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Modelling of Technical, Human and Organisational Factors of Ship Collision Accidents using BBN

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Summary

Statistics show that 13-28% of all maritime vessel accidents are collisions, and the causes for these collisions are usually in the interface between the human, technical equipment and the organization. When adding that there are 7 to 53 causes per collision accident one can understand that this is a highly complex, socio-technical system. A suitable modelling tool for such complex systems is the Bayesian Belief Network, which graphically illustrates the relationships between various factors and a given critical outcome. To quantitatively analyse the collision risk, which is important for deciding in which areas risk reduction is most beneficial, the various factors in the BBN need to be quantified.

In this thesis there are identified numerous of measurable indicators to the various factors of a BBN collision model. These indicators are identified based on a literature review. A result of the review is that the vast majority of collision accidents are due to human factors and only a small percentage are caused by technical failure of equipment. Another result is that the implementation of new technology for reducing the collision risk may also have some negative consequences in terms of workload for the operators and user errors due to lack of knowledge. This shows that to reduce the collision risk further, the focus should be directed towards risk reducing measures for the human factors rather than the technical factors.

Sammendrag

Statistikk viser at 13-28% av alle maritime ulykker er kollisjoner, og at årsakene til disse ligger i grensesnittet mellom menneske, teknologi og organisasjon. Når det legges til at det er 7 til 53 årsaker per kollision kan en forstå at dette er et høyst komplekst sosio-teknisk system. Er godt verktøy for å modellere slike komplekse systemer er Bayesianske nettverk (BBN), som grafisk kan illustrere relasjonene mellom ulike factorer og et gitt kritisk utfall. For å kunne kvantitativt analysere risikoen for kollisjon, noe som er viktig for å bestemme hvilke områder som har mest nytte av risiko-reduserende tiltak, må de ulike faktorene i nettverken kvantifiseres.

I denne oppgaven er det identifisert flere målbare indikatorer for de ulike faktorene i en BBN kollisjonsmodell. Disse indikatorene er identifisert basert på et omfattende litteraturstudie. Et resultat av dette studiet viser at majoriteten av kollisjonsulykker er forårsaket av menneskelige faktorer og kun en liten prosentandel er forårsaket av feil på teknisk utstyr. Et annet resultat er at implementering av ny teknologi for å redusere risikoen for kollisjon kan også ha negative konsekvenser i form av økt arbeidsmengde for operatørene og brukerfeil grunnet mangel på kunnskap om de nye systemene. Dette viser at for å redusere risikoen for kollisjon videre, burde det fokuseres mer på risiko-reduserende tiltak for de menneskelige faktorene heller enn de tekniske.

Preface

This report is the result of a Master Thesis within in the program Reliability, Availability, Maintenance and Safety (RAMS) within the Department of Production and Quality Control at the Norwegian University of Science and Technology (NTNU). The thesis is part of a bigger project collaboration, called National Ship Risk Model, which main objective is to develop a national risk model for maritime transportation in Norwegian waters, to better monitor and communicate the risk picture. The collaboration is between NTNU, Safetec, the Norwegian Maritime Authorities and the Norwegian Coastal Administration.

A special thank you to my supervisor Stein Haugen from the Department of Marine Technology at NTNU for giving me the opportunity to write this thesis and for his guidance.

Abbreviations

AIS	Automatic Identification System.
ARPA	Automatic Radar Plotting Aid.
BBN	Bayesian Belief Network.
BMT	Bridge Management Team.
BRM	Bridge Resource Management.
CCF	Common Cause Failure.
CPA	Closest Point of Approach.
CPT	Conditional Probability Table.
CRM	Crew Resource Management.
CTSB	Canadian Transportation and Safety Board.
ECDIS	Electronic Chart Display and Information System.
ECS	Electronic Chart System.
FAR	Fatal Accident Rate.
GPS	Global Positioning System.
GT	Gross Tonnage.
HCD	Human-Centered Design.
IBS	Integrated Bridge Design.
ICF	Immediate Catastrophic Failure.
IMO	International Maritime Organization.
IMO	The International Maritime Organization.
IRPA	Individual Risk Per Annum.

LTA	Less Than Adequate.
NASA TLX	NASA Task Load Index.
NIS	Norwegian International Ship Register.
NMA	Norwegian Maritime Authority.
NOR	Norwegian Ordinary Ship Register.
NTSB	National Transportation Safety Board.
OOW	Officer On Watch.
QRA	Quantitative Risk Analysis.
RADAR	Radio Detection And Ranging.
RIF	Risk Influencing Factor.
RLE	Reduction in Life Expectancy.
SAFECO	Safety of Shipping in Coastal waters.
SAGAT	Situation Awareness Global Assessment Technique.
SART	Situation Awareness Rating Technique.
TCPA	Time to Closest Point of Approach.
UCD	User-Centered Design.
VHF	Very High Frequency.
VTS	Vessel Traffic Services.
WMO	World Meterological Organization.

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1 Introduction

This master's thesis serves as a contribution to a bigger project called the National Ship Risk Model (NSRM), a project NTNU has in in collaboration with Safetec, The Norwegian Maritime Authority (NMA) and The Norwegian Coastal Administration (NCA). The main objective of the project is to develop a national risk model for maritime transportation in Norwegian waters, to better monitor and communicate the risk picture. This will lead to improved knowledge on maritime safety, which includes improved knowledge on maritime traffic, causes for accidents and other factors that play some role when it comes to maritime accidents. The NMA will use the model to ascertain which ship types are the most exposed in Norwegian waters and hence which ship types need the risk based inspections. The model will also affect regulations and safety improvement measures. Also, the NCA will use the risk model to improve their own risk assessments before they do changes in fairways and ports (from project description).

In this thesis, the studied accident is collisions between ships. As many cargoes contain hazardous materials, safe navigation is important for preventing accidents, which lead to increased risk of life, property and the environment (Toffoli, Lefêvre, Bitner-Gregersen and Monbaliu, 2005). A Bayesian Belief Network (BBN) for ship collisions has been provided by the NSRM project group and the purpose of this thesis is do develop suitable indicators for each of the factors in the network. This is done so that one can quantify the factors based on the indicators. The indicators are developed based on literature reviews, mostly from the maritime sector, but small parts may also be from other sectors as relevant information wasn't found within the maritime sector.

The use of indicators to quantify the various factors of a BBN for ship collision has not been found in any current research. The studies that are found utilizing a BBN to assess the risk, have quantified the factors based on expert judgement or statistical approaches using incident and accident data. A benefit of using indicators is that they take into account the present status (Øien, Utne and Herrera, 2011).

Unwanted events and accidents could often have been prevented if early warning signs had been detected and managed. These early warning signs can be detected by the use of the so-called proactive indicators (Øien et al, 2011), and hence the indicators can help prevent major accidents, which explains the reason for developing indicators in the NSRM project and this thesis. The thesis is not limited to a specific ship type, and the indicators are therefore to be considered as general.

1.1 Objectives

The objectives of this thesis are:

1. Review literature on ship collision and its causal factors.
2. Introduce theory about Bayesian Belief Networks (BBNs) and identify challenges in their quantification.
3. Describe the concept of risk influencing factors (RIFs) and indicators. Give an overview on the classification of indicators.
4. Identify suitable RIFs and indicators for BBN factors. Based on a literature review suggest possible scaling/weighing of parameters and investigate the influence of BBN nodes on the occurrence of collision accidents.

1.2 Structure

- Chapter 2 describes the approach used to write this thesis. It describes how the relevant literature is obtained and the steps used to quantify the BBN ship collision model.
- Chapter 3 introduces a definition of ship collision as well as statistics and causes for collisions.
- Chapter 4 introduces theory on Bayesian Belief Networks. It's explained how to construct a BBN and the challenges one will face with quantifying.
- Chapter 5 explains the terms Risk Influencing Factors and indicators. Different classifications of indicators are also presented.
- Chapter 6 presents the identified suitable indicators for the factors in the BBN collision model developed by NSRM. In this chapter the theory from chapter 4 and 5 is applied.
- Chapter 7 ends the thesis with a discussion of the results, conclusion and recommendations for further work.

2 Approach

This masters thesis is a theoretical study. It is mainly based on a literature study, where the main purpose is to gain knowledge about necessary theory and to investigate what other authors have studied and concluded with, on the various topics of the thesis.

When gathering literature the focus area was based on the purpose of the thesis and on necessary theory specified in the formulation of the thesis. The main keywords sought after for the theory chapters were ship collision, collision causes, Bayesian networks, Risk Influencing Factors, and risk indicators. The search for relevant information began in textbooks from NTNU to investigate what they had covered. To find more information, some of the references in the textbooks were studied, and the university library and google scholar were used. As there is a high degree of variability in the wanted information there were no restrictions regarding journals. Central search words are listed in table 1. Various combinations of these guide words were also searched.

Table 1: Central search words for theory chapters

Ship collision	Collision causes	Collision statistics
Collision risk	Maritime safety	Collision frequency
Human factors	Organizational factors	Technical factors
Bayesian belief	Bayesian network	BBN shipping
Quantifying BBN	Difficulties in quantification	
Risk Influencing Factors	Risk Indicators	Safety Indicators
Modelling risk	Modelling collision risk	Ship Safety

In addition to the above, search words relevant for the various factors in the BBN collision model are used.

The search words and the different combinations of them gave huge amounts of results. These results were mainly articles, but there were also some books. Based on the topics of the books and articles some of them were researched further. Those books and articles whose topic had some relevance were investigated further by reading and evaluating the summaries, this limited the amount of relevant sources. The whole article was read and analyzed if the summary indicated relevance. In books with relevance only certain parts were read and analyzed. To find further information some of the references in these relevant texts were found and studied. The relevant parts of these books and articles constitutes the theory chapters and gives a good overview of the different topics. Other literature that contained relevant information, but not new information relative to the already found literature, are in many cases not included. Exceptions are where multiple sources are used to underline a statement or result. This may have reduced the number of references, but not at expense of information.

For the development of the various indicators, the information presented in the theory chapters about BBN and RIFs and indicators was applied. To find information and research to investigate impacts on the factors, the same procedure as above was used, but with search words assessed as relevant for the various factors. There has not been developed indicators for the organizational factors as they were very difficult to find any measurable variables for. Also, what is to be considered a good organizations regarding maritime safety is outside the expertise of the author and therefore any developed indicators were assessed to be of insignificant value. Relevant literature was also difficult to obtain. As the organizational factors also have the furthest connection to the end node, collision, the focus was rather on finding good indicators for the factors with closer connections. However, the organizational factors are important and it is recommended that indicators are developed by people with expertise on the field.

3 Ship collision and causal factors

3.1 Definition and statistics

According to Kristiansen (2004) a collision represents an impact between two moving objects. The fact that both objects are moving is here important as it would be classified as stranding or grounding if one of the objects in the impact was not moving. This definition correlates well with this thesis as the subject is collision between ships. In 2001, 13% of all maritime accidents in the world fleet, leading to total loss, were collisions. Also, ship collisions accounted for 16 % of all severe maritime accidents during the years 1980-1989 (Kristiansen, 2004). In the Gulf of Finland collision between ships accounted for 20% of all maritime accidents in the period 1997-2006 (Kujala, Hänninen, Arola and Ylitalo, 2009). In Norway ships longer than 15 metres have to be registered either in the NIS register or the NOR register (Sjøfartsdirektoratet, 2016, 10.10). Kristiansen (2004) describes the characteristics of the registers as:

- NOR: Norway's ordinary register consisting mainly of its native coastal fleet, i.e. primarily smaller vessels.
- NIS: the norwegian “open" register consisting primarily of larger vessels operating in international trades.

Of the ships registered in NOR, about 13% of all losses and serious accidents in the years 1998-1999 were collision. For the ships registered in NIS, collisions accounted for about 28% of all losses and serious accidents in the same time period (Kristiansen, 2004).

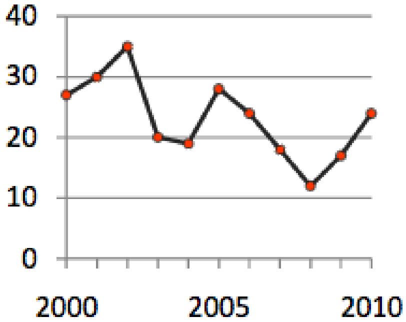


Figure 1: Development of ship-ship collision in the years 2000-2010. From sjofartsdirektoratet, 2011

The Norwegian Maritime Authority (NMA) have conducted a report on accident development in Norwegian waters from 2000 to 2010. The result regarding collisions can be seen in figure 1. The report shows that the number of collisions per year had its peak in 2002 with 35 collisions. From 2002-2004 the number decreased before hitting a new high in 2005 with

28 collisions. From 2005 to 2008 the number decreased again to 12, before increasing to 24 collisions in 2010 (Sjofartsdirektoratet, 2011).

3.2 Collision causes

Considering vessel collisions, "encounter" and "probability" are the key concepts (Mou, Tak and Ligteringen, 2010). They describe an encounter as when two vessels come close to each other so that the collision probability increases. Each ship has a so-called safety domain, and when another ship enters this domain it is considered an encounter. Goerlandt, Montewka, Kuzmin and Kujala (2015, p. 185) use the definition "the surrounding effective waters which a navigator of a ship wants to keep clear of other ships or fixed objects". Under normal conditions the safety domain is often approximated by using the length of the current ship, but in reality it should be decided by dynamic parameters as the navigator's skills and capability, weather, encounter angle and speed (Kujala et al, 2009).

A collision between two ships can mainly occur in three ways; head on, by overtaking or by crossing (Kristiansen, 2004), where overtaking collisions are the most frequent and head on the least frequent (Goerlandt and Kujala, 2011). According to Mou et al (2010) investigations of historical causality data show that crossing encounters are the most dangerous encounters and that overtaking encounters have the lowest risk of collision. Goerlandt et al (2015) present a model for classifying ship encounters in relation to collision course, as collision course from which no escape is possible is the final phase before a ship-ship collision. The model is shown in figure 2. The figure depicts four types of projected paths in relation to collision course. Type A is a projected collision course where the two vessels will reach the common spatial zone simultaneously and hence collide if no evasive action is taken. Type B and C are projected crossing courses where the common spatial zone is reached at different times and hence no collision will occur. These situations may however evolve to a Type A situation if one of the ships changes course or adjusts the speed. Type D is a projected diverging course where the paths don't overlap and a collision will not occur. For a collision to occur from a Type D situation, the situation must evolve to a Type A situation via a Type B or C situation. They also write that a collision can occur even though the ships are not on collision course at the given time, as changes in the spatial and/or temporal relation between the vessels may result in the ships being on collision course.

For avoiding collision at sea the closest point of approach (CPA) and the time to closest point of approach (TCPA) are the key parameters, shown both by theory and in practice. These parameters can be obtained by the Automatic Identification System (AIS), which transmits

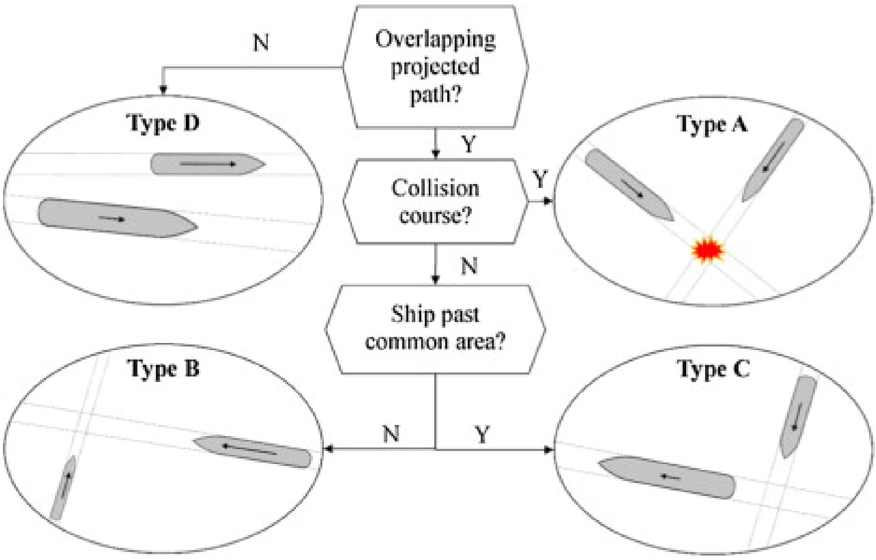


Figure 2: Model for classifying ship encounters in relation to collision course. From Goerlandt et. al, 2015

data at frequent intervals of 3-10 seconds (Mou et al, 2010). Therefore, by the help of the AIS the ships involved in a possible collision can alter their course or speed and hence increase the value of CPA and TCPA. According to expert judgement the relationship between CPA and TCPA values and risk is exponential; when CPA is zero the two ships will definitely collide, while when CPA is above 2 nautical miles the risk will approach zero (Mou et al, 2010). CPA value of 2 nautical miles is advised, but the analysis by Mou et al (2010) shows that only 40% adhere to this. Kristiansen (2005) concludes that collision risk is a function of traffic density and the distance of the fairway. He states that the probability of a collision between two ships is the product of the probability of losing navigational control and the likelihood of having an accident given that you have the incident of losing navigational control.

An accident is the result of a chain of a various number of failures or mistakes (Rothblum, 2000; Kristiansen, 2004). According to Rothblum (2000) the number of causes per accident ranges from 7 to 53. Røed-Larsen (2004) writes about causes for major accidents. His text is not limited to collision accidents, but major accidents in general. He writes that originally one would only classify a failure cause as human failure or technical failure. Later, researchers developed accident models that were based on system understanding and system factors. Now the accident was explained by identifying underlying causes such as working conditions, management, competence, training and safety relations within the organisation. Despite this, the human and technical failure classifications are still widely used. This is because the terms are well known and the process of identifying all underlying causes of every accident requires lots of resources (Sjofartsdirektoratet, 2011). Another argument is that almost all accidents are due to human actions. Humans design the machines, decide on maintenance requirements, which materials to use, safety cultures within organisations, attitudes towards safety etc. For this reason human errors account for 60% - 90% of all accidents in industry and transport (Rausand, 2011). According to Kujala et al (2009) 52,6% of all ship collisions in the Gulf of Finland were reported to be due to human factors, including routines, communication and organisation. Trucco, Cagno, Ruggeri and Grande (2008) report that 70-80% of all maritime accidents are due to human mistakes, or other events influenced by human behavior. In the report from Sjofartsfirektoratet (2011) it is written that most maritime accidents have many causes, not just one, which correlates with the previously mentioned statement from Rothblum (2000). Recurring causes are lack of lookout, administrative burdens, lack of sleep, several weeks shift system, bad communication, bad maintenance, ergonomics etc. From what is mentioned above one can conclude that accident causes are due to human, technical and organisational factors. This is also confirmed by Sjofartsdirektoratet (2011) who writes that causes for accidents are usually found in the interface between human, technical and the organisation. Rothblum (2000) writes about a dutch study on 100 accidents. Common for all of them was that in every causal chain there was at least one human error, and if the human error hadn't occurred the accident would be avoided, as the causal chain would be broken. Therefore, prevention of human errors, or an increase in the probability of discovering the human errors, would result in greater marine safety and fewer accidents (Rothblum, 2000).

Rothblum (2000) claims that technological, environmental or organizational factors often influence the way humans perform and therefore also influence the human errors. Due to this human errors are often a symptom of deeper and more complicated problems in the system, even though they are often blamed on simple inattention or mistakes by the operator. The design of technology can impact the way people perform as many technical systems are designed without thought to the user. Poor designs of technology can therefore lead to deficient understanding of the state of the system and hence poor decision making. The environment, including the weather, physical work environment, regulatory climates and economic climates, also affect human performance in various ways. Examples are high sea states and ship vibrations, which can affect locomotion, manual task performing skills, and cause stress and fatigue. Risk-taking can also be a result of tight economic conditions. Rothblum (2000) also writes that organizational factors, as company policies, crew size, training, hierarchical command structure and work schedules influence human performance and human errors. She says that as all these factors are to some degree incompatible with optimal human performance they “set up” the person to make mistakes. To resolve the problem the systems have to be adapted to the human, instead of the other way around as it mostly is in the maritime industry today. This human-centered approach for designing the various systems will increase efficiency, effectiveness and morale, and decrease errors, accidents, training costs, personnel injuries and lost time (Rothblum, 2000).

3.2.1 Human (and organizational) factors

The definition of human factors encompasses the effect individual, group and organisational factors have on safety (Gordon, 1998), which is why human and organizational factors here are grouped together. The U.S. Coast Guard conducted a study and found that the three largest problems of human factors were fatigue, inadequate communication and coordination between pilot and bridge crew, and inadequate technical knowledge (Rothblum, 2000). Human factors are not the same as human errors as human errors are the immediate cause of the accident while human factors are the underlying causes, or the so called latent errors (Gordon, 1998). Rausand (2011) defines human error as "An out-of-tolerance action, or deviation from the norm, where the limits of acceptable performance are defined by the system. These situations can arise from problems in sequencing, timing, knowledge, interfaces, procedures, and other sources". It is important to emphasize that human error is here only the errors committed by users or operators of technical systems.

The organizational factors are often overlooked in accident investigations, but they influence how individuals and groups behave (Rausand, 2011) and are therefore important to investigate. The organizational causes for accidents are often linked to the organization's safety culture, which is defined as: “The product of the individual and group values, attitudes, competencies, and patterns of behavior that determine the commitment to, and the style and proficiency of, an organization's health and safety management. Organizations with a positive safety culture are characterized by communications founded on mutual trust, by shared perceptions of the importance of safety, and by confidence in the efficacy of preventive measures.” (Rausand, 2011). Other organizational factors influencing safety are, among others, cost-cutting programmes, level of communication, safety training, stable workforce and commitment to safety (Gordon, 1998; Hetherington, Flin and Mearns, 2006). On group level the management's leadership and supervision, crew factors and the relationship between the people in a work group can affect the safety (Gordon, 1998). At the individual level, the person's competence, perceptual judgements, health, stress and motivation are among the factors influencing the safety (Gordon, 1998).

There are various classifications of human errors (Rausand, 2011), this chapter will introduce two of them and are both based on Rausand (2011) and Gordon (1998). The skill-, rule- and knowledge based error classification is a complex classification and needs and requires considerable training to understand and use for accident reports.

- **Skill-, rule- and knowledge based behaviour**
  - *Skill based* actions are subconscious and automated and depends the operator's practice and knowledge on performing the given task. Skill based errors are usually related to routine activities in familiar circumstances. Skill-based behaviour is less subject to errors and accidents (Kristiansen, 2004).
  - *Rule based* behaviour is when the operator hesitates in recalling a procedure, doesn't do the procedure in the correct sequence or doesn't perform some of the steps in the procedure. The operator doesn't have the same knowledge and practice as for skill based behaviour when performing the task.
  - *Knowledge based* behaviour is when an operator is in an unfamiliar situation and needs to understand and evaluate a situation, interpret information or make difficult decisions. Knowledge-based behaviour is applied when we deal with unfamiliar and difficult tasks. In case of error it is when this behaviour is applied we usually face the largest consequences, see figure 3. (Kristiansen, 2004).

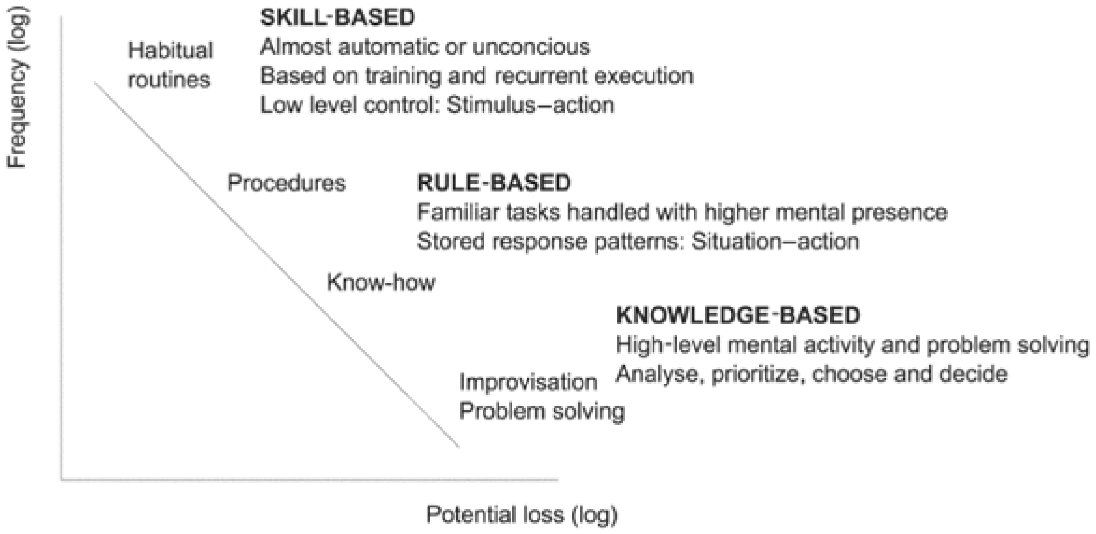


Figure 3: Human performance levels. From Kristiansen (2004)

- **Slips, lapses, mistakes and violations**
  - *A slip* is not planned and the faulty execution is the result of an unintended action with a correct intention. Slips are usually not dangerous events and will usually not be eliminated by training as they can be done by the most experienced people.
  - *A lapse* is when one has a lapse of memory or distraction, and one fails to execute a task correctly. Lapses may be dangerous, but will usually not be eliminated by training as these too can be done by the most experienced people.
  - *A mistake* is when one does something wrong and believe it's correct. Mistakes are usually more dangerous than slips and lapses, and training is important to avoid them as mistakes are often the result of inadequate training or lack of experience.
  - *A violation* is a deliberate and/or illegal action. Violations may remain as hidden failures as they are forbidden and the person doing them doesn't tell anyone about it.

There are also different types of human errors, figure 4 and 5 show the percentage of each error in maritime accidents. The figures are based on research done by Trucco et al (2008) and Kujala et al (2009)

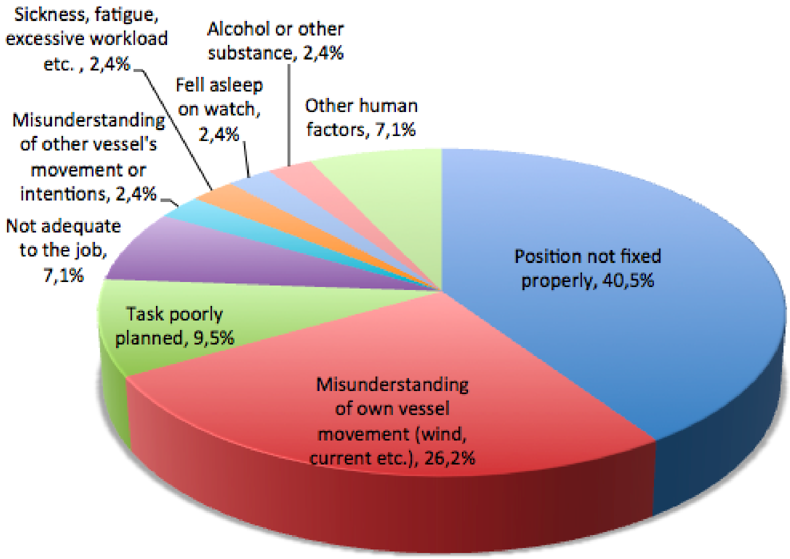


Figure 4: Types of human errors of accidents in the Gulf of Finland. Based on Kujala et al (2009)

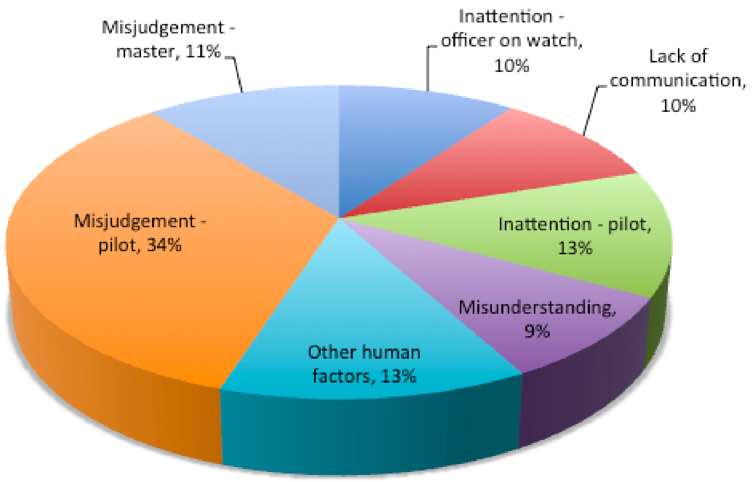


Figure 5: Types of human errors of accidents at sea. Based on Trucco et al (2008)

3.2.2 Technical factors

The technical systems of today's ships are advanced and highly reliable (Rothblum, 2000). The technical factors for maritime accidents include, among many others, failure of steering system or propulsion machinery (Hetherington et al, 2006), design errors and component failures (Shaluf, Ahmadun and Shariff (2003). Considering collision accidents, failure of the steering system or propulsion machinery would be crucial. Factors like defective equipment, faulty design, defective supplies and materials can create and/or amplify an accident (Shaluf et al, 2003). In the Gulf of Finland technical failures of the vessel's equipment only accounted for 4,76% of the collisions, but 11,9% of all the maritime accidents (includes groundings and other accidents) (Kujala et al, 2009), while Trucco et al (2008) report that technical factors account for 16% of the maritime accidents. The improvement of technical aids such as navigational aids has resolved many technical problems, which in turn has decreased the level of machine related errors, and this has further increased the relative level of human error (Hetherington et al, 2006).

4 Modelling

4.1 Bayesian Belief Networks

Bayesian Belief Networks is a method for graphically modelling and illustrating the relationship between various factors/variables and a given critical outcome (eks. Rausand, 2011). The method has many names and is among others also called causal network (Rausand, 2011), knowledge map (Charniak, 1991), and probabilistic network (Kjærulff and Madsen, 2013). In this thesis the expression Bayesian Belief Network will be used, with the abbreviation BBN. BBN is used more and more frequently as a modelling tool. A reason for this is that the method allows for cooperation between experts in different areas as well as it is well suitable for modelling complex systems (Langseth, 2008). BBN can be used as an alternative to both fault trees and cause and effect diagrams. What separates it from a fault tree is mainly that the BBN doesn't need binary outcomes of a cause and it doesn't use logic gates. The exclusion of logic gates also makes the BBN look like a cause and effect diagram. The main difference between the two is that the cause and effect diagram doesn't allow for quantitative analyses (Rausand and Høyland, 2004).

There are plenty of reasons as to why it is useful to model with BBN. Among these are the fact that all relevant factors are identified and one will get a clear picture of how these factors affect the unwanted outcome (Rausand, 2011). Another useful issue is that one can calculate the probability of the hazardous event occurring as well as identify the factors that contribute the most to the hazardous event (Charniak, 1991). BBN also allows for the use of sensitivity analyses and mutual information analyses. A sensitivity analysis examines how small changes in parameters affects the parameters of other factors by changing the parameters one by one and observing the changes in the other parameters. Mutual information analyses examines how much of the insecurity can be eliminated by observing the states of the other parameters (Hänninen, 2014). By doing these analyses one will have information about which factors are the most critical and which factors affect the uncertainty in the result the most.

The different factors in a BBN are represented by an ellipse, called a node, and the direct relationships between the various factors are represented by arcs (Rausand and Høyland, 2004). The network is constructed by using cause and effect relations (Kjærulf and Madsen, 2013). In some cases it will be most useful to place the various factors in bigger groups, for example technical factors, human factors and organizational factors (see figure 6) (Rausand and Høyland, 2004). A BBN has to be acyclic, which means that the arcs are not allowed to go in loops ((Rausand, 2011); (Kjærulff og Madsen, 2013); (Charniak, 1991)). Each node is represented by a random variable. The variable can have both discrete and continuous distribution, but because of the complexity with the use of a continuous distribution the discrete one is preferred (Rausand, 2011). Further can each variable have to or more states, which are the values of the variable. The fact that each node can have more than two states makes the BBN very suitable for modelling complex systems where all the variables are not binary (ex. true or false)(Rausand, 2011). Usually the construction of a BBN is an iterative process ((Kjærulf and Madsen, 2013); (Rausand, 2011)). Rausand (2011) also writes that it is easy to "upgrade" the model as you discover new information. This may also be one of the reasons to why this model is well suited for modelling complex systems.

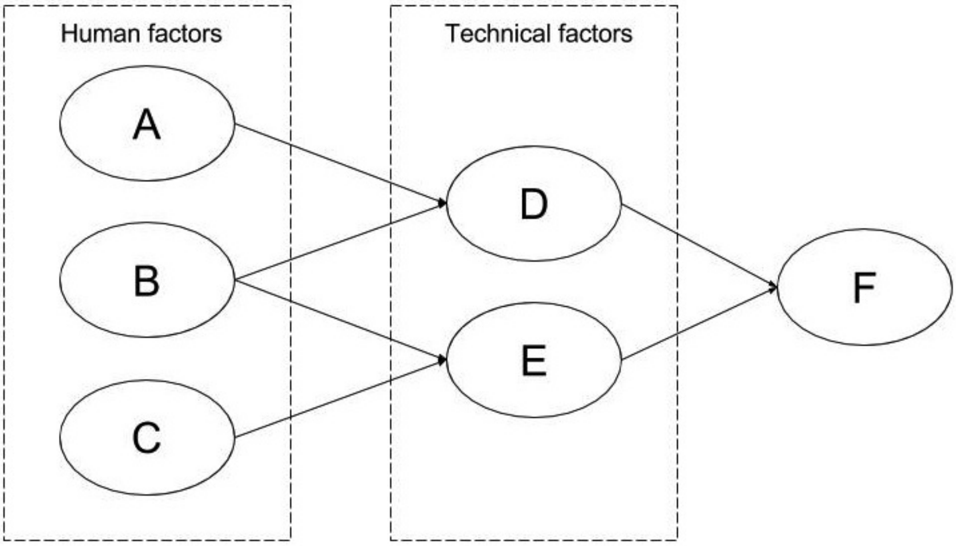


Figure 6: Example of a Bayesian Belief Network

Figure 6 shows a small example of a BBN. The figure illustrates that node D is affected by/dependent on node A and B. Because of this node A and B are called the parent nodes of D, and D is called the child node of A and B. Nodes that don't have any parent nodes are called root nodes. The nodes A, B and C are all called ancestors of F as they affect F through the parent nodes. For the same reason, F is called the descendant of the nodes A, B and C. With this known we can list some assumption. These assumptions are most important when doing a quantitative analysis, but it is also good to have knowledge about them even though one is only constructing the BBN to get an overview or to do a qualitative analysis.

- We assume that a node is independent of its ancestors when we know the states of its parent nodes

- Because both node D and E is affected by the same parent node B, the two are dependent on each other

- When two nodes aren't connected with any arcs, the two are said to be conditionally independent (Rausand, 2011)

Associated with every node is a conditional probability table (CPT). This table presents the probabilities for the node's different states based on different combinations of parent nodes (Rausand, 2011), and is the quantitative representation of the BBN (Kjærulff og Madsen, 2013). As these probabilities are conditional they are calculated using Bayes formula (1).

$$P(A|B) = \frac{P(A)P(B|A)}{P(B)} \tag{1}$$

The conditional probabilities have to be calculated for every single combination of parent nodes (Charniak, 1991). Based on this it is easy to understand that the complexity of the table increases with the number of parent nodes and the number of states of each node. As previously mentioned it is possible to transform a fault tree into a BBN. This might be because a BBN is a more general way to present causal relationships than a fault tree. The CPT enables the representation of the various ports.

4.2 Benefits and challenges of using BBN

Benefits:

- Intuitive representation of a complex system (Rausand, 2011)
- Flexibility in the modelling (Langseth, 2008). More flexible than a fault tree and can replace the fault tree (Rausand, 2011)
- It is adjustable to be both quantitative or qualitative, or a combination (Rausand, 2011)
- Can be updated as more information is retrieved (Rausand, 2011)
- Easy to use in collaboration with experts in various fields (Langseth, 2008; Hänninen, 2014)
- Can deal with insecurities and present them to the user (Hänninen, 2014)
- Can be used to model other problems than just events (Hänninen, 2014). BBN is among others widely used to formulate diagnoses (Charniak, 1991).
- Common cause failures (CCF) can be modeled with so called hidden nodes, which are nodes that are not allocated data (Hänninen, 2014). Hidden nodes will not be discussed any further in this thesis as it is not relevant regarding ship collision.

- Both Hugin expert and GeNIe, which are BBN softwares, can do sensitivity analyses and mutual information analyses, which helps in getting a more accurate representation of the system (Hänninen, 2014)
- Can deal with continuous variables (Langseth, 2008). This is however more complicated than using discrete variables.
- Can be used to model dynamic systems (Hânninen, 2014)

Challenges:

- Construction of a network requires training and experience (Rausand, 2011)
- Feedback loops are not possible, which means that events where one gets feedback for evaluation and improvement is not possible to model. However, this can to some degree be done by using a dynamic BBN or hidden nodes (Hånninen, 2014).
- The time spent on the modelling increases exponentially with the number of nodes (Charniak, 1991).
- There is limited data in the shipping industry, which is a challenge in all modelling (Hånninen, 2014). More about this will come in later chapters.
- By using expert's knowledge the implemented data is subjective. This can however be improved by introducing insecurities in the expert's data or by weighting (Hänninen, 2014).
- They are often based on subjective reasoning (Akhtar and Utne, 2014).

4.3 Challenges of quantifying a BBN

The quantitative BBN is complete when the CPT's of all the various nodes are complete. However, there may be challenges related to quantification of the nodes. Both small and large amounts of data regarding each node can give problems when quantifying. When a large amount of data (ex. reports, studies, databases) is available one can face problems of managing this data. Therefore, it is important to consider the feasibility of data use and the analysis, and if one has the ability to infer a structure of the data (Antao, Soares, Grande and Trucco, 2009). Despite the complexity of dealing with large data Antao et al (2009) write that it reduces the uncertainties one will face when using experts on the field or poor databases. On the contrary, scarce or incomplete data also pose an obstacle. This is because it will create difficulties of calculating more or less accurate frequencies, either due to the nature of the variable or because of sporadic frequencies (Antao et al, 2009). Maritime accidents are rather rare events and therefore data will be rather scarce. Collecting data from a long time period will not help either as there then might be changes in rules, regulations and safety culture (Hänninen, 2014).

Under-reporting of both accidents and incidents is also a challenge in the maritime sector (Hänninen, 2014; Psarros, 2010) together with the poor details, or missing data, in the databases (Akhtar and Utne, 2014; Hänninen, 2014). According to Hassel, Asbjørnslett and Hole (2011) the ”best” flag states report 94% of accidents, while the average is 50%. This will affect the accuracy of the quantification. When using statistical data one should always assume some degree of under-reporting (Akhtar and Utne, 2014), which is a reason for questioning uncritical use of historical data (Psarros, Skjong and Eide, 2010). Akhtar and Utne (2014) writes that this can be handled by using correction factors, safety margins or expert judgements. In cases where under-reporting is a big issue Akhtar and Utne (2014) suggest to rely on expert judgement. Rausand (2011) writes that when data is scarce or non-existing, expert judgement is a necessary tool and very useful in practical risk analyses. The expert judgment process may involve only one expert or a group of several experts who may have varying knowledge (Rausand, 2011; Akhtar and Utne, 2014). However, relying on experts isn't problem free either as the human mind has problems with processing small probabilities (Akhtar and Utne, 2014), and hence it may also be inaccurate. Expert judgment will always be subjective and reflect the expert's knowledge, which can be both a limitation and an advantage (Hänninen, 2014). In BBN software it is possible to include expert uncertainty and weights to the experts (Hänninen, 2014).

Another issue is that there are different practices of accident reporting in different organisations and countries. There is no common classification scheme for organisations (Akhtar and Utne, 2014; Hetherington et al 2006), some are more detailed than others, which makes it difficult to draw out frequencies and calculate probabilities. Also, there are different practices in different countries about reporting accidents and incidents. In Portugal there is no legal obligation to report maritime accidents in national waters (Antao et al, 2009). In Norway all serious maritime accidents, and all collisions and groundings, are to be reported to the NMA, and it is requested that incidents are reported as well (Sjøfartsdirektoratet, 2016, 26.10), melding og rapportering av ulykker, 26.10.16). However, there are 5000 registered accidents every year and the NMA don't have the resources to investigate all of them. The result of this is that the accidents are recorded only with causes stated by the reporter, which are often the most conspicuous ones (sjofartsdirektoratet, 2011). According to Hänninen (2014) this also a problem in Finland where only one collision or grounding cause was reported in 15% of the reported accidents, even though the former Finnish maritime accident database had enabled reporting up to four causes. The result of this is that most accident causes aren't detailed or systematic, and so one will face problems of managing the data. The overall result of different report practices in different countries and organisations is that comparisons will be false and give a wrong view of maritime safety.

4.3.1 Validation of the quantification

After the quantification is done the model has do be validated to assess if the given values are as correct as possible. The data inserted in the BBN are subjective, which creates uncertainty, and the BBN is therefore not complete until a validation process is done. This can for example be done by comparing various results with other statistics and studies or by expert judgments. However, when the model is already based on expert judgement a more comprehensive testing is required, as it is based on subjective opinions and beliefs. However, the size and construction of the expert group plays an important role. After the first validation the data needs to be updated, and then a new validation follows until the model passes the validation test. In other words the validation process is an iterative process (Akhtar and Utne, 2014).

5 Risk Influencing Factors and Indicators

5.1 Definitions

A Risk Influencing Factor (RIF) is defined as “an aspect (event/condition) of a system or an activity that affects the risk level of this system/activity” (Øien, 2001a, p. 130). The RIF is a theoretical variable and it is not specified how to measure it (Øien, 2001a). In a BBN the RIFs are the factors influencing the outcome, hence the nodes are the risk influencing factors (Rausand, 2011). The risk influencing factors may be regulatory, environmental, organisational, human or technical (Rausand, 2011). The RIFs and the risk indicators are connected in the sense that the indicators are the measurable representations of the RIF, and is also called the operational variable while the RIF is also called the theoretical variable (Øien, 2001a; Øien et al, 2011). Rausand (2011) defines a risk indicator as ’A parameter that is estimated based on risk analysis models and by using generic and other available data’. A RIF may be represented by one or more risk indicators (Øien et al, 2011). For example, for the RIF "competance" two suitable risk indicators could be "years of experience" and "years of education". The example also emphasises the need for introducing risk indicators as the RIF is not measurable in its self; this is called the measuring problem (Øien et al, 2011). Common risk indicators are FAR (Fatal Accident Rate), IRPA (Individual Risk Per Annum), RLE (Reduction in Life Expectancy) and the FN-curve (Rausand, 2011). These will however not be specified more in this thesis.

5.2 Characteristics of good indicators

- *Validity*. The indicator must be a valid measurement, and the further we move in the causal chain of an accident the less certain we can be on the validity of the measurement (Kjellén, 2009).

- *Reliable and robust measurement techniques*. It is important that under-reporting of accidents and incidents doesn’t exist and the indicator should be robust against manipulation (Kjellén, 2009)

- *Feedback on changes*. The indicator has to provide relevant statistics in a relevant time period, indicate the current level of safety, and indicate whether the safety level is improving or not (Kjellén, 2009).

- *Transparent and easily understood* (Kjellén, 2009).

5.3 Classification of Indicators

5.3.1 Risk Indicators vs. Safety Indicators

The classification depends on whether the RIF corresponding to the indicator is included in a risk model or not. By changing the risk indicator value(s) for a given RIF it is possible to determine its effect on the total risk. These risk indicators are developed through a risk based approach (Øien et al, 2011). It should be called safety indicators when the RIFs are not included in a risk model, but the the indicator affects some other safety measures as for example number of accidents. These indicators are often selected based on their assumed effects on safety, of through correlation and are often based on a safety performance-, incidence- or resilience based approach (Øien et al, 2011).

5.3.2 Personal vs. Process Safety Indicators

The difference between these indicators are whether they are indicators about personal safety or process safety. The distinction between personal and process safety is as follows; process safety incidents can lead to multiple fatalities or harm to the plant as they are incidents in the process plant. A such incident could be en explosion or leakage of toxic gas. Personal safety indicators are indicators about hazards affecting the individual personal safety. These hazard have nothing, or little, to do with the processing activities, but are rather incidents like falls, trips, electrocutions and vehicle accidents (Hopkins, 2009a)

5.3.3 Lead vs. Lag Indicators

To distinguish between lead and lag indicators can be rather problematic, although they are often mentioned. Lead and lag indicators can be present in both personal safety and process safety (Hopkins, 2009a). Defining the terms regarding process safety is the part that is somewhat complicated. In terms of personal safety lag indicators refer to injury and fatality rates, and lead indicators directly measures aspects of the safety management system, which could be frequencies or timeliness of audits (Hopkins, 2009a). In terms of process safety lag indicators are a type of "after-the-event" indicator, which means that one counts the number of accidents or incidents that have already occurred. Leading indicators looks at the underlying conditions of the factors leading to accidents. Hence, these indicators are proactive and provide feedback on performance before an accident or incident occurs, and therefore also functions as early warning signs (Øien et al, 2011), the leading indicator changes before the actual risk level changes (Kjellén, 2009). The information from both the leading and lagging indicators should be used in further work to correct errors in the safety management system, but only the leading can help prevent accidents and incidents (Øien et al, 2011).

The swiss cheese model can be used to illustrate leading and lagging indicators (Øien et al, 2011; Hopkins, 2009a). See figure 7 for illustration. When describing indicators in this model the holes in the 'cheese' represent a series of failings in the layers of defenses, barriers and safeguards. Leading indicators identify the holes, while the lagging indicators reveal the holes as a result of an accident or incident.

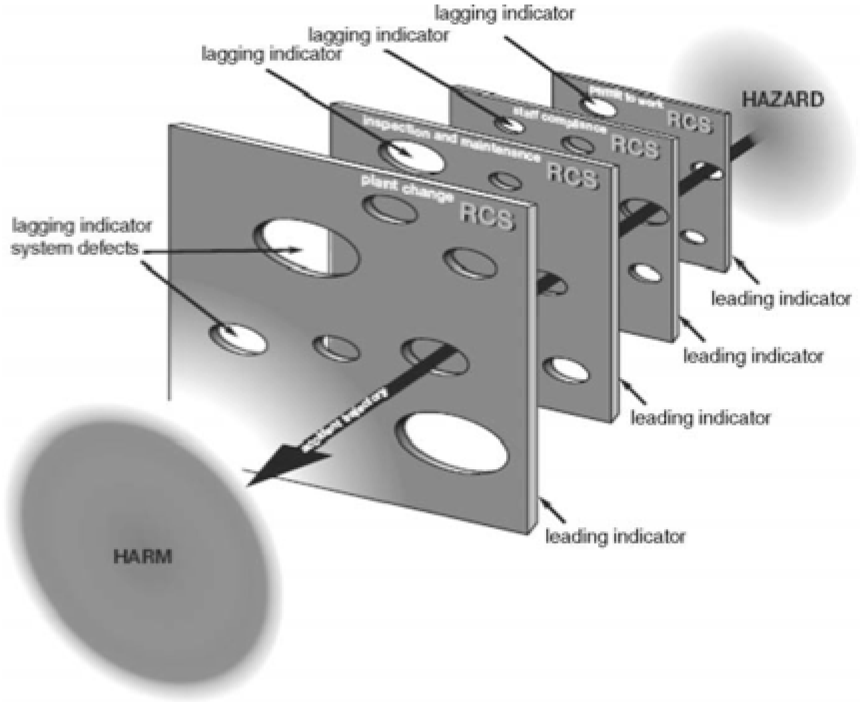


Figure 7: Illustration of leading and lagging indicators using the swiss cheese model. From Hopkins (2009a)

Hopkins (2009b) emphasises that there is not a clear distinction between leading and lagging indicators and that the meaning of them should be defined every time they are used to avoid confusion.

5.4 Establishment of RIFs and indicators

Øien (2001a, 2001b) has developed two approaches for establishing suitable RIFs and associated indicators, one for technical factors (Øien, 2001a) and one for ogranizational factors (Øien, 2001b). The use of these indicators together provides good tool for risk control during operations (Øien, 2001b).

5.4.1 Technical

The approach for establishing the technical RIFs and indicators was developed to monitor risk during operation of offshore petroleum platforms, but the method is applicable in any industry given that the risk is modeled and quantified in a risk analysis, because the RIFs are derived from a quantitative risk analysis (QRA) (Øien, 2001a). The steps are further described.

1. Selection of categories of accidental events contributing most to the risk. There are three criteria for this selection; the category must must have a large accident potential, give a significant contribution to the total risk of potential loss of lives, and one must be able to exercise some control over the development of the risk represented by the chosen categories.
2. Identification of all RIFs contributing to each of the categories modeled in the QRA.
3. Assessment of potential change in RIFs during the time period between each updating of the QRA. This is often done by using expert judgement.
4. Assessment of the effect of change of each RIF on the total risk. This is done by performing sensitivity analyses using the QRA.
5. Selection of significant RIFs. These are the RIFs that has the biggest effect on risk and therefore need surveillance
6. Initial selection of risk indicators for each selected RIF. Some of the RIFs may be directly measurable, but we still want to use the term risk indicator.
7. Testing and final selection of an appropriate set of risk indicators. Based on experience it is difficult to select appropriate risk indicators without testing if they are suited.
8. Establishment of routines for the use of risk indicators.

5.4.2 Organizational

The development of organizational RIFs and indicators is important as the organization may change in terms of e.g. training and quality of procedures, during operation. Also, due to the personnel being affected by the organization, almost all major accidents can be termed as an "organizational accident" (Øien, 2001b). Øien (2001b) presents a framework for establishing organizational RIFs and indicators, which include an organizational model, organizational risk indicators and a quantification methodology. This organizational model is connected to the technical model and the QRA. The framework is described below.

1. *Organizational model/factors*. The model is often illustrated using Bayesian networks (also called an influence diagram). The model has to be reasonably complete, practically usable and fit for the purpose.
2. *Rating of organizational factors*. With the use of expert judgments, qualitative tools or indicators the quality of the organizational factors are assessed, and it is a measure of the state of the given factor. It is not sufficient to distinguish between "good" or "bad" states, but it needs to be possible to distinguish between the states in a credible way, and therefore the scale cannot be too fine-graded either. In the article a five graded scale is suggested and the use of indicators are here preferred. The rating process gives input to the Bayesian network as state values.
3. *Weighting of organizational factors*. Weights are assigned to each of the organizational factors through expert judgment or data-driven approaches. The weights imply the effect/strength/impact that the factor has on risk directly or through intermediate factors or parameters in the model, and are the conditional probabilities given all possible combinations of states. The weights give inputs to the Bayesian network as conditional probability tables (CPT).
4. *Propagation method/algorithm*. The rates and weights are combined and aggregated to reflect the effect on total risk or a parameter in the risk model. This can be done by "the influence diagram technique" in which all the combinations of states of the factors are given a rate and weight that are multiplied and summarized.
5. *Modeling technique*. Bayesian networks are often used to model how the various factors affect each other. See chapter 4 for more about Bayesian networks.
6. *Link to risk model*. This could be a link to a technical risk model, e.g. in the article the organizational factors are linked to a leak frequency.
7. *Adaptation of risk model*.
8. *Re-quantification of risk*. The relative change of risk.

5.4.3 Quantitative organizational model

The qualitative model mentioned in the previous section is the basis for developing a quantitative model. Figure 8 shows an example of such a model where OF=organizational factor, lambda=incident frequency and #Obs=number of observed incidents.

All the organizational factors has to be assigned to a mutually exclusive state based on the current state of the factor. An example of such a division is shown in figure 9.

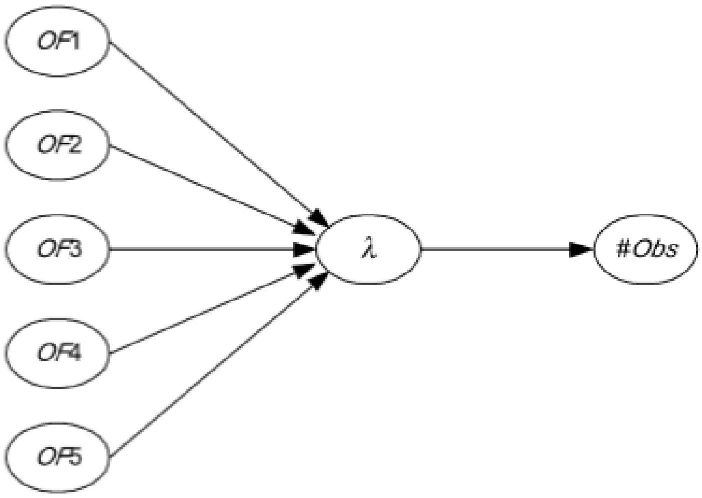
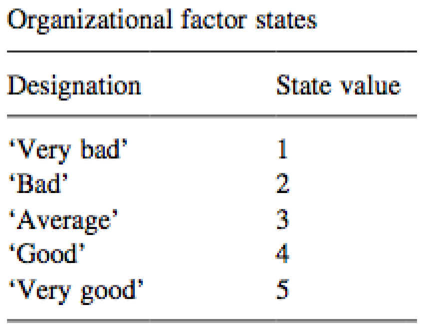


Figure 8: Example of a quantitative model. From Øien (2001b)



Organizational factor states

Designation	State value
'Very bad'	1
'Bad'	2
'Average'	3
'Good'	4
'Very good'	5

Figure 9: Example of organizational factor states. From Øien (2001b)

The rating of organizational factors is done by rating risk indicators for the specific factor. See figure 10 for illustration of the rating process. The organizational factor k, OF*k*, may be assessed by n_k different indicators. m_{kj} denotes the measured value of indicator *j* for OF*k* and these measurements are also rated from 1 to 5 where 1=very bad and 5=very good. The measured values for the indicators are then converted to a rating value and these are weighted by expert judgments to produce a weighted average as the rating value of the OF*k*, r_k, which is rounded of to an integer value from 1 to 5. For this calculation, equation 2 is used. The impact of each of the organizational risk indicators, $ORIkn_k$ (ref. figure 10), is assessed in what is called a weighting-process. This process may be data-driven or based on expert judgement, and the result is the weight of each factor, ν_{kn_k}.

$$r_k = \sum_{j=1}^{n_k} \nu_{kj} r_{kj} \tag{2}$$

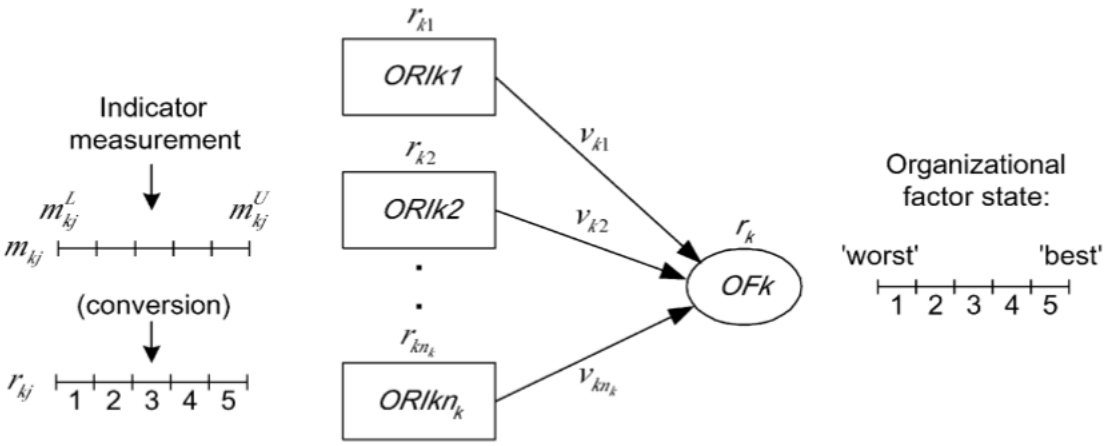


Figure 10: Rating process. From Øien (2001b)

6 Identification of suitable RIFs and indicators for the BBN factors

This chapter utilizes the theoretical background presented in the previous chapters for identifying suitable indicators for the various factors of the BBN collision model presented in appendix A. The BBN collision model will be analysed with respect to the immediate factors, human and technical factors and environmental factors. These factors are chosen as they have the closest connection to the end event, the collision. It is further assumed that all regulations and policies are followed.

6.1 Immediate factors

6.1.1 Vessel on collision course

A definition of collision course is "A situation in navigation in which a vessel will collide with another vessel unless one or both vessels alter course, or stop" (SeaTalk, Nautical Dictionary). However, being on collision course is not of importance if the meeting ship is hours away. Therefore, the distance between the ships determines the value of this indicator. The acceptable distance before maneuvering is a necessity and could be set as a standard distance applicable for all ship types and sizes, for example 1 nautical mile. Another option is that the acceptable distance varies with the size and speed of the current ship. This could be reasonable as smaller ships are easier to maneuver away from the meeting ship, than larger ships. It is very important that the distance is set so that the personnel have time to evaluate and adjust the course safely. According to Mou et al (2010) this distance, or as they call the CPA (closest point of approach) value, should be set to 2 nautical miles. Fowler and Sørgård (2000) has defined a critical situation as "when two ships come to close quarters—crossing within half a nautical mile of each other".

- Vessel on collision course (yes/no)

6.1.2 Vessel takes action in time

The BBN collision model by Hänninen and Kujala (2012) show that, as assumed, the most influential variable on whether there will be a collision is whether or not the ships change course when they know they are on collision course. If both ships change course the collision probability is 0.00001, while if neither of them change course the probability increases to almost 1.0 (Hänninen and Kujala, 2012).

Whether the vessel takes action on time is also dependent on when the detection of the possible collision is observed, which further depends on the experience and knowledge of the operator as (s)he is the one interpreting the various signals and information sources. The operator's competence is discussed further in a later section. Furthermore, the necessary time for action depends on the maneuverability of the vessel. Vessels with a high degree of maneuverability will be able to avoid collisions later than vessels with low degree of maneuverability. Maneuverability is discussed in more detail in section 6.2.13

Whether the vessel takes action in time or not can also be evaluated by checking if the vessel is still on collision course. If the vessel is no longer on collision course, action was taken in time. For this reason the indicator "vessel on collision course" is added for this factor as well.

Suggested indicators:

- Meeting vessel takes action (yes/no)
- Degree of maneuverability of own ship
- Vessel on collision course (yes/no)

6.2 Human and technical factors

This section presents the developed indicators for the human and technical factors in the BBN for ship collision. The structure is based on the categories given in the BBN and is as follows; operator actions, technical incidents, operator conditions, ship design and at last technical conditions.

6.2.1 Navigation

"The objective of ship navigation is to take the ship from one destination to another as safely as possible given the prevailing circumstances" (Nilsson, Gärling and Lützhôft, 2009, p. 189). Kulaja et al (2009) have studied accidents in the Gulf of Finland and found various causes for the collisions. Human failure represents 47.62% of the collision causes. Subgroups of these human failures include "Position not fixed properly" (40.5%), "misunderstanding of own vessel movement" (26.2%), and "misunderstanding of other vessel's movement or intentions" (2.4%), and these are here considered navigation failures. This means that 32% of the collisions have navigation failures as a cause, and it's mostly due to own ship.

When navigating through a fairway supervising position, steering and controlling speed are continuously required actions (Nilsson et al, 2009). Navigation can therefore be sub-grouped into course, speed and maneuver as is done in the BBN model. The level of safe navigation obviously also depends on the the operators competence, situational awareness etc., but the factor navigation cannot be measured by these terms, they only affect the navigation. Therefore, those factors are discussed in other sections and this section will only include indicators of the actual navigation itself.

Navigation errors may occur due to the lack of, or incorrect, information from one of the navigation systems. Also, it is shown that many mariners favor a piece of equipment which they rely on (Rothblum, 2000). One can see that when these two factors are combined it may have a undesired result. Due to the possible incorrect information it is therefore important that the operators check the available information from different sources before decisions are made or changed. This applies to both course, speed and detection of other vessels.

Based on the above the suggested indicators are:

- Frequency of controlling speed
- Frequency of controlling correct steering
- Frequency of controlling position
- Frequency of search for other vessels
- Use of multiple information sources (yes/no)
- Mean time to corrective actions after a deviation is identified

6.2.2 Effective lookout

For watch keeping personnel the vision is the main source of information (Kristiansen, 2004). Therefore, the factors affecting this part are mainly related to eye sight. Effective lookout is affected by many factors. The prolonged observation of a uniform field may lead to blanking out after 10-20 minutes. In addition to this, performance deteriorates sharply after around 30 minutes of vigilance. Kristiansen (2004) also refers to Teichner (1972) who found that the probability of detecting a visual signal is a function of the initial probability of detection and the duration of the watch. Figure 11 shows that if the initial probability of detection is low the deterioration with time is insignificant, while if the initial detection probability is high it deteriorates sharply during the first 30 minutes.

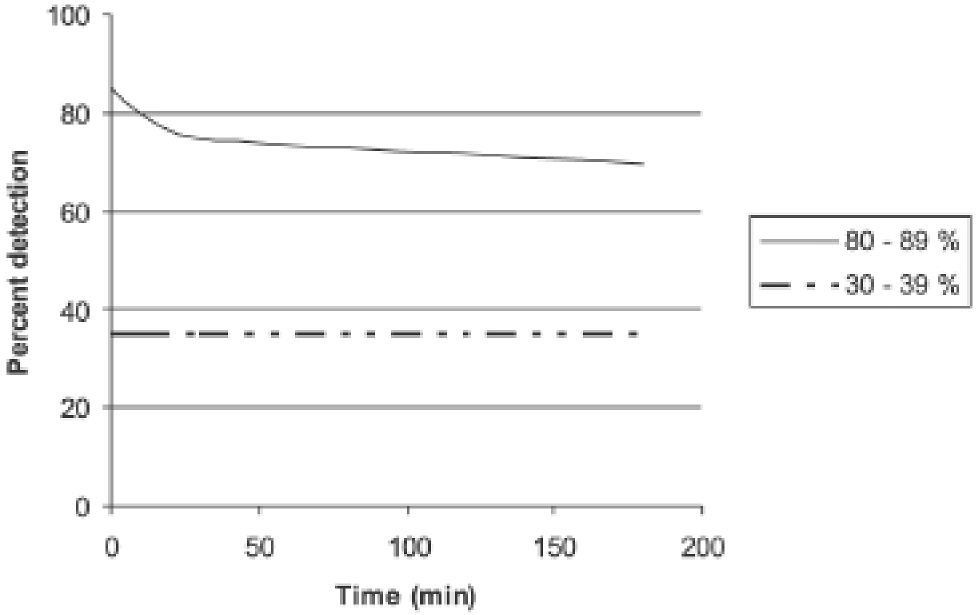


Figure 11: Initial detection probability versus time on watch for different initial detection probabilities. From Kristiansen (2004)

Visual illusions are very common and some factors for this are refraction, fog and haze and texture of an object (Kristiansen, 2004). Refraction is when different media (e.g. water) breaks the direction of light, and can result in wrong interpretations of the relative direction of other vessels or objects. In fog and haze objects may seem smaller than they actually are, which further makes them seem further away than they are, which can have serious consequences. The observed texture of an object may indicate it's distance from the vessel and therefore one may misjudge the distance of unusual objects. It is also shown that for assignments requiring vigilance, knowledge about the remaining time of the assignment has a positive effect on the performance of the operators (Kristiansen, 2004). The author believes that having more than one watch keeper will reduce the probabilities of the visual illusions. Another important factor for effective lookout is fatigue, which increases reaction time and reduces vigilance (Akhtar and Utne, 2014). The concept of fatigue is extensively covered in the section of physical and cognitive capabilities and this section will therefore not go into the details of fatigue. However, the indicators found for fatigue will be presented in this section as well as they are assessed as relevant for lookout.

There are also some factors that are of importance only during night watches or under dark conditions. The ability to observe under dark conditions is important even though the vessel has radar equipment (Kristiansen, 2004). Night blindness and the eyes' adaption to darkness may degrade the lookout function. Night blindness is a condition one may not know about or know the degree of (Kristiansen, 2004). It's a condition where the eye's adaptability to reduced lightning is weakened or completely missing, and could be congenital, or due to glaucoma or dietary deficiencies (Vitamin A) (Store norske leksikon, 2017, 02.02; Kristiansen, 2004). The condition also develops from around the age of 40 (Kristiansen, 2004). If the condition is due to dietary deficiencies it could be fixed by the supply of vitamin A (Store norske leksikon, 2017, 02.02). If one doesn't have the night blindness condition is takes around 25 minutes for the eyes to fully adapt to dark conditions after being after being exposed to sunlight or artificial lighting (Kristiansen, 2004). Therefore the time since starting a night watch is of importance. The illusion of autokinesis is also normal during dark conditions. One can see this illusion when staring at a single light against a dark background, one can see the light moving and sometimes in an oscillating fashion (Kristiansen, 2004). This is also a factor affecting the effectiveness of the lookout, but the author has not been able to conclude on how to reflect this in an indicator.

Based on the above the suggested indicators are:

- Hours of watch
- Number of watch keeping personnel working simultaneously
- Remaining time of watch known (yes/no)

Indicators related to fatigue:

- Vessel certifications and regulations (OK/LTA)
- Efficiency pressure
- Hours of sleep
- Watch schemes
- Sleep problems (yes/no)
- Tour length
- Hours of standing watch
- Ship type

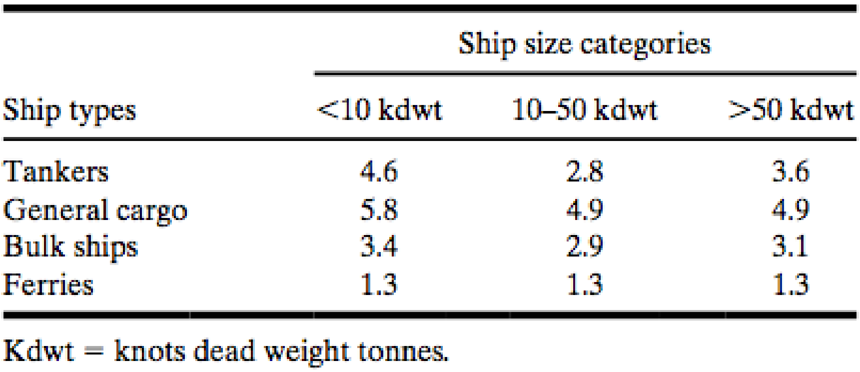
Extra indicators for use during dark conditions, where the three first indicators are for night blindness:

- Known night blindness condition (yes/no)
- Age of watch keeper
- Dietary deficiencies (yes/no)
- Time from start of dark adaption

6.2.3 Propulsion

Loss of the propulsion function is one of the most serious categories of hazardous events in shipping (Brandowski, 2009). Loss of propulsion include, among others, the loss of boiler or propeller and failure to the turbine or main diesel. Fowler and Sørgård (2000) write that results from the DAMA database show that about 2.8% of collision accidents in good visibility are caused by steering or propulsion failure, and that the probability for propulsion or steering failure, given a critical situation (here defined as when two ships are within half a nautical mile of each other), is estimated to 4.5E-6. They have also calculated the frequency of propulsion and steering failures based one fault trees which are based on interviews and expert judgments. In the calculation it is assumed that ships above 6000 gross tonne have 7000 operating hours per year and that ships below 6000 gross tonne have 6000 operating hours per year. The frequencies for ferries are based on another source than the other ship types. The result is shown in figure 12. Based on these results Eide, Endresen, Breivik, Brude, Ellingsen, Røang, Hauge and Brett (2007) rate on average 0.26 failures per ship-year for all ship types. It is however not given that the steering function fails as the propulsion function fails (Mohovic, Mohovic and Rudan, 2013). More about this is in the next section on steering.

Brandowski (2009) writes that the probability of propulsion loss is dependent on the reliability of the propulsion system as well as the operator. The assigned function of the propulsion system is generating the driving force of a defined value and direction (Brandowski, 2009). The operator performance is not mentioned in the article by Fowler and Sørgård (2009), which may indicate that their results only reflect direct failures of the propulsion system. The article of Brandowski (2009) presents a method for estimating the probability of propulsion loss based on expert opinions, with the intention of using it in situations with a shortage of objective reliability data. The consequences of propulsion failure are divided into to parts; immediate catastrophic failure and delayed catastrophic failure, where the former case of the



	Ship size categories		
Ship types	<10 kdwt	10–50 kdwt	>50 kdwt
Tankers	4.6	2.8	3.6
General cargo	5.8	4.9	4.9
Bulk ships	3.4	2.9	3.1
Ferries	1.3	1.3	1.3

Kdwt = knots dead weight tonnes.

Figure 12: Frequency (per 10.000 Ship Hours) for propulsion and steering failures. From Fowler and Soergaard,2000, modelling ship transportation risk.

forced stoppage is the one that creates a risk of damage or loss of ship, and is therefore the outcome studied further. The failure frequency depends mainly on type of propulsion system and the ship operation mode. Using the proposed method the probabilities of determined numbers of propulsion system failures during 1 year were calculated. The specific propulsion system consists of a low speed piston combustion engine driving a fix patch propeller installed on a container carrier ship. The result can be seen in the figure 13. ICF is the abbreviation for Immediate Catastrophic Failures. It can be seen from the figure that the largest probability is for 2 failures during a year, and the probability is 0.2565. The probability of zero failures is as low as 0.0821.

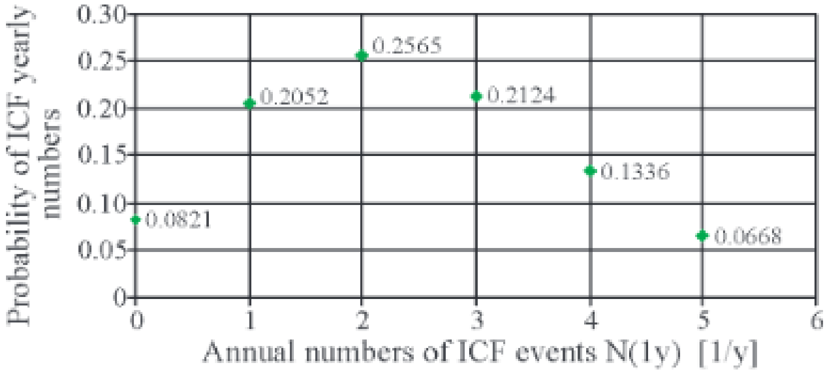


Figure 13: Distribution of immediate catastrophic propulsion failures. From Brandowski (2009)

Vessels with two main engines will have a lower probability of propulsion loss due to redundancy (Eide et. al, 2007). The same article also states that is important to note that the failure rates depend on maintenance, crew skills and other operational factors and points to the likelihood that substandard ships have higher failure rates.

It is important to understand that the loss of propulsion does not mean that the ship is still. The ship can still move due to the inertia at the moment of propulsion failure (Mohovic et al, 2013), and therefore propulsion failure can cause a collision accident.

Based on the above the suggested indicators are:

- Ship type
- Size of vessel
- Hours of maintenance per year
- Type of propulsion system
- Ship operation mode (speed)
- Immediate catastrophic propulsion failure (yes/no)

If the indicator "immediate catastrophic propulsion failure" has the value "yes", the other indicators are no longer of importance, this should be reflected in the weighting of the indicators.

6.2.4 Steering

With loss of steering a vessel loses its ability to navigate and hence also to maneuver when other ships are in the proximity. This can undoubtedly lead to collisions, which should be reflected in the weighing of the collision risk factors. However, grounding is the number one consequence of steering loss (Mohovic et. al (2013). The found articles present steering failures together with propulsion failures, therefore much of the relevant information on steering failures is given in the previous section on propulsion. Possible causes of steering failures are system failure of the command transmission between the navigation bridge and the rudder, failures on the power supply of the steering system and failures on the steering device (Mohovic et al, 2013).

As previously mentioned it is not given that the steering fails as the propulsion fails. When the propulsion system fails the ship can continue to move due to inertia at the moment of failure occurrence and if the steering function is still intact it is possible to keep the vessel on the planned trajectory (Mohovic et al, 2013). However, at a certain point it will no longer be possible to control the movement of the vessel due to the decreased flow of water around the rudder, which prevent the appropriate rudder deflection. The vessel will then continue to move, but without any control of the crew. The remaining inertia and the force from external conditions decides the further movement of the vessel (Mohovic et al, 2013).

Indicator:

- Loss of steering function (yes/no)

6.2.5 Navigation system

Navigational aids comprise both systems aboard and external systems like vessel traffic service and visual cues. This section will focus on the system on board and the various external navigation aids are covered in section 6.3.2. Issues related to the design of the navigation system will be addressed in section 6.2.12.

There has been a rapid development in technology related to the various bridge systems during the last decades, and among these are the computer systems for navigation. An example of a new computer system is the Electronic Chart Display and Information System (ECDIS). Compared to using navigational charts DNV (2007) states that the use of ECDIS can reduce the navigational risk as it reduces the workload of route planning, route monitoring and positioning. This instrument can be used to display and monitor a route plan without a paper chart, and obtain information about other ships' speed and information (Nilsson, 2007). An Electronic Chart System (ECS), which is an electronic representation of a traditional chart, can be considered an ECDIS if it can satisfy demands and guidelines issued by the IMO regarding technical standards of compatibility with other equipment (Nilsson, 2007). From the previously mentioned characteristics one can understand that ECDIS is an instrument that can replace several other instruments (Nilsson, 2007). The ECDIS is however a relatively new system and therefore not all ships have it implemented. All operators also do not know how to use it properly, nor do they know all its benefits and limitations (Jie and Xian-Zhong, 2008). For a better understanding of the functions and information flow of the ECDIS see figure 14. A study by DNV (2007) reveals that the implementation of ECDIS, assuming 100% coverage, will reduce the frequency of groundings by 38%. The study focuses on groundings, but it is also emphasized that ECDIS will have a great effect on collision frequencies as well. Also, the Norwegian Maritime Directorate believes that 75% of all maritime causalities related to navigation can be avoided by the use of ECDIS (Jie and Xian-Zhong, 2008).

The accuracy of nautical charts, both traditional and electronic, can vary and depends on how accurate the depth soundings have been done (Nilsson, 2007). This is confirmed by Jie and Xian-Zhong (2008) who write that over 50% of depth information on National Oceanic

Atmospheric Administration is based on surveys conducted before 1940, and this may cause errors. Also the GPS can produce inaccurate input to the ECIDS. In other words the data is not 100% reliable.

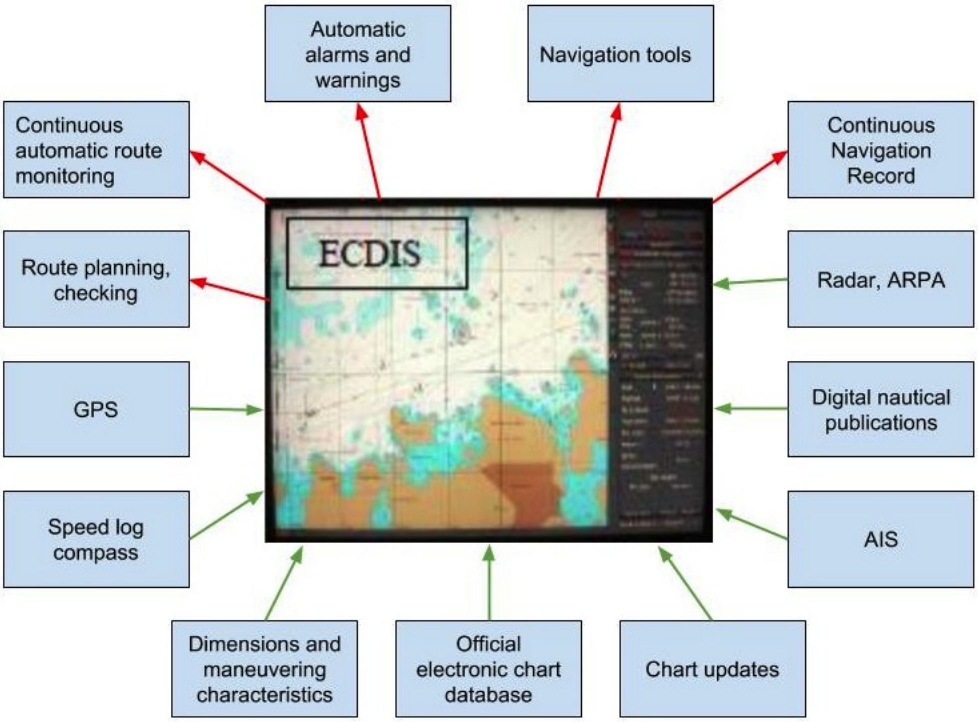


Figure 14: Functions and information flow of ECDIS. From Nilsson (2007)

Other important navigation systems on the bridge include RADAR, nautical charts, passage plan, GPS, AIS, means of communication, depth indicator, compass and speed indicator. Some of these will be presented further.

Radio Detection And Ranging (RADAR) is used both for navigation and traffic control and works by the use of radio waves. The distance and position of objects are then presented as an image on a screen. A special case of radar is also developed for the cause of collision warning, and is called Automatic Radar Plotting Aid (ARPA). The ARPA is connected to the RADAR and shows other ships' speed and course and therefore functions as an information source about the traffic situation and how the traffic changes due to other ships (Nilsson, 2007).

The Global Position System (GPS) is a radio navigation system, which based on satellite signals and a receiver on the ship determines the position of the ship. The accuracy of the position can vary also for the GPS. If more accurate positioning is desired there is another system, called Differentiated GPS, on the market, which utilizes an additional station on land that sends information regarding the reliability and corrections regarding the space satellites. As mentioned earlier the GPS can produce inaccurate positions, which can be due the position of the GPS antennae on board (Jie and Xian-Zhong, 2008). Additional information can be obtained by the Automatic Identification System (AIS), which can transmit information either between ships or between ship and land (Nilsson, 2007). This information includes name of the ship, course, speed, depth and destination. Information from the GPS is the basis for the AIS positioning system (Nilsson, 2007), and therefore one may also get faulty positions from the AIS.

For avoiding collisions it is crucially important to see other vessels, but it is equally import that other vessels see you. In the dark, or in restricted visibility, this is secured by the navigation lights mounted on the ship. The navigation lights also aid other vessels in determining your size, your direction relative to them and the status of your ship (Maritime Safety Queensland, 2017, 08.02). Regarding this there are different rules and regulations for different types of vessels and different sizes, but the general rule can be seen i figure 15. The rules for navigation lights for the specific ship should be examined and followed.

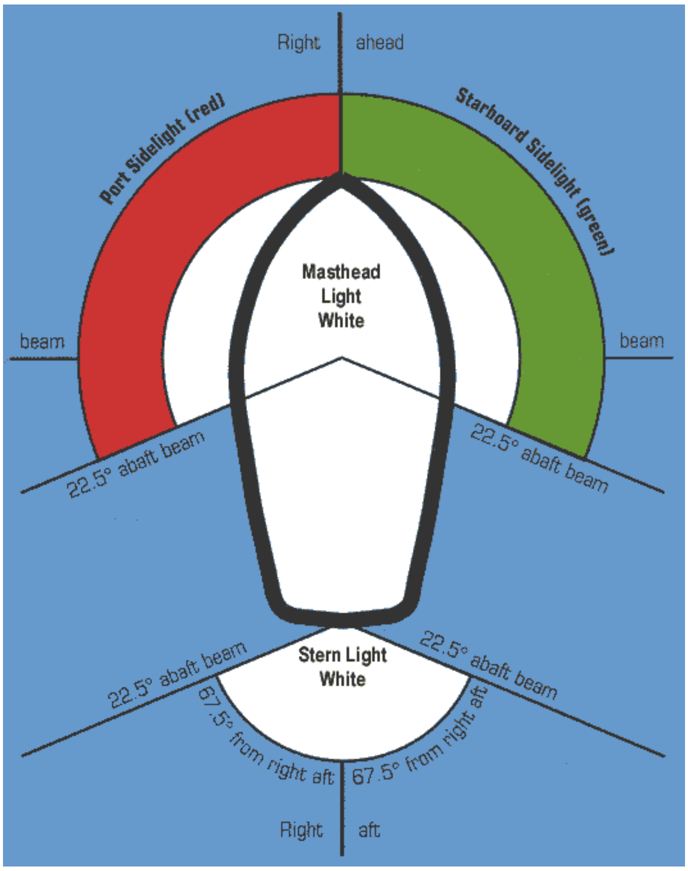


Figure 15: General rule for navigation lights. From Maritime Safety Queensland, 2017, 08.02

Based on the above the suggested indicators are:

- All required navigation equipment are functioning (yes/no)
- Frequency of chart and software updates
- Frequency of deviations
- Frequency of equipment testing
- All navigation lights are functioning (yes/no)
- All navigation lights are placed correctly (yes/no)

6.2.6 Competence

Competence can involve several disciplines, but this section will deal with the competence necessary for safe navigation, and further mainly the technical competence. As many of the considered necessary non-technical competences are covered in other sections (e.g. communication) they will not be covered in this section. Non-technical skills are nonetheless important and may reduce the number of incidents and accidents (Hetherington et al, 2006). The International Maritime Organization (IMO) also recognize the importance of non-technical competence. The Standards of Training Certification and Watchkeeping for seafarers (STCW) are international and imposes requirements for training and knowledge of seafarers on merchant vessels (Sjøfartsdirektoratet, 2016, 28.11). Among the non-technical skills it states that officers should have competence in crisis management and human behaviour, but the requirements does not specify the type of human behaviour skills or the adequate level of competence (Hetherington et al, 2006).

Rothblum (2000) refers to a study which shows that lack of general technical knowledge was responsible for 35% of ship causalities, the main contributor being lack of knowledge about proper use of technology. User errors of the equipment, which also includes depending on the wrong equipment when another source provides better information, are often due to the fact that many mariners don't understand how the automation works or under which settings and conditions the equipment is designed to work effectively. Lack of ship-specific knowledge is another contributing factor for ship causalities and Rothblum (2000) refers to a survey where 78% of mariners listed this as a problem. This is a problem because many mariners constantly work on different vessel types and sizes, which also have different equipment and carry different cargo. Because humans have a limited memory capacity this obviously causes problems. Decreasing the number of different vessels a mariner works on would be the ideal solution to this problem as it would enhance the knowledge about the current ship of deployment. However, Rothblum (2000) suggests that better training and standardized equipment design can help solve the problem.

To prevent accidents the Vessel Traffic Services (VTS) operators are also important. They guide traffic in harbours, rivers and approach areas, provide information on request and coordinate ships in conflict situations (Wiersma and Mastenbroek, 1998). In addition to a professional maritime background, simulator training with equipment and communication protocols and on-the-job training, they go through obligatory exams every third year to ensure that the competence level is maintained and that they keep up with the developments in equipment and procedures (Wiersma and Mastenbroek, 1998). This is considered an important factor as the technical instruments used by the VTS operators are constantly upgraded and new instruments are developed.

It is not found information regarding re-examination of on board operators, but it is thought by the author that this would enhance the competence level and hence also decrease the probability of collision. Therefore, the same indicators are given for both on board operators and VTS operators.

Based on the above the suggested indicators are:

- Frequency of vessel change
- Number of relevant qualifications
- Frequency of re-examination
- Approved training (both simulator and on-the-job) (yes/no)

A low value for the frequency of vessel change, and high values for the other indicators are desired.

6.2.7 Communication

Communication affects a team's situational awareness, the team work, and effective decision making. Issues considering communication can therefore often lead to errors or accidents (Hetherington et al, 2006) and good communication is therefore important in the shipping industry. Not only is there need for better communication within the vessel, but also between ships and ship-to-VTS (Rothblum, 2000). A review done by The Canadian Transportation and Safety Board (CTSB) revealed that 42% of incidents involved misunderstandings or lack of communication between the pilot and master or officer on watch (OOW), which also potentially can reveal lack of situation awareness and/or poor team work (Hetherington et al, 2006). According to the National Transportation Safety Board (NTSB) 70% of all major ship collisions occurred while a State or federal pilot was directing one or both vessels (Rothblum, 2000). This indicates that misunderstandings occur regularly and that communication is inadequate. Based on work done by CTSB quantifying communication based on interviews and questionnaires gives highly unreliable results as people's self-perception of effective communication doesn't comply with other's interpretations of the same communication. However, as the number of misunderstandings during a day is difficult to count or assess this will not be included in the indicators. Hetherington et al (2006) suggest that language problems could be one of the reasons for the communication problems. In the maritime industry it is very normal that people with different nationalities work together and even though there is a required level of fluency in the ship's declared working language it may not be followed, which causes communication problems. Studies also show that the results of bad communication vary in seriousness from mild annoyance to potentially hazardous outcomes (Hetherington et. al, 2006).

An example of where bad communication and lack of clarifications resulted in a hazardous outcome is the collision between the M/V SANTA CRUZ II and the USCGC CUYAHOGA, where 11 people lost their lives. In this accident the captain of CUYAHOGA ordered a turn because he perceived the size and heading of SANTA CRUZ II. The next human error was a lack of communication to clarify his order, as the crew realized the situation, but still thought the captain had a good reason for the ordered turn (Rothblum, 2000). With better communication between the captain and the crew the accident could have been avoided.

The U.S. National Transportation Safety Board (NTSB) recommends introducing Bridge Resource Management (BRM) training of vessel crew to improve communication and crew interaction (Rothblum, 2000; Hetherington et ak, 2006). BRM is the maritime equivalent of Crew Resouce Management (CRM) (O'Connor, 2011), which was designed for the aviation industry to improve teamwork and communication (Ford, Henderson and O'Hare, 2014). There are however researchers who disagree with the importance of BRM. Hänninen and Kujala (2012) has constructed a BBN for ship collision and by using this they assess the various factors influencing the probability for collision. They found that BRM seems to have a minor effect on the probability for collision. It is still adopted by many vessel companies as it is recommended by the International Safety Management (Hetherington et al, 2006).

It is concluded in this thesis that the implementation of BRM irrespectively will not influence the safety level negatively, and therefore the ships that have implemented BRM may have some lower probability of collision.

Based on the above the suggested indicators for communication are:

- Percentage of crew speaking working language fluently
- BRM implemented (yes/no)

6.2.8 Physical and cognitive capabilities

A person's physical and cognitive capabilities are determined by many factors, some are temporary and some are permanent. These factors will be described further in this section.

- Fatigue (mental and physical).
  Both physical and mental fatigue are included because they both decline alertness, mental concentration and motivation. The true extent of its effects and consequences in transportation are unknown, and the researchers disagree as the effects on cognitive performance are complex, but studies show a correlation between fatigue and the risk of accidents (Akhtar and Utne, 2014). Fatigued watch keepers have longer and more variable reaction times than rested watch keepers and this impacts their situation assessment and decision making negatively (Nilsson et al, 2009). Rothblum (2000) writes that fatigue contributes to 16% of critical ship causalities and 33% of personnel injuries, and that it has been cited as the number one concern of mariners. In 8 out of 88 ship groundings in Norway in 2006 the watch keeper had fallen asleep (Akhtar and Utne, 2014) and from another 98 ship causality reports fatigue was identified as a contributory cause in 23% of the cases, and a clear majority of sea officers report that fatigue has risen the last 3-10 years and that extra manning could reduce the level of fatigue (Hetherington et al, 2006). Also, 70% reported poor to very poor sleep to a study of Australian seafarers. Akhtar and Utne (2014) write that the probability of a seafarer to experience fatigue is approximately 0.4-0.5 and the probability of a member of the bridge management team to experience fatigue is calculated to 0.23 (not ferries and smaller vessels). They have done a study on the effect of the bridge management team's (BMT) fatigue on maritime groundings, and also examined what influences fatigue the most, using a Bayesian network. By using their BBN model they found that assuming no fatigue the probability of grounding was reduced by 9%, but assuming that fatigue is present in the crew increases the probability of grounding by 23%. This shows the strong effect of fatigue on grounding accidents. Even though their article is about the probability of grounding it is thought that many of the same factors contribute to the probability of collisions as well, which is the reason for why their results are presented

in this thesis. However, note that the numbers and percents may be some what different for a collision accident that for a grounding accident.

Mental fatigue has several negative consequences and among these are performance errors and ability to plan (Herzog, Hayes, Applin and Weatherly, 2011), general weariness, increase in reaction time, lower vigilance and disinclination for any kind of activity (Akhtar and Utne, 2014). Zhang, Zhao, Du and Rong (2014) have done a study on the effect of fatigue driving. Their results show that reaction to light and sound is significantly affected by fatigue. The author thinks it is reasonable to conclude that this also applies to the maritime industry. There is also a positive correlation of 0.65 between stress and mental fatigue (Herzog et al, 2011), which should be of consideration when weighting the indicator values.

Akhtar and Utne (2014) present useful information on the effects of fatigue and the most important measures to reduce fatigue and to reduce the consequence of groundings when fatigue is already present. Firstly, enough manning on all levels is crucially important as it will lead to adequate resources for administration and follow up of the fleet. It will also affect all the fatigue reducing measures as eating regular meals, having enough sleep, adequate rest periods, reducing administrative tasks and free time. Secondly, having all the certifications and regulations in place also have a great impact on reducing the probability of fatigue. Thirdly, the bridge management team should monitor the helmsman properly. Also, another important contributor is “efficiency pressure”, which is strongly influenced by the top management. The fatigue related factors contributing most to a grounding accident are identified as lapsing/micro sleep, missed observations and narrowing attention (Akhtar and Utne, 2014). According to Hetherington et al (2006) the ship type is also a contributor to fatigue as seafarers based on ferries report higher levels of fatigue than seafarers on other vessel types.

Another important contributor to fatigue is shift patterns. Lützhöft, Dahlgren, Kircher, Thorslund and Gillberg (2010) did a study on fatigue in 4 on, 8 off watch system against a 6 on, 6 of watch system. By using electrooculography, actigraphy, diaries, and reaction time tests they measured the effects of the shift system on fatigue and sleep. Their results show that sleepiness was higher during the night shift in the 6-on, 6-off system and the sleepiness also increased more during the watch in the 6-on, 6-off system compared to the 4-on, 8-off system. The 6 on, 6 off system also led to shorter sleep periods and the sleep was often in to split episodes. This shows that a 6 on, 6 off shift patterns affects the fatigue more negatively than a 4 on, 8 off shift pattern. However, many vessels still prefer the 6 on, 6 off scheme (or even 12 on, 12 off) as it demands a lower manning level than the 4 on, 8 off scheme, and a lower manning level is cheaper and easier for top management to manage and administrate (Akhtar and Utne, 2014). According to Hetherington et al (2006) longer tours equate to less fatigue, so therefore the tour length also needs to be of consideration when assessing the effects on fatigue.

Based on the above the following indicators for fatigue are suggested:

- Vessel certifications and regulations (OK/LTA)
- Efficiency pressure
- Hours of sleep
- Watch schemes
- Sleep problems (yes/no)
- Tour length
- Hours of standing watch
- Ship type

- Stress level.
  Both mental and physical health are affected negatively by elevated stress level for an extended time period and 84% of sea officers report that they feel stress is more prevalent now then earlier (Hetherington et al, 2006). A study by Herzog et al (2011) also show that duties and difficulties are strongly related to stress. High workloads detriments performance on a secondary task, which emphasizes the potential consequences of a high number of task or concurrent equipment monitoring (Hockey et al, 2003).

  Based on the above the following indicators for stress level are suggested:

  - Number of tasks per hour
  - Level of difficulty of tasks
  - Family/personal issues (yes/no)
  - Number of equipment to monitor concurrently

- Gender.
  Studies on navigational performance in virtual maze tasks and spatial learning from navigational experience indicate a male advantage. This is the result in both virtual and real simulated environments, but is most typical when one can learn from direct experience rather than from maps (Wolbers and Hegarty, 2010). Wolbers and Hegarty (2010) also write that female navigational performance can vary with hormonal fluctuations and that

females can perform as well as males when the estrogen level is low. However, females have the advantage when it comes to object location memory. Men and women also have differences when it comes to the navigational strategies and the usage of environmental cues. Both sexes have the same abilities on using landmarks as cues, but females navigate on the basis of local landmarks and familiar routes whereas men navigate using cardinal directions, environmental geometry and metric distances. Another finding is that to remain oriented or reorient women require more environmental cues than men, and have more difficulties of navigating using cardinal directions and metric distances (Wolbers and Hegarty, 2010). Wolbers and Hegarty (2010) also write that several evolutionary theories have been proposed to explain these differences, but these will not be mentioned further in this thesis. However, this indicates that female navigators pose some higher threat to safety in navigation than male navigators, and therefore the indicator value should be some what higher for females.

Based on the above the indicator is suggested below:

  - Female/male

- Age.
  The differences in individual navigational abilities become more prominent at later stages in life, and is prominent also between healthy elders, not only between healthy elders and elders suffering from dementia or other diseases. This result was shown in a study described by Wolbers and Hegarty (2010). The underlying causes for this are uncertain as the experiments so far have been cross-sectional. This means that they are uncertain whether the variability was present already at younger ages or due to different developmental trajectories. However, it was also shown that in total the elderly group performed worse than a young control group. Navigational abilities are also dependent on eye sight for lookout functions. It it shown that age is an important factor for e.g. night blindness, which usually develops around the age of 40 (Kristiansen, 2004). For these reasons it seems right to say that the probability of navigational errors increases to some degree with age, which should be reflected by this indicator value.
  Indicator:

  - age

- Physical health.
  Shift patterns contribute to poorer health and safety performance (Akhtar and Unte, 2014), but there is an absence of literature evaluating the relationship between seafarers' health and performance according to Hetherington et al (2006). Indicators are still developed, but this factor should be weighted low compared to the other factors.

The following indicators are suggested:

- BMI
- Smoker (yes/no)
- Handicap (yes/no)
- Exercise level

- Alcohol.

  Alcohol affects the same unsafe states as fatigue, and with similar probabilities. Putting evidence on alcohol in the BBN model by Akhtar and Utne (2014) increases the probability of grounding by 68%. Although fatigue and alcohol consumption are not directly related, the combination of both alcohol and fatigue being present increases the probability of grounding by 180% (see figure 16). Due to these facts the author believes that alcohol also influences the probability of collision, although perhaps not to an equally large extent as a meeting vessel can be easier to spot than a shallow and also since the meeting vessel can take actions to prevent a collision. Zhang et al (2013) studied the effect of drunk driving on the driver's physical characteristics. They found that reaction time to light, deviation of depth perception, eyesight, reaction time to sound and speed anticipation was significantly affected by alcohol. The author thinks it is reasonable to conclude that this also applies to the maritime industry. Marsden and Leach (2000) conducted a study on the effects of alcohol and caffeine on maritime navigation skills. The participants were given 75 ml of alcohol, more specific whiskey at 40 vol% (time frame is not specified), and their results show that alcohol impaired the performance on visual search and navigational problem solving. In Norway a standard unit of alcohol is 15 ml, which equals approximately 33 cl beer of 4.5 vol%, 15 cl wine of 12 vol%, 7.5 cl strong wine of 20 vol% or 4 cl liquor of 40 vol% (https://no.wikipedia.org/wiki/Alkoholenhet). Based on this the participants consumed a little less than two units and the effect was clearly noticeable.

  Based on this the proposed indicator is:

  - Number of alcohol units per hour
  - blood alcohol level

- Situational awareness.

  There are several definitions of situational awareness (Salmon, Stanton, Walker, Baber, Jenkins, Mcmaster and Young, 2008), and it is described by Hetherington et al (2006) as “the ability of an individual to possess a mental model of what is going on at any one time and also to make projections as to how the situation will develop" who also writes that 71% of human error types on ships are related to situation awareness. As mentioned in

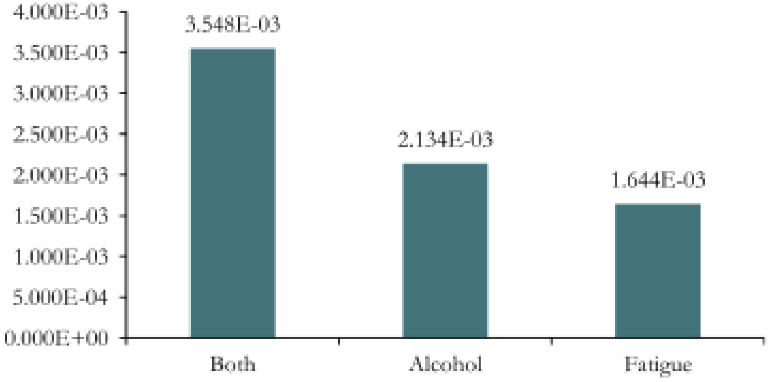


Figure 16: Changes in posterior probability of grounding with fatigue and alcohol. From Akhtar and Utne (2014)

chapter 6.2.7 on communication, lack of situational awareness can be revealed by the degree of misunderstandings (Hetherington et al, 2006). Wolbers and Hegarty (2010) write that the best navigators are the ones who are able to switch flexibly between different navigational strategies, depending on what is best in the given situation. The different strategies they mention are based on the navigators memory systems, where one system acquires sequences of actions and provides route representations, often in an egocentric reference frame and based on local landmarks, and the other system allows for planning direct paths, even in unfamiliar terrain, to an unseen location using observer-independent, flexible representations.

Situation awareness in relation to ship control and navigation also depends on ones self-motion perception. Variability in this perception could influence ones accuracy when keeping track of ones orientation and position (Wolbers and Hegarty, 2010), therefore the level of self-motion perception is also considered to be a useful indicator of situation awareness. There have also been developed several methods for measuring ones situational awareness. These are often task-based and use simulators (Sneddon, Mearns and Flin, 2012). Examples are Situation Awareness Rating Technque (SART), The Situation Awareness Global Assessment Technique (SAGAT), Computational Modelling and Task Performance Risk Space (Salmon et al, 2008). Whether to use only a measuring method as indicator or to include others as well could be discussed further, but the author thinks that the result would be more accurate when including the other proposed indicators as well as they are valued by other researchers to affect the situational awareness. Based on the above the proposed indicators are:

- Ability to switch navigational strategies
- Years of experience

  - Level of self-motion perception
  - Result from SART or SAGAT

- Work environment.

  Well-being and task performance is a function of climate, which includes temperature as well as humidity. In terms of human errors the number increases heavily around the effective temperature of 30 degrees, which is also the upper temperature for what one normally thinks is comfortable (Kristiansen, 2005). Figure 17 illustrates this relationship.

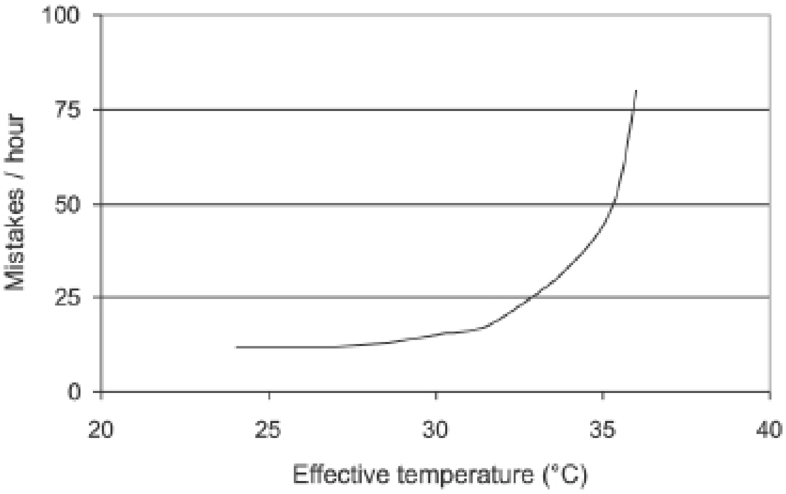


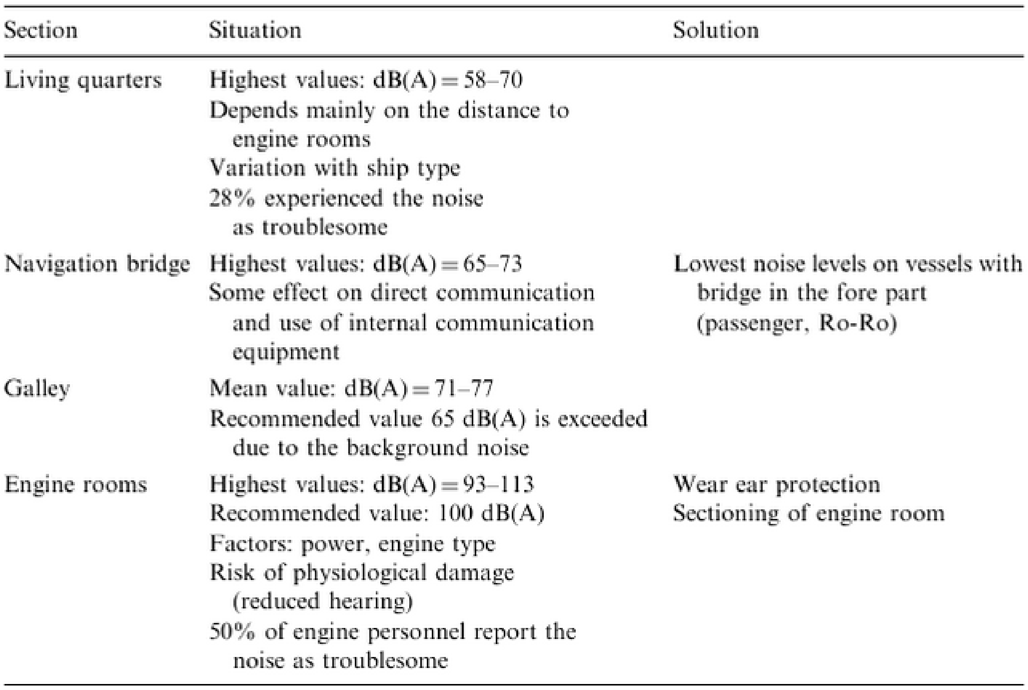
Figure 17: Monitoring mistakes as a function of effective temperature. From Kristiansen (2005)

High intensities of infrasound (acoustic waves below 20 Hz) are shown to have negative effects on a person's well being, tiredness and reaction time. As infrasound is present both on the bridge and in the engine control room it might have negative consequences for safety (Kristiansen, 2004). Figure 18 shows maximum recorded and recommended noise levels for the different main parts of a ship, as well as some possible solutions.

A significant part of the crew views vibrations as the most disturbing environmental factors on-board as complete restitution becomes a problem (Kristiansen, 2004), which further will reduce the ability to perform. The norm values for exposure time versus vibration, given by ISO in 1985, can be seen in figure 19.

Based on the above, suggested indicators for work environment are:

  - Temperature
  - Noise level
  - Vibration



Section	Situation	Solution
Living quarters	Highest values: dB(A) = 58–70 Depends mainly on the distance to engine rooms Variation with ship type 28% experienced the noise as troublesome	
Navigation bridge	Highest values: dB(A) = 65–73 Some effect on direct communication and use of internal communication equipment	Lowest noise levels on vessels with bridge in the fore part (passenger, Ro-Ro)
Galley	Mean value: dB(A) = 71–77 Recommended value 65 dB(A) is exceeded due to the background noise	
Engine rooms	Highest values: dB(A) = 93–113 Recommended value: 100 dB(A) Factors: power, engine type Risk of physiological damage (reduced hearing) 50% of engine personnel report the noise as troublesome	Wear ear protection Sectioning of engine room

Figure 18: Noise in vessels. From Kristiansen (2005)

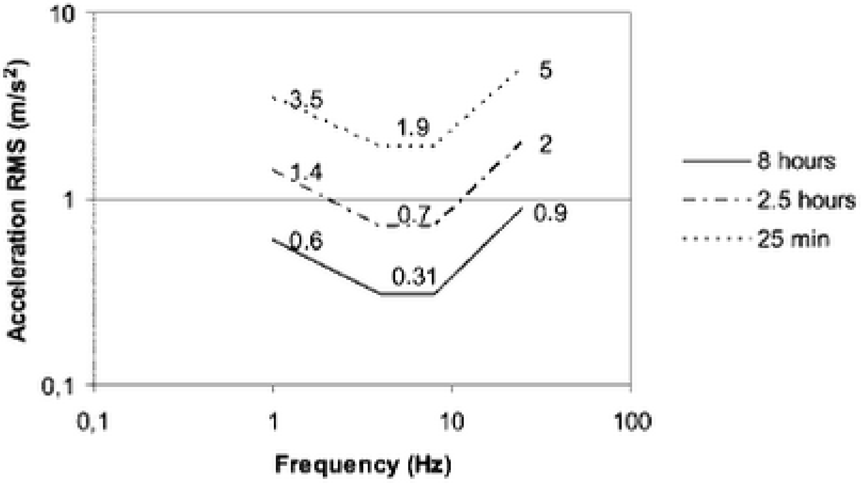


Figure 19: Vibration tolerance limits as fuction of exposure time. From Kristiansen (2004)

- Vibration exposure time

6.2.9 Number/complexity of tasks

Number and complexity of tasks is assessed as the same as workload, which is defined by Nilsson, Gärling and Lützhöft (2009, p. 189) as “the demand a task imposes on the operator with limited resources". As high workload over longer time periods can lead to exhaustion it can decrease performance and further increase risk. Also, high workloads combined with demanding decision making can lead to wrong decisions and hence also increase risk. High workloads can be handled by allowing task performance to degrade, performing the tasks more efficiently or shedding tasks considered as lower priority (Nilsson et al, 2009). Considering ship collision it may not be desirable to degrade performance as it can increase the probability of collision. Therefore, performing tasks more efficiently and shedding lower priority tasks are the only adaption methods that will be considered as useful in this thesis. It is also thought that performing tasks more efficiently can be realized by having a larger work force, but it will also depend on the operators experience with the equipment, tasks and the required sequence of the tasks. This was also found in the study by Nilsson et al (2009) where the participants had lower response times during the second simulation, when they had familiarity with the equipment and situation.

The study also showed tendencies that a conventional bridge require more work load than an advanced bridge. This should be reflected in the indicators, but be weighted relatively low as Nilsson et al (2009) also refer to another study by Sauer, Wastell, Hockey, Crawshaw, Ishak and Downing (2002) reporting higher workload for integrated displays. The last result was also based on subjective ratings and the result was not significant (Sauer et al, 2002). The major differences between the two bridge types are that the conventional bridge has paper charts and AIS through minimum keyboard display, while the advanced bridge has ECDIS and paper chart, AIS integrated in ECDIS or RADAR, possibility for overlay between RADAR and ECDIS, curved headline (indicates the future position of the ship given the current circumstances), and conning display. The conning display shows ship characteristics as for example heading, speed and draught on one screen, but the information retrieved from the conning display could be found at other locations on the bridge (Nilsson et al, 2009).

NASA Task Load Index (NASA TLX) is a subjective measure of workload, which has a long history of use and can be combined with other measurements (Nilsson et al, 2009). In this measurement the operators rate their experiences of workload in mental demand, physical demand, temporal demand, performance, effort and frustration, and further weigh the six dimensions by comparing them pairwise against each other. Based on the subjective results from the NASA TLX Nilsson et al (2009) concluded that the workload is slightly lower on the advanced bridge than on the conventional bridge.

Another possible measure of workload is the method used in the research by Sauer et al (2002). This only measures mental workload and includes the operators answering to the questions "How much effort did you put into the task?", "How difficult did you find the task?" and "How much did you feel under time pressure?" (Sauer et al, 2002, p. 339), and to rate how well they thought they were able to identify targets and how well they were able to plan and predict the development of the situation with the given information. All questions were to be rated from 0-100. It was based on the answers to these questions Sauer et al (2002) got the result of slightly higher workload for integrated displays.

Without references it is also thought that number and complexity of tasks can be reflected by the work hours, and the amount of finished work on schedule. If the tasks require overtime to be completed, it may prove that the they are even too many or too complex, or a combination of both.

Based on the above the suggested indicators are:

- Bridge type (conventional vs advanced)
- Manning resources
- Operators years of experience with current equipment
- Possibility for prioritizing tasks (yes/no)
- NASA TLX score
- Mental workload score (from Sauer et al, 2002)
- Hours of overtime per week
- Percentage of finished tasks by the end of original work hours

6.2.10 Bridge design

There is not a standard design of the bridge. The layout varies from each ship, partly due to unique changes on each ship done over years. However, a typical bridge layout can be seen in the figure 20. Typical equipment on a traditional bridge includes navigational aids, communications equipment and equipment for safety systems, engine management and alarm management. Navigational aids include ARPA, ECDIS, GPS, conning, AIS and classic hard paper charts. Communications equipment are the Very High Frequency (VHF) radio and phone for internal communications. Equipment for safety systems, engine and alarm management include fire and watertight door control, sprinkler system control, drencher system control, navigational lights control, hull monitoring and stability monitoring. The key instruments in a collision scenario are the navigational aids and radio communication (Garrè, Perassi, Raffetti and Rizzuto, 2010).

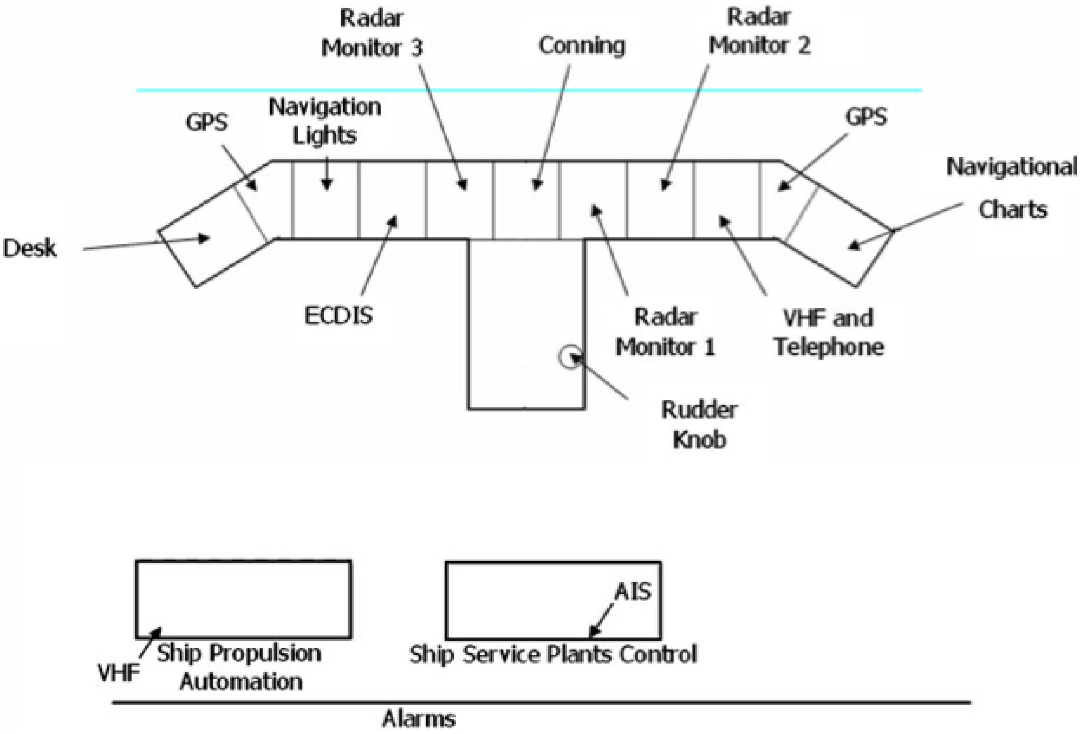


Figure 20: A typical traditional bridge layout. From Garrè et. al (2010)

In the later years Integrated Bridge Systems (IBS) define the configuration of bridge layouts on commercial ships. With an IBS configuration several modules, each devoted to a particular aspect of the ship operation, are integrated into the same platform and are no longer dispersed as earlier. The IMO defines IBS as: "a combination of systems which are interconnected in order to allow centralized access to sensor information or command/control from workstations, with the aim of increasing safe and efficient ship's management by suitably qualified personnel" (International Maritime Organization, 2017, 12.01). Redundancy may be created by repeating the integrated systems (Garrè et al, 2010). The integration of all navigational systems into one single console gives better reading and identification of the traffic scenario around the vessel. Also, if all the safety management systems are integrated the sought effect is a complete and prompt control of the functions and systems of the ship at the same time from a single console. The benefits of IBS are the optimization of time and effort for the operator and increased safety in abnormal situations i.e. a collision scenario (Garrè et al, 2010).

The functionality of the bridge design should be assessed based the ergonomics and functionality experienced by the operators. Ships are usually built without a designated crew in mind and therefore there are no obvious end-users to appoint to a user-centered design process (Österman, Berlin and Bligård, 2016). With a user-centered design (UCD) process human capabilities and limitations are taken into account in every stage of the process (Costa and Lützhoft, 2014). Bringing operators into the design process brings important knowledge that contributes to the quality and acceptance of the outcome. Also, the participatory approach and focus on ergonomics creates feelings of ownership and commitment for the operators (Österman et al, 2016). User-centered design is also called human-centered design (HCD), and the design process is shown in figure 21.

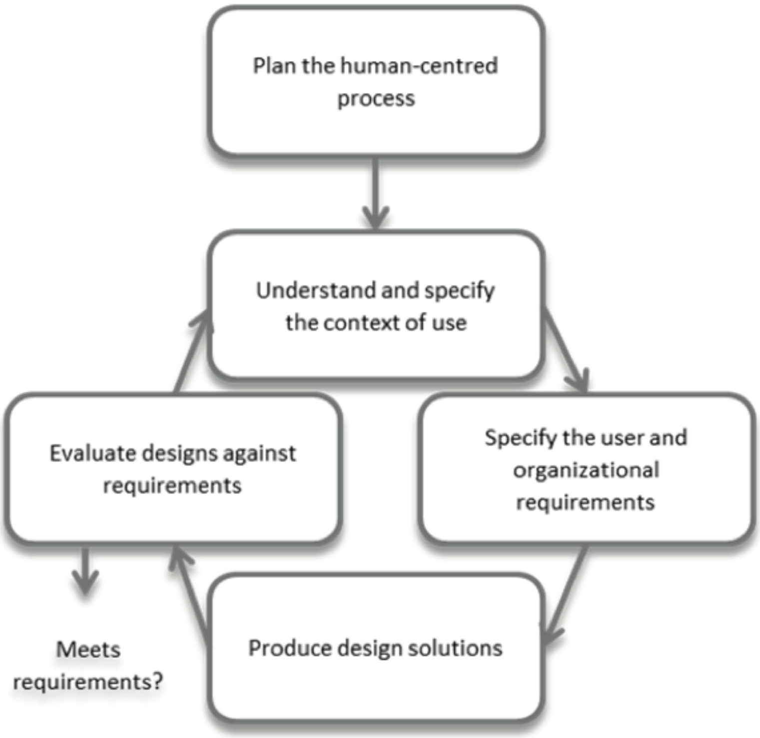


Figure 21: Human-centered design process. From Costa and Lützhoft (2014).

Österman et al (2016) did a study where representative users assessed bridge designs to elicit design feedback. Much of the feedback concerned visibility and line of sight within the ship bridge area, as visibility has an important impact on many activities and design elements concerning maneuvering of the ship.

Design dimensions were also commented on by the users (Österman et al, 2016). The design should allow for movement and performance of tasks for all body types. Therefore it is important to consider all heights and weights when designing the bridge. Height-adjustable tables and panels were suggested as solutions. Also, the possibility for two people to co-pilot and discuss information were pointed to as desired possibilities without the space getting to cramped. Simple things as where to place plates, papers and coffee mugs were also commented on (Österman et al, 2016). Such changes that may seem minor can have a great effect as it will make it easier for the operators to eat and drink proper amounts. Annoyances over the above mentioned elements may impact the performance as the operators may have temporarily decreased focus on the navigation task. Costa and Lützhoft (2014) list numerous benefits of UCD within the sectors of economy, communications, control, maintainability and workability. Costa and Lützhoft (2014) list numerous benefits of UCD within the sectors of economy, communications, control, survivability, maintainability and workability. Considering maintainability Costa and Lützhoft (2014) suggest to design hardware adaptable for change so that adding lots of new hardware is not necessary.

Based on the above the suggested indicators are listed below. All the indicators are to be answered with Yes or No and to achieve the highest total value for the factor ”bridge design” all indicators must be answered with "yes".

- All necessary equipment is present
- Changeable systems and hardware
- Space for two pilots
- Equipment for two pilots
- Possibility to adjust heights individually
- Free lookout seated and standing
- Proper space for extra "things" (cups, plates, extra charts etc.)
- Most important equipment is in within reach for each operator

6.2.11 Size of vessel

The size of a vessel is usually measured in gross tonnage (GT) (Li, Yin and Fan, 2014), but Fowler and Sørgaard (2000) use the term knots dead weight tonnes (kdwt). Rømer, Petersen and Haastrup (1995) have studied and compared marine accident frequencies reported in 20 different sources. Considering vessel size it was found that increased vessel size lead to increased collision frequencies. This is also confirmed in the study by (Li et al, 2014) who write that the safety level decreases with increasing vessel size (see figure 22). This may seem reasonable as larger vessels may have less maneuverability. Rømer et al (1995) didn’t find any firm trend from the effect of type of vessel as Fowler and Sørgaard (2000) found. The results from Fowler and Sørgaard (2000) on vessel type and size considering propulsion and steering failure can be seen in the figure 23. They emphasize that the values for ferries are based on other sources than the rest. The effect of vessel type was also found by Li et al

(2014) who found that the safety level varies among different types of ships. In increasing order the ships were rated general cargo, passenger, container and bulker, and at least tanker, which can also be seen in figure 22.

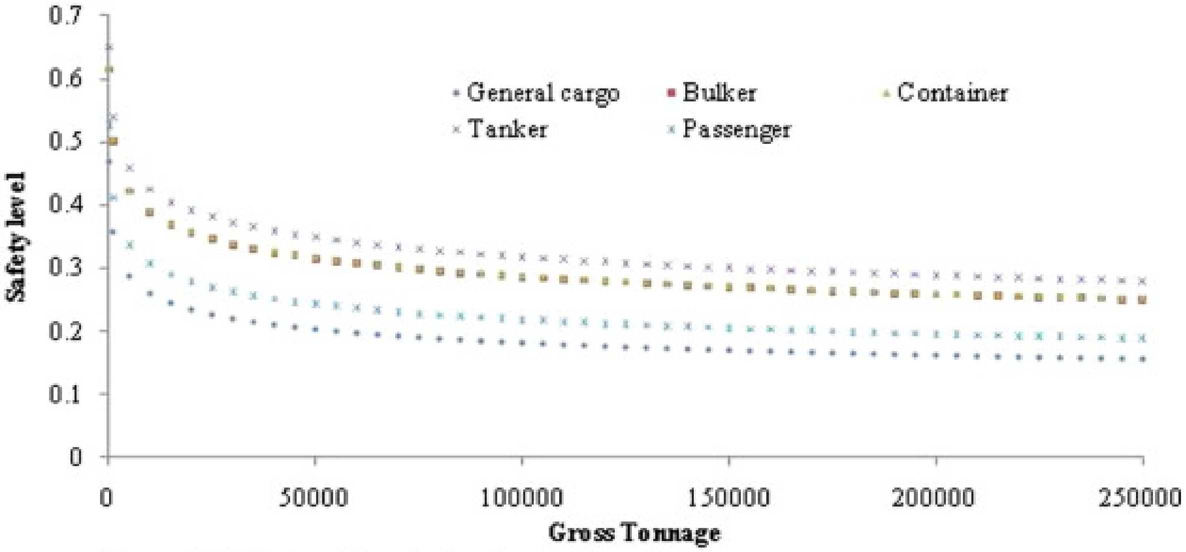


Figure 22: Effect of tonnage and vessel type on the safety level. From Li et. al (2014)

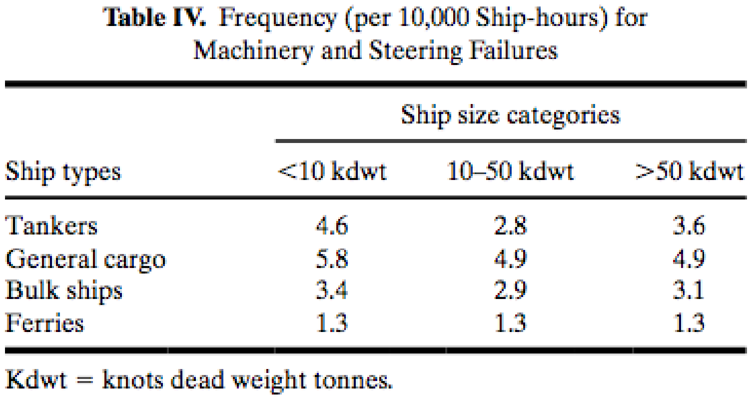


Table IV. Frequency (per 10,000 Ship-hours) for Machinery and Steering Failures

	Ship size categories		
Ship types	<10 kdwt	10–50 kdwt	>50 kdwt
Tankers	4.6	2.8	3.6
General cargo	5.8	4.9	4.9
Bulk ships	3.4	2.9	3.1
Ferries	1.3	1.3	1.3

Kdwt = knots dead weight tonnes.

Figure 23: From Fowler and Soergaard (2000)

In the analysis done by Mou et al (2010), they found that the length of she ship had a slight influence on the chosen CPA (Closest Point of Approach), which means that larger ships in general apply some larger CPA. The author therefore believes that the length of the ship may contribute to decreasing the probability of collision as they generally apply a larger safety domain.

Based on the above the proposed indicators are:

- Size of ship (GT)
- Length of ship

From the sources found it seems clear that the size of the ship (GT) increases the probability of collision more than the length of the ship decreases the probability, and therefore the indicator “Size of ship" should be weighted as more important than “Length of ship".

6.2.12 Navigation system design

This section will focus on the hardware and software design and user interface of the various navigation systems. These topics are important both for optimal navigation by the operators. As this thesis is considering the risk of collision, indicators reflecting other means than safe navigation are not included.

Systems are often designed without sufficient thought to how the end user can access necessary and/or critical information (Rothblum, 2000). Sometimes the information is difficult to interpret and sometimes it is even not displayed at all. This can obviously lead to unwanted outcomes and potentially dangerous situations. In one third of major marine causalities poor equipment design was stated as a causal factor (Rothblum, 2000). The way to solve this problem is for manufacturers to focus more on human centered design, so that they are aware of how the equipment will support the mariner in his/hers tasks and also how it will function together with other the other navigational equipment (Rothblum, 2000). The lack of human focus in design can lead to poorer operations and increased risk of failing to do various tasks (Costa and Lützhoft, 2014), so this particular element is important.

The study by Costa and Lützhoft (2014) point to many important elements on systems design. Standardized equipment with the possibility of personalized adjustments, menus and settings would according to Costa and Lützhoft (2014) support familiarity, time saving and avoidance of misunderstandings. Standardized equipment could be an important factor as many mariners work on different vessel types (Rothblum, 2000). Efficiency can be increased by the same elements, but also by intuitive systems where the repetition of parameters is reduced to the absolutely relevant and necessary (Lützhoft, 2014). By increasing this efficiency the situational awareness will also increase as the operators have more time to focus on the surroundings and other important elements.

The author believes that sound signals should alert in critical situations. What the system should consider a critical situation should be possible to modify in settings by the operators.

Also, how often the displayed information is updated is assessed to be of importance as many factors can change relatively quick.

Based on the above the suggested indicators are:

- Adjustable menus (yes/no)
- Opportunity to switch modes (yes/no)
- Repetition of parameters is reduced to a minimum (yes/no)
- Standardized equipment (yes/no)
- Frequency of information update
- Sound signals for critical situations (yes/no)

6.2.13 Manoeuevrability

The IMO has developed standards for ship maneuverability, which specify the type of standard maneuvers and associated criteria (American Bureau of Shipping (ABS), 2006). Maneuverability is measured by turning ability, course changing and yaw checking ability, initial turning ability, stopping ability and straight-line stability and course keeping ability. All of these will be described further.

Turning ability is the measure of the vessels ability to turn using hard-over rudder. To measure this one has to do a turning circle test to starboard and port and measure the tactical diameter, advance and transfer. The rudder angle while turning is not required to be more then 35 degrees, but should be the maximum angle permissible at the test speed. These measures can be seen in figure 24. To comply with the standard the tactical diameter has to be less than 5 ship lengths (L) and the advance less than 4.5L.

The initial turning ability is the change-of-heading response to a moderate helm, in terms of heading deviation per unit distance sailed or the distance sailed before a certain heading deviation is detected. To evaluate the initial turning ability a 10/10 zig-zag test should be performed to both port and starboard. ABS (2006) explains the steps in a zig-zag test: A specified rudder angle is applied to an initially straight approach. Then the rudder angle is alternately shifted to either side after a specified deviation from the vessel's original heading is reached. In a 10/10 zig-zag test the rudder angle is 10 degrees to either side after a 10 degree heading deviation from the vessel's original course.

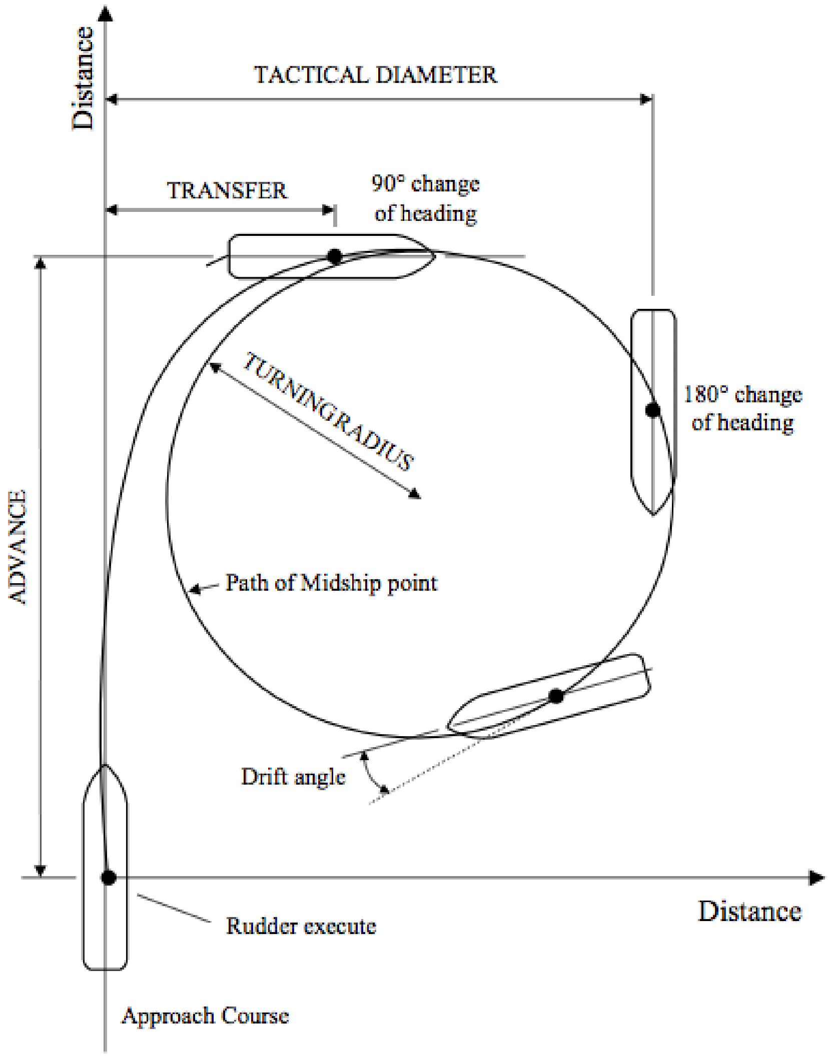


Figure 24: Measures of circle test. From ABS (2006)

The criterion is that the vessel should not travel more 2.5 ship lengths (L) before the heading has changed 10 degrees ($\ell_{10} \leq 2.5L$).

Yaw checking ability is "a measure of the response to counter-rudder applied in a certain state of turning, such as the heading overshoot reached before the yawing tendency has been cancelled by the counter-rudder in a standard zig-zag maneuver" (ABS, 2006 p. 12). To measure the yaw-checking ability both a 10/10 zig-zag test and a 20/20 zig-zag test should be performed to port and starboard. The 10/10 test is described above and in the 20/20 zig-zag test the rudder angle is 20 degrees to either side after a 20 degree heading deviation from the original course.

For the 10/10 test the first overshoot angle, $\alpha 10_1$, the criterion is

$$\alpha 10_1 \leq f_{101}(L/V)$$

where

$$f_{101}(L/V) = \begin{cases} 10.0 & \text{if } L/V \leq 10sec \\ 5 + 0.5(L/V) & \text{if } 10s < L/V < 30sec \\ 20.0 & \text{if } L/V \geq 30sec \end{cases}$$

where

L = Vessel length in meters
V = Vessel speed in m/s

For the 10/10 test the second overshoot angle, $\alpha 10_2$, the criterion is

$$\alpha 10_2 < f_{102}(L/V)$$

where

$$f_{102}(L/V) = \begin{cases} 25.0 & \text{if } L/V \leq 10s \\ 17.5 + 0.75(L/V) & \text{if } 10s < L/V < 30s \\ 40.0 & \text{if } L/V \geq 30s \end{cases}$$

Figure 25 shows these measures graphically.
For the 20/20 zig-zag test, the IMO standard only gives a criterion for the first overshoot angle, $\alpha 20_1$. The criterion is $\alpha 20_1 \leq 25$.

Stopping ability is measured by track reach and head reach during a stopping test, which is using a full astern crash stop maneuver at a certain test speed. Track reach is defined as "a distance along the vessel's track that the vessel covers from the moment that the “full astern” command is given until ahead speed changes sign" (ABS, 2006 p.15). Head reach is defined as "a distance along the direction of the course at the moment when the “full astern” command was given. The distance is measured from the moment when the “full astern” command is given until the vessel is stopped dead in the water" (ABS, 2006 p.15). The IMO standard requires that track reach generally is less then 15L, but for large, low powered vessels the limit is 20L. The value of head reach has no standard. The measures can be seen in figure 26.

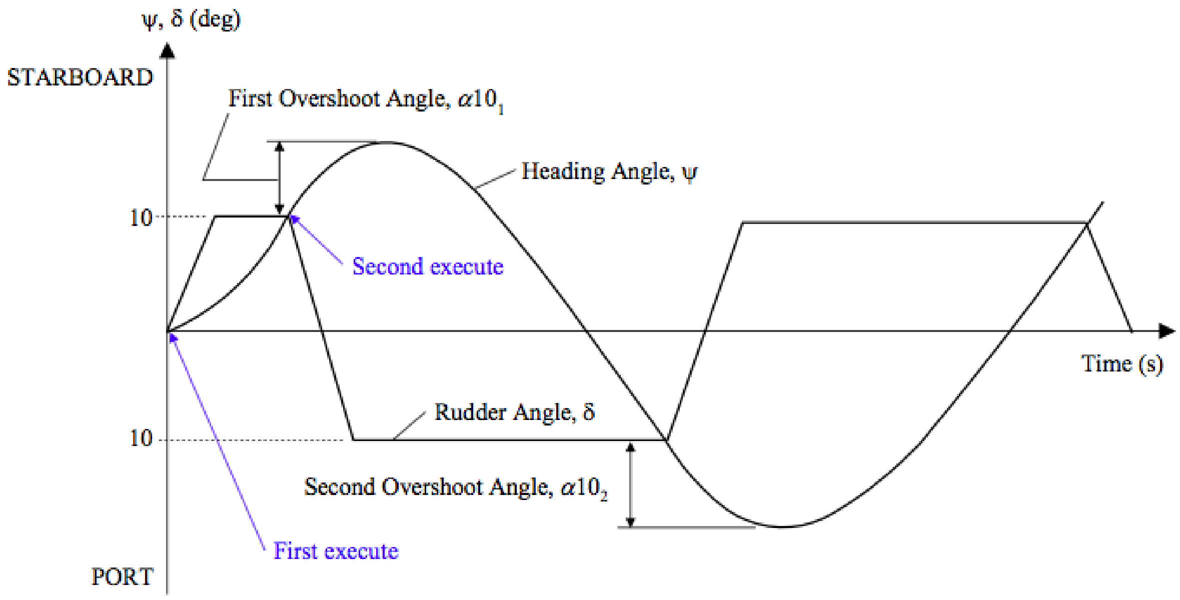


Figure 25: 10/10 zig-zag maneuver test. From ABS (2006)

Straight-line stability is if a vessel, after a small disturbance, soon settles on a new straight course without any corrective rudder. The measure for straight-line stability is the residual turning rate, which is determined by a so called pull-out test. For path-unstable vessels one also measures the width of instability loop. The pull-out test determines the dynamic stability of a vessel, and is often performed in connection with the turning circle test, zig-zag test or initial turning test. After a full turn the rudder is returned to neutral position and kept there until a steady turning rate is obtained. In the case of stability, the turning rate will decay to zero for turns to both starboard and port. In the case of instability the turning rate will reduce to some residual rate of turn, which indicates the magnitude of instability. See figure 27 and 28 for illustrations.

If there is straight-line instability there needs to be assessed if a average helmsman can control the vessel. This is done by assessing the magnitude of the instability loop. The maximum magnitude of the width is specified by the following formula:

$$\alpha_U \leq f_U(L/V)$$

$$f_U(L/V) = \begin{cases} 0 & \text{if } L/V < 9s \\ (\frac{1}{3}\frac{L}{V} - 3) & \text{if } 9 \leq L/V < 45s \\ 12 & \text{if } L/V \geq 45s \end{cases}$$

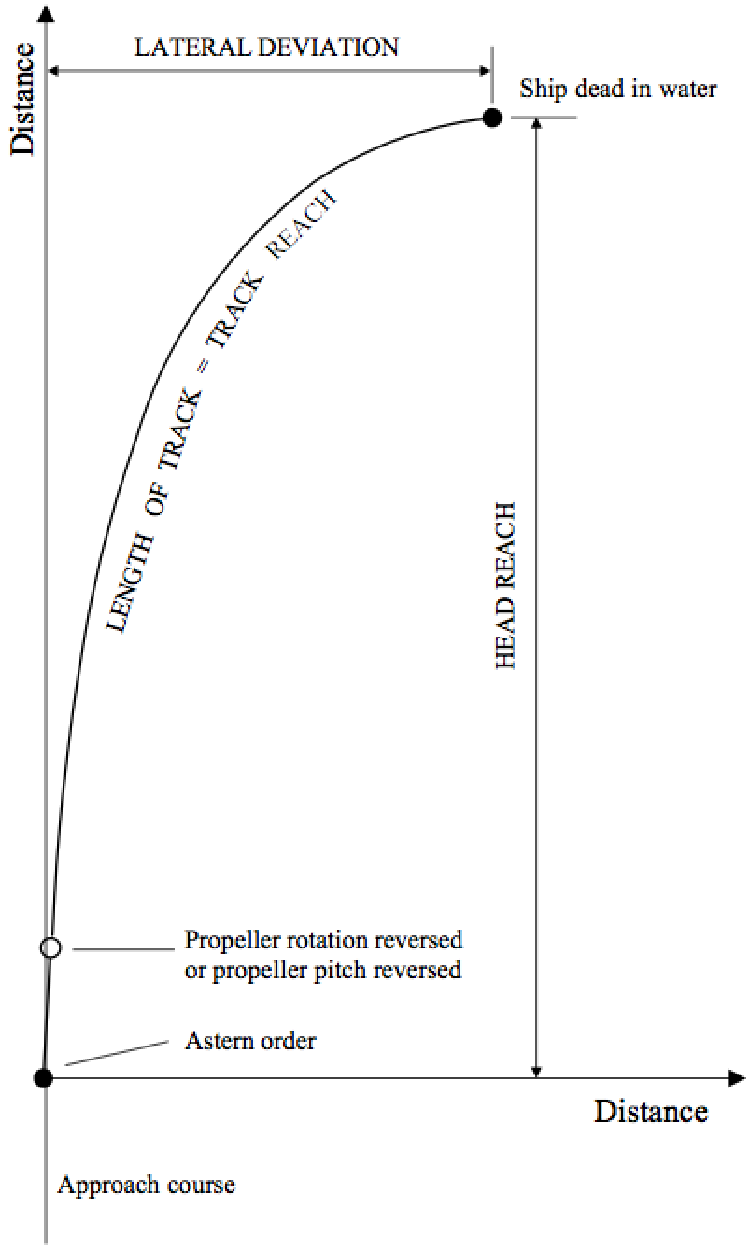


Figure 26: Measures in a stopping test. From ABS (2006)

where

L = Vessel length in meters
V = Test speed measured, in m/s

The acceptable region for where a average helmsman can control the ship can be seen in figure 29.

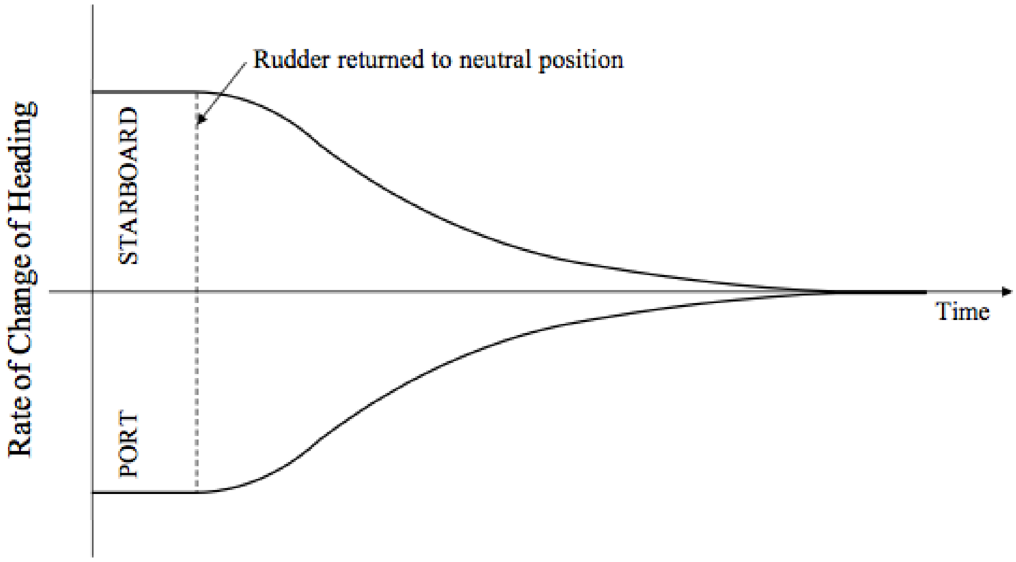


Figure 27: Straight-line stable ship. From ABS (2006)

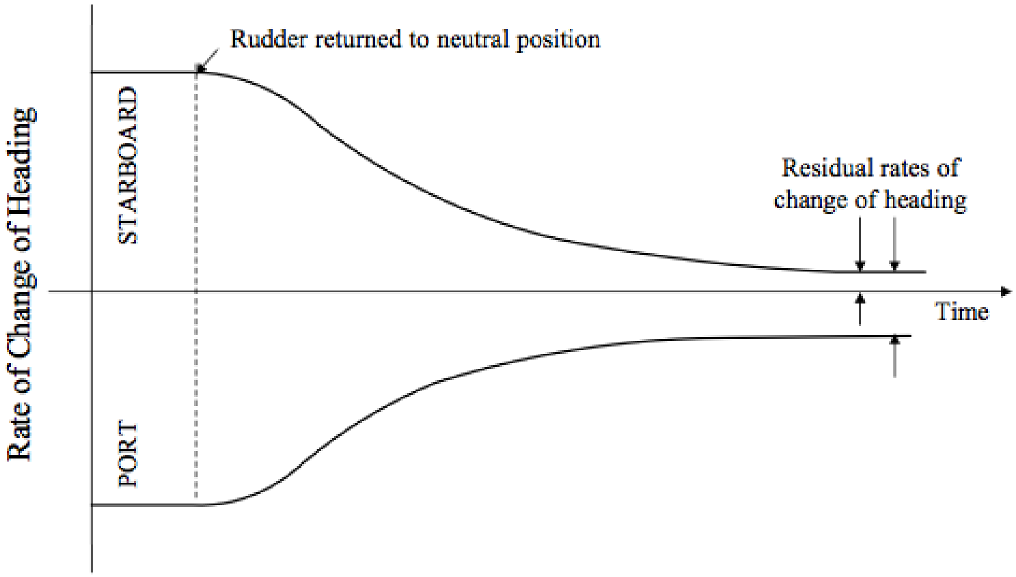


Figure 28: Straight-line unstable ship From ABS (2006)

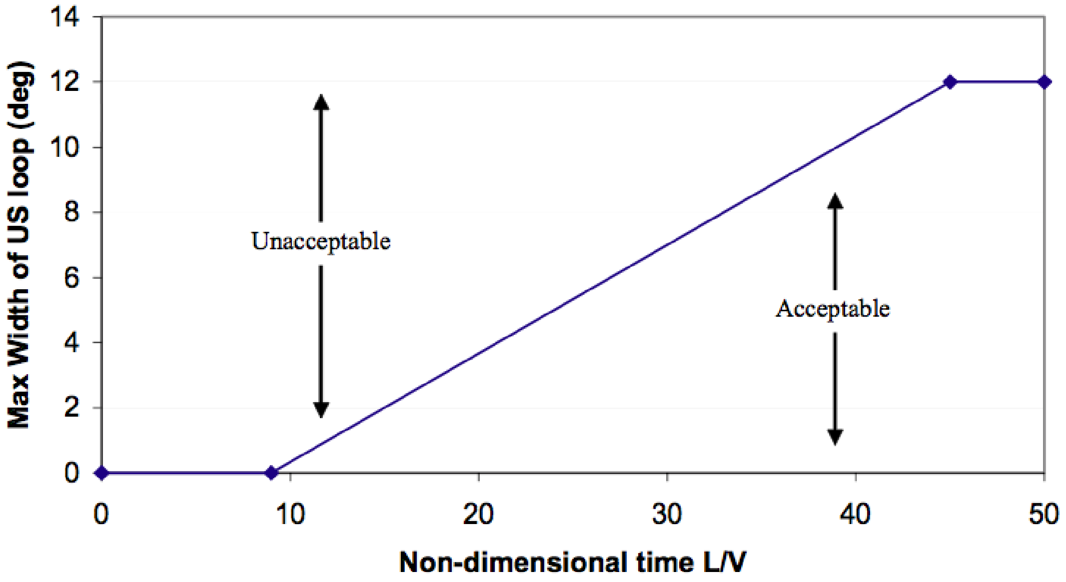


Figure 29: Maximum width of unstable loop. From ABS (2006)

Based on the above the suggested indicators are:

- Tactical diameter < 5L (yes/no)
- Advance < 4.5L (yes/no)
- Track reach < 15L (20L for large, low powered vessels) (yes/no)
- $\ell_{10} \leq 2.5L$ (yes/no)
- $\alpha 10_1 \leq f_{101}(L/V)$ (yes/no)
- $\alpha 10_2 < f_{102}(L/V)$ (yes/no)
- $\alpha 20_1 \leq 25$ (yes/no)

6.3 Environmental factors

This section presents the indicators developed for the environmental factors. These are factors that are outside the control of operators and influence their actions and handling of different situations.

6.3.1 Area of operations

The world oceans are divided into 31 navigation zones and these different zones affect the safety of the vessels (Li et. al, 2014). The division of navigational zones can be seen in figure 30. The most dangerous zones (ref figure 30) are the zones 3, 6, 8, 9, 10, 16, 17 and 18. It is important to notice that the decrease in safety level of these zones are due to different reasons. Zones 12 (Southern China Sea) and 13 (Eastern Asia) have a large number of accidents, but they are still not considered as the dangerous zones. The high number of accidents are instead due to the large number of passing vessels. Zone 6 is the Suez Canal and is here assessed as a dangerous zone. Due to the high number of passing vessels in this canal it has an important effect on the maritime safety level. Areas with high traffic densities have a particular high risk of ship-ship collisions (Kujala et al, 2009), this is further descibed in section 6.3.3.

Considering Norway, the inshore coast with extreme weather, long periods of darkness and thousands of islets, shallows and narrow straits are among the most challenging navigation areas in the world (Gould, Røed, Saus, Koefoed, Bridger and Moen, 2009).

Kujala et. al (2009) have analysed the marine traffic safety on the Gulf of Finland. Based on the DAMA-database for 10 years, they have found the proportions of navigational areas

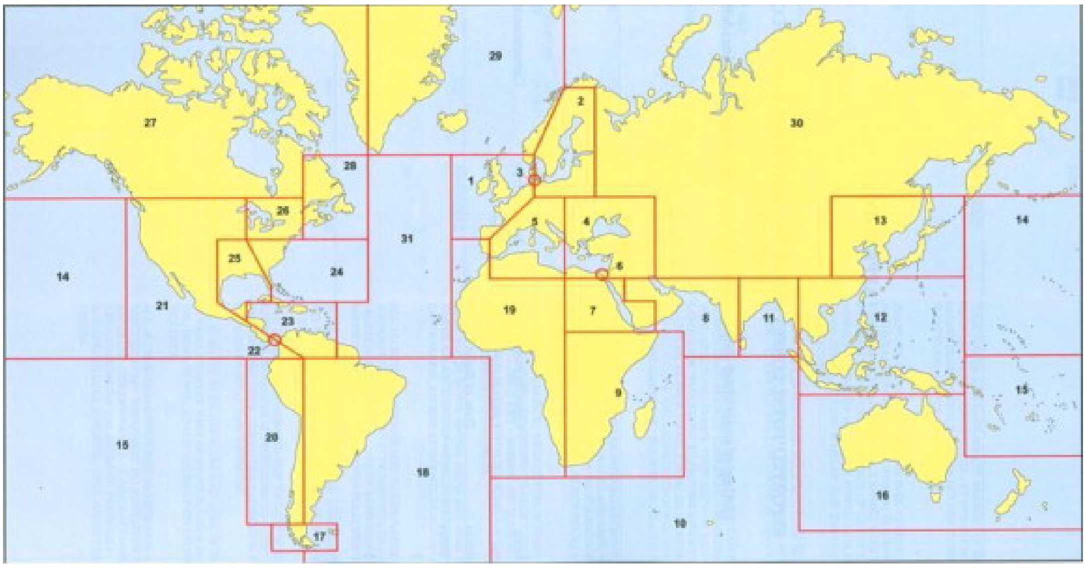


Figure 30: Geographical division of zones. From Li et. al (2014)

where various types of accidents have occurred. Their results considering ship-ship collisions can be seen in the table 2. In channels, rivers, straits, at quay and in dock there have not been found any cases of collisions. It seems likely to the author that these results are representative for other navigational zones as well. The low amount of collisions may cause some bias in the percentage, but no larger scale studies on the subject were found.

Table 2: Water area proportions of accident registrations in the Gulf of Finland based on DAMA-data during the time period under review.

Water area	Number of collisions	Percentage
Port area (1)	3	21.43
Inner coastal area (2)	1	7.14
Open coastal area (3)	4	28.57
Outer coastal area (4)	4	28.57
Open sea (5)	2	14.29
Total	14	100

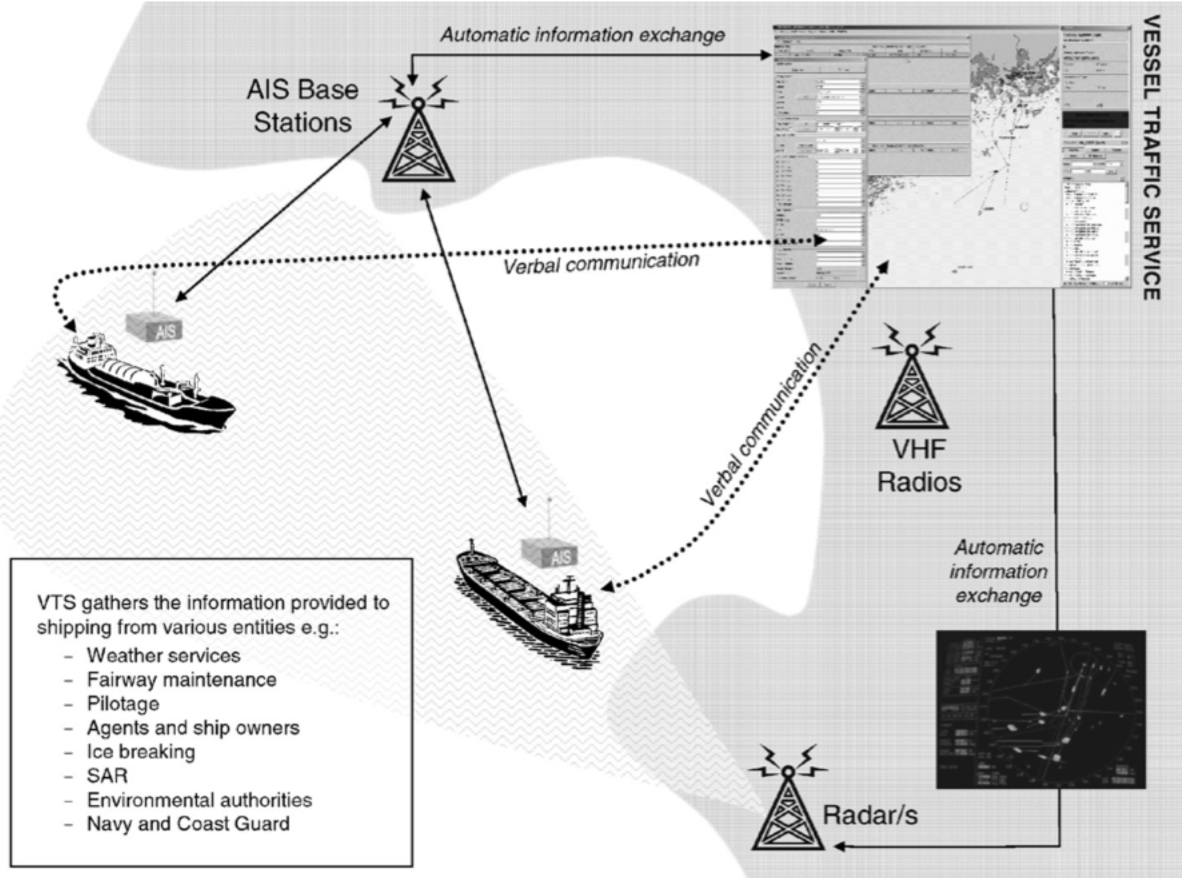
Proposed indicator:

- World navigation zone (1-31)
- Water area (Number according to the table above)

Along with these indicators needs to be complete information about the various navigation zones and water areas to assess the risk.

6.3.2 External navigation aids

Vessel Traffic Services is a socio-technical system provided by the maritime authority or port organizations (Nuutinen, Savioja and Sonninen, 2007). It is a risk assessment tool for improved traffic management, and it actually reduces risk by 20-80% depending on geography, traffic density and the resources available to the VTS (Eide et al, 2007). The service provides online monitoring of vessel traffic, information on crossing and on-coming traffic, defects in navigation aids, weather conditions, ice and navigational hazards, and guidance from the shore-based VTS centres. By these services VTS aims to prevent dangerous situations. The AIS is an important tool for the VTS together with the basic tools as online radar-based monitoring system, VHF radios and various computers (Nuutinen et al, 2007). The AIS system enables ships to automatically transmit and receive static (ship identity, destination, cargo etc.) and dynamic (speed, course, position etc.) information, with intervals of 6 min and 3 sec respectively, and it therefore enables the VTS-centres to monitor and track vessels on large stretches of coastline (Eide et al, 2007). Figure 31 shows the transmission of information between the ships, radars, AIS and VTS.



VTS gathers the information provided to shipping from various entities e.g.:
- Weather services
- Fairway maintenance
- Pilotage
- Agents and ship owners
- Ice breaking
- SAR
- Environmental authorities
- Navy and Coast Guard

Figure 31: general information exchange in the VTS operations. (SAR: Search and Rescue.) From Nuutinen et al (2007)

As seen in the figure the VTS centres communicate verbally with the vessels. For effective observation of many ships simultaneously the VTS centres filter out unwanted traffic patterns and high risk ships for follow up and further observation (Eide et al, 2007). Therefore, frequency of VTS contact may not be a good indicator as one may have less contact in good situations since the ship is not at risk and therefore not prioritized. In the case of using frequency as a measure after all a higher frequency would indicate higher risk. However, the author still believes that a frequency measure would not be a good indicator of the state of the VTS as a navigational aid. The state of the VTS should rather be measured by the technical state of the various VTS equipment (radars, AIS, radio etc.) and the competence of the operators. The operators are important factors as they guide the traffic in and out of harbours, provide information and coordinate ship movement in (emerging) conflict situations (Wiersma and Mastenbroek, 1998). According to Wiersma and Mastenbroek (1998), a high level of competence of VTS operators is ensured by extensive simulator training and on-the-job training, as well as obligatory triennial qualification examinations.

Visual navigational cues at sea exist in many varieties and include lighthouses, buoys, cairns, beacons, lanterns, painted spots on shore etc. Such a mark or cue should never be passed without being certain of its meaning. The Norwegian coast is covered by these visual cues (Livredd.no, 2017, 09.01), which reduces the risk of sailing. In open waters one could sail safely without visual navigational cues, whereas in more complicated waters with sheers and less space there is need for aids for safe navigation. Therefore, higher complexity of the water will require a higher density of markers, and this should be reflected by the indicators.

Piloting is another external aid for safe navigation through difficult areas. The concept involves an external, local expert boarding the vessel temporarily to help navigating safely through the archipelago, fairways and harbours (Nilsson et al, 2009). Piloting is required in archipelago routes and when approaching harbours, but can also be acquired by the bridge crew in other waterways (Norros, 2004). The state, or quality, of this external aid depends on the competence of the external pilot, both on maneuvering a ship and on local waters. It is thought that knowledge of local waters can be measured by the years of experience in current water and the frequency of navigation in the same waters. Competence on maneuvering is discussed in an earlier section and therefore those indicator will be used in this section as well without further explanation or discussion.

Based on the above the suggested indicators are:

- All instruments work properly (yes/no)
- Operator triennial re-examination conducted (yes/no)

- Approved training (both simulator and on-the-job) (yes/no)
- Number of visual cues per nautical mile

Competence and knowledge of external pilots:

- Number of relevant qualifications
- Frequency of re-examination
- Approved training (both simulator and on-the-job) (yes/no)
- Years of navigation in the local area
- Frequency of navigation in the local area

6.3.3 Traffic density

In assessing collision frequencies traffic models are very often used as the number of collision candidates depends inter alia on the traffic intensity (Montewka, Hinz, Kujala and Matusiak, 2010), which is given by geographic location and time (Goerlandt and Kujala, 2011). Busy waterways with high traffic density have a relatively high probability of collisions (Mou et al, 2010), which is also confirmed by the study by Goerlandt and Kujala (2011) who writes that "areas with intense traffic of a certain ship type are naturally more prone to collision with that ship type involved" (p. 102). The study by Kujala et al (2009) also concluded that the collision risk is highest in areas with high traffic intensity. Kristiansen (2004) describes traffic density as “the mean number of meeting ships within a square nautical mile of the fairway”. It can be calculated as the number of ships entering the fairway within a time period relative to an area characterized by the width of the fairway and the sailed distance of the first meeting ship. Equation 3 will be used to calculate the traffic density indicator.

$$\rho_s = \frac{N_{m1} * T}{(v_1 * T) * W} = \frac{N_{m1}}{v_1 * W} \tag{3}$$

where ρ_s = Traffic density of meeting ships ($ships/nm^2$)
N_{m1} = Arrival frequency of meeting ships ($ships/unitoftime$)
T = An arbitrary time period ($hours$)
v_1 = mean speed of meeting ships ($knots$)
W = width of fairway

Indicator:

- Traffic density

6.3.4 Weather

Historical accident data indicate that most structural accidents happen under extreme weather conditions, but the relationship is not quantified (Fowler and Sørgård, 2000). Also, statistics found worldwide report sea and weather among the main causes for accidents (Antao et al, 2009). Antao et al (2009) reviewed 857 maritime accidents from the Portuguese Maritime Authority from the last 10 years and found that sea and weather accounted for 23% of the accidents. Accident statistics from the Gulf of Finland showed that accidents had happened almost as frequently in good light as in the dark (Kujala et al, 2009).

Visibility is defined by the World Meterological Organization (WMO) as "the greatest distance at which a black object of suitable dimensions located near the ground can be seen and recognized when observed against a scattering background of fog, sky etc." (Meteotechnology.com, 2017, 02.01). Various authors disagree about the importance of visibility and darkness on maritime accident risk. Rømer et al (1995) found that collision frequency increase with decreasing visibility and brightness. Kristiansen (2004) also conclude that the collision risk increases with decreasing visibility. Kujala et al (2009) found another result in their study; they found that there were almost as many accidents in good light as in dark, and in 63.8% of the accidents the visibility had been over 10 km. However, in the later study by Goerlandt and Kujala (2011) they write that Bayesian Network studies show that visibility has a significant impact on the collision probability. In the SAFECO project 4 km was considered as good visibility, and it's assumed that poor visibility occurs 5% of the time (Fowler and Sørgård, 2000). Kristiansen (2004) state that visual lookout is important for position assessment in restricted seaways and for detecting and monitoring traffic, even though all vessels are equipped with radar and especially important is the ability to observe under dark conditions. As it takes around 25 minutes for the eyes to fully adapt to dark conditions after exposure to sunlight or artificial light, he states that many collision accidents occur just after a watch has been relieved.

Visibility codes developed by the WMO can be seen in table 3. Indicators for visibility will be according to these codes. However, the importance of visibility is not concluded on by the author as the different sources have concluded differently.

Sea states are often results of the wind conditions and therefore the wind speed is of importance. Wind conditions are often described by the Beaufort scale which is an empirical measure relating wind speed to observed conditions on wind or land. The WMO has also described the various wind conditions. The relationships can be seen in table 4. Only the observed conditions on sea are included in the table as the observed conditions on land are

Table 3: Horizontal visibility. (National centers for environmental information, 2017, 02.01)

Code	Meters	Approx. nautilcal miles
0	Less than 50 m	Less than 0.03 nm
1	50 - 200m	0.03 - 0.1 nm
2	200 - 500m	0.1 - 0.3 nm
3	500 - 1000m	0.3 - 0.5 nm
4	1 - 2 km	0.5 - 1 nm
5	2 - 4 km	1 - 2 nm
6	4 - 10 km	2 - 5 nm
7	10 - 20 km	5 - 11 nm
8	20 - 50 km	11 - 27 nm
9	50 km or more	27 nm or more

assessed to not be of importance. The Beaufort scale will be used as indicator value.

Although many maritime accidents are due to human errors, they also still occur because of unexpected and dangerous sea states, which lead to loss of control over she ship (Toffoli, Lefèvre, Bitner-Gregersen and Monbaliu, 2005). The significant wave height and mean wave period are the two most used parameters to describe the sea state, but Toffoli et. al (2005) claim that these are not sufficient to evaluate the risk of dangerous wave events. They introduce the term wave steepness, which is the ratio between wave height and length, as an important parameter as a steeper sea might yield dangerous dynamic effects. In the research done by Kujala et al (2009), 76.1% of the accident reports which informed about sea state reported that the wave height was not bigger than 0.50 m. The research by Toffoli et al (2005) also show that most accidents occur under relatively low wave heights. In 2 out of 3 accidents the significant wave height was lower than 4 metres. Considering wave steepness Toffoli et. al found that 3 out of 5 accident occurred at sea states where the wave steepness was between 0.030 and 0.450. Statistics of the wave height in the Baltic Sea is given in table 5 (Montewka et al, 2014). It can be seen that in 75% of the time the wave height is between 0 and 2 metres, which can to some degree explain why so many of the accidents occurred at low wave heights; due to the fact that there usually are relatively low waves. The wave height is definitely an important parameter of the sea state and will therefore be included as an indicator, but as the studies show that the wave height is not of great importance for accidents, and therefore also for ship collisions, it should be weighed lower than the other indicators.

Table 4: Beaufort wind scale. (Storm Prediction Centre, 2017, 03.01)

Beaufort scale	**Wind speed [knots]**	**WMO classification**	**Observed conditions on sea**
0	Less than 1	Calm	Smooth and mirror-like surface
1	1 - 3	Light air	Scaly ripples, no foam crest
2	4 - 6	Light breeze	Small wavelets, crests glassy, no breaking
3	7 -10	Gentle breeze	Large wavelets, crests begin to break, scattered whitecaps
4	11 - 16	Moderate breeze	Small waves 1 - 4 ft. becoming longer, numerous whitecaps
5	17 - 21	Fresh breeze	Moderate waves 4 - 8 ft. taking longer form, many whitecaps, some spray
6	22 - 27	Strong breeze	Larger waves 8 - 13 ft., whitecaps common, more spray
7	28 - 33	Near gale	Sea heaps up, waves 13 - 19 ft., white foam streaks off breakers
8	34 - 40	Gale	Moderately high waves (18 - 25 ft.), waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks
9	41 - 47	Strong gale	High waves (23 - 32 ft.), sea begins to roll, dense streaks of foam, spray may reduce visibility
10	48 - 55	Storm	Very high waves (29 - 41 ft.) with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility
11	56 - 63	Violent storm	Exceptionally high waves (37 - 52 ft.), foam patches cover sea
12	64 +	Hurricane	Air filled with foam, waves over 45 ft., sea completely white with driving spray

Sea state level codes developed by the WMO can be seen in table 6. Indicators for sea state will be according to these codes. The table formulates descriptions of the sea state as well as the wave height, but it is not expected that the captain or other operators should know the exact wave height, therefore the codes are usually assigned based on the textual descriptions.

Table 5: Wave statistics for the Baltic Sea including the Gulf of Finland

Wave height [m]	Probability of occurrence
0 - 1	0.345
1 - 2	0.390
2 - 3	0.185
3 - 4	0.062
4 - 5	0.015
5 - 6	0.003

Table 6: Sea state levels. (National centers for environmental information, 2017, 02.01)

Code	Description	Height in metres
0	Calm (glassy)	0
1	Calm (rippled)	0 - 0.1 m
2	Smooth (Wavelets)	0.1 - 0.5 m
3	Slight	0.5 - 1.25 m
4	Moderate	1.25 - 2.5 m
5	Rough	2.5 - 4 m
6	Very rough	4 - 6 m
7	High	6 - 9 m
8	Very high	9 - 14 m
9	Phenomenal	More than 14 m

Toffoli et al (2005) suppose that also crossing seas may be dangerous as the entire hull will be exposed to the wave impact when the wave trains come form different directions. Crossing seas does affect the sea state and since this chapter is for indicators describing sea state it will be included in the indicators but it should be kept in mind that this particular indicator does not impact the collision risk but rather ship structure failures.

Based on the above the suggested indicators are:

- Sea state code
- Visibility level code
- Wave height

- Wave steepness
- Crossing seas (yes/no)
- Wind speed

6.3.5 Other vessel

Clear actions minimize uncertainty for others and lets them anticipate possible worst-case scenarios (Hockey, Healey, Crawshaw, Wastell and Sauer, 2003). Their study shows that uncertainty about the actions of others increases the possibility for collisions (or near collisions) due to the fact that the time for information gathering and decision making is decreased. Unexpected turns, caused by technical failure or human error, by meeting vessel also increase collision risk as such deviations may transform a Type B, C or D encounter into a Type A encounter, which is collision course (ref chapter 3.2, see figure 32) (Goerlandt et. al, 2015).

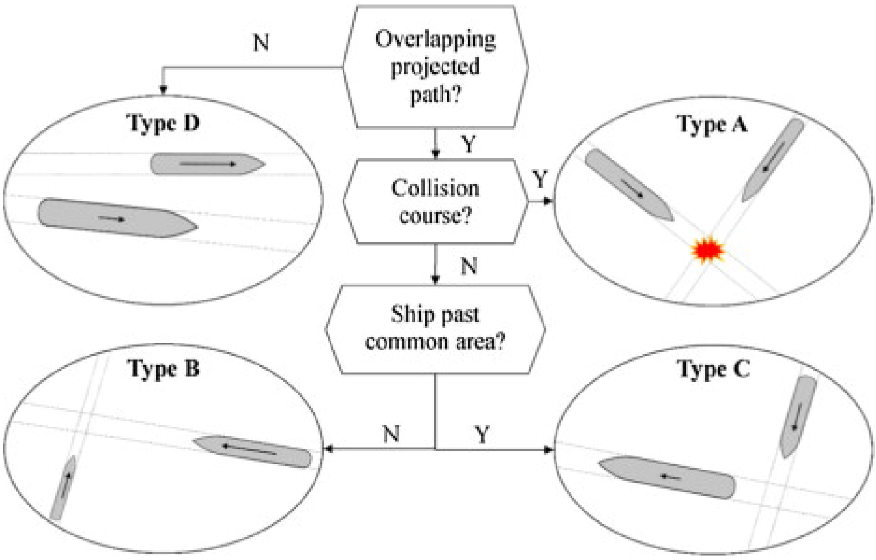


Figure 32: Model for classifying ship encounters in relation to collision course. From Goerlandt et al, 2015

To decrease the uncertainty about actions, vessels who encounter each other within half a mile are required to use sound signals explaining their actions. The initiating vessel initiates a maneuver to which the responding vessel must agree or disagree (boaterexam.com, 2017, 02.02). The various sound signals can be seen in table 7.

In addition to the mentioned decreased time for decision making, Goerlandt et. al (2015) also point to the inertia of own ship's turning as a cause for increased collision risk when the other ship turns unexpectedly. Rule violations pose an additional uncertainty because the

Table 7: Sound signals. From boaterexam.com, 2017, 02.02

Sound signal	**Description**
1 short blast (1 second)	I want to pass you on my **port** side
2 short blasts	I want to pass you on my **starboard** side
3 shorts blasts	Engine is in reverse
5 short blasts	Danger, or do not understand approaching boat's intentions
1 prolonged blast (4-6 seconds)	Warning: • Entering or exiting a blind turn • Nearing an obstructed area • Leaving a dock or a berth
1 prolonged blast every 2 minutes	Power-driven vessel operating in low or restricted visibility
1 prolonged blast + 2 short blasts every 2 min	Sailing vessel operating in low or restricted visibility

meeting vessel behaves in unexpected ways, which in turn will increase the possibility of collision, but also can result in neglect of monitoring of auxiliary functions such as engine monitoring (Hockey et al, 2003).

When considering Closest Point of Approach (CPA) the analysis by Mou et al (2010) show that the CPA value is not strongly determined by own ship, which means that it is also strongly determined by other ship. To the author this seems reasonable, but how to reflect it as one or more indicators is not concluded on. Notice that the indicators listed below applies to the meeting vessel.

Based on the above the suggested indicators are:

- Sound signals used correctly
- Large changes of course (a minimum of 30 degrees according to Hocket et al, 2003) (yes/no)
- Maneuvers in sufficient time
- Violates rules (yes/no)
- Has navigation lights (yes/no)

7 Discussion

Some of the factors had more obvious indicators than others, due do the different levels of complexity of the various factors. The author experienced the human factors to be the hardest ones to develop indicators for as the human mind and capabilities are affected by many more factors than initially can be thought. For even more specified indicators one or more experts on human behaviour should have participated in this study. Also, even though the author's knowledge about ships and various systems on board have increased during the writing of this thesis, it is still limited, which can have affected the results of the indicators for the technical factors. To increase the knowledge about the technical systems, one or more experts on this field could be involved as well. This inclusion of experts would enhance the quality of the study, but was outside the scope of this thesis.

In section 5.4.1 about establishment of technical RIFs and indicators it is stated that the last step of the establishment process should involve testing of the developed set of indicators. This is due to the difficulty of selecting appropriate indicators without testing their suitability due to the complexity of the problems. The testing is outside the scope of this thesis and therefore some of the selected indicators may be found to not be appropriate. On chapter 5 it also written about the quantification of technical and organizational indicators. This theory is based on the literature review and in the section about the technical indicators it is not said anything about weighting the indicators as it is in the section about quantifying the organizational indicators. The author believes that the weighting of indicators is important, whether it is for human, technical or organizational factors. This can be exemplified by section 6.2.7 about communication, where the indicator "Percentage of crew speaking working language fluently" should be weighted as more important than the indicator "BRM implemented". This is due to the disagreement between researchers about the importance of BRM, and also because if none of the drew speak the working language fluently it doesn't matter if BRM is implemented or not as the level of communication still would be unacceptable.

The developed indicators are limited to the outcome from the literature study, which means that there may be deficiencies, but the author has tried to minimize these as much as possible by doing extensive research. The analysis may also be subject to subjective interpretations and understandings, which may have lead to both positive and negative outcomes. The analysis could therefore benefit from collaborating with others, both to eliminate the negative outcomes of the subjectivity and to increase the positives.

8 Summary and Conclusions

This thesis started with an introduction to the theme by introducing a definition and statistics of ship collision. The used definition is that a collision is an impact between two moving objects, where the term "moving" is essential (Kristiansen, 2004). Statistics show that 13-28% of all vessel accidents are collisions, where the variations are due to the years of data, destinations and the use of different data registers (Kristiansen, 2004; Kujala et al., 2009)

The causes for collisions are usually in the interface between human, technical and the organization (Sjøfartsdirektoratet, 2011). The number of causes for collisions range from 7 to 53 per accident (Rothblum, 2000) and the various sources show that human factors account for 52.6 - 90% of the accidents (Kujala et al, 2009; Trucco et al, 2008; Rausand, 2011). The reason for the high number is that humans in some way or another are partakers; they design the machines, decide on maintenance and material requirements, decide on safety culture within the organization etc., therefore it is important to notice that there are other human factors than the primary operator. Other human causes include, among many others, bad communications, lack of sleep and lack of lookout. In accident investigations organizational factors are often overlooked, but they are important to investigate as they influence how individuals and groups behave (Rausand, 2011). The organizational factors include, among others; safety culture, training, working conditions and management. Technical failures of equipment were only a part of 4,76% of collisions in the Gulf of Finland (kujala et al, 2009). When including all types of maritime accidents the sources claim that they account for 11,9-16% (Kujala et al, 2009; Trucco et al, 2008). In the later years technical equipment have gone through big improvements, which has decreased the probability of accidents due to technical errors. However, this has also increased the relative level of human errors (Hetherington et al, 2006).

The next section introduced Bayesian Belief Networks (BBN) and the challenges in their quantification. Such a network is a method for graphically modelling and illustrating the relationship between various factors/variables and a given critical outcome (Rausand, 2011). The method is useful in the context of ship collisions as it is well suited for modelling such complex systems (Langseth, 2008), and it also allows for quantitative analyses (Rausand and Høyland, 2004).

Quantification of the BBN is done by collecting data or/and by use of expert judgements. Both large and small amounts of data pose obstacles (Antao et al, 2009). With large amounts of data one can face problems of managing and structuring them, and one also has to consider their feasibility. Despite this, if one can manage the large amount of data it can reduce the uncertainties one will face when using expert judgement or poor databases. Small amounts of data will create difficulties of calculating more or less accurate frequencies, either due to the nature of the variable or due to sporadic frequencies. As maritime accidents are relatively rare the data is usually scarce (Hänninen, 2014).

Under-reporting of maritime accidents is another issue, which will affect the accuracy of the quantification when using existing data (Hänninen, 2014; Psarros, 2010). On average each flag state only report 50% of the accidents (Hassel, Asbjørnslett and Hole, 2011). Where data is scarce and/or under reporting is a big issue, the use of expert judgement is a good tool (Akhtar and Utne, 2014; Rausand, 2011). However, the human mind has problems with processing small probabilities (Akhtar and Utne, 2014) and the expert's judgement will always to some degree be subjective and reflect his/hers knowledge on the subject (Hänninen, 2014). To account for this, BBN software can include expert uncertainty.

The third part addresses risk influencing factors (RIFs) and risk indicators. A RIF is defined as "an aspect (event/condition) of a system or an activity that affects the risk level of this system/activity" (Øien, 2001, p. 130). In a BBN the various nodes are the risk influencing factors (Rausand, 2011). The risk indicators are the measurable representations of the RIF as the RIF is usually not measurable in itself (Øien, 2011). Each RIF may be represented by one or more indicators (Øien et al, 2011). An indicator can be classified as either risk or safety indicator, process or personal indicator and lead or lag indicator (Øien et al, 2011; Hopkins, 2009).

In the final part of the thesis numerous indicators are developed for the various factors in the given BBN collision model. Developing these indicators was easier for some of the factors than others, for example weather and traffic density as the measurements of these are quite intuitive.

The most influential variable is shown by Hänninen and Kujala (2012) to be whether the vessels take action knowing they're on collision course. If both vessels take action the probability of collision is 0.00001 and if neither of them take action it increases to almost 1.0. Therefore the indicator "vessel takes action in time" is essential.

In 32% of vessel collision accidents, navigational failures are a cause. These failures are mostly due to own ship, and very few due to misunderstandings of the movements of meeting vessels (Kujala et al, 2009). The navigational failures are mostly due to lack of, or incorrect, information, and favoring of equipment (Rothblum, 2000). It is therefore important that mariners check available information from different sources before making decisions or changes. Considering navigation systems, implemetation of ECDIS is thought by the NMA to reduce navigation related causalities by 75% (Jie and Xian-Zhong, 2008). Although the movements of meeting ships are rarely misunderstood, the meeting ships play a significant role considering the closest point of approach (CPA) (Mou et al, 2010). Considering the design of the various navigation systems it is important that the manufacturers have a user-centered approach to the design process, so that they know how the new equipment will support the operator and how it will function with the existing equipment. This is important as poor equipment design was stated as a causal factor in one third of marine causalities (Rothblum, 2000).

Operators' lack of general technical knowledge was responsible for 35% of ship causalities, the main contributor being lack of knowledge on proper use of technology (Rothblum, 2000). This could be solved by better training and standardized equipment. This also shows that the implementation of new technology for reducing accidents isn't always the best solution as the operators often don't have the knowledge to use it. Also, there are disagreements between researchers whether new technology can lead to a higher workload. This is discussed about the use of conventional versus advanced bridges (Nilsson et al, 2009; Sauer et al, 2002).

Communication is another factor that is important for avoiding collision accidents. According to CTSB 42% of all incidents involved misunderstandings og lack of communication between the pilot and master or OOW (Hetherington et al, 2006). The problem when quantifying communication is that peoples' perceptions of their own communication skills doesn't comply with others' perceptions regarding the same communication. One of the problems may be language issues as people from many different nationalities work together (Hetherington et al, 2006).

Considering size and type of vessel it is shown that collision risk increases with size (Petersen and Haastrup, 2009; Li et al, 2014). Li et al (2014) also found that safety level varies with vessel type. In increasing order the types were rated general cargo, passenger, container and bulker, and at last tanker ships.

Considering that the human factors represent such a big percentage of the collision causes it is concluded in this thesis that to reduce the collision risk further there should be more focus on risk reducing measures for the human factors rather than for the technical. This is also confirmed by Rothblum (2000) who states that by preventing human errors, or increasing the probability of discovering the human errors, the marine safety would be enhanced and fewer accidents would occur.

9 Recommendations for further work

Further research should be done on the various factors of the BBN to possibly develop more indicators for an even more accurate quantitative representation of the risk picture. There should also be developed indicators for the organizational factors, which are not developed in this thesis. Cooperating with experts will benefit the development of the organizational indicators, as relevant literature on the field was difficult to obtain. The organizational factors are important as they often are the basis for how individuals and groups work, which is why indicators of these factors should be developed.

Testing of the indicators should also be done to validate the indicators before selecting a final appropriate set of risk indicators. This testing can conveniently be done in cooperation with a shipping company as this will show how each indicator works in practice and not just theoretically. The impact of each of the indicators should also be weighted, this applies to all the indicators, both human, technical, organizational and environmental. In addition to weighting the indicators the various RIFs should also be weighted. The weighting of RIFs and indicators can be done by using accident and incident data and with the use of expert judgement. After the RIFs are weighted the quantitative representation of the BBN also needs to be fully established. This is done by establishing conditional probability tables for each of the nodes (the RIFs) in the BBN based on their parent nodes.

To evaluate the influence each of the RIFs have on the collision risk a sensitivity analysis should also be conducted. The sensitivity analysis can be done by the BBN software. Based on the results from this analysis further measurements to prevent collision accidents can be developed. At last routines for the use of risk indicators should be established, and risk indicators as a tool for risk control needs to be implemented in the maritime industry. It is first then that the development of the risk indicators has an effect.

10 Appendix A - The BBN collision model

Figure 33: BBN collision model developed by the NSRM project

References

[1] M. J. Akhtar and I. B.. Utne. “Human fatigue’s effect on the risk of maritime groundings – A Bayesian Network modeling approach”. In: Safety Science 62, 427–440, 2014.

[2] Pedro Antao et al. *Analysis of maritime accident data with BBN models*. Safety, reliability, risk analysis: theory, methods and applications. London, UK: Taylor & Francis Group., 2009.

[3] *boaterexam.com, 2017, 02.02.* URL: `http://www.boaterexam.com/navigationrules/sounding-off.aspx`.

[4] Alfred Brandowski. “Estimation of the probability of propulsion loss by a seagoing ship based on expert opinions”. In: Polish maritime research 16(1), 73-77, 2009.

[5] Eugene Charniak. “Bayesian networks without tears”. In: AI Magazine Volume 12 Number 4, 1991.

[6] N. A. Costa and M. Lûtzhöft. “The values of ergonomics in ship design and operation”. In: Human Factors in Ship Design & Operation, 26-27 February 2014, London, UK, 2014.

[7] DNV. “Effect of ENC coverage on ECDIS risk reduction”. In: Report No. 2007-0304, 2007.

[8] Magnus S. Eide et al. “Prevention of oil spill from shipping by modelling of dynamic risk”. In: Marine Pollution Bulletin 54(10), 1619-1633, 2007.

[9] Jane Ford, Robert Henderson and David O’hare. “The effects of Crew Resource Management (CRM) training on flight attendants’ safety attitudes”. In: Journal of Safety Research 48, 49-57, 2014.

[10] L Garrè et al. “An application of Bayesian networks for the optimization of a bridge layout”. In: Journal of Engineering for the Maritime Environment 224(1), 73-85, 2010.

[11] Floris Goerlandt and Pentti Kujala. “Traffic simulation based ship collision probability modeling”. In: Reliability Engineering and System Safety 96, 91-107, 2011.

[12] Floris Goerlandt et al. “A risk-informed ship collision alert system: Framework and application”. In: Safety science 77, 182-204, 2015.

[13] Floris Goerlandt et al. “A risk-informed ship collision alert system: Framework and application”. In: Safety science 77, 182-204, 2015.

[14] Rachael P.E. Gordon. “The contribution of human factors to accidents in the offshore oil industry”. In: Reliability engineering and system safety 61, 95-108, 1998.

[15] Kristian S. Gould et al. “Effects of navigation method on workload and performance in simulated high-speed ship navigation”. In: Applied Ergonomics 41(1), 103-114, 2009.

[16] Bjørn Egil ; Hole Lars Petter Hassel Martin ; Asbjørnslett. “Underreporting of maritime accidents to vessel accident databases”. In: Accident analysis and prevention 43, 2053-2063, 2011.

[17] Thomas R. Herzog et al. “Incompatibility and mental fatigue”. In: Environment and Behavior 43(6), 827-847, 2011.

[18] Catherine Hetherington, Rhona Flin and Kathryn Mearns. “Safety in shipping: The human element”. In: Journal of Safety Research 37, 401–411, 2006.

[19] G. Robert J. Hockey et al. “Cognitive Demands of Collision Avoidance in Simulated Ship Control”. In: Human factors 45(2), 252-265, 2003.

[20] Andrew Hopkins. “Reply to comments”. In: Safety science 47(4), 508-510, 2009b.

[21] Andrew Hopkins. “Thinking about process safety indicators”. In: Safety science 47, 460-465, 2009a.

[22] Maria Hänninen. “Bayesian networks for maritime traffic accident prevention: Benefits and challenges”. In: Accident Analysis and Prevention 73, 305–312, 2014.

[23] Maria Hänninen and Pentti Kujala. “Influences of variables on ship collision probability in a Bayesian belief network model”. In: Reliability Engineering and System Safety 102, 27-40, 2012.

[24] *Integrated Bridge System*. URL: `www.imo.org/en/OurWork/Safety/SafetyTopics/Pages/IntegratedBridgeSystems.aspx`.

[25] *International Maritime Organization, 2017, 12.01)*. URL: `www.imo.org/en/OurWork/Safety/SafetyTopics/Pages/IntegratedBridgeSystems.aspx`.

[26] U. Kjellen. “The safety measurement problem revisited”. In: Safety science 47(4), 486-489, 2009.

[27] Uffe B. Kjærulff and Anders L. Madsen. *Bayesian networks and influence diagrams: A guide to Construction and Analysis*. Springer New York, 2013.

[28] Svein Kristiansen. *Maritime transportation: Safety management and risk analysis*. Butterworth-Heinemann, 2004.

[29] P. Kujala et al. “Analysis of marine traffic safety in the Gulf on Finland”. In: Reliability engineering and system safety 94, 1349-1357, 2009.

[30] Helge Langseth. “Bayesian networks in reliability: The good, the bad and the ugly”. In: Safety Science 46, 221–229, 2008.

[31] Kevin X. Li, Jingbo Yin and Lixian Fan. “Ship safety index”. In: Transportation Research Part A: Policy and Practice 66, 75-88, 2014.

[32] *Livredd.no, 2017, 09.01.* URL: `http://www.livredd.no/files_doc/livredd_kap6.pdf`.

[33] Margareta Lützhöft et al. “Fatigue at sea in Swedish shipping—a field study”. In: American Journal of Industrial Medicine 53(7), 733-740, 2010.

[34] *Maritime Safety Queensland, 2017, 08.02.* URL: `http://www.msq.qld.gov.au/Safety/Navigation-lights`.

[35] Graham Marsden and John Leach. “Effects of alcohol and caffeine on maritime navigational skills”. In: Ergonomics 43(1), 17-26, 2000.

[36] *Meteo-technology.com, 2017, 02.01.* URL: `http://www.meteo-technology.com/visibility.htm`.

[37] Dani Mohovic, Robert Mohovic and Igor Rudan. “Simulation of ship movement after steering system failure to determine the worst case scenario of grounding”. In: Traffic and transportation 25(5), 457-466, 2013.

[38] Jakub Montewka et al. “Probability modelling of vessel collisions”. In: Reliability Engineering and System Safety 95(5), 573-589, 2010.

[39] Jun Min Mou, Cees van der Tak and Han Ligteringen. “Study on collision avoidance in busy waterways by using AIS data”. In: Ocean Engineering 37, 483-490, 2010.

[40] *National centers for environmental information, 2017, 02.01.* URL: `https://www.nodc.noaa.gov/woce/woce_v3/wocedata_1/woce-uot/document/wmocode.htm`.

[41] Robert Nilsson. “‘What are your intentions? –On Understanding Ship Bridge Decision Making”. In: Department of Shipping and Marine Technology, CHALMERS UNIVERSITY OF TECHNOL- OGY, Goteborg, Sweden, 2007.

[42] Robert Nilsson, Tommy Gârling and Margareta Lützhöft. “An experimental simulation study of advanced decision support system for ship navigation”. In: Transportation Research Part F 12, 188–197, 2009.

[43] Leena Norros. “Acting under uncertainty”. In: VTT PUBLICATIONS 546, 2004.

[44] Maaria Nuutinen, Paula Savioja and Sanna Sonninen. “Challenges of developing the complex socio-technical system: Realising the present, acknowledging the past, and envisaging the future of vessel traffic services”. In: Human F513-524actors in Ship Design & Operation, 26-27 February 2014, London, UK, 2014.

[45] Paul O’Connor. “Assessing the Effectiveness of Bridge Resource Management Training”. In: The International Journal of Aviation Psychology 21(4), 357-374, 2011.

[46] George Psarros, Rolf Skjong and Magnus Strandmyr Eide. “Under-reporting of maritime accidents”. In: Accident analysis and prevention 42, 619-625, 2010.

[47] Marvin Rausand. *Risk Assessment: Theory, Methods, and Applications*. John Wiley & Sons, 2011.

[48] Marvin Rausand and Arnljot Høyland. *System Reliability Theory: Models, Statistical Methods, and Applications*. John Wiley & Sons, 2004.

[49] A. M. Rothblum. “Fra ragnarok til Rocknes - storulykker og ulykkesgranskning”. In: National Safety Council Congress and Expo, Orlando, FL., 2000.

[50] Anita M. Rothblum. “Human error and marine safety”. In: In National Safety Council Congress and Expo, Orlando, FL., 2000.

[51] Sverre Røed-Larsen. *Fra ragnarok til Rocknes - storulykker og ulykkesgranskning*. Tapir akademiske forlag, 2004.

[52] Hans Rømer, H. J. Styhr Petersen and Palle Haastrup. “Marine Accident Frequencies – Review and Recent Empirical Results”. In: The journal of navigation 48(3), 410-424, 1995.

[53] Paul M. Salmon et al. “What really is going on? Review of situation awareness models for individuals and teams”. In: Theoretical Issues in Ergonomics Science 9(4), 297-323, 2008.

[54] Juergen Sauer et al. “Effects of display design on performance in a simulated ship navigation environment”. In: Ergonomics 45(5), 329–347, 2002.

[55] *SeaTalk Nautical Dictionary*. URL: `http://www.seatalk.info/cgi-bin/nautical-marine-sailing-dictionary/db.cgi?db=db&uid=default&FirstLetter=c&sb=Term&view_records=View&nh=8`.

[56] American Bureau of Shipping. “Guide for vessel maneuverability”. In: 2006.

[57] *Sjøfartsdirektoratet, 2011. Ulykkesutvikling 2000-2010*. URL: `https://www.sjofartsdir.no/globalassets/sjofartsdirektoratet/fartoy-og-sjofolk---dokumenter/ulykker-og-sikkerhet/rapporter/ulykkesstatistikk/ulykkesutvikling-2000_2010.pdf`.

[58] *Sjøfartsdirektoratet (2016, 10.10)*. URL: https://www.sjofartsdir.no/sjofart/registrere-naringsfartoy-i-nisnorbygg/.

[59] *Sjøfartsdirektoratet (2016, 26.10)*. URL: https://www.sjofartsdir.no/contentassets/ff266cac3b78444781587c893bbb5b03/melding-og-rapportering-av-ulykker.pdf.

[60] *Sjøfartsdirektoratet, 2016, 28.11*. URL: https://www.sjofartsdir.no/sjofart/regelverk/#conventions.

[61] Mearns K. Sneddon A. and R.. Flin. "Stress, fatigue, situation awareness and safety in offshore drilling crews." In: Safety Science 56, 80 – 88, 2013.

[62] *Store norske leksikon, 2016.02.02*. URL: https://snl.no/nattblindhet.

[63] *Storm Prediction Centre, 2017, 03.01*. URL: http://www.spc.noaa.gov/faq/tornado/beaufort.html.

[64] A. Toffoli et al. "Towards the identification of warning criteria: Analysis of a ship accident database". In: Applied Ocean Research 27(6), 281-291, 2005.

[65] P. Trucco et al. "A Bayesian Belief Network modelling of organisational factors in risk analysis: A case study in maritime transportation". In: Reliability Engineering and System Safety 93, 823–834, 2008.

[66] Jie Wang and Hu Xian-Zhong. "Legg til i lagrede treff The error chain in using Electronic Chart Display and Information Systems". In: IEEE International Conference on Systems, Man and Cybernetics, 1895-1899, 2008.

[67] E. Wiersma and N. Mastenbroek. "Measurement of vessel traffic service operator performance". In: AI & SOCIETY 12(1), 78-86, 1998.

[68] *WMO - visibility*. URL: www.meteo-technology.com/visibility.htm.

[69] Thomas Wolbers and Mary Hegarty. "What determines our navigational abilities?" In: Trends in Cognitive Sciences 14(3), 138-146, 2010.

[70] Xingjian Zhang et al. "A Study on the Effects of Fatigue Driving and Drunk Driving on Drivers' Physical Characteristics". In: Traffic injury prevention 15(8), 801-808, 2013.

[71] Cecilia Österman, Cecilia Berlin and Lars-Ola Bligård. "Involving users in a ship bridge re-design process using scenarios and mock-up models". In: International Journal of Industrial Ergonomics 53, 236-244, 2016.

[72] K. Øien. "A framework for the establishment of organizational risk indicators". In: Reliability Engineering & System Safety, 74(2), 147 – 167., 2001b.

[73] K. Øien. “Risk indicators as a tool for risk control”. In: Reliability Engineering and System Safety 74(2), 129-145, 2001a.

[74] K. Øien, I. Utne and I. Herrera. “Building safety indicators: Part 1 - theoretical foundation.” In: Safety Science, 49(2), 148–161, 2011.