lawrence Seaway.

Ranking	Risk factors	Effect of the risk factors on unsafe supervision (Percent contribution to sensitivity analysis)
1	Inadequate route selection	25.7
2	Failure to continue a safe operation in ice	24.8
3	Failure to continue a safe distance in ice	13.4
4	Failure to maintain a safe distance between 2 ships and failure to maintain a safe distance between an icebreaker and a leading ship of a convoy	6.30

Table 7: Percentage of contribution of the risk factors on organizational factors during a convoy on the St. Lawrence Seaway.

Ranking	Risk factors	Effect of the risk factors on organizational factors (Percent contribution to sensitivity analysis)
1	Lack of emergency preparedness	25.7
2	Risk taking	23.4
3	Management practices	6.90
4	Crew overloaded	6.10
5	Lack of training, maintenance, and scheduling	5.70

Table 8: Percentage of contribution of the risk factors on extra factors during a convoy on the St. Lawrence Seaway.

Ranking	Risk factors	Effect of the risk factors on extra factors (% contribution to sensitivity analysis)
1	Design error	30.3
2	Faulty company policies and standards	28.9
3	Tight economic pressures	27.7

Table 9 shows the failure probabilities of the nodes and their effects on accident probabilities. Table 9 also shows that sudden traffic jam, critical density, deceleration probability, and maximum velocity have a major influence on accident probabilities in convoying on the St. Lawrence Seaway. Moreover, the analysis shows that around 19% of the organizational factors, 18% contribution of unsafe supervision and external factors, and 18% contribution of unsafe acts and precondition of unsafe acts in deceleration probability, maximum velocity, critical density, and sudden traffic jam can further increase the accident probabilities during the convoying.

Table 9: Failure probabilities of the nodes and their effect on accident probabilities during a convoy on the St. Lawrence Seaway. Low (↓), High (↑), P means 'present'.

Ranking	Nodes	Failure Probabilities	Effect of the nodes on accident probabilities (% contribution sensitivity analysis)
1	Sudden traffic jam	0.06	65.9
2	Critical density	0.06 (↓)	64.6
3	Deceleration probability	0.03 (↑)	37.8
3	Maximum velocity	0.05 (↑)	37.8
4	Organizational factors	0.01 (P)	13.2
5	Unsafe supervision	0.02	12.9
5	External factors	0.07	12.9
6	Unsafe acts	0.10	12.8
6	Precondition of unsafe acts	0.11	12.8

4. CONCLUSIONS

This study proposed two models, both of which have been applied to a convoy navigating through St. Lawrence Seaway. The first model, HFACS-MCTAI, is used to identify and classify the contributing risk factors during a convoy in ice-covered waters. In the present study, we have also developed the cause-consequence relationships between the risk factors of the model. The relationships have been developed through a BN. The main purpose of developing the cause-consequence relation is to estimate the accident probabilities of the risk factors, and also to investigate the most frequently occurring risk factor in a convoy. The model, along with the BN of risk factors (which developed a cause-consequence relationship), when applied on the St. Lawrence Seaway, demonstrated that preconditions for unsafe acts are the most frequent contributing risk factor. This conclusion is based on the highest probability of occurrence (see Table 2) during a convoy on the St. Lawrence Seaway followed by unsafe acts, external factors, unsafe supervision, and organizational factors respectively.

The second model is the IAM model. This model is an extension of the earlier model proposed by the authors in the work of (Khan *et al.*, 2019). The extension is conceived in terms of integration of an updated NaSch model with an HFACS-MCTAI model. This integrated model considers an operator's behaviour and links it with the occurrence of various risk factors during a convoy, such as the physical environment, technical faults, organizational, and external factors identified and classified through HFACS-MCTAI. The IAM model is innovative: it aims to estimate the effects of unsafe acts, preconditions for unsafe acts, unsafe supervision, organizational factors, and external factors on maximum velocity, deceleration probability, critical density, and sudden traffic jam during a convoy. IAM also estimates the accident probabilities of ship-ice collision, collision between two ships, and collision between an icebreaker and the leading ship of a convoy in ice-covered waters.

The present study estimated the critical density of a convoy needed to avoid sudden jams and collisions during a convoy on the St. Lawrence Seaway. The study also demonstrated that sudden traffic jam, critical density, deceleration probability, and maximum velocity greatly influence the accident probabilities.

The proposed method is used to identify the contributing risk factors that can help in preventing accidents during a convoy in ice-covered waters. The methodology is also useful in route identification and selection during a convoy. This study introduces two new risk factors: crew reduction, and crew overloaded, in the risk layer of organizational factors. These risk factors do not directly influence the accident probability of organizational factors. However, a small increase in these factors greatly influences the risk of an accident. For example, based on the sensitivity analysis, it is determined that about a 17% contribution of crew reduction and about a 24% of contribution of crew overloaded increase the contribution of risk taking by an amount of approximately 93% in the overall risk of accidents. The accident probabilities obtained through the integrated model will be helpful in decision making concerning safe operations during a convoy in ice-covered waters. To obtain reliable results, it is necessary to have reliable prior beliefs for BNs. 1n the present study, we have attempted to model human errors. The quantification of human error is a challenging job, especially in a maritime risk assessment context. Therefore, some of the values that have been used in the study are based on assumptions. The collection of near-miss data and human error data similar to that collected in the aviation domain would be helpful in generating reliable prior beliefs in future. Nevertheless, the proposed models can be useful in developing a collision monitoring system that provides a real-time estimate of collision probabilities. The present study can also be extended by using the evidential reasoning method and fuzzy set theory in combination with the proposed model. This would help to reduce data uncertainty.

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