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Simplified Risk Analysis of Tanker Collisions in the Gulf of Finland

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ABSTRACT: Maritime traffic poses various risks in terms of human casualties, environmental pollution or loss of property. In particular, tankers pose a high environmental risk as they carry very large amounts of oil or more modest amounts of possibly highly toxic chemicals. In this paper, a simplified risk assessment methodology for spills from tankers is proposed for the Gulf of Finland, for tankers involved in a ship-ship collision. The method is placed in a wider risk assessment methodology, inspired by the Formal Safety Assessment (FSA) and determines the risk as a combination of probability of occurrence and severity of the consequences. The collision probability model is based on a time-domain micro simulation of maritime traffic, for which the input is obtained through a detailed analysis of data from the Automatic Identification System (AIS). In addition, an accident causation model, coupled to the output of the traffic simulation model is proposed to evaluate the risk reduction effect of the risk control options. Further development of the model is needed, but the modular nature of the model allows for continuous improvement of the modules and the extension of the model to include more hazards or consequences, such that the effect of risk control options can be studied and recommendations made. This paper shows some preliminary results of some risk analysis blocks for tanker collisions in the Gulf of Finland.

1 INTRODUCTION

In recent years, the volume of maritime traffic has significantly increased in the Gulf of Finland, especially because of the expansion of the Russian oil exports from harbors such as Primorsk and Vysotskiy. Up to the recent economic recession, the volume of oil exported from Russia has increased every year, and it is expected to keep increasing in the future (Kuronen et al. 2008, Helcom 2010). With this increasing traffic density, inherent risks such as oil spills are of special concern due to the highly vulnerably marine ecosystem of the Gulf of Finland (Helcom 2010).

Analysis of historic shipping accidents show that worldwide, groundings, collisions and fires are the most common accident types (Soares 2001), while in the shallow, island-littered waters of the Gulf of Finland, groundings and ship-ship collisions are most frequent (Kujala et al. 2009). This justifies the concern of this paper with the risk of oil tankers involved in ship-ship collision accidents.

The main driving idea of the model presented in this paper is the societal trend towards science-based risk-informed decision making, an idea supported by organizations such as the IMO or IALA. In the maritime field, the Formal Safety Assessment provides a framework for this aim.

2 OUTLINE OF RISK ASSESSMENT METHODOLOGY

The risk assessment methodology is rooted in the commonly accepted framework of the Formal Safety Assessment (FSA) (Kontovas and Psaraftis, 2005). The conceptual FSA-methodology is shown in Fig. 1. It starts with an identification of hazards, followed by an analysis of the risk. Thereafter, risk control options are defined, the effect of which should be evaluated using the risk analysis method.

This should be followed by a cost-benefit analysis and recommendations as to which risk control options to implement. It is therefore essential that the risk analysis methodology is able to provide a reliable evaluation of the effect of the risk reducing measures.

The system risk is defined based on the definition of Kaplan (1997) as a set of triplets:

$$\{(s_i, l_i, c_i)\}, i=1, 2, 3,\ldots \quad (1)$$

Here, s_i defines the context of the accident scenario, l_i the likelihood of the accident occurring in that scenario and c_i the evaluation of the consequence in the scenario.

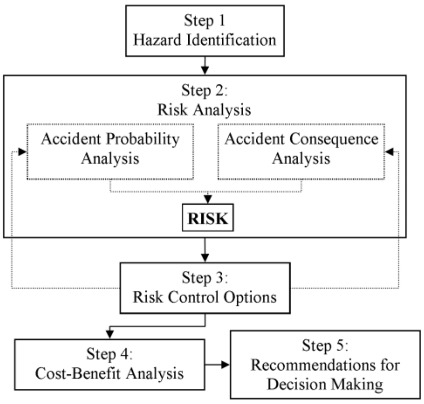

Fig. 1. General outline of FSA methodology

It is important to indicate that l_i and c_i are dependent on the accident scenario s_i, which is to be seen as a multi-parameter set, i.e. a range of variables relevant to the evaluation of the accident probability l_i and the consequence c_i.

The risk analysis methodology is based on a system simulation of the maritime traffic in a given area. The overall flowchart, focusing on the risk of ship collision, is shown in Fig. 2. The various modules of this model, insofar these are already available, will be introduced below.

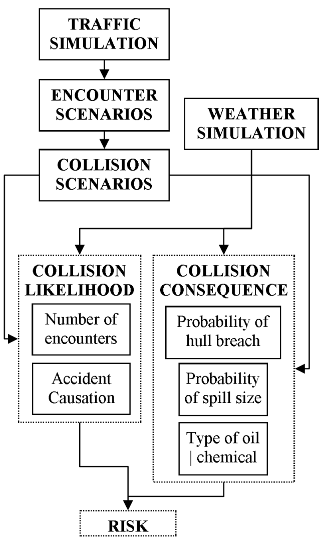

Fig. 2. General outline of FSA methodology

At present, the model is capable only to assess the risk of ship-ship collision, which is the second most important hazard in the Gulf of Finland, based on the accident statistics of Kujala et al. (2009). The methodology can in principle be extended without too many difficulties to other accident types such as ship grounding and fires.

3 TRAFFIC SIMULATION AND COLLISION ENCOUNTER SCENARIO MODEL

The traffic simulation and collision encounter scenario detection module is one of the core units of the overall risk assessment model. The basic idea is to simulate the traffic on a micro-scale. For each vessel sailing in the area, the trajectory is simulated, while assigning a number of parameters to this vessel. These include departure time, ship type, length, loading status, cargo type and ship speed, as illustrated in Fig. 3. The simulation of all vessels in the area provides a traffic simulation and the subsequent detection of the vessels which collide, assuming that no evasive action is made, results in the definition collision encounter scenarios.

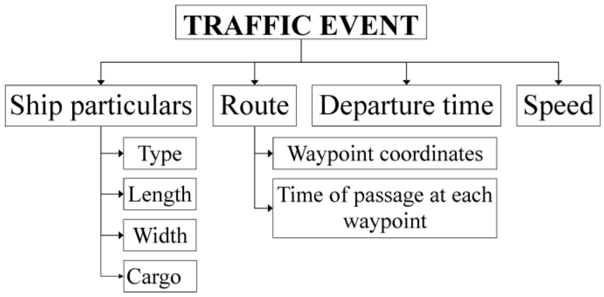

Fig. 3. Generated data for each simulated vessel (traffic event)

The input for this model is taken from data from the Automatic Identification System (AIS), augmented with statistical data from harbors concerning the traded cargo types. Details on how this simulation and collision candidate detection is performed, is given in Goerlandt and Kujala (2011).

As an illustration of the input for the simulation model, Fig. 4 shows the departure time distribution for vessels sailing from Helsinki to Tallinn. Fig. 5 shows the ship length distribution for tankers to Sköldvik and Primorsk. Fig. 6 shows the average ship speed distributions for all considered ship types. This information is used as a first estimate of the ship speed before the collision candidates are obtained. After detection of a collision candidate in a specific area, the speed is resampled from ship type specific speed distributions by location, as shown in Fig. 8. This speed is then updated in the collision encounter scenario.

Table 1 shows the harbor-specific data for cargo types of chemical tankers, for the port of Hamina. The cargos carried by the simulated vessels are sampled from this information, after a more in-depth analysis of which trade routes represent which cargo types. Fig. 7 shows the simulated traffic in the Gulf of Finland, based on the input obtained from AIS.

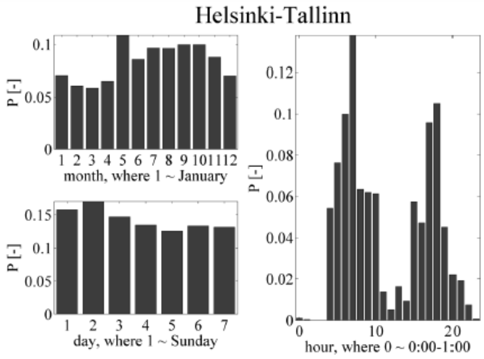

Fig. 4. Departure time distributions, traffic from Helsinki to Tallinn

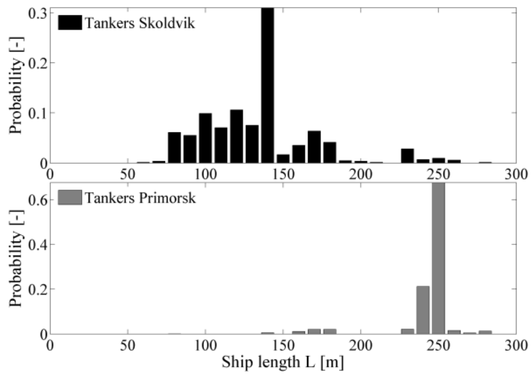

Fig. 5. Length distribution of tankers to Sköldvik and Primorsk

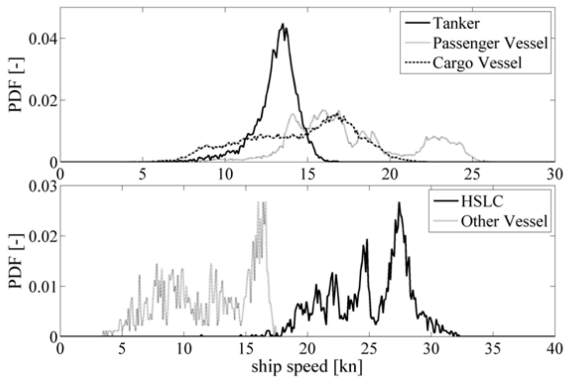

Fig. 6. Speed distributions of vessels in the Gulf of Finland

In Table 2, an example of output obtained from the collision encounter simulation model is shown. This is to be interpreted as the accident scenario context using the definition of Kaplan (1997) as presented in Section 2.

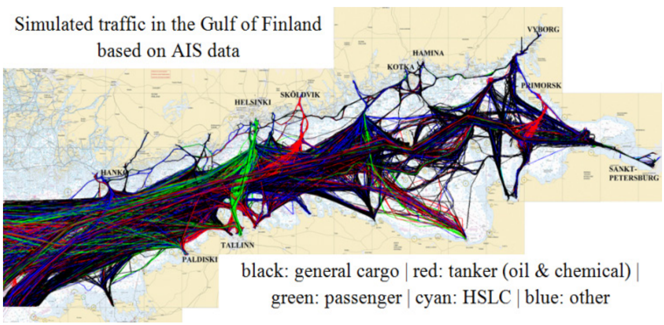

Fig. 7. Simulated traffic for one year
map: © Merenkulkulaitos lupa nro 1321 / 721 / 200 8

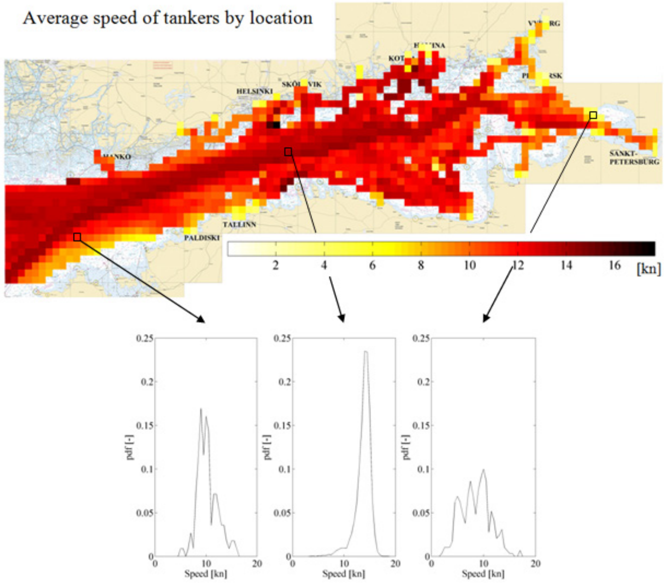

Fig. 8. Average speed of tankers in the Gulf of Finland and local speed distributions, based on AIS data of 2006-2009
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Table 1. Example of data concerning harbor-specific trade volume: port of Hamina, Finland (Hänninen and Rytkonen, 2006)

IMPORT PRODUCTS			
Product	**Vol. [ton]**	**Product**	**Vol. [ton]**
Butadiene	53926	Sulphuric acid	39492
Buthyl acrylate	12233	Styrene monomer	3380
Phenol	1038	Vinyl acetate	1457
Caustic Soda	78547	Methyl ketone	501
EXPORT PRODUCTS			
Product	**Vol. [ton]**	**Product**	**Vol. [ton]**
Butane	741	Methyl-butyl ether	83104
Isoprene	8271	Nonylphenol	48830
Methanol	762012	Propane	2839
Styrene monomer	9602	Vinyl acetate	457
Propylene	5897		
COMMON ORIGINS		**COMMON DESTINATIONS**	
St. Petersburg		Rotterdam, Antwerpen, Teesport, Hamburg, Gdynia	

Table 2. Examples of encounter scenarios obtained by the model of Goerlandt and Kujala (2011)

Location [long | lat]	**Time [m.h:m]**	**Origin**	**Type‡ Struck**	**Striking**	**Speed [kn]**
24.60|59.82	01.05:10	Hamina	C	P	V_{loc} †
22.31|59.34	03.08:47	Sköldvik	GC	GC	V_{loc}
27.96|60.17	03.13:32	Kotka	OT	GC	V_{loc}
24.10|59.55	04.21:10	St. Petersb	GC	OT	V_{loc}
25.23|57.53	06.09:05	Vyborg	P	GC	V_{loc}
29.11|59.95	07.14:13	St. Petersb	GC	GC	V_{loc}

† V_{loc} is the local speed distribution for the relevant ship types

‡ Type: C = chemical tanker, P = passenger vessel, GC = general cargo ship, OT = oil tanker

4 COLLISION SCENARIO AND WEATHER MODEL

While the collision encounter scenario model is able to partly define the accident context, this is insufficient to accurately define either the likelihood of the accident l_i or the consequences c_i.

As a first concern, it should be noted that an encounter scenario, which depends only on the nature of the maritime traffic flows, is not equivalent to the actual collision scenario. In particular, due to possible evasive maneuvers made prior to collision, essential parameters such as vessel speed and collision angle may deviate significantly from the encounter conditions. This has an important effect on the evaluation of the consequences c_i, as can be evaluated by inspecting the collision energy models of Zhang (1999) or Tabri (2010).

Several authors have proposed models for the parameters relevant to the collision scenario, usually based on accident statistics. Some of these proposals are briefly described in Table 3. However, at present no reliable model exists linking the encounter scenario and the collision scenario. This has been investigated by Goerlandt et al. (2011) using a comparison of the hull breach probability for various collision scenario models, based on a collision energy model by Zhang (1999) and a criterion for the critical energy the ship hull can withstand before breach of the double hull. The results of the local probability of oil spill resulting from the various collision scenarios from Table 3, is shown in Fig. 9.

Table 3. Impact scenario models available in literature

Impact model by Rawson (1998)	
Collision angle:	U(0,180)
$V_{striking}$:	Truncated bi-normal N(5,1) | N(10,1)
V_{struck}:	Idem as $V_{striking}$
Collision location:	U(0,180)
Impact model by NRC (2001)	
Collision angle:	N(90,29)
$V_{striking}$:	W(6.5, 2.2)
V_{struck}:	E(0.584)
Collision location:	B(1.25,1.45)
Impact model by Lützen (2001)	
Collision angle:	T(0, α_{enc}, 180)
$V_{striking}$:	Below .75V_{enc}: U(0, .75V_{enc}) Above .75V_{enc}: T(.75 V_{enc}, V_{enc})
V_{struck}:	T(0, V_{enc})
Collision location:	Empirical distribution, see Lützen (2001)

† U: uniform | N: normal | W: weibull | E: exponential | B: beta | T: triangular distribution

For a proper formulation of the accident context, a weather model, capable of predicting the factors which are needed in the evaluation of the accident likelihood and consequences, is needed as well. These factors include wind velocity, sea state and visibility. At present, this weather simulation module has not been implemented in the presented maritime accident assessment methodology.

In terms of the parameters defining the accident context, denoted s_i in the formulation of Kaplan (1997), the weather model adds certain parameters to the values obtained from the collision scenario model, as given in Table 2. These weather-related factors affect the likelihood of the accident l_i and the effectiveness of response to oil spill.

The collision scenario model adds certain parameters such as which is the striking and struck ship and the location of the collision along the struck ship hull. In addition, this model should modify certain parameters such as the collision angle and vessel speed of striking and struck vessel, which have an important contribution to the consequence assessment, i.e. c_i in the Kaplan-nomenclature of Eq. 1.

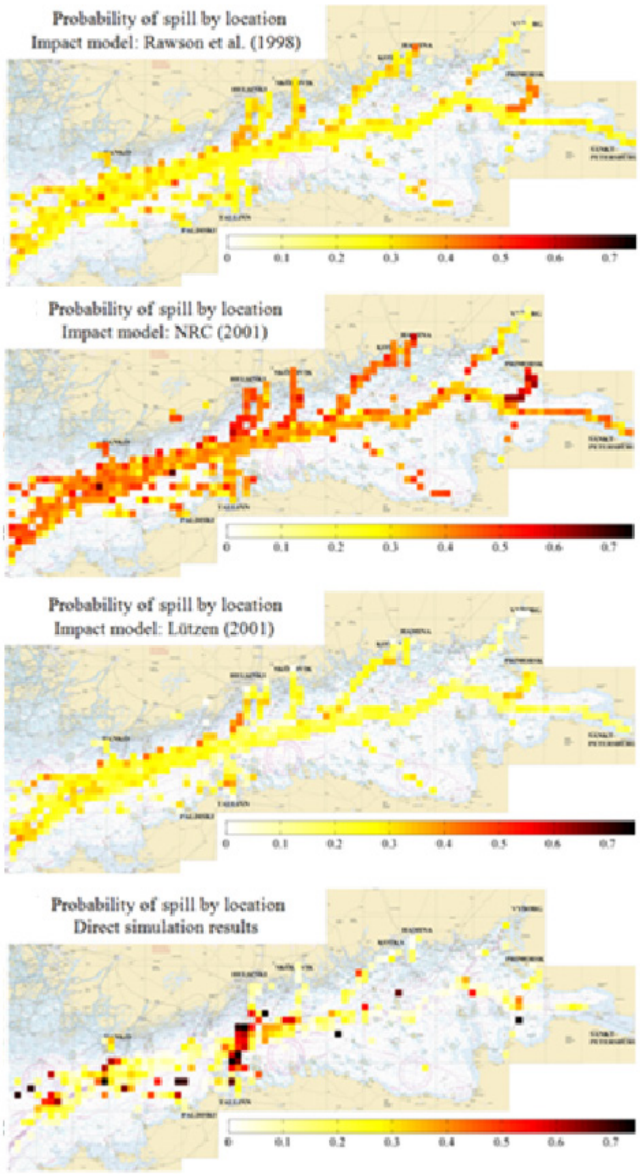

Fig. 9. Results of location-specific spill probability according to algorithm in Fig. 9 and (Eq. 4), impact models: see Table 5, map: © Merenkulkulaitos lupa nro 1321 / 721/ 200 8, taken from Goerlandt et al. (2011).

5 ACCIDENT CAUSATION MODEL

The accident causation model gives a probability of a collision accident occurring in a given context, in terms of the system risk definition by Kaplan (1999), this is the scenario specific likelihood of accident l_i.

This accident causation module from Fig. 2 is constructed using the methodology of the Bayesian Belief Network (BBN). The model is shown in Fig. 10, and is discussed in more detail in (Hänninen and Kujala 2009, Hänninen and Kujala 2011).

The model is rooted in expert opinion, accident and incident data, with the understanding that some parameters are taken directly from the output of the simulation model, in particular the traffic encounter scenario model and the weather model. For instance, the values for the nodes for encounter type, ship types and sizes, time of year, daylight condition and whether or not the encounter location is in a VTS area can be derived from the encounter scenario module as explained in Section 3. The visibility and weather conditions could be derived from the weather model as discussed in Section 4.

Table 4 gives an overview of the groups of nodes in the Bayesian Network, giving a number of examples of some nodes in these groups. The parameters which are directly taken from the traffic and weather simulation models are marked in italics.

The accident causation model is an important element in the study of the risk control options, as discussed in more detail in Section 7.

Table 4. Node groups in the Bayesian model with examples

Visual detection	**Management factors**
Visibility *Other ship size* Bridge view *Daylight*	Safety culture Maintenance routines Bridge resource management
Navigational aid detection	**Human factors**
Radar detection AIS installed AIS signal on radar screen Collision avoidance alarms	Stress Competence Situational assessment Familiarization
Support	**Evasive actions / overall**
VTS vigilance Pilot vigilance Other internal vigilance	*Encounter type* *Give way situation* *Time of year* *Weather* *Ship type*
Technical reliability	
Steering failure Radar functionality AIS functionality	

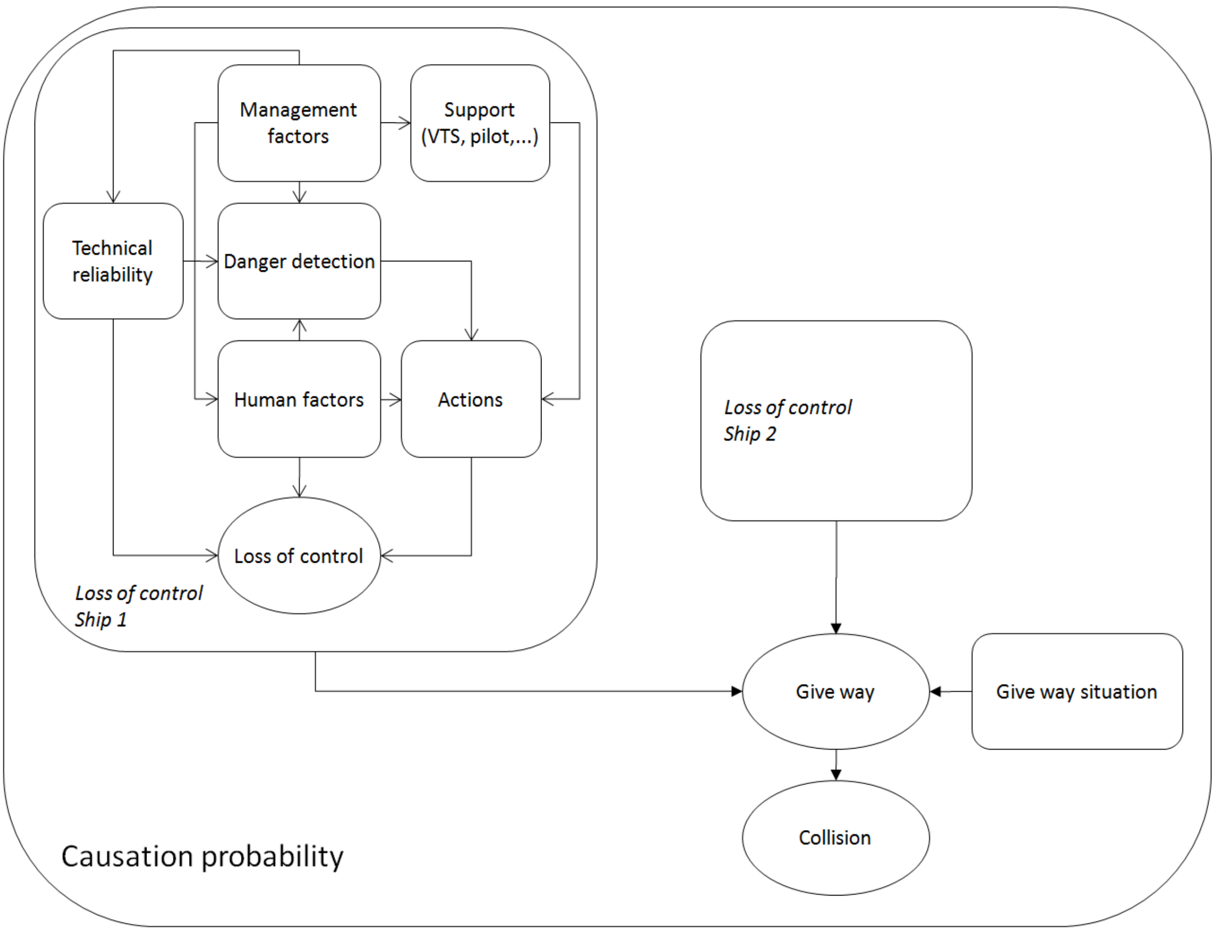

Fig. 10. Causation probability model

6 HULL BREACH PROBABILITY AND SPILL SIZE

In terms of collision consequences c_i, the focus of this paper is limited to the probability of spills from oil tankers. The environmental or socio-economic damage or implications for oil combating operations is at present not considered.

The hull breach probability can be determined based on a comparison of the available deformation energy in the collision scenario, compared to the energy which the ship structure can withstand before the inner hull is breached.

For the available deformation energy, a number of models is available. Zhang (1999) proposed a relatively simple analytical model, assuming rigid bodies and 2-dimensional ship motions. Brown (2002) proposed a simplified model taking the interaction between inner mechanics (i.e. the structural deformation) and the outer mechanics (i.e. the ship motions in a collision) into account, limited to 2-dimensional ship motions. Tabri (2010) proposed a full 6 degrees of freedom model, coupling inner and outer mechanics and taking the sloshing of liquids in a tank into account.

For the ship structural energy, methods such as finite element calculations, e.g. as proposed by Ehlers (2010) could be used. In Goerlandt et al. (2011), a simple criterion based on regression of available ship structural data is proposed.

The methodology to compare the available deformation energy and the hull structural strength is outlined in detail in Goerlandt et al. (2011). Also the work by Klanac et al. (2010) uses a variation of this approach to assess the hull breach probability.

For the oil spill size, a number of models has been proposed in the literature. Examples are a probabilistic extension of the IMO-tanker design criteria as proposed by Montewka et al. (2010). A related methodology has been proposed by Smailys and Cesnauskis (2006). A simple oil volume outflow model based on statistics of tank sizes has been proposed by Gucma and Przywarty (2007). While these models have their merits, they are very simplified and do not take the detailed information from the accident scenario si into account.

On the other hand, the model proposed by van de Wiel and van Dorp (2009) is capable of predicting the size of both a cargo oil spill and of a bunker oil spill using a number of variables determined in the collision accident scenarios. Such variables are the vessel sizes, speeds, collision angles and collision location along the struck ship hull. Thus, this model provides a good match with the information of the accident scenario information si. However, as indicated in Section 4, there exists a significant uncertainty concerning the validity of the available models for the collision scenarios.

The model is based on a combination of collision energy calculations, used to determine the damage length and width, and a limited reference ship database. Based on this information, it is assessed whether or not the hull is breached, and in the case it is, how much oil will flow out of the ship. The model can also be used for estimating the spill in case of grounding.

Since chemical tankers have a significantly different structural arrangement, the above mentioned methods can not directly be used for estimation of spill sizes of this vessel type. Also consequence evaluation based on structural damage for other vessel types is at present not available. However, the principle behind the methods proposed by Ehlers (2010) and Tabri (2010) can be used to get reliable results for these accident types.

7 OVERALL RISK ASSESSMENT: APPLICATION

The application of the risk assessment methodology is to be done by modifying the values for the risk control options in the model to evaluate the effect on the risk level. With an estimate of the cost of implementation of the risk control options and the saved cost due to the reduced risk, an informed decision can be made.

A number of risk control options are related to the accident likelihood l_i. For instance, the VTS vigilance, pilot vigilance, safety culture, navigator competence, navigational equipment and aids to navigation are taken into account in the accident causation model, as described in Section 5. Also the ship routing affects the accident likelihood, which in principle can be studied by modification of the traffic streams in the traffic simulation model, resulting in less and/or safer encounters.

Other risk control options affect the severity of the consequences in case of an accident. Examples of these are the speed limits in local sea areas and the encounter situation, which directly affect the available collision energy. Also the structural strength of the ship hull is an important factor in the severity of the consequences. The accident response effectiveness in terms of number, location and equipment of the available oil response or search and rescue fleet, can also be studied based on the risk maps produced in the risk analysis step.

It should be noted in this context that estimating the accident costs is a difficult task in itself due to the highly complex nature of the studied system. For instance, for an oil spill due to collision, apart from the spill size, the ecological and socio-economic value of the environment in which the spill may occur, should be considered.

It may therefore be more feasible to study the relative risk reduction of the measures as such, and comparing these to the costs of the risk control options. This will also lead to a decent risk-informed decision, if a certain expertise is available to interpret the results of the risk assessment.

8 CONCLUSION AND FUTURE WORK

It should be clear that the evaluation of the risks related to maritime traffic in the framework of a Formal Safety Assessment is a very wide and laborious task, not in the least because of the multidisciplinary nature of the studied system. Such fields as logistics, maritime engineering, systems analysis, operations research and environmental modeling should be combined in an overall FSA-framework.

The maritime system simulation methodology starts from the premise that the likelihood and consequence of each relevant accident type can be calculated based on situational information, as suggested by Kaplan (1997). The aim of determining each of the modules building up the model for maritime system risk in a scientifically sound manner is to be seen as an attempt to rationalize the decision making process in risk related matters.

It is clear that even though the scope of the current model is rather limited (only the probability of collision of ships in open waters and the consequences in terms of oil spill size are included as yet), and even within these models certain improvements could be made (e.g. the collision scenario model linking encounter scenario to actual impact conditions), the modular nature of the model allows for gradual improvement and extension of the models to include additional hazards, risk analysis blocks or risk control options.

Consequently, the remaining work is still very significant before any proper conclusions can be made. Firstly, other hazards (ship grounding, fire) should be included. Secondly, a weather model should be coupled to the accident scenario generation. Thirdly, for ship collisions, the consequences for other ship types (chemical tankers, passenger vessels), should be determined in terms of economic loss due to structural damage or loss of human life. There is also significant work to be done in the understanding of accident causation, and for various accident types, there is a lack of consequence models.

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