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Modelling of Technical, Human and Organisational Factors of Ship Grounding Accidents with the use of Bayesian Belief Networks

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MASTER THESIS

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Preface

This Master Thesis is written in culmination of the 2-years International Master Programme in Reliability, Availability, Maintainability and Safety (MSc RAMS) within the Production and Quality Engineering Department (IPK) at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. This work has been performed during the spring semester 2016 in continuation of the Specialisation Project written during autumn semester 2015.

This study is prepared in collaboration with the ongoing research project *National Ship Risk Model*, which intends to develop a risk model for traffic in Norwegian waters. Partners of this joined project are the NTNU Social Research's department Studio Apertura, NTNU Department of Marine Technology, Safetec, the Norwegian Maritime Authority (Sjøfartsdirektoratet) and the Norwegian Costal Administration (Kystverket).

The intended reader for this report should have a background in areas related to risk analysis. In addition, practical experience within the maritime shipping industry is an advantage but not a prerequisite.

Trondheim, 2016-05-31

Elisa Baumgärtner

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Last but not the least, I personally would like to thank my family and friends for supporting and motivating me throughout the years of studying at NTNU and living abroad in Norway.

E.D.B.

Summary and Conclusion

In recent years, the management of risk has developed towards a risk based approach. Thus, industries need to have a comprehensive understanding of why accidents occur and how they develop. In order to act successfully in the prevention of accidents, the areas in which risk reduction is most beneficial need to be identified. For this reason, quantitative risk analysis has developed onwards. One method, which will be considered in detail to support these investigation, is the Bayesian Belief Network.

A Bayesian Belief Network (BBN) is a graphical model which visualises the causal relationship between different factors and the final outcome. It represents a flexible approach which can be used qualitatively and quantitatively.

Current research on the quantification of these factors in BBN models are mainly based on statistical approaches evaluating incident and accident reports. This approach however comprises some problems related to a lack of data, data overload and underreporting. Thus, it needs to be decided on a correction factors, a safety margin or to rely on expert judgement. For that reason another approach based on a framework of risk influencing factors (RIFs) and risk indicators can be used to measure the effect on risk covering the overall socio-technical system.

This master thesis focusses on the identification of suitable RIFs and indicators for technical, human and organisational factors of a BBN ship grounding model. Based on a literature review the influence of BBN nodes on the occurrence of grounding accidents is investigated.

The analyses show that 80 % of causes are human and organisational related, whereas only 20 % represent technical causes. Often a range of causes need to be considered in order to understand the whole complexity behind grounding accidents. The introduction of new technology and automation does not always benefit marine navigation. It results in a polarised workload structure, the reduction of task-related communication and a decrease in situation awareness. Furthermore, the individual risk perception was found out to influence peoples behaviour.

This explains the occurrence of groundings also in good weather and good technical conditions of ships. For that reason, one should improve the human-machine interface rather than adding new technology. One beneficial method could be user-centred design combined with regular and better trainings of personnel.

In summary, the identification of indicators represents a complex process that due to various approaches and context-specific understanding cannot give one ultimate outcome. The implementation of risk indicators in an operational context, represents a beneficial tool for performance surveillance and risk control.

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Chapter 1

Introduction

In this first chapter the reader shall be familiarised with the thesis, its background and objectives. The introduction also includes information about the research project *National Ship Risk Model*, and describes the scope and limitations of this study.

1.1 Background

Nowadays many tools for managing risk are applied among different industries, but a trend can be identified toward the categorisation of actions based on the analysis of risk (Studio Apertura, 2014). The prioritisation of actions based on the highest risk promises more efficiency and reduced costs. In Norway at first the Petroleum Safety Authority (PSA) and the Directorate for Civil Protection (DSB) carried out analyses to quantify risk and to determine a risk level. Hence, the Norwegian maritime industry became also interested in developing a risk-based framework (Studio Apertura, 2014).

The Norwegian Maritime Authority (NMA) (Sjøfartsdirektoratet), which is responsible for supervision of Norwegian vessels worldwide and foreign vessels visiting Norwegian ports, developed a risk-based supervision strategy. This approach helps to focus on the "areas that provide greatest safety and environmental benefits" (Sjøfartsdirektoratet, 2011, p. 9). Thus, the overall safety performance shall be improved and a risk profile developed. Furthermore, the NMA describes a general risk level for Norwegian ships in their annual risk report, taking accident statistics and expert judgement into account. Based on that, the wish arose to investigate a comprehensive risk model for individual ship types. For this purpose a first pre-project with the Norwegian University of Science and Technology (NTNU) was initiated, later the research project *National Ship Risk Model* (NSRM) was founded by the NMA, the Norwegian Costal Administration (NCA) (Kystverket), Safetec and the NTNU (Studio Aperura, 2014a).

The NSRM project aims to develop a risk model for ships in order to monitor and communicate the risk picture of maritime activities in Norwegian waters. This risk-based approach supports decision making regarding development of regulations and safety improving measures (Studio Apertura, 2014). In particular the method of Bayesian Belief Networks (BBN) is applied to model the complex causal relationships between factors influencing the occurrence of ship grounding and collision accidents.

The analysis of such maritime traffic accidents represents an intricate task, since the number of causal factors ranges usually from 7 to 58 (Rothblum, 2000) and the causal chain of events normally involves one or more human errors at different organisational levels (Hänninen and Kujala, 2012). Therefore it requires a holistic view on human, organisational and technical factors, in order to understand the accident development and to be able to control the risk.

Current research on the quantification of these factors in BBN models are mainly based on statistical approaches evaluating incident and accident reports, or the use of expert judgement (Hänninen et al., 2014; Kujala et al., 2009; Antão et al., 2009). However, in order to measure the effect on risk a framework of risk influencing factors (RIFs) and risk indicators promises beneficial input (Haugen et al., 2012; Øien et al., 2011a). Thus the need for the development of indicators arises, which are not limited to monitor safety performance and performance of technical systems, but also covering the overall socio-technical system (Haugen et al., 2012).

The evaluation of risk indicators during operation represents moreover a valuable tool for performance surveillance and risk control giving information on areas where risk reduction is most necessary and thus lead to a wider understanding of maritime accidents and their causes.

1.2 Objectives

The main objectives of this Master's project are:

1. Review literature on grounding 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 grounding accidents.

1.3 Limitations

The scope of this thesis is limited to ship grounding accidents and their causal factors. This is because the thesis is carried out in cooperation with the research project *National Ship Risk Model* (NSRM). Against this background, analysis will be based on the current status of the ongoing research project.

The analysis is based on the proposed BBN grounding model from the NSRM project. The development of another grounding models is not within the scope of the thesis. While some parts will give an overview of theoretical knowledge related to BBN, RIFs and indicators, the analysis of the causal factors will be linked to the background of the NSRM.

The development of RIF and indicators respectively, is limited to outcome of the literature review. A development of indicators based on incident and accident data as well as the testing of the identified indicators will not be a part of this thesis.

Since the probability of the basic event *Grounding* in the BBN, can be determined solely by quantifying the events directly linked to the end event, the main focus is set to the nodes with the closest connection to the basic event, such as the immediate factors, human and technical factors as well as the environmental conditions.

1.4 Approach

The master thesis begins with a qualitative literature review to gather information about grounding and related causes. Different approaches to define grounding are presented and background knowledge on technical, human and organisational factors is conveyed.

An introduction on theoretical knowledge about BBN models follows, which furthermore expands on reviewing literature dealing with challenges of BBN quantification in a maritime context. Explaining the concept of RIFs and indicators guide the reader to the method adopted in this thesis. The approach combines earlier required theoretical knowledge about BBN and RIFs/indicators to identify suitable RIFs and indicators for the BBN nodes. This is shown by the following steps:

- **Step 1: Identification of RIFs for the nodes in the BBN**
  The nodes represent human, organisational and technical factors as well as environmental conditions. RIFs will be defined by means of literature analyses. Sources of information also include literature from other industries dealing with highly complex socio-technical system and a similar human factor problematic e.g. aviation, nuclear industry, control room operations. Since some nodes represent already RIFs (e.g. weather), it is not necessary to develop further RIFs. Then Step 2 is applicable directly.

- **Step 2: Identification of suitable indicators**
  The identified RIFs are further described by one or several indicators, which represent a measurable variable. This is based on criteria, such as validity, sensitivity to change and measurability.

- **Step 3: Scoring/ Rating the indicators based on gathered data**
  Now for each indicator a scale consisting of different mutually exclusive states needs to be defined. Decisions on which scale is appropriate for the single indicators need to be decided based on literature study. Then the different indicators need to be scored based on their influence on the RIF.

Over the spring semester 2016, the author has been engaged in a dialogue with the NSRM project team to gain perspective on current developments.

1.5 Structure of the Report

The rest of the report is organised as follows:

- **Chapter 2** introduces different definitions and classifications of grounding accidents, and conveys basic knowledge about the three main causal group of factors: technical, human and organisational factors.

- **Chapter 3** gives an overview of Bayesian Belief Networks (BBNs) and associated challenges related to their quantification.

- **Chapter 4** presents the relationship between risk influencing factor (RIFs) and indicators, their classification and describes how they can be quantified.

- **Chapter 5** connects knowledge of Chapter 3 and Chapter 4 to focus on the identification of RIF and indicators for the technical, human and organisational factors in BBN grounding model.

- **Chapter 6** presents conclusions from the work and gives recommendations for future work.

Chapter 2

Ship grounding and causes

This chapter imparts basic knowledge about grounding as one type of maritime traffic accidents. Firstly, based on a literature study, different definitions and classifications of grounding accidents are addressed. Then follows an introduction about causal factors with respect to human, organisational and technical factors.

2.1 Grounding

Ship grounding accidents can be defined as "a type of marine accident that involves the impact of a ship on seabed or waterway side." (Mazaheri et al., 2014, p.269). This may result in damages to the ship's hull leading potentially to water ingress and affecting the structural integrity of the vessel. Severe accidents can lead to hull breaches, cargo spills, total loss of the vessel, and in the worst case, human injuries and fatalities (Mazaheri et al., 2014). Thus, grounding has the potential to lead to damage to humans, assets and/or the environment (Kristiansen, 2004).

Ship grounding is categorised into two main groups (DNV, 2003, p.8):

- **Powered grounding:** An event in which grounding occurs because the vessel proceeds down an unsafe track, even though it is *able* to follow a safe track, due to errors related to human or technical failure. Since the ship is moving forward with a certain speed when it runs aground, deformations in longitudinal directions are likely to occur (Simonsen and Hansen, 2000).

- **Drift grounding:** An event in which grounding occurs because the vessel follows an unsafe track because it is *unable* to follow a safe track due to equipment failure, anchor failure, assistance failure, or adverse environmental conditions. In this case, gravity, tide, wind, current and wave action are the driving forces causing lateral damage (Simonsen and Hansen, 2000).

Brown et al. (1998) show that powered grounding has the largest portion of total groundings. Amrozowicz et al. (1997) identify deficiencies in passage planning, planning information (e.g. outdated nautical chart) and piloting to be the most frequent causes for powered grounding. On the other hand, drift groundings occur mainly due to steering or engine failure limiting the ships' ability to navigate. Subsequently, the vessels' movement is depending on wind, wave action and current (Fowler and Sørgård, 2000). Further categorisation of grounding damage is done by (Simonsen and Hansen, 2000, p. 201):

- **Soft Grounding:** Ship grounds on soft ocean beds. This kind of accident is unlikely to cause extensive crushing and tearing damage, but damage can be caused by lateral indentation into the hull and possibly hull girder breakage. In literature this is also referred to as stranding damage.

- **Hard Grounding:** Ship grounds on rocks or is smashed to the rocky side of the coasts by wind or waves causing longitudinal crushing and tearing of the structure in the entire length of the ship.

It was found out that in the literature the terms grounding and stranding are used in an identical manner, expressing that a ship being stuck in shallow waters or on shore, or impacting the ground of the sea (Mazaheri, 2009). However, Kristiansen (2004) points out that stranding is used for the impact with the shoreline and include stranding on beach or coast. Whereas grounding occurs when the bottom of a ship hits the seabed e.g. due to navigation through individual shoals and islands in the fairway.

For this thesis, the term grounding will be used for both grounding and stranding, since this terminology is generally used in the literature.

2.2 Grounding causes

Marine shipping represents a complex socio-technical system which is often characterised by economic pressure and difficulties in international regulations. In order to understand the causes behind these accidents, it requires a holistic view of the complexity of the system with respect to human, organisational and technical factors.

2.2.1 Human and organisational factors

The human factor represents a scientific discipline studying the human abilities (perceptual, physical and mental) and limitations in relation to the system design (Koester, 2001), often referred to as the man-machine interaction (Hänninen, 2008). Besides the term human factor, the human element is often used similarly in the literature (Hetherington et al., 2006; Koester, 2001). More recently, human factors also include the effects of individual, group and organisational factors on safety related behaviour at work (Gordon, 1998; Hetherington et al., 2006). The framework of underlying human factors and the immediate human errors are shown in Figure 2.1.

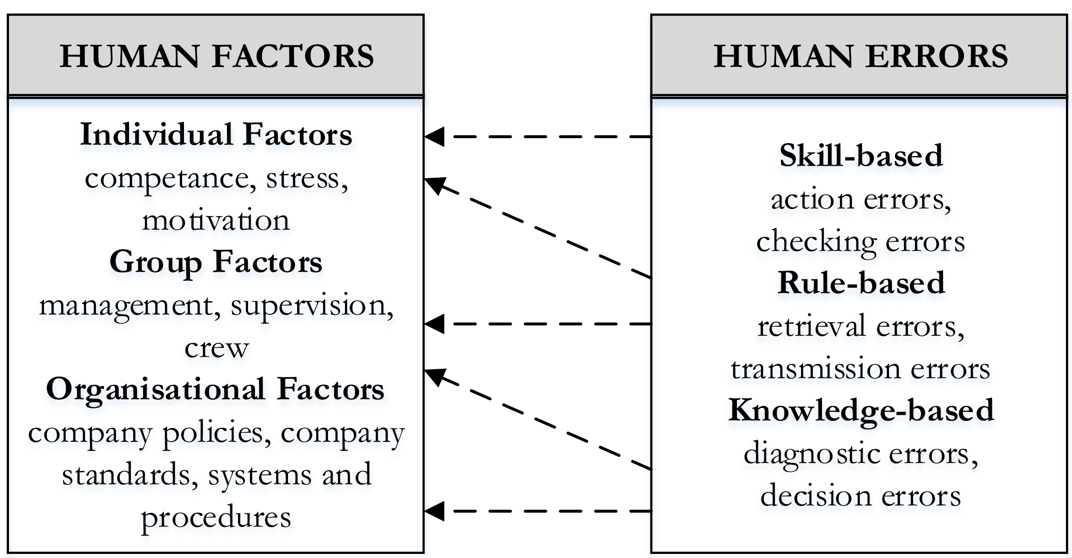


Figure 2.1: Framework of the relationships between the underlying causes of accidents (human factors) and their immediate causes (human errors) (Gordon, 1998)

The term human factor is often mixed with the term human error. Human error is defined by Rausand (2011) as an out-of-tolerance action, or a deviation from the norm where the limits of acceptable performance are defined by the system. These situations can arise from problems e.g. in sequencing, timing, knowledge, interfaces and procedures. While human error is the immediate cause of accidents, human factors are considered as the underlying causes (Gordon, 1998).

Based on Reason (1997) the following four categories of human error can be defined. For the sake of completeness, the category violation is also included, even though these kind of actions with the prior intention to damage the system, are not considered in this thesis.

- **Slip:** an action that is carried out with a correct intention, but a faulty execution. (i.e. pushing the wrong button, reading error etc.)
- **Lapse:** a failure to execute an action due to a lapse of memory or because of a distraction. (i.e. wrong sequence of action, omitting steps in a sequence etc.)
- **Mistake:** A correct execution of an incorrect action. (i.e. inadequate judgement/conclusion due to fatigue, competence, information, time pressure or workload etc.)
- **Violation:** a person deliberately applies a rule or procedure that is different from what he/she knows is required, even though he/she may do it with good intent

In maritime traffic accidents the human failure is reported as the most frequent cause, but studies vary a lot and describe that 43% - 96% of accidents are caused by humans (Grabowski et al., 2009; Hetherington et al., 2006; Kujala et al., 2009; Rothblum, 2000). Analyses by Kujala et al. (2009) identify the human failure as the biggest causal group with 67.6% for grounding and with 52.6% for ship-ship collisions. Including all maritime accidents from this study, 40.5% of the accidents occurred due to a human factor. Trucco et al. (2008) also revealed the human factor with 74% as the most contributing cause. In Figure 2.2 a sub-distribution of causes is shown. In general however, a lack of specification is criticised by presenting usually the all human factors in one pie chart without separating the blunt end (nearest management) factors and the sharp end (at the scene) factors (Akhtar and Utne, 2014).

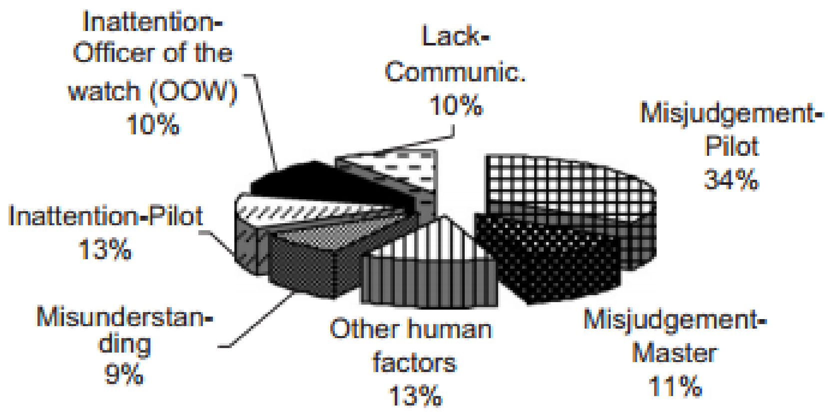


Figure 2.2: Types of human errors in accidents at sea (Trucco et al., 2008)

Hänninen (2008) identify that often environmental factors have been mentioned as the cause of marine traffic accidents, but the actual cause has been insufficient compensation or reaction by the mariners to these conditions. Thus, it could be stated that nearly all marine traffic accidents are caused by human erroneous actions. Since technological devices are designed, constructed and taken care of by humans, technical failures could also be thought as human failures (Hänninen, 2008). Therefore it is possible to draw the following picture and address the human error at an organisational, personnel and design level as illustrated in Figure 2.3) (Hetherington et al., 2006).

Both presented frameworks in this section encompass organisational factors to give an overall view over human factors. Even though it can be concluded that nearly all accidents are related to a human failure, humans do also have the ability to prevent accidents and create safety through their experience, situation awareness and by means of teamwork. Furthermore, it is important to mention the inclusion of design-/automation-related factors, since due to reduced manning levels in the maritime industry and increased technological progress, there is now an emphasis on automation. This in turn affects the role of mariners, their work environment and may lead to over-reliance on machines (Hetherington et al., 2006).

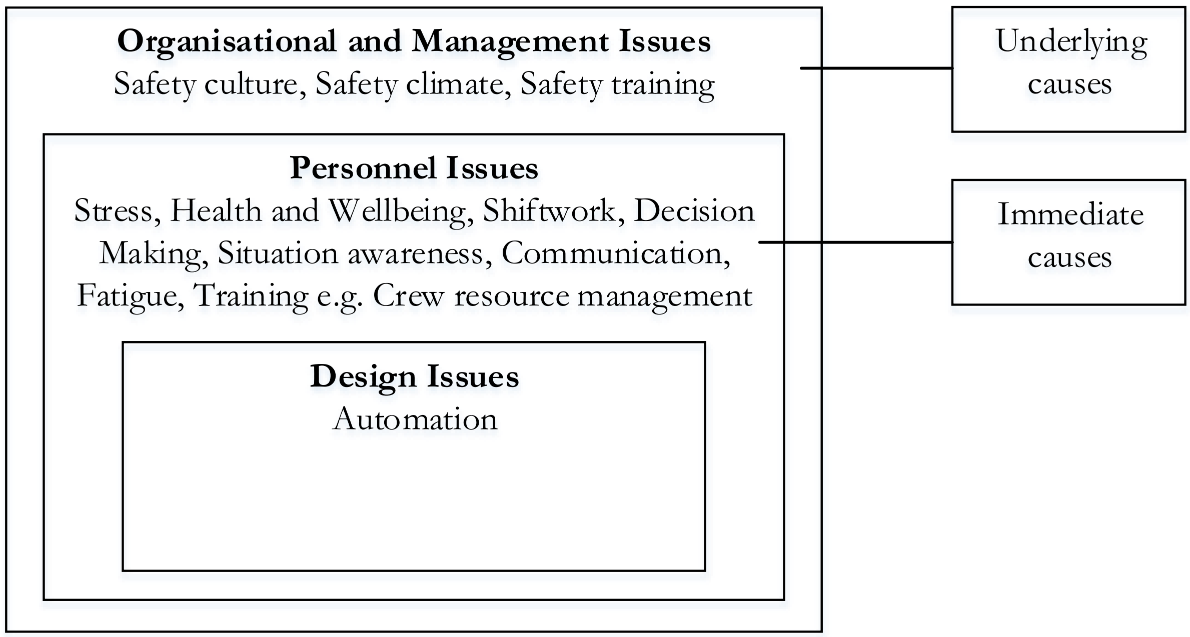


Figure 2.3: An organising framework for human factors which contribute to accidents in shipping (Hetherington et al., 2006)

2.2.2 Technological Factors

Technological factors refer to equipment, hardware, software and design (Rausand, 2011). Causes for accidents can be, for example defective equipment and faulty design, contaminated or defective materials and supplies, and faulty technical procedures (Shaluf et al., 2003).

A general rule of thumb implies that around 80% of causes are human and organisational related, while 20% represent technical causes (Shaluf et al., 2003). Trucco et al. (2008) confirm this by revealing that 20% of shipping accidents occurred due to technical failures, whereas Hetherington et al. (2006) identify 35%.

Especially the loss of propulsion or steering due to technical failures affects the vessel's ability to change the course and prevent a grounding or collision accident. Maritime statistics illustrate that the improved technology, such as enhancing navigation aids, which has decreased the level of machine related errors, appear to have increased the relative contribution of human error in accident causation (Hetherington et al., 2006).

Chapter 3

Bayesian Belief Network

This chapter introduces the basic concept of Bayesian Belief Networks (BBNs). The reader shall get an overview about the methodology and construction of BBNs. Furthermore, different quantification approaches and related challenges with the quantification process are introduced.

A BBN is a graphical model to present causal relationships between factors. It can be used for both, qualitative and quantitative analysis (Rausand, 2011). In the NSRM project the method of using BBN for modelling was found out to be the most beneficial approach due to the models flexibility (Studio Apertura, 2014).

3.1 Construction of a BBN

A Bayesian Network can be described as a Directed Acyclic Graph (DAG) consisting of nodes and arcs (Kjærulff and Madsen, 2008). The nodes are random variables and represent a state or condition, but do not necessarily represent events such as in Fault Tree or Event Tree Analysis (Rausand, 2011). Nodes are rather factors contributing to the main problem. Arcs indicate a direct influence (Rausand, 2011) and specify the independence assumptions that must hold between the random variables (Charniak, 1991).

A graphical network can be constructed which indicates a causal relationship of the kind:

$A \rightarrow B$, where A (parent node) is the cause of B (child node)

A node without a parent node is called root node, which is node A shown in Figure 3.1. The nodes that can be reached on a direct path from A are descendants of A, nodes from which A

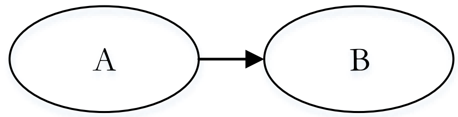


Figure 3.1: A simple BBN

reaches on a direct path are ancestors of A. The BBN is an acyclic graph, which means that a node can never be its own ancestor or descendants (Rausand, 2011).

The basic rule for the calculation of a Bayesian Network was provided by Thomas Bayes (1702–1761), which describes conditional probabilities as follows:

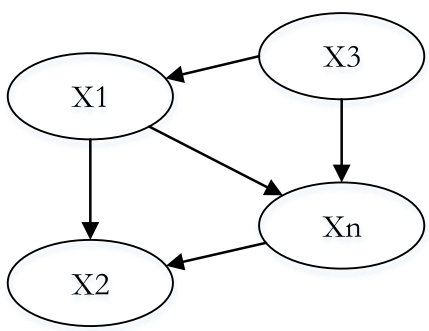
$$P(X_2 \mid X_1) = \frac{P(X_1 \mid X_2) \cdot P(X_2)}{P(X_1)} \tag{3.1}$$

where $P(X_2)$ is the prior probability of the hypothesis i.e. the likelihood that X_2 will be in a certain state, prior to consideration of any other relevant information (evidence) which is X_1. $P(X_1 \mid X_2)$ represents the conditional probability (likelihood of evidence given the hypothesis to be tested), and $P(X_2 \mid X_1)$ is the posterior probability (likelihood of X_2 being in a certain state, conditional on the evidence provided) (Akhtar and Utne, 2014). This shows that the probability of event X_2 is known once the probability of X_1 is established.

In order to establish a BBN, the identification of relevant nodes and their causal relationship needs to be stated and verified (Kjærulff and Madsen, 2008). With respect to the risk analysis approach, Rausand (2011) underlines the identification of all relevant factors that can significantly influence a critical event, e.g. hazardous event or accident. Once the model structure has been determined through a process involving testing of variables and their conditional independences, and verification of the directionality of the linkages, the values need to be included (Kjærulff and Madsen, 2008). The parameters of a probabilistic network can be retrieved from databases, based on expert knowledge or established through a mathematical model (Kjærulff and Madsen, 2008).

A BBN can be used both qualitatively and quantitatively. Through the graphical topology it creates an intuitive understanding of the causal influence among the variables and returns information on the flow of information moving through the model (Antão et al., 2009). Additionally, quantitative analysis on the (conditional) dependencies and independencies can be performed.

To calculate the probabilities in a BBN it is assumed that each node is conditionally independent in the model when the states of all its parents is known. By analysing the parameters first, the root nodes shall be assigned with probabilities. The next step is to set a conditional probability to the next level of nodes given the parent node. This is continued until the end node/s is/are assigned. A conditional probability table (CPT) includes then every node, representing the likelihood based on prior information or past experiences and gives the distribution of each combination of variables (Rausand, 2011). In Figure 3.2 an example of a BBN and a CPT is shown. The CPT is obtained by combining all possible states (e.g. y=yes, n=no) of the input nodes and the child nodes by inserting the corresponding probability value p_i for each one (Antão et al., 2009). The states are mutually exclusive, which means that the node can only take on one value at the time. For example either yes or no in this case.



	X_1			
	y		**n**	
	X_2		X_2	
X_3	**y**	**n**	**y**	**n**
y	p_1	p_2	p_3	p_4
n	$1-p_1$	$1-p_2$	$1-p_3$	$1-p_4$

Figure 3.2: Example of a BBN and a CPT (Antão et al., 2009)

In the quantitative analysis, computer applications are mostly used due to the complexity of the network and the high number of nodes. Furthermore, sensitivity analyses help to rank the variables to their importance of influence to the end variable of a BBN (Rausand, 2011).

3.2 Advantages and Limitations

The advantages of BBNs are related to their ability to model complex systems with up to thousands of variables (Langseth and Portinale, 2007) and to give a compact representation (Kjærulff and Madsen, 2008). The graphical model creates an intuitive understanding of the causal influence among the variables and can easily be adjusted in case more relevant data are gathered (Rausand, 2011). Thus, the BBN can be used in a solely qualitative way but also as a quantitative approach.

The Bayesian network framework can furthermore be extended to model decisions by using the so called influence diagrams (Langseth and Portinale, 2007). Then, the expected utility can be calculated for each decision option. "The result is an optimal policy, which for any state of the environment selects a decision of maximal expected utility." (Langseth and Portinale, 2007, p. 3). The BBN represents a more flexible approach than using Fault Tree, since a binary representation of events is not required (Rausand, 2011). Therefore it has the ability to replace Fault Tree Analysis within a risk analysis. The BBN nodes do not necessarily represent events, as it is the case Fault or Event Trees. Nodes rather represent factors contributing to the main problem.

The limitations of BBN are related to the workload which increases significantly with the number of nodes in the network (Rausand, 2011). For quantitative analysis, even for very small BBNs, a computer programme is necessary (Rausand, 2011).

3.3 Challenges of BBN Quantification

When it comes to quantifying a BBN different challenges have to be faced. First of all a lack or incompleteness of data, simply due to the nature of the variables or less frequent occurrence of events to gather data, pose an obstacle (Antão et al., 2009). On the other hand, the availability of a large number of data (e.g. studies, databases, official reports) demands a structured approach of data management. In this case the feasibility of data use and analysis as well as the capability to infer a structure from data need to be considered (Antão et al., 2009).

Within the international shipping industry, the collection and evaluation of maritime accident data is left to each nation. Different maritime organisations investigate accidents and log their findings in their databases. In Portugal for example, there is no legal obligation to register maritime accidents in national waters in a systematic form (Antão et al., 2009). Whereas in Finland all maritime traffic accidents occurring in the Baltic Sea are gathered by the Helsinki Commission (HELCOM) (Hänninen and Kujala, 2014). However, there is no international consistent classification scheme used (Akhtar and Utne, 2014).

Analyses of accident reports are therefore often challenging due to underreporting and inconsistencies. Antão et al. (2009) list the lack of causes, lack of accident type or location. There is also a lack of focus on human factors, which are often grouped only into one category (Akhtar and Utne, 2014). This in turn influences what data are selected and analysed finally. Underreporting of accidents in the maritime community and the poor details in national and international databases present a big problem for maritime researchers (Akhtar and Utne, 2014). In addition, due to the low quality of statistics and the few parameters used in accident databases the performance of pure statistical analysis is not always possible (Akhtar and Utne, 2014).

The crucial issue now is to assign probabilities to each node in a BBN. Due to the aforementioned problems by using statistical data, the use of correction factors, a safety margin or to rely on expert judgement need to be decided (Akhtar and Utne, 2014).

In order to cope with poor databases or to reduce uncertainty the use of experts' judgement is a common practice (Antão et al., 2009). Expert judgement elicitation is a process for obtaining data directly from experts in response to a specified problem (Rausand, 2011). This process may involve one or a group of experts with various types of expert knowledge (Rausand, 2011). Hänninen et al. (2014) describe the approach of expert judgement for obtaining probability estimation for quantifying a Bayesian network model of maritime safety management.

Firstly, each expert is introduced to the concepts of probability and the Bayes' theorem, the BBN model and details about each model variable. Secondly, the expert then assesses the conditional probabilities for each variable with support of a pie chart probability tool (available in GeNIe Bayesian network software). With the pie chart, the probability mass of each state can be adjusted and the resulting discrete probability distribution can also be immediately graphically visible. Thirdly, variability in the model parameters due to potential expert differences is included in the BBN model by introducing a variable 'Expert' into the model with weighing each expert equally.

Another approach of quantifying nodes in a BBN uses a framework of risk influencing factor and risk indicator assessment which studies the relationship between risk influencing factors (RIF) and their effect on the probability of a specific major accident event. In the next chapter the reader will be introduced to the concept of RIFs and indicators. The detailed quantification process based on RIFs and indicators is presented in Section 4.6.

Chapter 4

Risk Influencing Factors and Risk Indicators

In this chapter the relationship between risk influencing factor (RIF) and indicator shall be presented. Different classifications of indicators, with especially giving an overview on the debate of leading and lagging indicators, will be included. Basic requirements all indicators should fulfil will be specified. The chapter deals also with different methods on how to establish indicators and how to quantify them. This chapter will lay the theoretical basis for the introduced and applied methodology in the case study in the next following chapter.

4.1 Introduction

In response to major accidents, such as the Texas City disaster in 2005, where 15 workers were killed, the effort to identify early warning signals to prevent such accidents increased explicitly (Øien et al., 2011a). Discussion on the need for meaningful indicators to measure safety within major hazard facilities developed (Hopkins, 2009). Major accidents are characterised by "low frequencies but extensive consequences in terms of several serious injuries and/or loss of human life, serious harm to the environment and/or loss of substantial material assets.” (Haugen et al., 2012, p. 1).

Ship grounding accidents can therefore be categorised as major accidents. Haugen et al. (2012) emphasises moreover on the complex causal chain behind those accidents, often involving a large number of people, organisations as well as technical systems.

Although the research on indicators is not a new field area, still ongoing challenges are focussed. Various definitions and development methods on indicators exist, not at least due to the multidisciplinary nature of the safety community (Øien et al., 2011a).

4.2 Definition

In the development of indicators it is necessary to show the basic connection between risk influencing factors (RIFs) and indicators. RIFs can be defined as "an aspect (event/condition) of a system or an activity that effects the risk level of this system or activity" (Øien, 2001b, p. 130). The RIF thus may have a direct or indirect influence on the probability major accident occurrence (Haugen et al., 2012). The factor can be classified e.g. to be technical, organisational or operational. The interaction between them can be modelled with e.g. a BBN, as shown in Figure 4.1. One factor can have the ability to influence various other factors. Arrows from the technical factors towards the basic event imply a direct influence on the probability of the basic event.

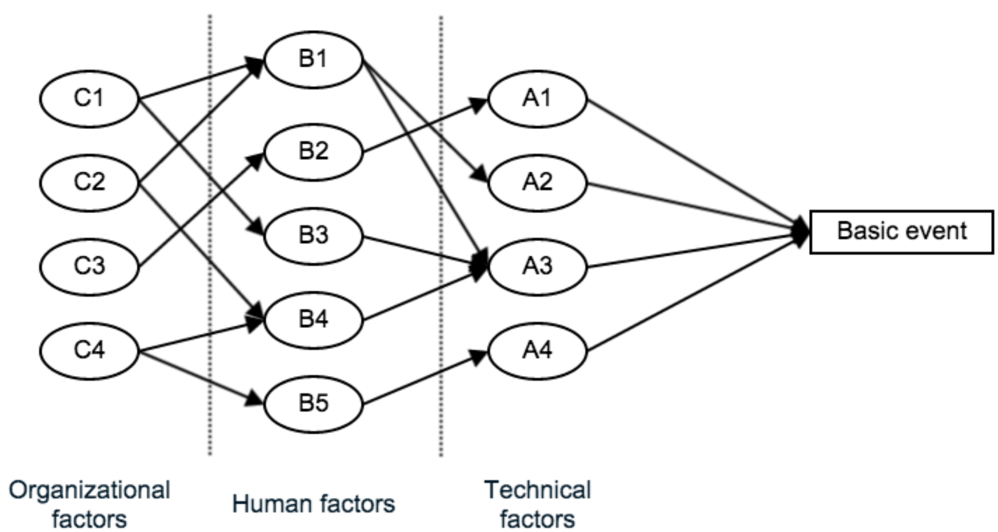


Figure 4.1: BBN with technical, human and organisational factors (Rausand, 2011)

Since RIFs in general are not quantifiable directly, the so called *measuring problem* occurs. For example Haugen et al. (2012) list the factor *Maintenance crew*, which is due to its complexity not directly quantifiable. For that reason an operational variable, the indicator, needs to be introduced.

An indication can be defined as “a measureable/operational variable that can be used to describe the condition of a broader phenomenon or aspect to reality” (Øien, 2001b, p. 130). The broader phenomenon mentioned presents the RIF (Haugen et al., 2012).

One factor can further be represented by only one or a number of indicators (Øien et al., 2011a). If the factor itself is a quantifiable variable, it can be considered as an indicator (Haugen et al., 2012). This relationship between indicators, RIFs and the event is shown in Figure 4.2. The different indicators (I1, I2 and I3) quantify the risk influencing factor (I) which directly influences the probability of the event.

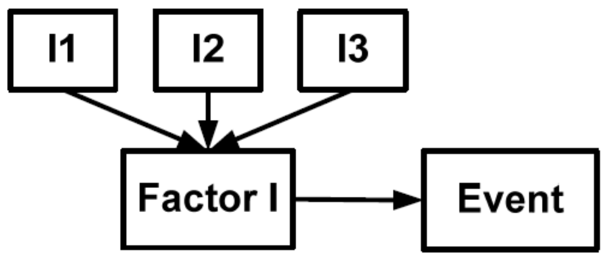


Figure 4.2: Relationship between indicators, factor and event (Haugen et al., 2012)

The selection of *proper* indicators leaves room for interpretation due to a subjective and a context-specific understanding. There is no universal model or method for the development of indicators (Øien et al., 2011a). This represents a possible source of errors (Øien, 2001b). Reiman and Pietikäinen (2012) underline:

> "No organization is able to monitor all variability in its environment and thus the selection of what to monitor should be done with care. Thus it should be remembered that there is always variability in both the internal and external environment of the organization, making precise predictions of future outcomes impossible." (Reiman and Pietikäinen, 2012, p. 1996)

Hence, indicators are not able to measure all dimensions of a factor and can lead to some uncertainty (Haugen et al., 2012). This situation is shown in Figure 4.3.

In practice there is a tendency to put everything under the umbrella of indicators (Øien et al., 2011a). Whereas some highlight the properties of indicators to provide numerical values for some selected determinants of a system updated within a regular time periode, others state that indicators not necessarily have to be limited to numerical values (Øien et al., 2011a).

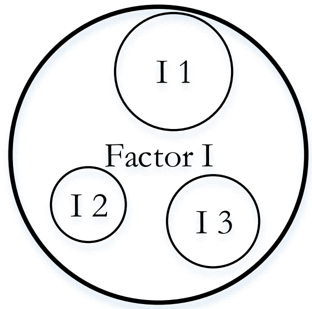


Figure 4.3: Example of the fraction of a factor measured by indicators (Haugen et al., 2012)

In the safety audit system domain for example, the assessment of safety by questionnaires is regarded as indicators as well. However, safety audits represent a qualitative type of assessment, whereas indicator fill the quantitative assessment (Øien et al., 2011a; Øien, 2001a). Reiman and Pietikäinen (2012) argue that indicators can be considered as any measure that seeks to produce information on an issue of interest in a quantitative or qualitative way.

4.3 Classification of indicators

4.3.1 Safety and risk indicator

Both terms are used interchangeable (Øien et al., 2011a). The definition describes indicators which quantify RIFs, have a causal connection through a risk model and aim to determine the effect of risk, are defined as risk- or risk-based indicators. They are obtained through a risk based approach (Øien et al., 2011a). If the factors and indicators are selected based on their effect on safety, then safety influencing factors with safety indicators are denoted. They may be obtained through safety based, incident based or resilience based approaches (Øien et al., 2011a).

4.3.2 Process and personal safety indicators

Hopkins (2009) separates safety indicators into two groups depending on different types of hazards: personal safety and process safety indicators. The process safety hazards are related to the production activities and have the potential to harm the plant and/or cause fatalities e.g. release of hazardous substances and release of flammable material which could lead to a fire/explosion. The personal safety hazards affect the individuals but may have little to do with the processing activity of the plant. For example falls, trips and vehicle accidents. Hopkins (2009) points out that the majority of injuries/fatalities are dependent on personal safety hazards rather than process hazards. Based on this he claims: "injury and fatality statistics tend to reflect how well an organisation is managing personal safety hazards rather than process safety hazards." (Hopkins, 2009, p. 460) The establishment of process safety indicators is therefore necessary in order to evaluate the management of process safety hazards.

4.3.3 Leading and Lagging Indicators

Furthermore are leading and lagging indicators of process safety distinguished (Hopkins, 2009). Lagging indicators, which are also denoted as direct, reactive or outcome based indicators, include data after-the-event (e.g. accidents, incidents, near misses). They are moreover related to reactive monitoring since they indicate failures or non-achievement with a desired safety outcome (e.g. failures of safety critical instrumentation/alarms) (Øien et al., 2011a). They are however not very useful as pre-warnings or early warnings (Øien et al., 2011a).

In order to understand causes which lead to an accident, leading indicators help. They are also referred to as indirect, proactive or activity based indicators. They fulfil a pre-warning, early warning function and sign of deterioration in safety performance (e.g. training, supervision) (Øien et al., 2011a). They should change before the actual risk level of the organisation has changed (Kjellén, 2009).

Leading indicators are related to active monitoring since they provide performance feedback before an accident or incident occurs and can be used as inputs that are essential to achieve the desired safety outcome (Øien et al., 2011a; Reiman and Pietikäinen, 2012).

Recently a discussion was conducted about the distinction between leading and lagging indicators in general. Due to the use of inconsistent terminology and different point of views, a debate among the safety society was initiated. Initially Hopkins (2009) points out that the differentiation between leading and lagging indicators in the area of process safety has no clear meaning and it is of relatively little value. Based on the fact that the bow-tie model does not provide a good basis for the distinction between lead and lag (Øien et al., 2011a).

Research findings emphasise on the importance to use both, leading and lagging indicators, and call this approach *dual assurance*. Thus a compensation shall be achieved if either leading or lagging indicators are ineffective within an area (Øien et al., 2011a). Both kinds of indicators measure the present status of a factor and provide early warnings if potential problems arise (Haugen et al., 2012). Contrary to this approach, Vinnem (2010) prefers leading over lagging indicators and concludes: "There is more motivation in reporting performance of preventative measures, compared to performance in the sense of occurrence of near-misses and incidents." (Vinnem, 2010, p. 776).

The debate revealed a common agreement on the need for meaningful indicators measuring the state of safety management systems (Hopkins, 2009). The understanding of precursor events as early warnings should provide a trigger for investigation and actions among the industries (Øien et al., 2011a). In particular, Grote (2009) stresses that sound knowledge of cause-and-effect relations lays the foundation to predict safety performance from a set of indicators. It is therefore necessary to understand the pattern of accident and incident events which can lead to a negative safety outcome (Grote, 2009). Øien et al. (2011a) concluded that the debate showed the distinction between leading and lagging may be of interest in a theoretical way, but can be counterproductive in practice.

4.3.4 Monitor, drive and outcome indicators

The distinction made by Reiman and Pietikäinen (2012) classifies leading indicators in monitor and drive indicators. The main function of monitor indicators is to show the organisational potential to achieve safety.

They reflect the organisation's dynamics considering practices, routines, abilities, skills and motivation of the personnel. Some examples are 'the extent to which safety-conscious behavior and uncertainty expression is socially accepted and supported', 'the extent to which personnel consider safety as a value that guides their everyday work' and 'the extent to which the personnel understands the hazards that are connected to their work' (Reiman and Pietikäinen, 2012, p. 1997).

On the other side, drive indicators guide the socio-technical activity in an organisation by motivating certain safety-related activities. They indicate the development of activities aiming at improving safety. Some examples are 'a system for reporting and analysing incidents is implemented', 'the availability of sufficient workforce is controlled' and 'risk assessment is done for organizational changes' (Reiman and Pietikäinen, 2012, p. 1997). Figure 4.4 illustrates the distinction between monitor and drive indicators, and introduces outcome indicators.

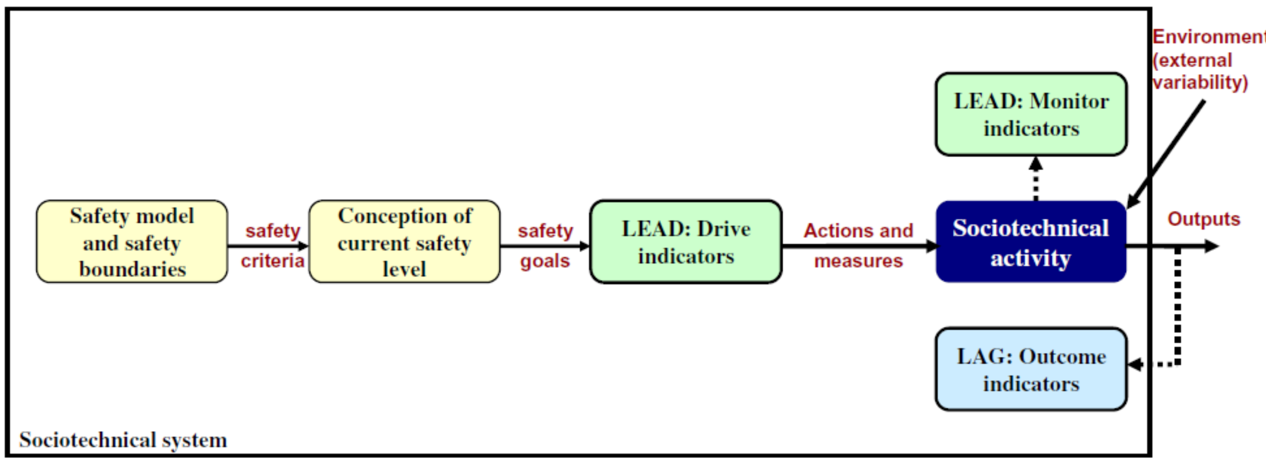


Figure 4.4: System model showing the different indicator types (Reiman and Pietikäinen, 2012)

The *Safety model* of an organisation provides the criteria for analysing the prevalent safety level. Safety boundaries refer to the perceived hazards of the organisation and the space that these hazards leave for carrying out activities safely (Reiman and Pietikäinen, 2010).

The *Conception of current safety level* describes the perception on the organisation's safety level held by the top management and other people involved in selecting and interpreting safety indicators (Reiman and Pietikäinen, 2010). These criteria in turn influence the selection of drive indicators to influence the *Sociotechnical activity* in the next step. They measure the fulfilment of selected safety management activities. The drive indicators are turned into control measures that are used to manage the system: to change, maintain, reinforce or reduce something (Reiman and Pietikäinen, 2012).

Monitor indicators reflect on the internal dynamics of the sociotechnical system and indicate the potential of the organisation to perform safely. They are further used to monitor the environmental variability outside the actual organisation, e.g. changes in social and technical infrastructure, legislative requirements. This gives indications of the conditions and contingencies that the sociotechnical system will face.

Outcome indicators provide a view on the outputs of the sociotechnical system. An outcome means a temporary end result of a continuous process or an activity, which is always the result or consequence of some other factor or combination of factors and circumstances. However, it has to be reminded that safety is not an outcome and thus cannot be measured with outcome indicators.

Outcome indicators are often used in the wrong way, namely to make conclusions about the level of safety, but they can only provide information on the functioning and failure of safety barriers. Due to external influences on the sociotechnical system, such as external circumstances, situational variables and chance, a direct prediction of the safety-related outcomes is not achieved.

Reiman and Pietikäinen (2012) make clear that the understanding of the sociotechnical system lays the basis for selecting and using indicators. The safety model shows that safety indicators are defined to be able to measure (monitor indicators) or facilitate (drive indicators) the presence of sociotechnical activities.

4.3.5 Overview

On the basis of various definitions and interpretations on the term indicator, which even end in a debate, the conclusion must be to carefully define the concept indicators before use (Reiman and Pietikäinen, 2012). The safety community eventually agreed on the need to develop indicators, to be able to predict the future safety performance and thus to prevent major accidents from occurring.

Overall understanding of the underlying socio-technical system is the basis to a successful use of indicators. Thus joint knowledge of both social and natural science is required. Ongoing re-evaluation and adjustment of indicators might also be necessary, since data, input knowledge and system environment can change over time (Øien et al., 2011b).

4.4 Properties of Indicators

In order to select appropriate indicators for further analysis it is important to consider certain properties an indicator should fulfil. Haugen et al. (2012) and Kjellén (2009) list the following aspects:

- **Validity**: Indicator must represent a valid measurement of the related RIFs.
- **Sensitivity to change**: Indicators must be able to reflect changes in the underlying phenomenon (RIFs).
- **Measurability and Comparability**: Indicator must be recordable, quantifyable and comparable with previous and future data results. The measuring process must remain the same over time in order to measure changes of the factors, and not deviations due to another measurement method. Adjusting the status of an indicator to a scale e.g. high/medium/low, bad/average/good or grading from A-F, is also a suitable way.
- **Comprehensibility**: The causal relationship between indicators and RIF is comprehensible, transparent and easily understood.
- **Reliability**: Different observers must obtain same results from measuring the status of indicators at the same point of time.

Kjellén (2009) adds that the indicator must be robust against manipulation.

Selected indicators should also fulfil the criteria to be able to be improved. This means that the user should have the possibility to influence the indicators status (Haugen et al., 2012), e.g. to increase the number of hours of training per operator.

The cost-benefit relationship between the effort of gathering data for indicators and the actual use of the outcome is moreover important to consider (Haugen et al., 2012). If gathering data is far to complex this can influence the selection of indicators and the time interval for repetitive measurement.

Complete indicator sets should fulfil the following criteria (Haugen et al., 2012):

- **Size**: Balancing the cost versus completeness of indicator sets.
- **Dual assurance**: Combining leading and lagging indicators (section 4.3.3).
- **Alarm and diagnosis**: Combining indicators which show that *something is wrong* (alarm indicators) and *what is wrong* (diagnosis indicators).
- **Frequency of measurement**: Combining frequently measured indicators (e.g. monthly) and less frequently measured indicators (e.g. quarterly, annually or more seldom).

4.5 Establishment of Risk Indicators

Regarding a socio-technical system, three levels of performances can be measured: technical, human and organisational (quality of procedures, training) (Øien, 2001a).

4.5.1 Technical risk indicators

The following risk-based approach to establish risk indicators focusses to derive RIFs from a quantitative risk analysis (QRA) (Øien, 2001a,b):

1. **Selection of categories of accidental events**, which contribute the most to the total risk (the first screening).
2. **Identification of risk influencing factors (RIFs)**, which are modelled in the QRA for the prior categories of accidental events.
3. **Assessment of potential change in RIFs** within a certain time period and analysing the causal relationship between RIFs and risk.
4. **Assessment of effect of change on risk** due to changes of RIFs is carried out by a sensitivity analysis, where every parameter is changed one by one.
5. **Selection of significant RIFs**.

6. **Initial selection of risk indicators**, e.g. based on the following criteria: a measurement must give sufficient amount of data, observations should preferably be registered in existing information systems and a strong relationship between risk indicator and risk level. (More information given in the section 4.4.)

7. **Testing and final selection of risk indicators** in order to test the appropriateness of the selected risk indicators.

8. **Establishment of application routines** focussing on involvement on decision making of a company.

Due to the performance of a sensitivity analysis (step 4) including expert judgement (step 3), the most contributing RIFs are selected (step 5). For these ones indicators need to be assigned.

4.5.2 Organisational risk indicators

Øien (2001a) uses risk indicators to monitor changes in RIFs, in order to measure the relative change in risk. By focussing especially on organisational risk indicators as a tool for frequent risk control, the Organizational Risk Influence Model (ORIM) was developed.

ORIM includes three main parts: organisational model, organisational risk indicator and a quantification methodology. The focus is on a comprehensive qualitative and quantitative use (Øien, 2001a). Results should provide input to risk control by assessing quantitatively the impact of changes in organisational factor states on risk (Øien, 2001a).

The following 8 steps are included in the ORIM (Øien, 2001a, p.154):

1. **Organisational model/ factor**, e.g. BBN model presenting causal relationship linking organisational factors to the quantitative risk model. The BBN indicates direct and indirect influence on nodes.

2. **Rating of organisational factors**, i.e. assessing the quality of the factor by using expert judgement, qualitative tools similar to safety audit tools or the use of indicators. ORIM focusses on the use of indicators. Due to incremental changes in the states of the organisational factor, rating in good or bad is sometimes not sufficient. Therefore another

scaling needs to be considered. How fine-graded a scale effects the number of states and this in turn the extent of the quantification process (Øien, 2001a).

3. **Weighing of organisational factors**, i.e. assessing the effect and strength that the factor has on risk by using expert judgement and a data driven approach. This step aims to fill the conditional probability table (CPT) for each node in the BBN.

4. **Propagation method/ algorithm**, i.e. way in which the rates and weights are combined and aggregated. The influence diagram technique can be used for this step. It gives every possible combination of states of organisational factors a rate (unconditional probability) and a weight (conditional probability) which are multiplied and summarised.

5. **Modelling technique**, e.g. BBN are used for quantification, since the relations and states can be represented in a probabilist way.

6. **Link to risk model**, i.e. link to a more technical risk model in the QRA.

7. **Adaption of risk model**, i.e. sensitivity analysis determine which factors are most contributing to the risk.

8. **Re-quantification of risk** , i.e. relative change in risk.

4.6 Quantification of risk indicators

The following section describes a quantitative method for assessing the effect on risk by using a BBN. An introduction about BBN is given in Chapter 3. Here the focus will be to present the quantification of indicators described by ORIM (Øien, 2001a) as shown in Figure 4.5.

The schematic illustrates a simple BBN where one (non-observable) unknown variable λ influences directly the basic event. To show the effect of changes in the organisational factors on risk through the unknown variable λ, ORIM includes different organisational risk influencing factors in the next level (OFk), where k represents the number of organisational factors.

The OFk represent the input node/ parents to λ (Øien, 2001a). Since RIFs represent theoretical variables, a number of indicators (ORIkj) as a measurable variable are introduced. Each factor may be assessed by several indicators, ORIkj, where j represents the number of indicators.

To measure the indicator a scale mkj from m^L_{kj}, denoting a lower value e.g. 1 = very bad, to m^U_{kj}, upper value e.g. 5 = very good. Between these limits a linear scale is introduced, such as 2 = bad, 3 = average, 4 = good.

The next step will be the rating. The measured values of the indicators are converted to a value from 1 to 5 which are weighed to produce a weighted average of OFk. r_k is the rating value of OFk, as follows:

$$r_k = \sum_{j=1}^{n_k} v_{kj} r_{kj} \tag{4.1}$$

with

$$r_k = \textstyle\sum_{j=1}^{n_k} v_{kj} = 1 \tag{4.2}$$

The rating value r_k of the RIF OFk, as calculated with (4.1), is then rounded off to an integer value from 1 to 5 by standard rounding rules, illustrated with the scale above λ. The weights $v_k n_k$ are assigned by expert judgement and are assumed to remain constant over time.

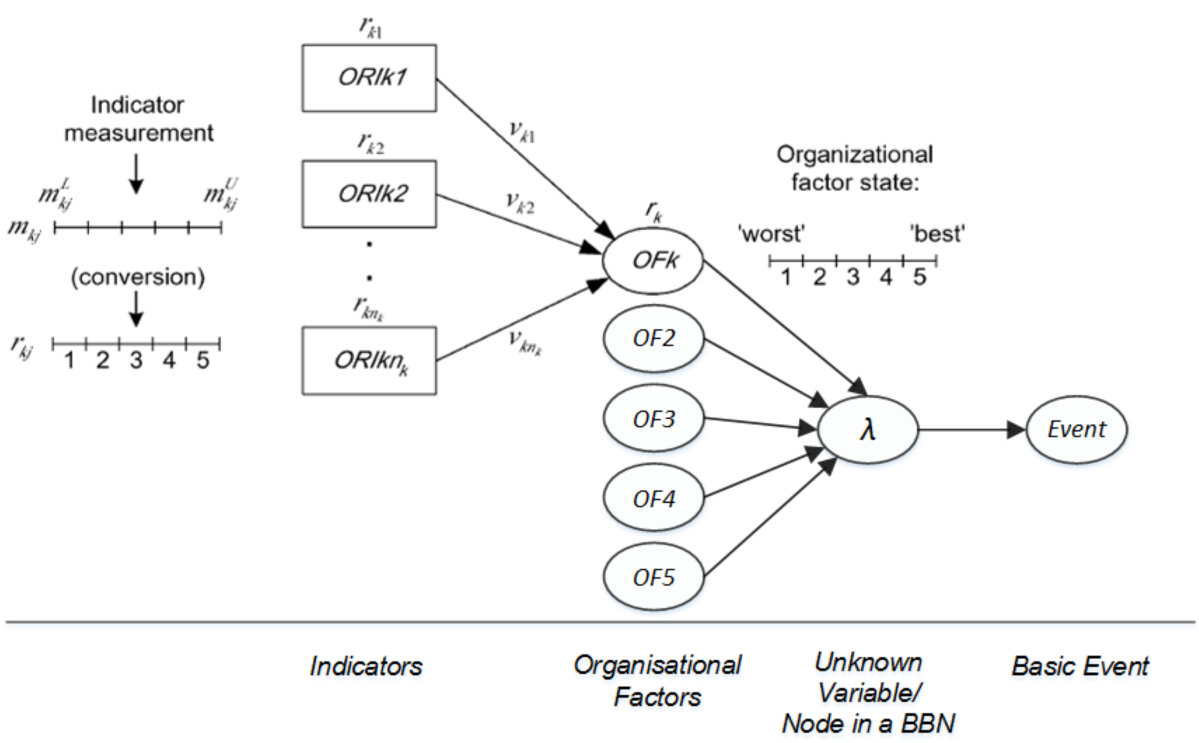


Figure 4.5: Quantitative model with rating process (Øien, 2001a)

Chapter 5

Modelling Technical, Human and Organisational Factors

In Chapter 3 and 4 knowledge about Bayesian Belief Networks (BBN) and the connection of risk influencing factors (RIFs) and indicators was presented. This chapter will bind the previous chapters by analysing the BBN grounding model from the NSRM project with respect to its technical, human and organisational factors. The BBN grounding model is attached in Appendix B.

On the basis of the quantification approach for indicators in section 4.6, the following steps are adopted in this study. The detailed approach is described in section 1.4. It essentially comprises the identification of RIFs for certain BBN nodes as well as the identification of suitable indicators. Figure 5.1 illustrates how BBN nodes, RIFs and indicators are distinguished by different colours within this chapter.

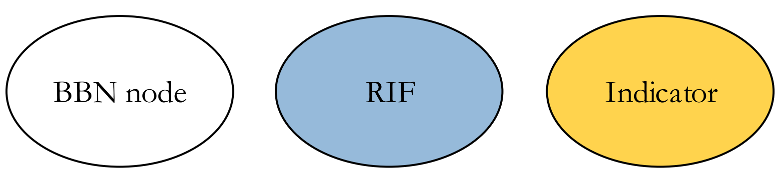


Figure 5.1: Colour code for BBN nodes, RIFs and indicators

5.1 Immediate Factor: Vessel takes action on time

The immediate factors in the BBN model represent the pre-conditions for the grounding event itself. Either the ship is on grounding course without noticing it which will consequently lead to grounding without any intervention, or the crew detects the deviation and has the possibility to intervene before an accident occurs.

Now the factor "Vessel takes action on time" will be analysed. Although this node is applicable for both types of groundings, drift and powered grounding, a model by Eide et al. (2007) to describe the probability of drifting ships running aground is introduced. The model comprises three main factors shown in Figure 5.2, such as drift time to shore, tug response time and self repair. The tug response time, furthermore, is determined by (1) reaction time (1.5 h), (2) mobilisation time (1.5 h), (3) sailing time from tug initial position to ship and (4) time required to connect the ship and the tug (2 h). The listed time estimates in brackets are obtained from Norwegian Coastal Administration reports (Eide et al., 2007). These estimates however include a high uncertainty and especially a weather dependency with respect to the element (4) time required to connect the ship and the tug.

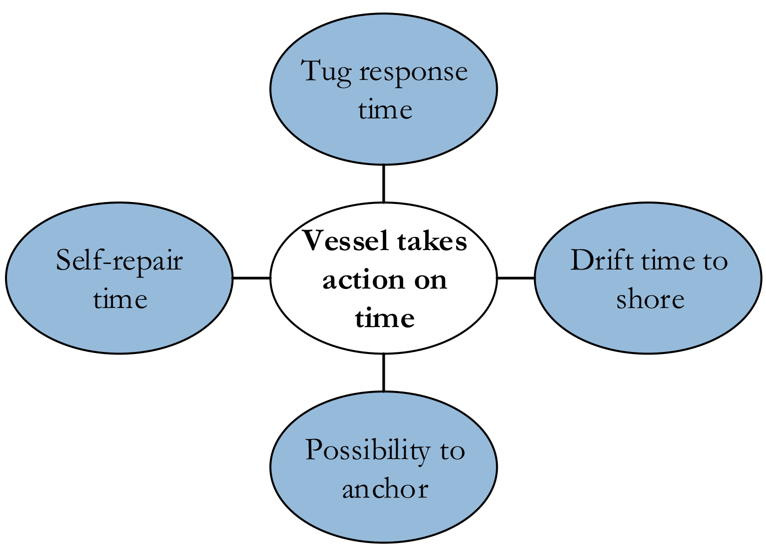


Figure 5.2: Influencing factors on "Vessel takes action on time"

Another RIF mentioned in Figure 5.2 is the "Possibility to anchor", which is introduced by Fowler and Sørgård (2000). Drifting ships may avoid further grounding by deploying their anchor systems. This strategy however is only likely to be successful in areas where the depth variations are not too steep, soft sea bottom conditions are present and close to the coast. Possible areas are for example, the coasts along Denmark, Germany, the Netherlands, Belgium, Northern France, the south-east and southern coast of England (Fowler and Sørgård, 2000). In other areas, such as Norway, Ireland, and most of the UK anchor saves are not possible (Fowler and Sørgård, 2000). The Finnish Transport Safety Agency mentions in their annual review that groundings in Finnish waters surprisingly often involved an anchored ship (TraFi, 2013). With respect to the aforementioned suitable areas for anchoring, Fowler and Sørgård (2000) state a probability for successful anchoring under calm conditions to be 0.99, but to decrease to 0.95 under stormy conditions.

5.2 Human and Technical Factors

In this section the human and technical factors of the BBN model are included. The structure of this section is not completely based on the order of sub-categories (Operators Action, Technical Failure, Ship Design) from the BBN. Firstly, the central task of "Navigation" will be analysed. Subsequently, the node "Navigation system" follows and the design-related factors.

5.2.1 Navigation

"Safe navigation means that the ship is not exposed to undue danger and that at all times the ship can be controlled within acceptable margins" (International Chamber of Shipping, 1998, p. 5). This definition from the *Bridge Procedure Guide* expresses the crews' task to guide a ship from one destination to another as safely as possible given the prevailing circumstances (Nilsson et al., 2009). The complexity of the navigational task can vary due to environmental and ship-related factors, such as load, propulsion and ship design.

A study by Kristiansen (2004) on grounding accidents of ships over 1599 GT (Gross Tonnage) defines *Navigational Failures* as one causal group which is further separated into being related to the *own ship* or *other ships*. Navigational failures of *own ship* were revealed to be 22.9 %, whereas 1.4 % were caused by *other ships*. The *own ship*-related navigational failure are composed of failure in navigation and manoeuvring (11.7 %, failure in observation of fixed markers (8.4 %, failure in observation of equipment (2.4 % and failure in understanding of traffic situation (0.5 % (Kristiansen, 2004, p. 43).

Kujala et al. (2009) analysed maritime traffic in the Gulf of Finland from 1997 till 2003 and came up with a human failure contribution of 46 % for grounding accidents, which indeed represent a primary cause. Breaking down this human factor the majority of factors are related to navigational failures, for example crew being uncertain of the ship's position (40.5 %, misunderstanding of own vessel movement (wind, current etc.) (26.2 % and misunderstanding of other vessel's movement or intentions (2.4 %(Kujala et al., 2009, p. 1352).

In Figure 5.3 possible RIFs and indicators for the node "Navigation" are presented.

When navigating a ship through a fairway it demands continuous monitoring and supervision actions like supervising position, steering and controlling speed (Nilsson et al., 2009).

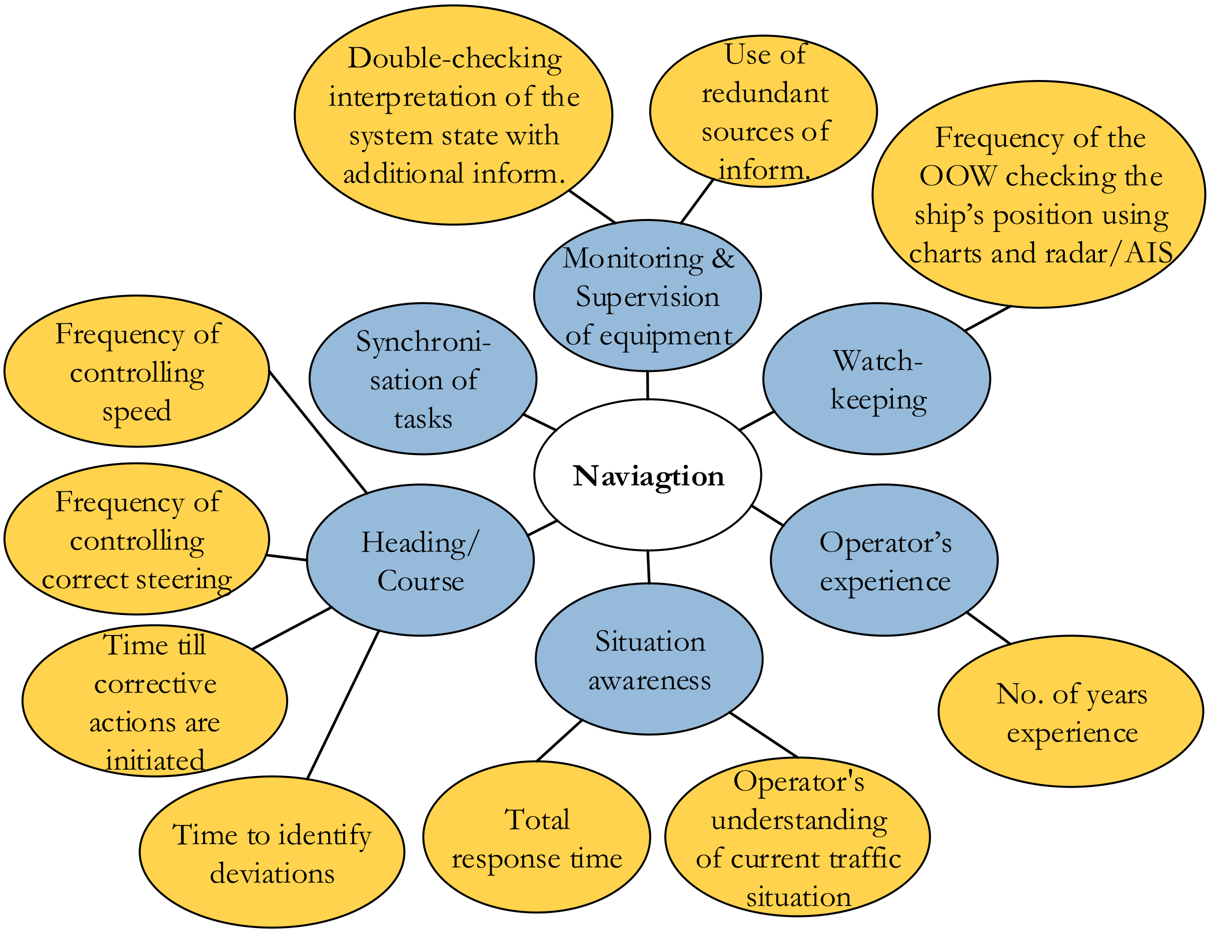


Figure 5.3: RIFs and indicators of the BBN node "Navigation"

This creates the complexity of the navigational task. In order to develop possible indicators for the RIF "Monitoring & supervision of equipment" a study of simulating operators behaviour in the main control room of a nuclear power plant by Norros and Nuutinen (2005) are used. Both tasks, ship navigation and control room operation, comprise a notable complexity within a socio-technical system.The development of indicators includes three interactions, which are the *way of decision making*, the *way of collaborating* and the *way of coping with problem situations* (Norros and Nuutinen, 2005, p. 336). The way of decision making which can be analysed by observing to what extent the crew has comprehended the situation-specific possibilities to act, the following indicators were included: "Use of redundant sources of information" and

"Confirm/double-checking the interpretation of the system state with additional information".

Studies within the maritime industry confirm that both aforementioned indicators are applicable for the maritime sector (Jie and Xian-Zhong, 2008; Kujala et al., 2009). Inaccurate or infrequent position monitoring as well as a lack of double-check by another method or person were observed (Jie and Xian-Zhong, 2008). Although mariners are charged with making navigation decisions based on all available information, a tendency to rely on either a favoured piece of equipment or the memory occurs (Rothblum, 2000). Deficits in using functions and alarms, automatic or manual data input as well as selecting the right mode may lead to casualties (Jie and Xian-Zhong, 2008). Furthermore, critical information may be lacking or incorrect leading to navigation errors, e.g. bridge supports often are not marked, or buoys are off-station (Rothblum, 2000). Based on that, indicators emphasising on the consideration of distinct information sources, double-check and the indicators developed from the RIFs "Observation" and "Heading" are important to include.

Quantifying the efficiency of navigational performance, often the operators' time for navigation through a predefined route, the so called total response time, is measured (Nilsson et al., 2009). The total response time also provides input on the situation awareness of the crew aboard, which can be defined as follows:

> "Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." (Wiersma and Mastenbroek, 1998, p. 80)

Different methods exist to measure situation awareness. The Situation Awareness Global Assessment Technique (SAGAT) represents a global tool for measurement of situation awareness in military aviation. The Situation Awareness Test was developed within the study by Wiersma and Mastenbroek (1998) to measure situation awareness of VTS (Vessel Traffic Service) operators. Subjective situational descriptions by the operators were analysed with a scoring system developed by different experts. Measuring situation awareness should cover the perception and comprehension of the current situation and projection of future status (Wiersma and Mastenbroek, 1998).

The navigational performance in connection with years of experience was subject in studies by Nilsson et al. (2009). The main outcome was that experienced navigation officers performed better on the conventional bridge than on a technically advanced bridge, whilst the opposite was the case for less experienced navigation officers. Although the introduction of a technical advanced navigation system lead to higher performance, it may incur higher operator fatigue. The study revealed moreover that several navigating officers left the autopilot in favour of a more manual approach, which can be explained with the human wish to maintain control (Nilsson et al., 2009).

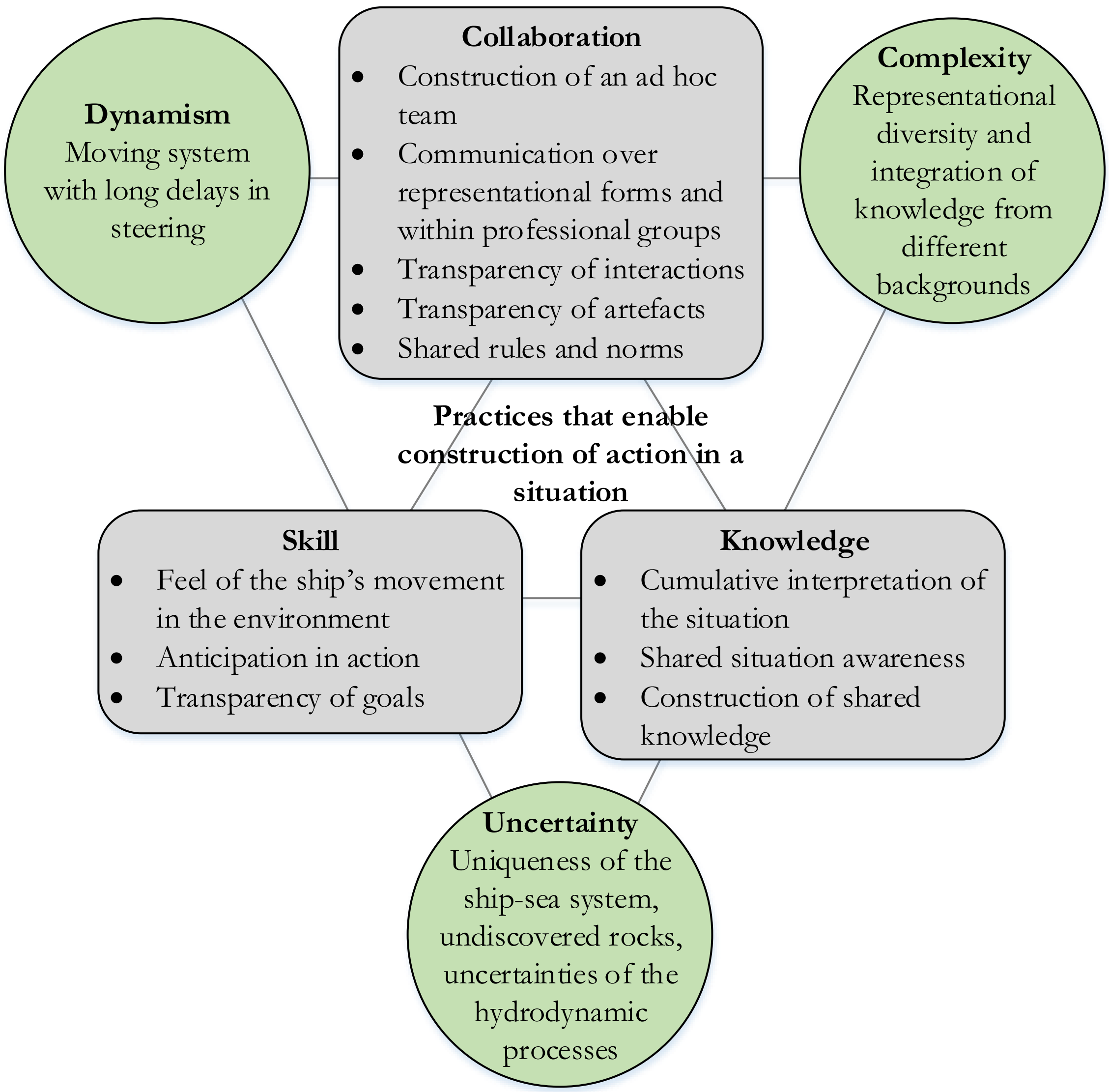


Figure 5.4: Core-task model of the piloting activity (Norros, 2004, p. 190)

The navigational task is influenced by a dynamic, complex and uncertain work environment (Norros, 2004; Nuutinen and Norros, 2009), which in turn requires particular qualifications of skills (*How to act?*), knowledge (*What to do?*) and collaboration (*How to share actions?*) (Figure 5.4). The BBN model also takes up this structure and represent skills by the node "Physical and Cognitive capabilities", knowledge by the node "Competence" and collaboration can be included in the node "Communication". Nuutinen and Norros (2009) developed 27 indicators, listed in Appendix C, to analyse the task of sea piloting. These indicators might be difficult to measure but they represent a structured way of accessing the piloting task which is a kind of navigation. Based on the working practice indicators, the RIF "Balancing between contradicting goals" was defined to include the way how the crew behaviour to manage the simultaneous workload.

5.2.2 Navigation system

Navigational systems aid the movement of a vessel from one place to another, e.g. radio, radar, GPS, AIS, alarms, which are going to be explained in more detail in this chapter. External navigational aids, e.g. lighthouses and buoys, are part of section 5.3.2.

Due to technical progress within the last decades the ship bridge equipment went through immense changes. With the introduction and implementation of computer aided systems the number of equipment specified by ISO-standards at the main work station increased from 22 to 40 items between 1990 and 2006 (Lützhöft et al., 2006). Although the general belief is that using new technology will improve safety, efficiency and economy, weaknesses are addressed by several authors like Nilsson et al. (2009), Lützhöft et al. (2006) and Jie and Xian-Zhong (2008).

The growing number of equipment results in an information overload and difficulties in achieving and maintaining situation awareness (Jie and Xian-Zhong, 2008). Learning on the job is often not possible and comprises inherent risk, e.g. integrity of watch-keeping. Therefore is practical experience rather gained by simulation training, but academies often cannot keep up to provide adequate training due to the annual market cycle of revision and ‘improvement’ of maritime technologies (Lützhöft, 2004). Thus, the majority of training centres cannot afford to renew their equipment every year.

Traditionally navigation was solely based on **nautical charts** representing the topography of the sea bed and water depth. Nowadays these paper charts are represented electronically using an Electronic Chart System (ECS). This allows an integration with other systems, for instance RADAR or AIS (Automatic Identification System). A standardised ECS which is compatible with other equipment mentioned in IMO guidelines, can be considered as an **Electronic Chart Display and Information Systems (ECDIS)**. This system is one integral instrument of an Integrated Navigation System onboard a ship. It is used to create, display and monitor the ship's route plan and provides detailed information about the position, course and speed of one's own and others ships in a chart context (Nilsson et al., 2009). This information had to be gathered before from different sources and conventional paper charts (Nilsson et al., 2009). Thus, ECDIS replaces paper charts and the necessity for manual plotting of position (Sauer et al., 2002). Information is presented in a central area on the bridge, so that the navigating officers do not need to leave their central supervisory position to retrieve chart information (Nilsson et al., 2009). Figure 5.5 illustrates the functions and information flow of an ECDIS.

Although seafaring benefits from ECDIS, it introduces at the same time related human, equipment and operational errors (Jie and Xian-Zhong, 2008). Over reliance in provided information by ECDIS need to be avoided, since it does not release the navigator from proper watch-keeping. Studies by Det Norske Veritas (DNV) show that the number of grounding accidents will be reduced by about a third through the use of ECDIS. The Norwegian Maritime Directorate is further convinced that ECDIS can make a significant contribution towards reducing about 75 % of all navigation related casualties. In fact, ECDIS implementation along with proper training already showed a reduction of grounding events by 40 % to 70 %. Studies by Nilsson et al. (2009), Donderi et al. (2004) and Gould et al. (2009) also confirm the lower workload and better performance when using ECDIS compared to separated displays. An independence of the factor speed of vessel and course-keeping performance of mariners was also discovered (Gould et al., 2009). Due to the high impact on both grounding and collision accidents, it might be reasonable to add a BBN node whether ECDIS is implemented aboard or not.

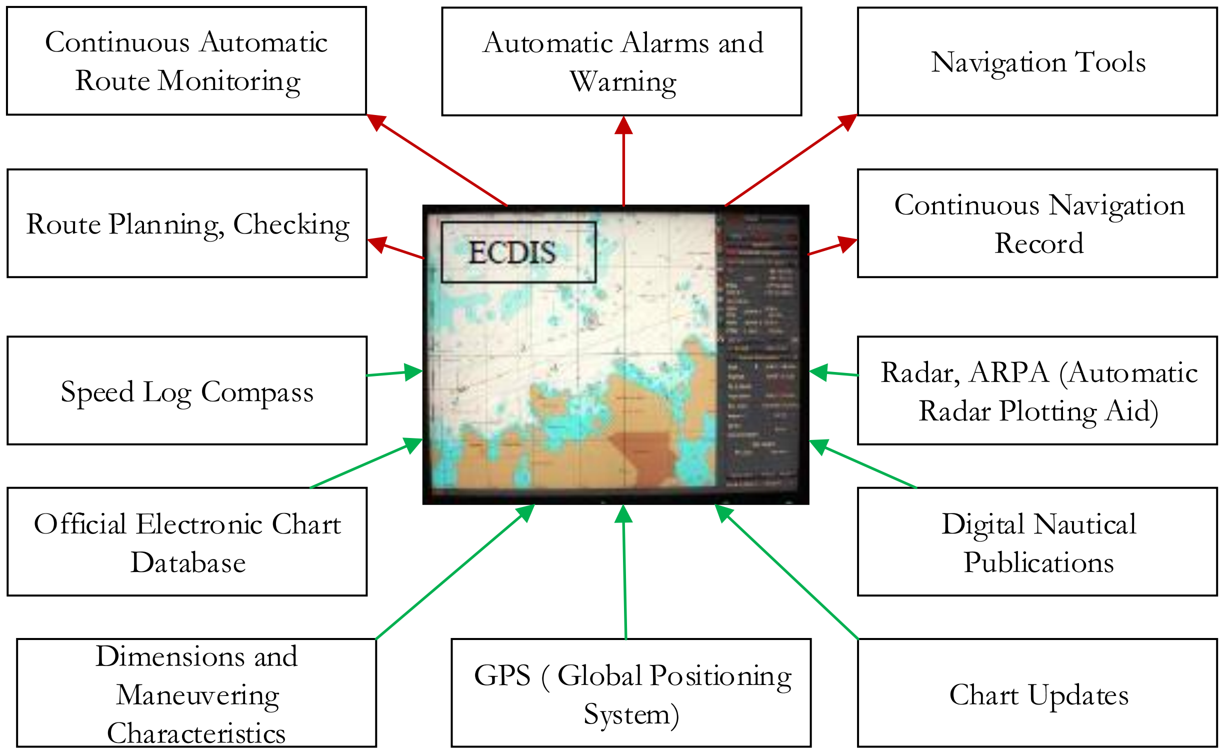


Figure 5.5: Functions and information flow in and out of an ECDIS (Nilsson, 2007)

ECDIS integrates position information from the Global Positioning System (GPS) or the Differential GPS (DGPS), and other navigational sensors, such as radar, Automatic Identification Systems (AIS) and autopilot (Jie and Xian-Zhong, 2008).

GPS (Global Positioning System) is a radio navigation system, which is based on satellites sending signals containing position information. These signals are in turn collected by a receiver on the ship and allow the system onboard to determine the ship's position. For more accurate data than the one provided by the GPS, the **DGPS (Differential GPS)** can be used. The DGPS-system is enhanced through an additional land-based reference station which sends information about reliability and corrections regarding the satellites in space. Thus, more precise position data is obtained (Nilsson, 2007). However, inaccurate input from the GPS- or DGPS-system is often caused by the relative position of the GPS antenna on board of especially large vessels. This poses a potential error source when viewing the vessel icon in ECDIS (Jie and Xian-Zhong, 2008). In Figure 5.6 therefore the RIF "Reliability" is shown indicating the aforementioned error due false sensor positioning ("Number of inaccurate input from sensor") and deviations due to equipment failures ("Number of deviations per equipment per month"). Furthermore, lacking maintenance influences the accuracy of sensors and equipment.

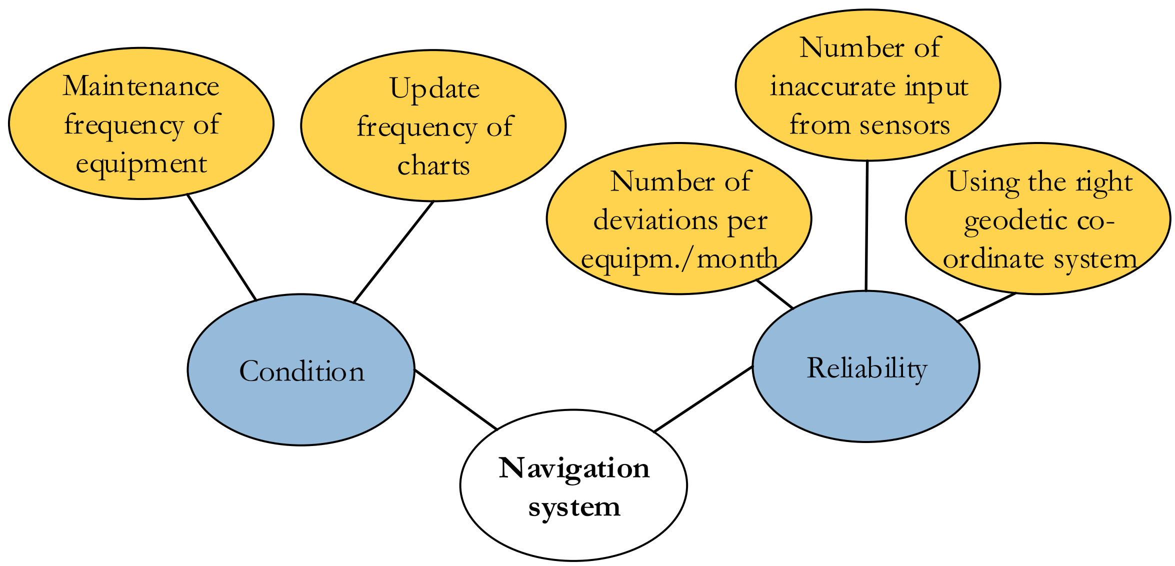


Figure 5.6: RIFs and indicators of the BBN node "Navigation system"

RADAR (Radio Detection And Ranging) is used for navigation and traffic control, providing information of the surroundings by sending out radio waves. These radio waves are reflected by different objects in the surroundings and then received. The distance and position of objects is then presented as an image at a screen.

Further data about other ships can be obtained by the **Automatic Information System (AIS)**. It provides continuous and autonomous information about other ships, e.g. identity, position, speed, course, destination and other data of critical interest for navigation safety and maritime security (Nilsson et al., 2009; Tetreault, 2005). The positioning system in AIS is based on GPS information (Nilsson, 2007). Possible ways of communicating information include ship-to-ship, ship-to-shore and shore-to-ship (Tetreault, 2005). All information is presented to the operator as a text display or integrated display with other navigation equipment, e.g. RADAR, **Automatic Radar Plotting Aid (ARPA)**, ECDIS or an Electronic Chart Systems) (Tetreault, 2005). ARPA is a collision warning system which is RADAR connected. It gives information about other ship's speed and course and provide thereby information about the current traffic situation and how it is changing due to other ships (Nilsson, 2007).

Another crucial point is working with different geodetic co-ordinate systems. Due to misunderstanding and lack of training the wrong choice of datum can lead to severe navigational deviations. As ECDIS is totally dependent on GPS- or DGPS-signal, the choice of chart datum influences the accuracy of the system significantly (Jie and Xian-Zhong, 2008).

As mentioned in section 5.2.1 a tendency to rely on a favoured piece of equipment among mariners was observed (Rothblum, 2000). In the following study pilots were ask to spontaneously mention the most important navigation instrument. Surprisingly none of them asked for a picture of the bridge layout (Nilsson, 2007, p. 40). Pilots gave the highest priority to the RADAR, (D)GPS, ENC (ECDIS) and AIS. With RADAR being the most valued navigation instrument. The lower ratings of (D)GPS, ENC (ECDIS) and AIS may represent personal differences. Often the preferences depend on the individual 'style' of the navigator rather than on available equipment on the bridge (Norros, 2004). This could lead to a 'irrational' choice of equipment and lacking navigational performance. Working in a complex environment with a high pace of change may therefore lead to resistance to use new equipment, and instead create the strategy 'you do what you have always done' (Nilsson, 2007).

Consequently a simplification of the BBN model can be suggested in joining the nodes "Navigational aids" and "Navigation system". The technical condition of the navigational aids can be evaluated through measuring the frequency of chart updates and assessing the maintenance of the overall navigational system.

5.2.3 Bridge Design

Ship bridges are control centres to operate and manage a ship. Bridge management teams are confronted with many interfaces depicting information about the ship and maritime environment. This demands on one hand a certain cognitive ability, for instance supervision and monitoring of technical systems, steering the ships under consideration of variable environmental conditions (more information in section 5.2.11). On the other hand, operators have to deal with managing cargo, personnel and communication with traffic control centres, the ship owner, charterer and other ships simultaneously (Brüggemann and Strohschneider, 2009).

For that reason Integrated Bridges System (IBS) are installed to allow an interconnection of different instruments and data exchange in various ways. This creates a centralised information access as well as command and control actions from the bridge to increase safety and efficiency in ship management (Lützhöft, 2004). In Figure 5.7 such a ship bridge is presented.

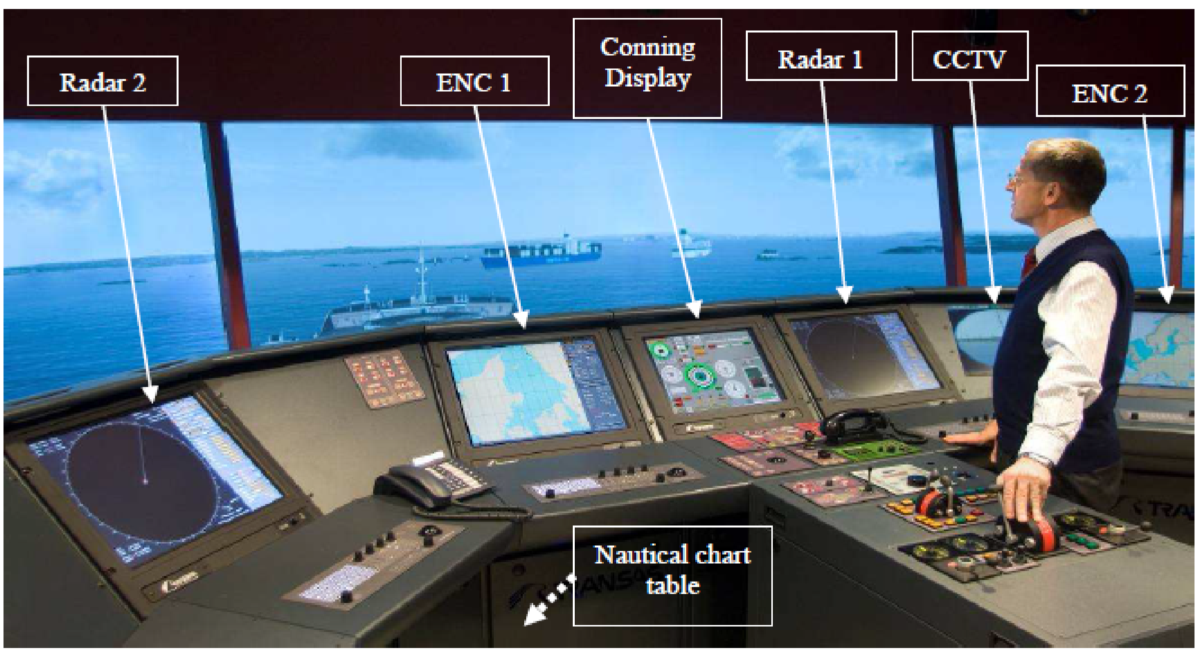


Figure 5.7: Layout of a ship bridge and positions of instruments (Nilsson, 2007)

In the centre, instruments and controls for navigation are shown. Electronic Navigation Charts (ENC) and RADARs are available on both sides of the centre table. The conning display in the middle of the displays provides information about the ship like speed, draught and course. CCTV (Closed Circuit Television) is a monitor used to show the function of binoculars in a simulator. (The table for nautical charts is not shown in Figure 5.7, since it is placed right beneath the position of the camera taking the picture.)

After presenting the typical bridge layout, the next part concentrates on the design related issues. Figure 5.8 shows the identified RIFs and indicators, which are further explained in the text.

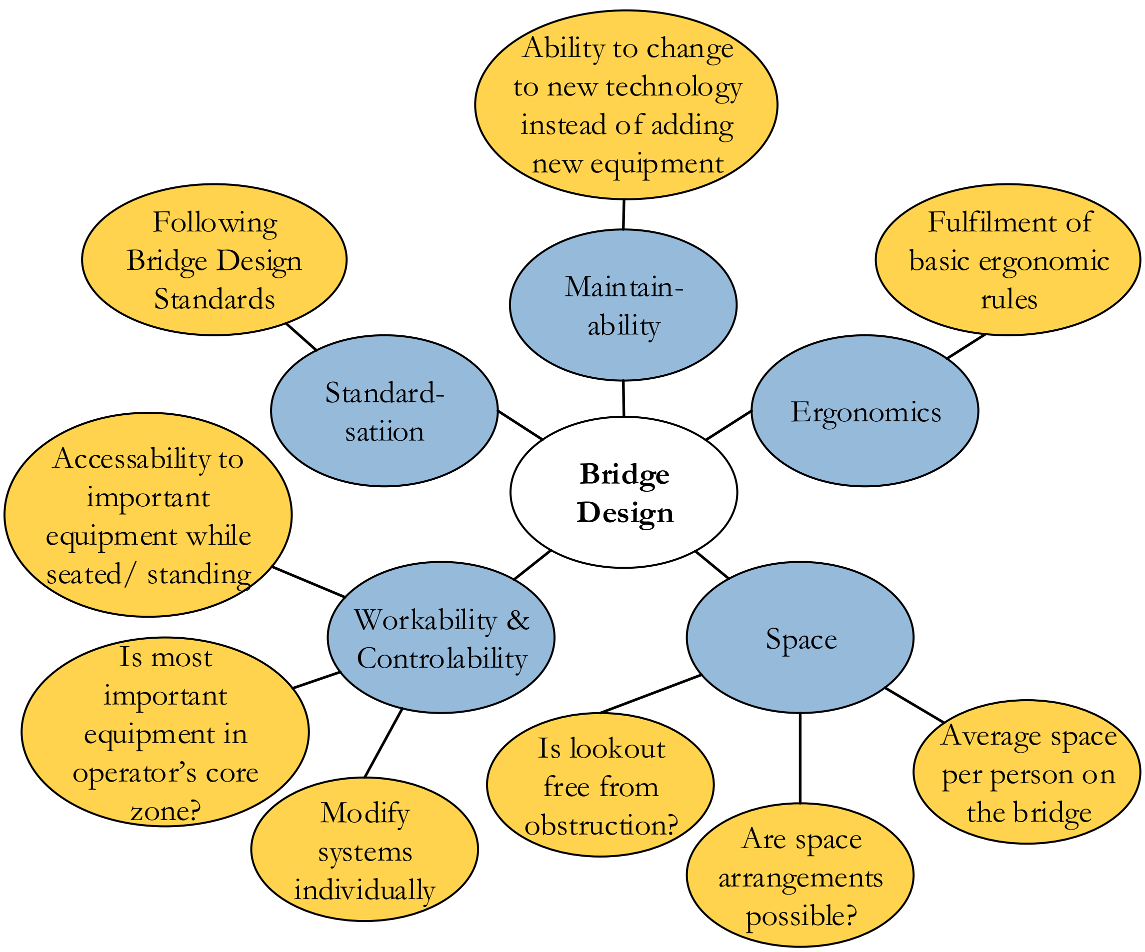


Figure 5.8: RIFs and indicators of the BBN node "Bridge Design"

First of all it is important to notice that there exist no standard design of ship bridges in general. Regulatory bodies only assist with guidelines and rules. This in combination with the fact that every ship bridge is unique adjusted over years of use by building in new equipment, leads to lose the focus on the end user.

The user-centred design (UCD)(Costa and Lützhöft, 2014) or human-centred design (HCD) (Rothblum, 2000) play therefore a central role when it comes to both bridge and navigation system design. UCD describes the process of applying human factors knowledge to design. That is, to take into account human capabilities and limitations at each stage of the design process (Costa and Lützhöft, 2014). However, the development of ship bridges is rather a technical-driven approach than user-oriented accompanied by the permanent expansion of rules and regulations by international bodies (Lützhöft, 2004).

In order to illustrate this some points are presented based on the SOLAS (International Convention for the Safety of Life at Sea) Regulation V/15 on Principles relating to bridge design, design and arrangement of navigational systems and equipment and bridge procedures (Lützhöft, 2004, p. 9):

All decisions [...] shall be taken with the aim of:

1. Facilitating the tasks to be performed by the bridge team and the pilot in making full appraisal of the situation and in navigating the ship safely under all operational conditions;

2. Promoting effective and safe bridge resource management;

3. Enabling the bridge team and the pilot to have convenient and continuous access to essential information which is presented in a clear and unambiguous manner, using standardized symbols and coding systems for controls and displays;

4. Indicating the operational status of automated functions and integrated components, systems and/or sub-systems;

5. Allowing for expeditious, continuous and effective information processing and decision-making by the bridge team and the pilot;

6. Preventing or minimizing excessive or unnecessary work and any conditions or distractions on the bridge which may cause fatigue or interfere with the vigilance of the bridge team and the pilot;

7. Minimizing the risk of human error and detecting such error if it occurs, through monitoring and alarm systems, in time for the bridge team and the pilot to take appropriate action.

However, in reality, IBS are not focused on the end user. This is reflected especially in a lack of dedicated space which does not facilitate work with paper charts or notebooks (Lützhöft, 2004). For that reason the indicators "Modify systems individually" as well as "Are space arrangements possible?" are listed in Figure 5.8. This might also have an influence on the "Use of redundant source of information" which is mentioned as an indicator in section 5.2.1.

Studies have shown that through UCD the human errors can be reduced significantly (Rothblum, 2000). Costa and Lützhöft (2014) identify benefits of UCD for seafarers:

- **Workability, Physical Ergonomics & Usability:** focussing on users, tasks, equipment, procedures, work environment e.g. positioning screens properly for reducing useless motions, creating intuitive systems, variable systems that can adapt to the individual (developed indicators: "Is most important equipment in core zone of operator?", "Accessibility to important equipment while being seated/ standing")

- **Harmonisation & Standardisation of bridge layout and equipment:** avoiding incongruence due to building in instruments produced by different manufacturers, standardising hardware and software, allowing for individualised profiles to support familiarity, avoidance of misunderstandings (developed indicators: "Following Bridge Design Standards")

- **Maintainability:** arranging space for change, considering the lifecycle of the ship (i.e. instead of adding a lot of new hardware, existing hardware should be adaptable to change) (developed indicator: "Ability to change to new technology instead of adding new equipment")

A central point when designing a ship bridge is ergonomics, which is defined by the International Ergonomics Association (IEC) as follows:

> "Ergonomics is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance." (International Ergonomics Association, 2016)

Since crews today are considerably diverse and change ships frequently, the design must account for every possible user (Costa and Lützhöft, 2014). The fulfilment of basic ergonomic rules is therefore important. Indicators, such as "Average space per person on the bridge", "Fulfilment of basic ergonomic rules" and "Is the lookout free from obstructions", help to assess the work surroundings.

5.2.4 Navigation system design

The previous sections focussed already on navigation systems (section 5.2.2) and their arrangement in the ship bridge (section 5.2.3). This part will now deal with design requirements related to displays and interface design.

Maritime accidents caused by poor design of automation account for around a third of major marine casualties (based on Wagenaar W.A. and Groeneweg J., 1987 as quoted in Rothblum, 2000). For instance, a misinterpretation of RADAR displays may cause ship collisions, poorly designed overfill devices can result in oil spills and poor design of bow thrusters may lead to allisions (Rothblum, 2000). The growing number of screens and systems contributes furthermore to information overload and makes achieving situation awareness more difficult (Zhang et al., 2013).

As already introduced in section 5.2.3, user-centred design is regarded as the solution to develop technology that will support the operators' task (Rothblum, 2000). The implementation of adaptable equipment represents one solution, including e.g. multifunction display/mode switching and multifunction input for a flexible use (Costa and Lützhöft, 2014). Based on that the indicator "Mode switching opportunity" is included in Figure 5.9.

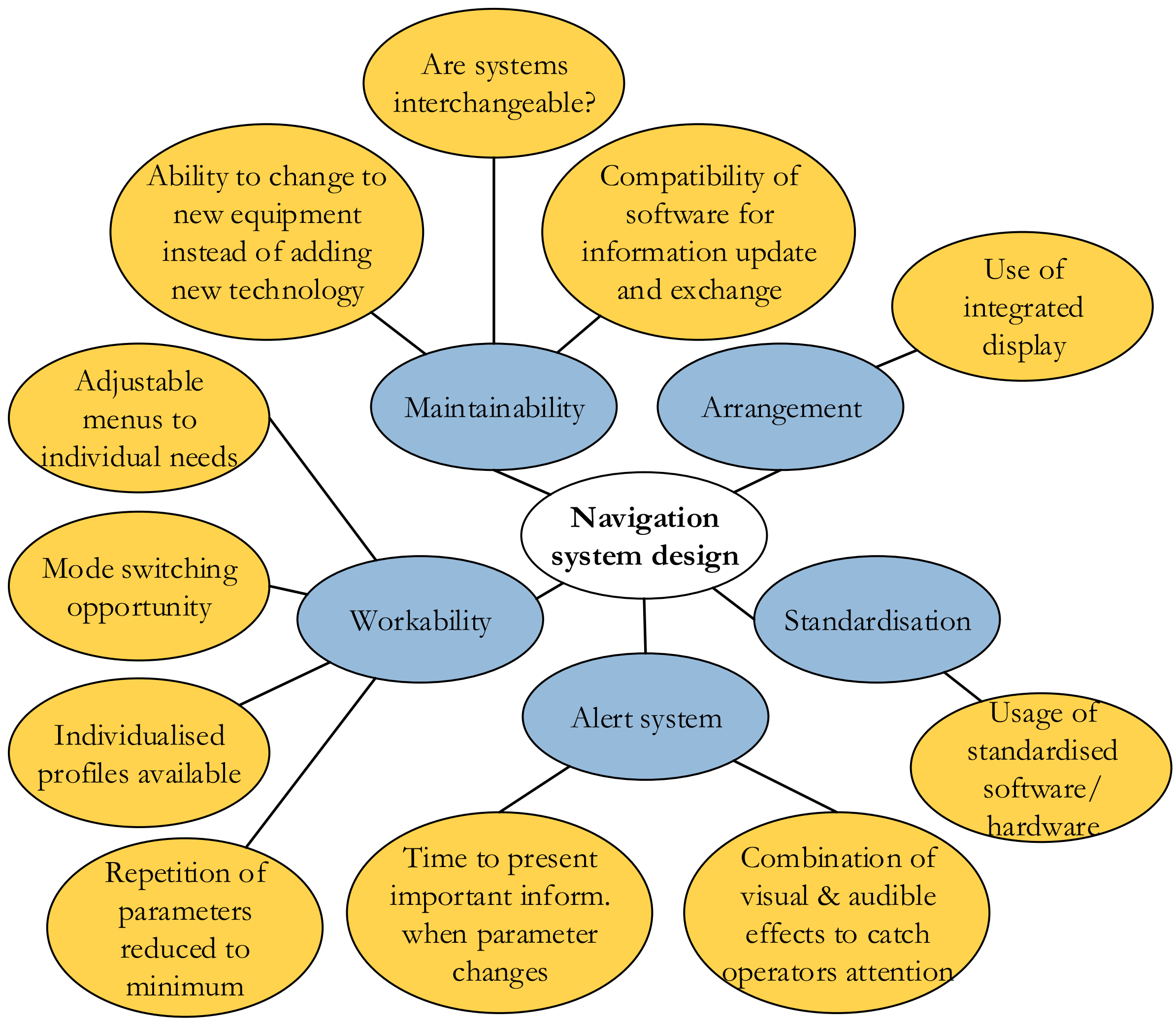


Figure 5.9: RIFs and indicators of the BBN node "Navigation system design"

In order to prevent information overload not all parameters on displays are important all the time and should be filtered accordingly (Costa and Lützhöft, 2014). Thus, indicators like "Repetition of parameters is reduced to minimum" and "Adjustable menus to individual needs" are defined. The indicators "Are systems interchangeable?" and "Ability to change to new equipment instead of adding new technology" consider ships lifespan. Instead of adding a new piece of hardware when software outdated, equipment should be adaptable to change.

A lack of standardised equipment and manufacturer-specific parameters represent another challenge for the bridge team. Harmonised hardware and software combined with individualised profiles would support familiarity, save time and avoid misunderstandings (Costa and Lützhöft, 2014). Thus, the following indicators were developed: "Usage of standardised software/ hardware" and "Individualised profiles available". The "Compatibility of software for information update and exchange" represents the integration of different equipment and interfaces, including e.g. communication facilities, controls, displays, alarms and lights. The user should be able control several systems with only one device.

Many authors highlight the advantages of such an integrated display design (Costa and Lützhöft, 2014; Sauer et al., 2002; Nilsson et al., 2009), but a spatially separate display interface design resembles most closely current ship bridges. The results show a slight navigational advantage (reduced cross track error) of integrated displays over functionally-separate and spatially separate displays (Sauer et al., 2002). However, it also incurred fatigue and the occurrence of more complex scenarios were associated with increased workload and reduced performance and situation awareness. It is moreover shown that the spatial display is preferred over a single physical source with sequential switching (temporal integration) when it comes to retrieve simultaneous information (Sauer et al., 2002). One factor may be the greater *visual momentum* (Wickens 1992, as quoted in Sauer et al., 2002) for spatially separate display, facilitating more easily the transition between different displays. Another study by Nilsson et al. (2009) supports that integrated navigation system by using conning display improve the response time. A conning display shows ship characteristics, for example heading, speed and draught on one screen. Information displayed on the conning display could also be found at other locations on the ship bridge. Based on these studies the "Use of integrated display" as an indicator is included.

Ahlstrom (2015) studies how weather display symbology affects plane pilot's behaviour and decision-making. The results prove an existing correlation between symbol discriminability and pilot behaviour dependent on different symbol elements. Particularly challenges of colour selection providing sufficient luminance contrast and legibility regardless of the background were identified. Other human factor issues, like salience, colour recognition and training, are always present as long as users have to interpret symbols. Thus, Ahlstrom (2015) suggests in the case of weather displays not to solely relying on weather symbology. Rather to use weather data to automatically track hazardous conditions and alert pilots of potential weather conflicts or changes. This leads to the development of the following indicators: "Time to present important information when parameter changes" and "Combination of visual and audible effects to catch operators attention".

5.2.5 Propulsion

A loss of the propulsion system describes the ship's inability to propel through water due to e.g. loss of boiler, turbine, main diesel, loss of propeller, broken shaft, which eventually could result in a drift grounding accident.

Failure rates for propulsion and steering are often categorised by ship type, engine type and ship size. Therefore, a direct influence from vessel age to both, steering and propulsion, can be drawn. Eide et al. (2007) rates on average 0.26 failures per ship-year for all kind of ships, but points to significant variations due to the abovementioned factors. In Mitja et al. (2007) the probability of failure of propulsion is 0.14 per ship year. Redundancy represent an other influencing factor, since two main engines reduce the probability of a total loss of propulsion significantly (Eide et al., 2007). Mitja et al. (2007) lists the values: probability of not starting or remaining in operation of the redundant propulsion system 0.03 and probability of redundant system not fulfilling 72 h mission 0.09.

5.2.6 Steering

The loss of steering results in the ship's inability to control the rudder, e.g. steering gear/motor, jammed or lost rudder, which can lead to a drift grounding accident. Steering affects the manoeuvrability of a vessel and thus the navigation. Therefore, an influence arrow can be drawn from steering to navigation. Fowler and Sørgård (2000) gives an overview of the frequency (per 10,000 Ship-hours) for machinery and steering failures (Table 5.1).

Table 5.1: Frequency (per 10,000 ship-hours) for machinery and steering failures for three ship size categories (kdwt: 1000 deadweight tonnes) (Fowler and Sørgård, 2000)

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

5.2.7 Age of the Ship

Ship age is one of the most important characteristics of a vessel, since it might be generally assumed that the relationship between vessel age and its safety level is negative.

Cariou et al. (2008) state that the probability of belonging to the 'always deficient' group, implying that at least one deficiency was always noted during Port State Control inspections, is highest for vessels between 25 and 30 years.

Investigation by Samuelides et al. (2009) prove as well that older ships (21–30 and 30+ years old) contribute the most to grounding accidents, shown in Figure 5.10. Younger vessels (1-10 years old) present the smallest problems with groundings. This might be due to the advanced navigational equipment onboard of new ships. Therefore an influence arrow can be drawn from age of ship to navigation system.

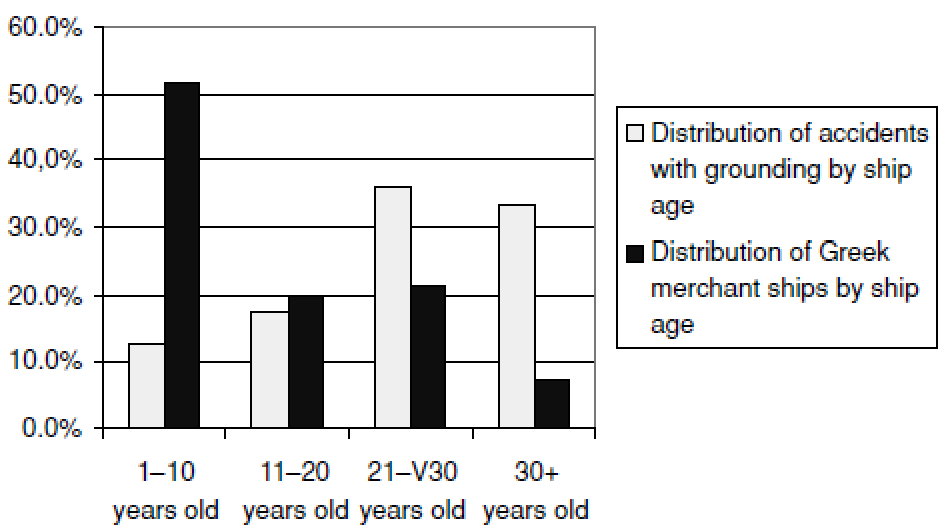


Figure 5.10: Groundings and fleet in relation to ship age (Samuelides et al., 2009)

In contrast, Li et al. (2014b) state that "an increase in vessel age is associated with an increase in the vessel safety level" (Li et al., 2014b, p. 81). Explicitly mentioned is the increase by 0.001 of the safety level per ship year, as shown in Figure 5.11. The higher the safety index value, the better the vessel's safety level. The scaling defines 0.9-1 as the highest safety level (i.e. probability of an accident is the lowest), 0.8–0.9 as average, and less than 0.8 as the lowest safety level with the highest probability of accidents. This may be explained by the 'selection effect', meaning that only vessels in a good operational state based on proven quality or good maintenance are still functioning after two or three decades (Cariou et al., 2008).

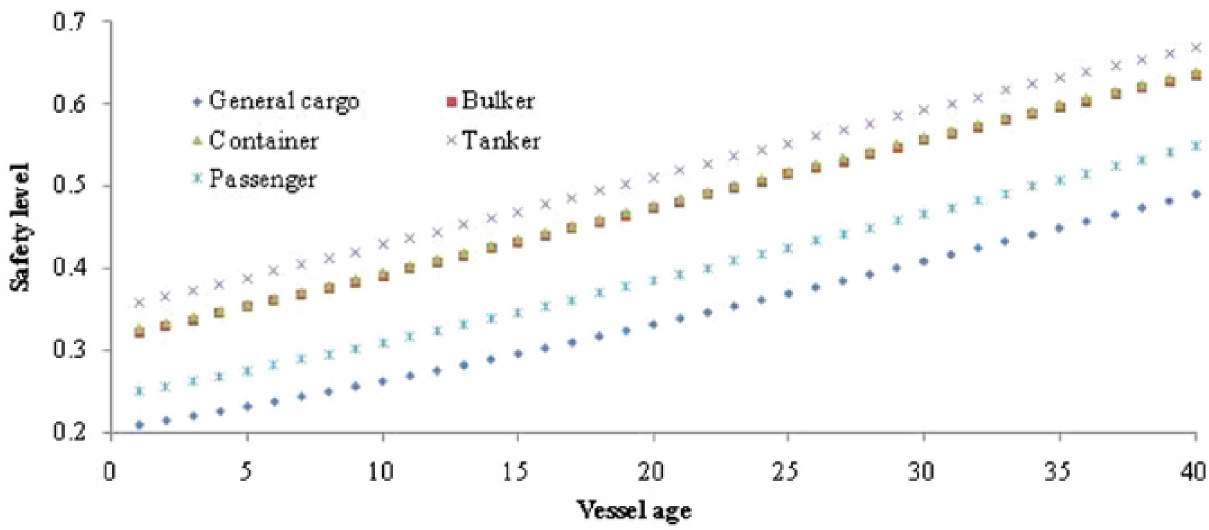


Figure 5.11: Effect of vessel age and vessel type on safety level (Li et al., 2014b)

Analyses by Li et al. (2014a) state that with increased ship age the occurrence probability of a total loss decreases. The total loss probabilities of new, medium and old vessels will be 12.61 %, 12.87 % and 10.70 % respectively. This may reflect the fact that vessel owners pay more attention to improve the safety level of older vessels than those of younger ones. Since some authors identify a positive and others a negative relation between ship age and accidents, it might be concluded that age has a limited influence or a relatively low impact on the occurrence of grounding accidents.

5.2.8 Size of vessel

The size of vessel is often characterised by Gross Tonnage (GT). Zhang et al. (2013) refers to values from the navigational risk index which increase consistently with growing ship size. The following categories were defined: 300 or less , 301 – 1000, 1001 – 2000, 2001 – 5000 and over 5000 GT. It is concluded to focus on large ships, e.g. ships greater than 2000 GT, to prevent large losses due to marine accidents.

With increased vessel size, manoeuvrability can decrease and thus lead to a greater chance that accidents occur (Li et al., 2014a). Li et al. (2014b), who investigate the relation between safety level and ship size, conclude that the safety level decreases with increasing ship size. This relation is shown in Figure 5.12. In numerical terms, the safety level decreases by 0.008 % with the gross tonnage increase of 1 %.

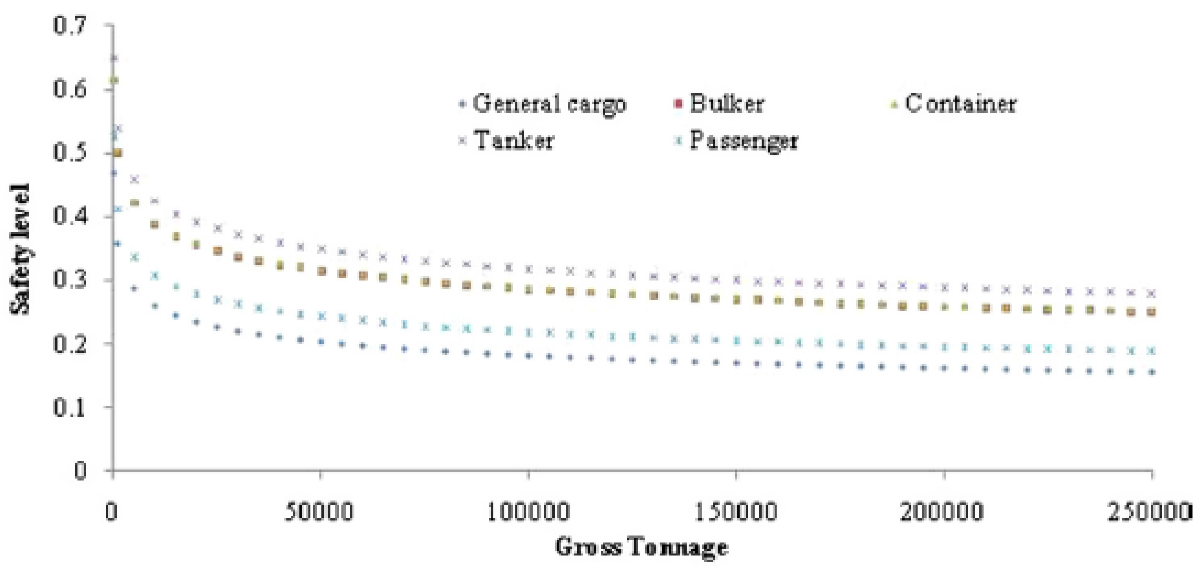


Figure 5.12: Effect of tonnage and vessel type on the safety level (Li et al., 2014b)

In Figure 5.13 the distribution of groundings with regard to ship size and the respective distribution of the Greek merchant fleet from 1992 to 2005 is shown. Most groundings happened to vessels between 100 and 1000 GT, which account for more than 50 % of the Greek fleet. It is shown, furthermore, that larger ships (>30,000 GT) give the best performance records. This could be explained by the fact that smaller ships usually operate closer to ports and coasts,

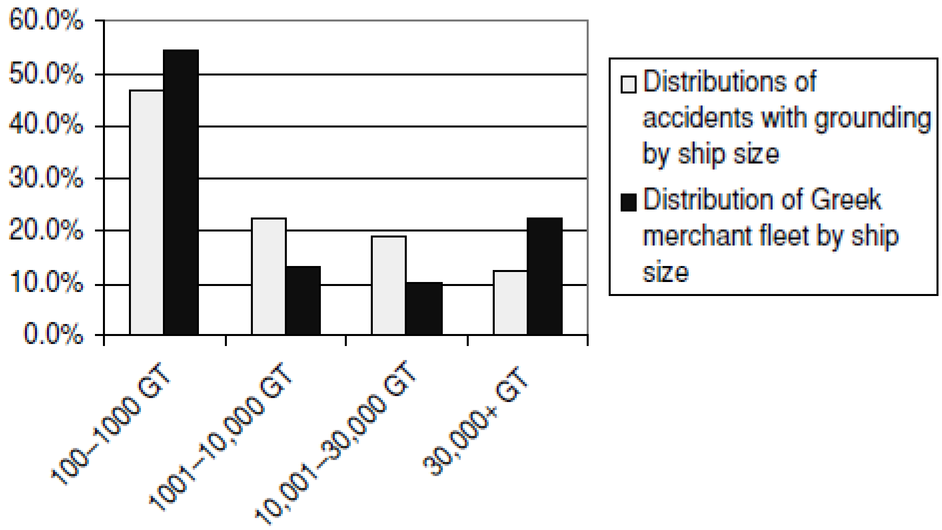


Figure 5.13: Groundings and fleet in relation to size (GT) (Samuelides et al., 2009)

where the probability of a grounding occurrence is proven to be more significant (Psaraftis et al. 1998 quoted in Samuelides et al., 2009). Another reason might be the advanced navigational aids that big ships carry on board.

Samuelides et al. (2009) evaluated the Greek fleet from 2001 to 2005. Here, the small ships (> 500 GT) and large ships (< 30,000 GT) present a lower probability of grounding than the rest. This is explained by the lower draught of small ships and the better equipment of large ships.

However, by particularly analysing the Greek fleet (1992-2005) implies growing vessel size more likely to be involved in a grounding accident than in any other types of marine accidents (Samuelides et al., 2009). The 10 accidents of small ships (100–1000 GT) comprise 4.2 grounding events and 5.8 other types of accidents, whereas 6.7 groundings and 3.3 other types of accidents involving large ship (30,000+ GT).

Eventually, it seems that the occurrence of groundings rises with the size of the vessel, even if scattered sample sizes may give other results. That smaller ships have a higher probability to run aground might be more related to their operating area which is usually near the coastline.

5.2.9 Competence

By fulfilment of basic training requirements a maritime operator is certified with a certain competence. This is however basically premised on knowledge about a technical system. Incrementally recognises the International Maritime Organization (IMO) the increased need for non-technical skills and competences.

The Standards of Training Certification and Watchkeeping for seafarers (STCW) specify a required level of training of seafarers. Hetherington et al. (2006) criticise however, that the STCW code does little to suggest what the human behaviour skills may be or what an adequate level of competence is. Gatfield (2006) agrees and highlights that the competence assessment criteria which are just based on generalised statements of performance outputs, are highly subjective and freely interpretable.

Studies show that 35 % of casualties are due to lacking general technical knowledge. The main contributor to this category is especially insufficient knowledge of proper use of technology, such as RADAR (Rothblum, 2000). Mariners often do not understand how the automation works or under what set of operating conditions it was designed to work effectively. This results in errors while using the equipment, creates dependability on a certain instrument and obviates the use of various sources to gather information. Another reason is the job rotation, which entails many difficulties for crews and pilots who have to deal with ships of different size, varying equipment and transporting different cargoes. The lack of ship-specific knowledge was mentioned as a problem by 78 % of the mariners. A combination of better training, standardised equipment design, and an overhaul of the present method of assigning crew to ships can help to solve this problem (Rothblum, 2000).

Training plays a key role when it comes to gain and maintain competence (Wiersma and Mastenbroek, 1998). The training of VTS operators comprises an extensive simulator training with equipment and communication protocols as well as on-the-job training in order to establish a high level of professional competence. Obligatory and regular re-qualification examinations ensure moreover that competence level is maintained and operators keep up with new developments in equipment and procedures (Wiersma and Mastenbroek, 1998). Therefore the factors "Knowledge" and "Training" as well as their indicators are defined in Figure 5.14.

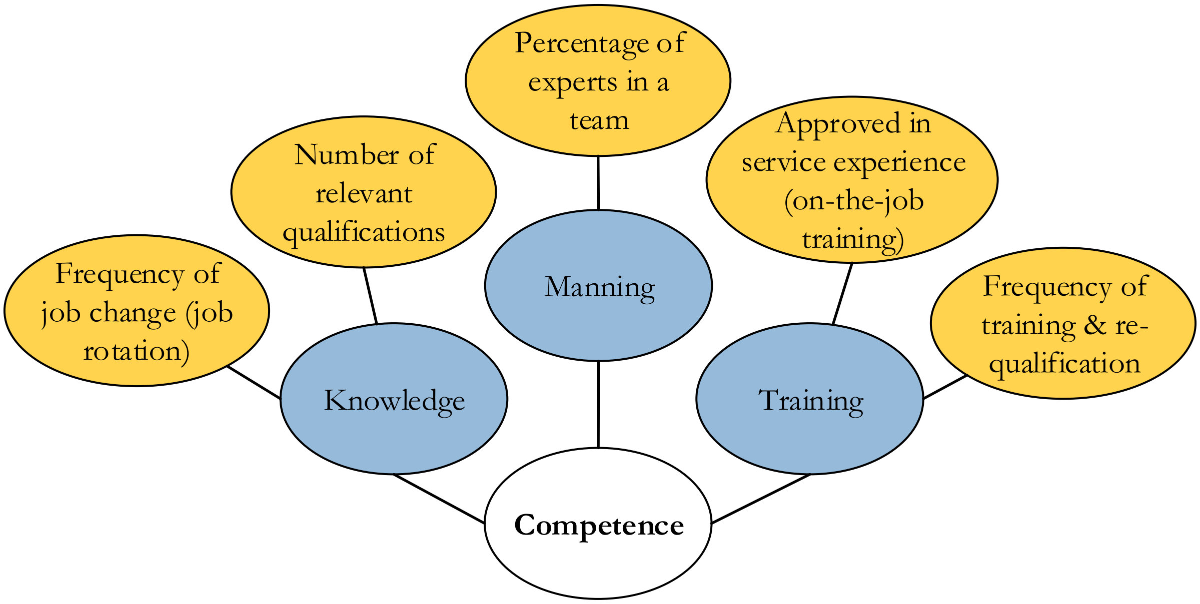


Figure 5.14: RIFs and indicators of the BBN node "Competence"

The influence of experience on crew's performance depending on the bridge type was studied by Nilsson et al. (2009). The results show that the performance of teams with no experts improved from the conventional to the advanced bridge, whereas the reverse was true for teams with at least one expert. Performance of teams with two experts was worse on both bridges. It can be concluded that an advanced bridge is an advantage for rather inexperienced mariners.

One reason for this could be the importance of habits and work strategies in relation to existing technology. Experienced mariners already developed their skills and strategies, which may be difficult to transfer them to a new (advanced) bridge type. Hence, the advanced bridge "would not differ from the less advanced, when the more experienced navigating officer is trying to apply established work strategies" (Nilsson et al., 2009, p.196). This would lead to the presumption to rather improve training and teamwork than equipment.

5.2.10 Communication

Communication can be described as a core skill which influences situation awareness, working behaviour as well as effective decision making (Hetherington et al., 2006).

Studies document that in 42 % of incidents misunderstandings or lack of communication between pilot and master or the officer of watch (OOW) are involved. Especially language problems are mentioned as a crucial factor, due to different nationalities and language diversities onboard (Hetherington et al., 2006). Although STCW specify a required level of fluency in the ship's declared language, in practice there is solely compliance with "the unavoidable minimum requirements in terms of communication" (Hetherington et al., 2006, p. 406). Although agreeing on a working language, studies found out that the consequences of miscommunication ranged from mild annoyance to formation of potentially hazardous situations (Hetherington et al., 2006).

Rothblum (2000) refers to the National Transportation Safety Board report which states that 70 % of major marine collisions and allisions occurred while a pilot was directing one or both vessels. This shows inadequate communication between shipmates, masters and pilots, ship-to ship and ship-to-VTS. Hence, the implementation of a Bridge Resource Management (BRM) as well as better procedures and training shall create better communication (Rothblum, 2000).

Bridge Resource Management (BRM) is an organisational tool which teaches officers about working as a bridge team. Participants become more aware of the different ways that humans think, solve problems and teamwork (Lützhöft, 2004). Even though strong bridge teams are developed, a reoccurring challenge in compensating the absence of team members and in including new members (a person or new technology) still exists. For instance ECDIS appeares to improve navigation performance compared to navigation using paper charts, but leading to a reductions in task-related communication on the bridge (Gould et al., 2009). Hänninen and Kujala (2012) state that a BRM has a rather minor effect on the probability of ship collisions modelled with a BBN.

Gatfield (2006) develops "behavioural markers" for a maritime assessment framework. Behavioural markers represent basically what here is referred to as indicators, for instance (Gatfield, 2006, p. 16):

- Ratio of the degree of feedback control to the degree of predictive control (indication of the level of situational awareness)
- Number of unfinished sentences
- Number of alternative hypotheses and actions communicated to team members
- Communicating in a way that shares ones mental model

Although these indicators give a good approach on how to assess the factor communication, to measure them might not be practically possible in this context. Therefore they are illustrated in Figure 5.15 with dashed arrows.

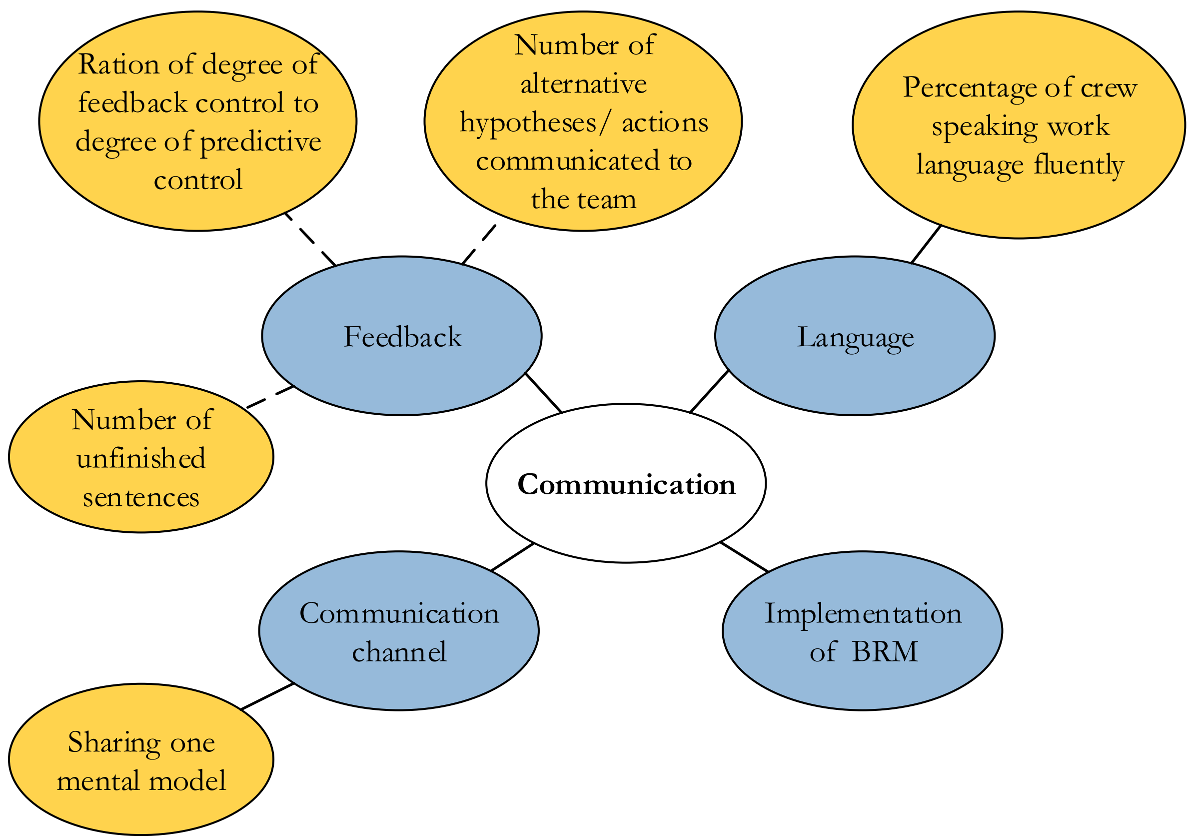


Figure 5.15: RIFs and indicators of the BBN node "Communication"

5.2.11 Physical and cognitive capabilities

Physical and cognitive capabilities describe the functional capacities of operators to undertake physical and mental tasks.

A paper by Wolbers and Hegarty (2010) gives valuable input on a psychological view by trying the answer the question "*What determines our navigational abilities?*". Spatial navigation can be categorised into external representations, such as based on maps or diagrams and internal representations derived from sensory experience. Ship navigation is mainly based on external representations. Even though Wolbers and Hegarty (2010) focus more on internal representations, some aspects are also interesting for ship navigation.

Internal representations includes the percipience of multiple sensory cues, creating and maintaining spatial representations in short- and long-term memory as well as using these representations to perform a navigational task.

In the following main factors which influence the ability to navigate are further explained. The derived RIFs and indicators are shown in Figure 5.16.

- **Navigational strategies:** Some people prefer featural cues and landmarks to maintain orientation and to infer spatial relationships, others focus on geometric properties such as the layout of an environment. Other strategies are related to how people gather spatial information, e.g. route-based strategy or cognitive mapping.

  Good navigators need fewer cues to orientate themselves. They are able to switch flexibly between navigational strategies based on information availability, task demands and the reliability of available cues (Wolbers and Hegarty, 2010).

- **Self-motion perception:** The accuracy with which people keep track of their orientation and position relative to the environment also influences their ability to navigate themselves.

- **Age:** At later stages in life, individual differences in navigational abilities are particularly salient. A study, analysing how aging humans navigate through a virtual water maze, revealed that often inefficient search strategies are used. Moreover, the test persons took longer to find the platform and travelled a longer distances in the first trial when spatial representations were yet to be formed.

- **Experience:** No clear evidence is explored yet by researches which proves that extensive navigational experience lead to acquire new spatial representations more easily or accurately. For now, research only proves that extensive navigational experience leads to structural changes in the brain.

- **Gender:** Qualitative differences in orientation and navigation of women and men were discovered. Whereas women typically use local landmarks and familiar routes to orientate themselves, men prefer cardinal directions, environmental geometry and metric distances. Women also require more environmental cues to remain oriented in an environment and have difficulty following navigation directions based on cardinal directions and metric distances. "In terms of causal factors, there is increasing evidence for the influence of sex hormones on navigational performance, and several evolutionary theories have been proposed. However, men and women also differ in navigational experience and there is some evidence that wayfinding anxiety mediates the differences between the sexes in navigational performance" (Wolbers and Hegarty, 2010, p.140)

Fatigue can also be classified into the physical and cognitive (mental) category (Akhtar and Utne, 2014). Studies on the topic critical vessel casualties and personnel injuries, identify that fatigue contributed to 16% of the vessel casualties and 33% of the injuries (Rothblum, 2000). Mental fatigue is believed to be psychological in nature. Physical fatigue in contrast is related to muscle fatigue (Lal and Craig, 2001). Both physical and mental fatigue cause decreased alertness, mental concentration and motivation. The speed of cognitive processing is reduced and lead to weariness, increased reaction time as well as lower vigilance (Sneddon et al., 2013).

Dorrian et al. (2011) use the *7 point Samn-Perelli Fatigue Scale* to rate workers level of fatigue within the Australian Railway Branch. The scale rates: 1 = fully alert, wide awake; 2 = very lively, responsive, but not at peak; 3 = okay, somewhat fresh; 4 = a little tired, less than fresh; 5 = moderately tired, let down; 6 = extremely tired, very difficult to concentrate; 7 = Completely exhausted, unable to function effectively.

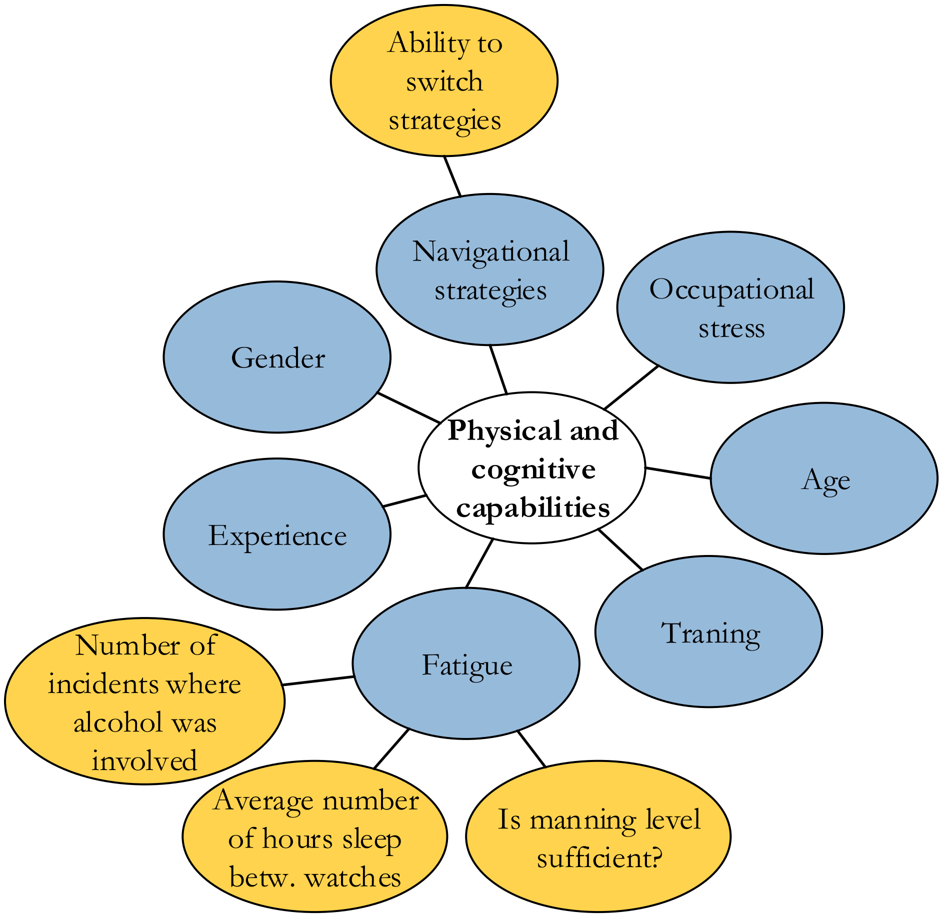


Figure 5.16: RIFs and indicators of the BBN node "Physical & Cognitive capabilities"

The study reveals an average fatigue level of 4 *a little tired, less than fresh* which is concluded to be within the limits. However, participants received 5h or less sleep in the prior 24h on 13 %, were awake for at least 16 h at the end of 16 % and worked at least 10h on 7 % of shifts. On 13 % of shifts workers reported state 6 *extremely tired, very difficult to concentrate* or 7 *completely exhausted, unable to function effectively*. This indicates that still a notable amount of the crew is likely to suffer high levels of work-related fatigue. Further results indicate that, in addition to sleep length, wakefulness and work hours, workload significantly influences fatigue (Dorrian et al., 2011).

Akhtar and Utne (2014) conclude that a fatigued operator raises the probability of grounding by 23 %. The strongest fatigue-related factors of their BBN model related to top management are vessel certifications, manning resources and quality control. When the state of the nodes "vessel certifications", "manning resources" and "quality control" are in OK, the probability of fatigue is reduced from 0.23 to 0.20.

Fatigue reducing measures, e.g. eating regular meals, having enough sleep, adequate resting periods, reduced administrative tasks and free time, are dependent on sufficient manning levels onboard. Comparing different watch shift systems (6–6 and 12–12), the 8–4–4–8 system seems to generate the least fatigue. In practice, the 6–6 and 12–12 watch systems reduce the probability of fatigue more than the 8–4–4–8 system when other fatigue-related factors also were considered. Particularly, an adequate manning level is crucial for a successful implementation of the 8–4–4–8 scheme (Rothblum, 2000).

The BBN analysis by Akhtar and Utne (2014) shows that alcohol influences the same unsafe states as fatigue, even though they were not directly connected in the model. A fatigued bridge team has about 16 % higher probability of grounding than a non-fatigued team. Alcohol influences the cognitive function and psychomotor skills and leads to an increased mental work load (Kim et al., 2007). It affects information processing and memory, increasing the time required for input, reflection and response and hence causing more mistakes (Kim et al., 2007).

Occupational Stress is another factor influencing the operator's physical, psychological and physiological conditions. Physical in terms of e.g. temperature, weather, noise and psychological in terms of e.g. subjective experience of inability to cope with the job, milder forms of mental disorder, job related factors such as separation from family. Inadequate rest between watches, sleep loss and irregular working times lead to physiological stress (Kristiansen, 2004). Occupational stress has been identified as a contributory factor to the productivity, personnel health and welfare (Hetherington et al., 2006). However, research still needs to evaluate the relationship between seafarers health and performance (Hetherington et al., 2006).

5.2.12 Number and complexity of task

The number and complexity of task has influence on the crew leading to dangerous failures due to overwork. Thus, the factor workload is considered in detail. Workload is defined as: "the demand a task imposes on the operator with limited resources" (Nilsson et al., 2009, p. 189). The exposure to high workload over a long period of time results in exhaustion. Another danger is related to the complexity of the task and time pressure which influences decision making (Nilsson et al., 2009). For handling excessive workload different methods exist, such as allowing task performance to degrade, performing the tasks more efficiently and shedding tasks according their priority (Nilsson et al., 2009). This is also shown by the developed indicators in Figure 5.17.

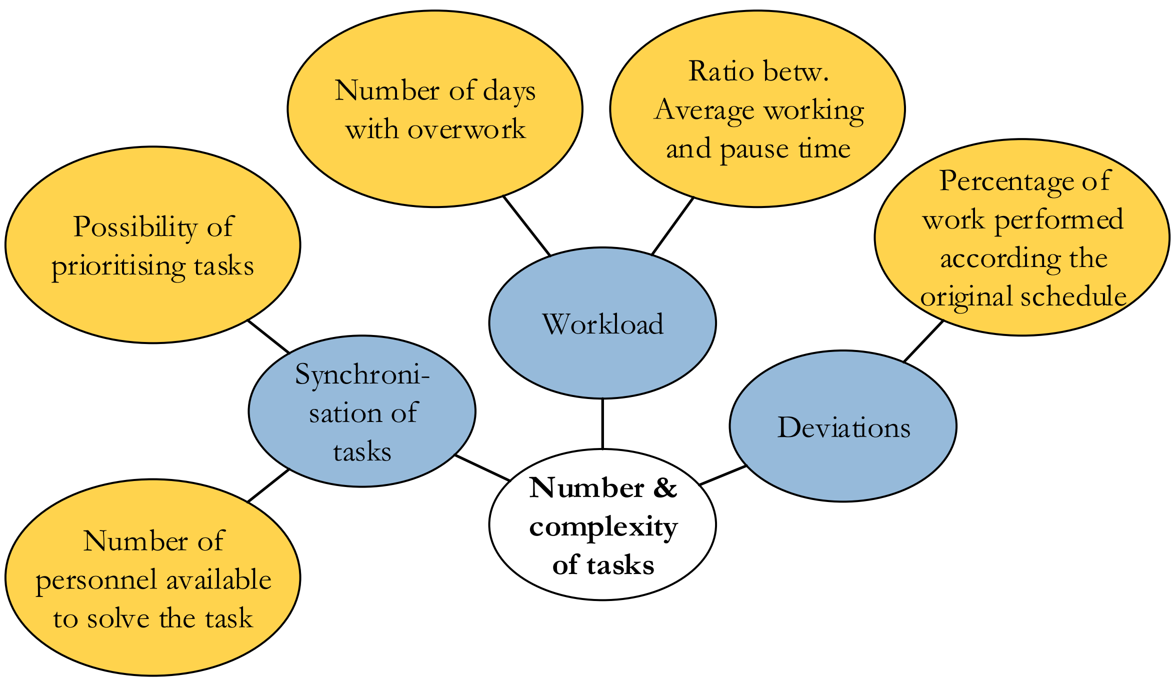


Figure 5.17: RIFs and indicators of the BBN node "Number and complexity of tasks"

Workload can be assessed by the NASA Task Load Index (NASA TLX) which defines workload as the "cost incurred by human operators to achieve a specific level of performance" (Nilsson et al., 2009, p. 190). Operators rate their experienced workload by answering standardised questions of six fields, that are Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration (Nilsson et al., 2009, p. 193). This approach is widely used to evaluate the workload imposed by complex cognitive and motor tasks (Donderi et al., 2004).

By using NASA TLX for different navigation situations (paper charts, no overlay, ECDIS with overlay) under good and poor visibility, Donderi et al. (2004) revealed that the highest overall demand by use of paper charts under poor visibility conditions. Both ECDIS conditions produced lower workload demands and better self-rated performance under good and poor visibility. The lowest overall demand occurred in the ECDIS condition without overlay under good visibility. The highest self-rated performance occurred under the two ECDIS conditions under good visibility (Donderi et al., 2004). Nilsson et al. (2009) confirm that the workload on the conventional bridge is rated slightly higher than on the advanced bridge. Although Sauer et al. (2002) report slight navigational advantages of the integrated display, more complex scenarios were associated with impaired performance, increased workload and reduced situation awareness.

Increased workload due to automation is explained by the extension of the human operator's 'span of control' (Sauer et al., 2002) . One single operator is thus in charge to manage various sub-systems simultaneously such as navigation, engine control and cargo control. This results in a polarising workload structure consisting of underload or overload (Sauer et al., 2002). Gould et al. (2009) identify a number of navigation related tasks, which are performed with lower frequency when ECDIS is used, e.g. "Identify and communicate landmarks" and "Communicate next course and distance to turn". This underlines the risk of mental underload associated with ECDIS.

Another approach to measure mental workload is the three-item scale based on the Subjective Workload Assessment Technique (SWAT), which includes the following 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). The SWAT approach combined with an assessment of situation awareness, shows a reduced monitoring behaviour, increased omissions (failures to detect drift states) and increased prospective memory errors as a function of increasing workload (Sauer et al., 2002).

5.3 Environmental conditions

Environmental conditions are external conditions which cannot or only partly be influenced by humans. These factors influence the prevailing surroundings of the ship and its crew. External navigational aids and traffic density for instance could partially be influenced, whereas weather and given properties of the operation area cannot be changed.

5.3.1 Weather

Analysis of maritime accidents show that weather conditions can be seen as a predominant accident cause (Antão et al., 2009; Kristiansen, 2004). Analyses of 857 ship accidents from the Portuguese Maritime Authority indicate that 23 % of the accidents are related to sea and weather conditions (Antão et al., 2009, p. 3268).

In many cases the occurrence of accidents and bad weather conditions were linked with situations where the crew present a low risk perception or a high risk acceptance. Antão et al. (2009) particularly point that out to be the case for recreation and fishing vessels. In the latter case, a high risk acceptance occurs due to social-economical factors related to the dependence of catch quota and the fishers' income.

Humans modify the behaviour according to their individual perception of risk. This explains why also accidents occur in good weather and/or in good technical condition of the ships.

Studies by Kristiansen (2004) revealed that 39.9 % of grounding accidents (for ships over 1599 GT) are related to external conditions, such as influencing navigational equipment (1.9 %), less than adequate buoys and markers (6.4 %), reduced visual weather conditions (12.5 %) as well as influence of channel and squat effects (18.9 %) (Kristiansen, 2004).

Investigations on maritime accidents in Finnish waters carried out by Kujala et al. (2009) split the weather factor into light conditions, visibility, wind force, wind direction and sea state. Grounding accidents were identified to occur mostly in late autumn and early winter where harsh weather conditions occur (Kujala et al., 2009).

When analysing maritime accidents resulting from bad weather, the significant wave height representing the sea severity is considered. Investigations show that rather low values occurred during those ship accidents, which have been reported as being due to bad weather (Toffoli et al., 2005). The recorded wave parameters at the time of ship accidents revealed the occurrence of apparently rather low sea states. The following example underlines this: "Although the significant wave height was recorded as sometimes larger than 9 m, accidents to container ships also happened with relatively low waves (significant wave height lower than 4 m)." (Toffoli et al., 2005, p. 288) This shows that the wave hight has a relatively low influence on the occurrence of accidents.

Furthermore, the wave steepness is introduced to provide information about the enhancement of risk of extreme waves. "Steeper sea states might yield dangerous dynamic effects due to ship motion (e.g. slamming), even though the significant wave height is not particularly large."(Toffoli et al., 2005, p. 285). Investigations reveal that a reactively high wave steepness was observed during moderate wave heights and large steepness is often correlated with wind activities (Toffoli et al., 2005). Therefore an overall assessment of weather should pay especially attention to the rapid change of sea state.

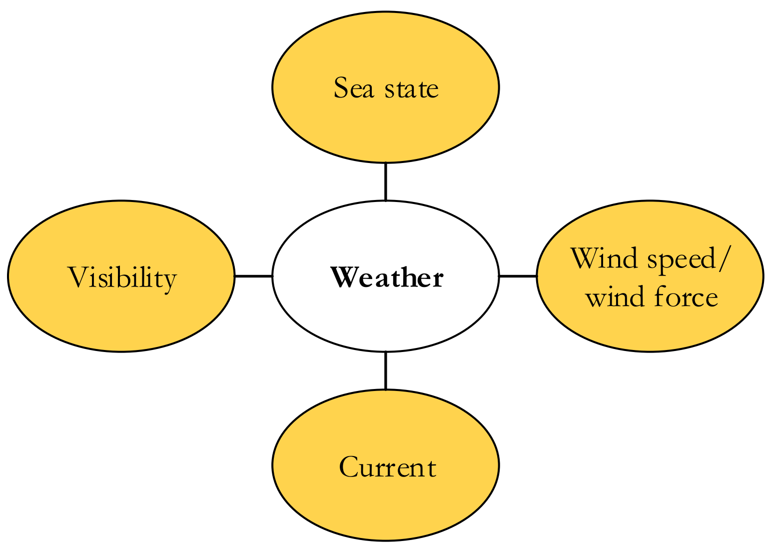


Figure 5.18: Indicators of the BBN node "Weather"

Based on Stornes (2015), Kujala et al. (2009) and Hänninen (2005) the following general parameters for weather properties shown in Figure 5.18 can be defined: visibility, sea state, wind speed/force and current. Since accidents happened almost as frequent in good light as in dark (Kujala et al., 2009); navigational aids developed significantly within the last 30 years (Hänninen and Kujala, 2012), a limited influence of daylight is achieved. Thus, lighting conditions are disregarded. The weather node is treated as a RIF, therefore indicators are developed directly.

Sea state describes surface conditions of the sea including effects due to wind, swells and currents and can be described based on the WMO (World Meteorological Organization) Code 3700. The classification distinguishes different wave heights and formulates descriptive criteria to express the sea state conditions. Table 5.2 gives an overview.

Table 5.2: World Meteorological Organization's codes for sea state (WMO, 1997)

Code	Wave Height (in meters)	Characteristics
0	0	Calm-glassy
1	0 - 0.10	Calm-rippled
2	0.10 - 0.50	Smooth-wavelet
3	0.50 - 1.25	Slight
4	1.25 - 2.50	Moderate
5	2.50 - 4	Rough
6	4 - 6	Very rough
7	6 - 9	High
8	9 - 14	Very high
9	Over 14	Phenomenal

Stornes (2015) suggests to condense the 9 WMO sea state levels to 3 categories: calm/smooth, slight/moderate and rough/high/phenomenal.

An observation by Toffoli et al. (2005) discovers a connection of sea state and ship characteristics. Ship accidents occurred when the wavelength was systematically above half the ship length. In Figure 5.19 this is shown by the dashed line. To derive additional information on the ship size, tables about "Typical vessel dimensions" were used to estimate ship length as a function of tonnage. Considering that specific ships are vulnerable to particular wavelengths, it was observed that only a few cases of accidents occurred with wavelengths lower than half the ship's length. It is therefore recommended, that captains should interpret the marine forecasts with respect to their ship type and loading state (Toffoli et al., 2005).

Visibility is differently interpreted among the authors. Fowler and Sørgård (2000) define good visibility conditions from more than 4 km (2.16 nautical miles), whereas Hänninen and Kujala (2012) propose a value of 1 nautical mile (ca. 1.8 km). Table 5.3 shows the differentiation by the WMO Code 4300. According to Stornes (2015) the following visibility categories can be

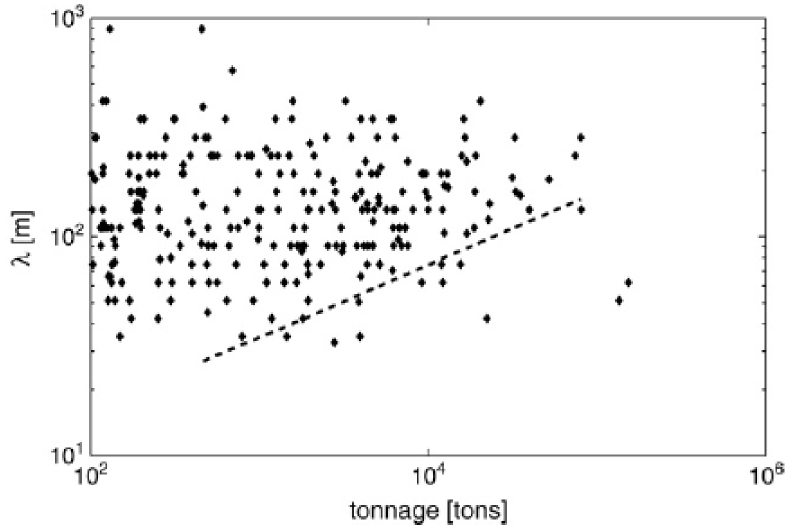


Figure 5.19: Scatter plot of the wavelength versus ship gross tonnage. A lower limit exists for wavelength equal to half the ship length (dashed line). (Toffoli et al., 2005)

defined, such as good (over 5 nm), moderate (2.1 to 5 nm), poor (0.5-2 nm) and dense (0 - 0.5 nm). This scale can in turn be reduces to distinguish clear weather, mist/fog and thick/dense (Kristiansen, 2004).

Analyses of different data based on maritime accidents reveal that, the powered grounding probability is 3 to 6 times higher in poor visibility compared to good visibility (Fowler and Sørgård, 2000).

Table 5.3: World Meteorological Organization's codes for horizontal visibility (WMO, 1997)

Code	Horizontal visibility
0	Less than 50 m
1	50 - 200 m
2	200 500 m
3	500 - 1000 m
4	1 - 2 km
5	2 - 4 km
6	4 - 10 km
7	10 - 20 km
8	20 - 50 km
9	50 km and more

Wind at sea is often described according to the Beaufort scale by estimating the wind forces. For each Beaufort number a range of wind speeds is established empirically (Beaufort equivalents) by the WMO. This is shown in Table 5.4. Stornes (2015) suggests the following three distinctions: weak winds (including calm, light air and light breeze referring to the Beaufort scale), moderate winds (including moderate and fresh breeze) and strong winds (including strong breeze, high wind, gales, storms and hurricanes).

Table 5.4: World Meteorological Organization's codes for wind force (WMO, 1997)

Code	Description	Wind force in knots	Wind force in m/s
0	Calm	0 - 0.9	0 - 0.2
1	Light air	1 - 3	0.3 - 1.5
2	Light breeze	4 - 6	1.6 - 3.3
3	Gentle breeze	7 - 10	3.4 - 5.4
4	Moderate breeze	11 - 16	5.5 - 7.9
5	Fresh breeze	17 -21	8.0 - 10.7
6	Strong breeze	22 - 27	10.8 - 13.8
7	Near gale	28 - 33	13.9 - 17.1
8	Gale	34 - 40	17.2 - 20.7
9	Strong gale	41 - 47	20.8 - 24.4
10	Strom	48 - 55	24.5 - 28.4
11	Violent storm	56 - 63	28.5 - 32.6
12	Hurricane	64 - 71	32.7 - 36.9

Based on considerations by Zhang et al. (2013) it might also be possible to add a **current** parameter. The scaling could include, e.g. calm, slight, moderate, rough current as or using the speed (m/s).

5.3.2 External navigational aids

External navigational aids are Vessel Traffic Services (VTS) and other shore-based information systems providing data about weather, traffic, vessel position and other safety relevant input. Moreover, visual cues aiding safe marine traffic, such as lighthouses, lights, buoys, other navigational marks and signage.

Maritime authority or port organisations guide marine traffic to ensure safety at sea by online monitoring of traffic, information dissemination and guidance from the shore-based VTS centres (Nuutinen et al., 2007). Figure 5.20 illustrates the VTS system. Figure 5.21 includes VTS under "External consulting". VTS support operators with information on crossing and oncoming traffic, weather conditions and navigational hazards. Three different services are provided, such as information, navigational assistance and traffic management (Nuutinen et al., 2007). Studies indicate that the risk-reducing effect of a VTS centre is between 20 % and 80 %, depending on the geography, traffic density and available reseources to the VTS (Danish Maritime Authority & Royal Danish Administration of Navigation and Hydrography, 2002 quoted in Eide et al., 2008).

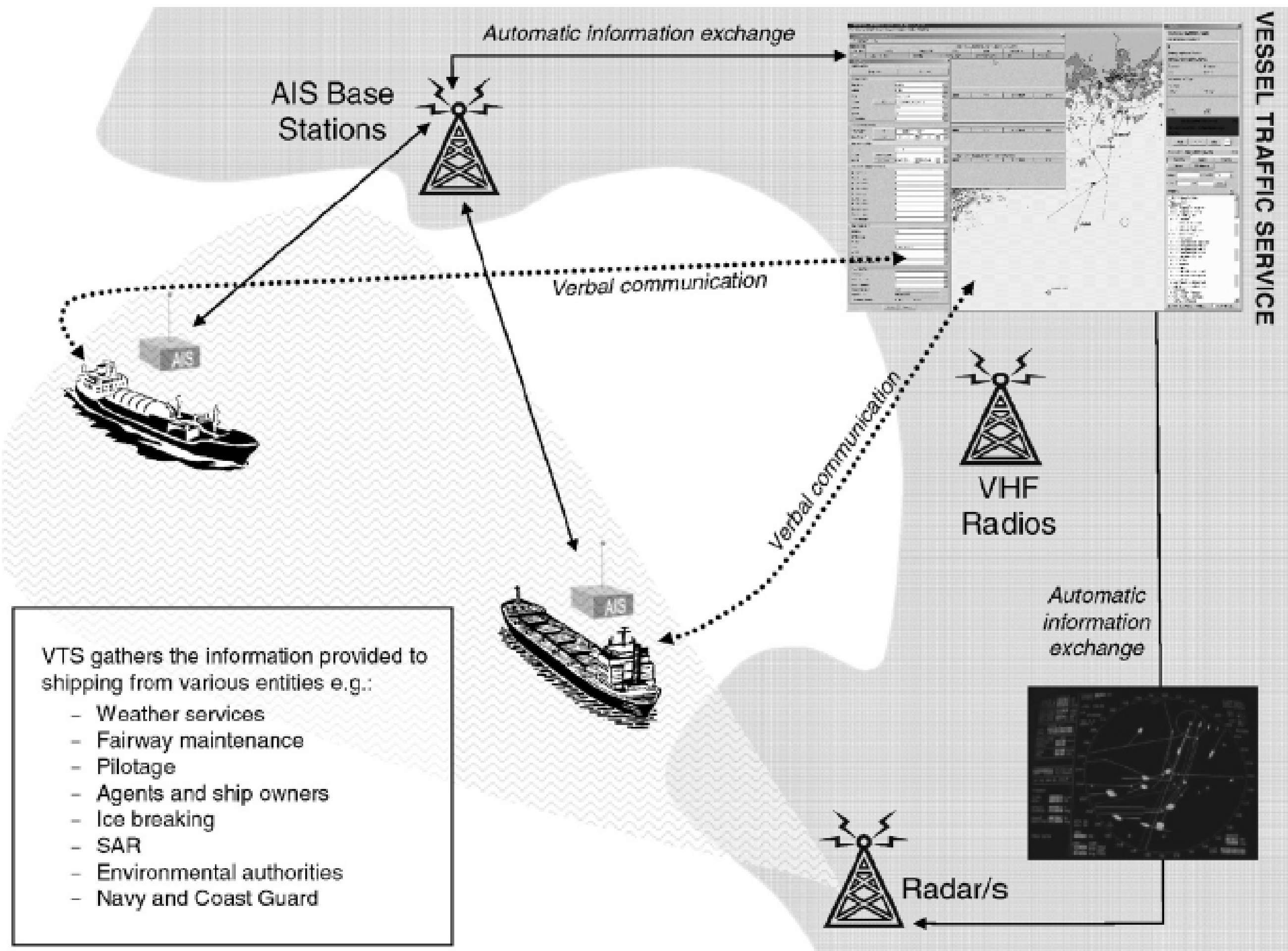


Figure 5.20: Means of general information exchange in the VTS operations. (SAR: Search and Rescue) (Nuutinen et al., 2007)

The Enhanced Navigation Support Information (ENSI) navigation service mentioned by Hänninen et al. (2012), presents an valuable contribution to safe marine navigation. The ENSI system transmits the ship's electronic route plan to the VTS and checks the route. In return, the VTS service sends real-time data as well as route-specific information to the ship, e.g. weather data, traffic conditions, destination and possible disturbances on the route. The influence of ENSI was investigated by tankers operating in Finnish waters. The tankers send their route plans to the VTS centre and receive information on their ENSI tablets onboard in return, but do not receive the route plans of the other tankers. The results show a reduction of collisions and groundings of respectively 6 % and 24 %. Then another ENSI system was tested, including transferred route plans of other tankers on the ENSI tablet onboard. Hence, the number of collisions and grounding decreased by respectively 10 % and 21 % compared with no implementation of ENSI. It is concluded that especially for groundings the service is quite efficient. Overall one fourth of the groundings during open water season could be prevented with ENSI (Hänninen et al., 2012). So far, the ENSI system is coordinated by the Finnish Transport Agency which equips more and more tankers sailing in the Gulf of Finland (John Nurmisen Säätiö). Currently, successful discussions with Russian and Estonian authorities on the service deployment promise the further development (John Nurmisen Säätiö).

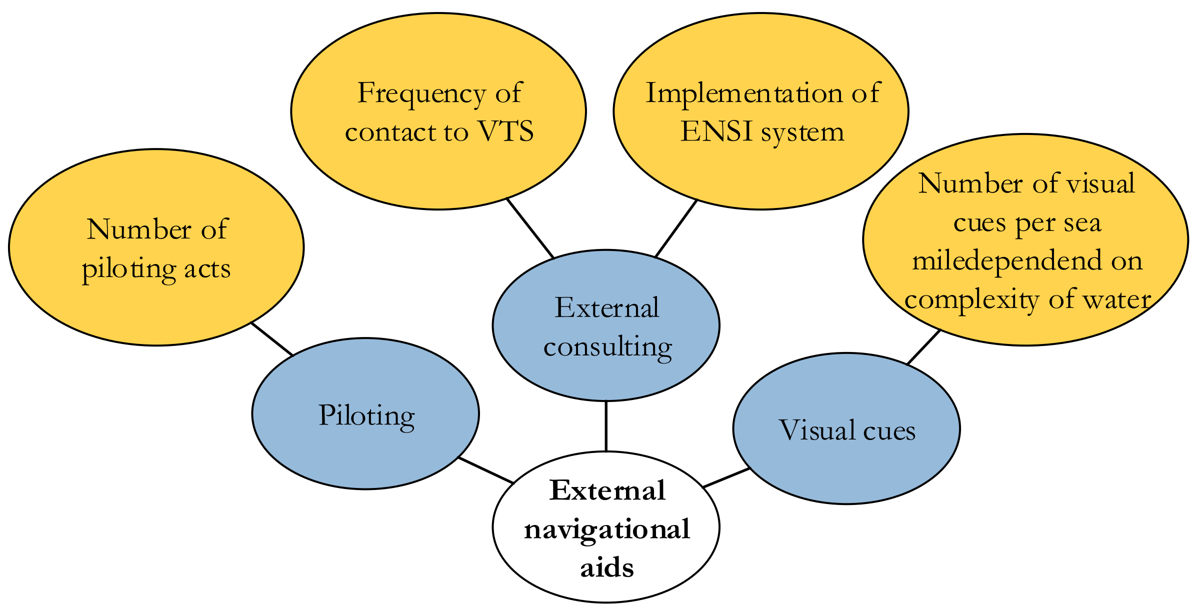


Figure 5.21: RIFs and indicators of the BBN node "External navigational aids"

Another system implemented by the Maritime Administration of Finland, Russia and Estonia is called Vessel Traffic Management and Information Services (VTMIS) system. It aims to avoid maritime traffic accidents in the Gulf of Finland and comprises a new ship routing system. The identification of vessels will be based on AIS and the overall system is equal to a Vessel Traffic Service (VTS) operation. Investing in a VTMIS system will decrease the annual number of collisions by 80 % (Rosqvist et al., 2002).

Piloting represents another kind of external navigational aids. An external, local expert is taken temporarily onboard the ship when sailing through an area of difficult navigation in order to prevent accidents and environmental damages caused by vessel traffic (Nilsson et al., 2009). The captain is still legally responsible and liable for the ship but is expected to yield to the judgement of the more experienced pilot (Hetherington et al., 2006).

Successful piloting is dependent on the communication on the bridge as well as the communication with external partners, e.g. e.g. harbour authorities and VTS, the use of the steering and navigation equipment as well as the applying norms and procedures (Norros, 2004). The core task of piloting corresponds to the general task of navigation as shown Figure 5.4. It illustrates the relation between skills, knowledge and collaboration by performing the navigation task.

5.3.3 Area of operation

Oceans in the world are divided into 31 navigation zones. Analysing these zones with respect to their safety level, revealed that the zones 3 (Kiel canal), 6 (Suez canal), 8 (Gulf), 9 (East African coast), 10 (Indian Ocean, Antarctic), 16 (Australasia), 17 (Cape Horn) and 18 (South Atlantic, East coast South America) are the most dangerous (Li et al., 2014b). Among of them the Suez Canal (zone 6), which is passed through by about 25,000 vessels every year. Other zones, e.g. the Southern China Sea (zone 12) or the Eastern Asian (zone 13), have no significant effect on decreasing the safety level. It is mentioned, that the large number of accidents may be because the number of vessel voyages via these two zones is larger (Li et al., 2014b). This would indicate a relation between area of operation and traffic density.

Analyses of grounding accidents in the Gulf of Finland show that about 50 % of the groundings happened in inner coastal areas (Table 5.5) (Kujala et al., 2009). Also Samuelides et al. (2009) agree that in areas closer to ports and coasts, the probability of grounding is proven to be more significant. It is further reported that 90 % of all marine accidents happen in confined waters, such as channels and inshore traffic zones (Cockroft, 1984 quoted in Gould et al., 2009).

The inshore coast of Norway is particularly mentioned as "perhaps one of the most challenging navigation areas in the world, characterized by extreme weather, long periods of darkness, and thousands of islets, shallows and narrow straits" (Gould et al., 2009, p. 103).

Table 5.5: Water area proportions of grounding accidents in the Gulf of Finland (Kujala et al., 2009)

Water area	No. of grounding events	%
Port area	12	24
Inner coastal area	12	48
Open coastal area	8	16
Outer coastal area	2	4
Open sea	0	0
Channel, river, strait	2	4
At quay, in dock, etc.	0	0
Other	1	2
Unknown	1	2

Another factor describing the area of operation is the complexity of waters. The environment can add to the uncertainty of navigation through the presence of invisible dangers e.g. shallow waters and submerged rocks.

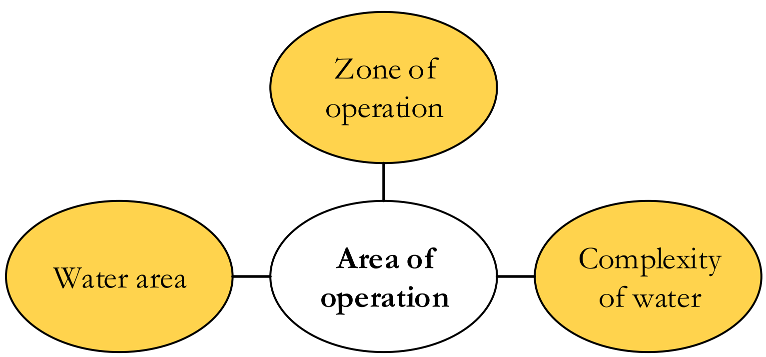


Figure 5.22: Indicators of the BBN node "External navigational aids"

Figure 5.22 gives an overview which indicators could be defined to measure the factor "Area of operation". Generally a zone of operation can be identified and merged to low/medium/high risk zones (Li et al., 2014b). In more detail, distances from land or the water area can be identified (Kujala et al., 2009). Here, the scaling could distinguish in port area/channel/rivers, coastal area and open sea.

5.3.4 Traffic density

Ship traffic is one factor included in the majority of existing grounding models and is widely considered as one of the affecting factors on the probability of grounding accident. Traffic density is defined as the number of ships per unit area of the waterway within a desired time window and can be assessed based on AIS data (Mazaheri et al., 2013).

Traffic density could be measured by arrivals per unit time of the ships, the distance between ships sailing in similar directions or the spatial distributions of ship routes within an navigation area.

However, it is criticised that based on the correlation of ship-ship collisions, the relation between groundings and ship traffic is simply generalised and adopted. Research in this particular area is lacking and a direct causal link between ship traffic and groundings is not found in the literature. A study of 112 grounding accidents in the Gulf of Finland identifies no correlation between traffic density and the grounding accident, but further investigation for more clarification needs to be done (Mazaheri et al., 2013).

Based on that it is concluded that the node "Traffic density" has no influence on the occurrence of groundings and can be extracted from the BBN model.

Chapter 6

Summary and Recommendations for Further Work

The last chapter gives a final conclusion of the work that has been done. The results are discussed, findings documented and recommendations for further work given.

6.1 Summary and Conclusions

Analysing grounding accidents with respect to their human, technical and organisational factors represents a complex task. Mainly, one direct cause cannot be defined and thus always a range of causes need to be considered in order to understand the whole complexity behind these accidents.

The literature review in Chapter 2 shows that the majority of causes (80 %) are human and organisational related, whereas only 20 % represent technical causes. This is in accordance with the fact that powered grounding has the largest portion of total groundings (Brown et al., 1998). The review reveals that there is much to be done to gain insight into the composition of the human factor and understanding of the way in which increased technological progress shape mariners' task, work environment and work behaviour.

Modelling such causal influences between factors in a graphical and intuitive way, a BBN model represents a beneficial approach. Chapter 3 indicates further challenges of quantification due to lack of data or data overload. Particularly within the international shipping industry, the collection and evaluation of maritime accident data is left to each nation. No common classification taxonomy exists. Accident reports are characterised by a lack of focus on human factors as well as underreporting . Therefore the use of correction factors, a safety margin or to rely on expert judgement needs to be decided (Akhtar and Utne, 2014).

In Chapter 4 another approach of quantifying nodes in a BBN by using a framework of risk influencing factors (RIFs) and risk indicator assessment is therefore introduced. Indicators represent an operational variable which is monitoring the condition of a RIF (Haugen et al., 2012). They should be able to predict future performance, to provide comparable measurements and to be sensitive to change (Kjellén, 2009). Often indicators are established on the basis of combining performance data of the system, risk assessment and expert judgement (Øien et al., 2011a).

Chapter 5 focusses on the chosen factors from the BBN grounding model to analyse their relation to each other and investigate how they can be quantified by using RIFs and indicators. This method represents an applicable approach, since the BBN nodes cannot be quantified directly.

Analyses of the factors show that the introduction of new technology and automation seems not always valuable for marine navigation. Increased workload due to automation is explained by the extension of the human operator's 'span of control' (Sauer et al., 2002). Although technical support (e.g. ECDIS) appeared to improve navigation performance compared to navigation using paper charts (Donderi et al., 2004; Nilsson et al., 2009), it leads to a reduction in task-related communication among the bridge team (Gould et al., 2009). The same applies to integrated displays which imply slight navigational advantages, but when it comes to more complex scenarios reduced performance, increased workload and decreased situation awareness are the results (Sauer et al., 2002). It can be concluded that automation polarises workload structure into underload or overload.

For that reason better training and improvements regarding the human-machine interface should rather be considered than adding new technology. The analysis show that user-centred design plays a crucial role in a socio-technical system. Only through understanding human actions and human errors, design can be changed accordingly. For that reason the connection between bridge layout and navigation system design influencing the navigation task is one important and central point.

Considering the ship age factor this analysis concluded no significant influence in the BBN model, since some authors found a positive and others a negative correlation. However, an influence of ship age on the status of navigational equipment was found. Analysis on the ship size factor concluded that the occurrence of groundings rises with the vessel size, even if scattered samples may give other results. That smaller ships have a higher probability to run aground might be more related to their operating area which is usually near the coastline. In these areas, ports and coasts, the probability of grounding is proven to be more significant (Samuelides et al., 2009).

Analyses on the weather factor identify that bad conditions not necessarily increase the occurrence of groundings. The weather condition combined with the prevalent human related factors should be taken into consideration. Since individual risk perception significantly influences humans behaviour, this explains the occurrence of accidents also in good weather and good technical condition of ships.

Finally, the identification of indicators represents a complex process that due to context-specific and subjective understanding cannot give one ultimate outcome. A generic method for identifying indicators is still under development (Haugen et al., 2012). For the future work this means, it is supportive to record consistent definitions and describe the chosen approach stepwise, in order to ensure a comprehensive common understanding of risk influencing factors and indicators.

6.2 Discussion

The method to quantify BBN nodes based on RIFs and indicators presented in Chapter 4.6, represents a beneficial approach. However, not all parts of the analysis could completely be applied. The scoring/rating of indicators and the following weighing process of RIFs was only possible to a limited extent, since the use of incident and accident data as well as expert judgement was not within the scope of this study.

The literature review gives valuable input for the two first steps: identification of RIFs and possible indicators. However, assessing the "measurability" of indicators is not that clear. To measure indicators implies an organisational challenge since crew members/technical conditions or management flows need to be investigated and measured over a certain period of time. It should also be considered that indicators can only measure the relative change in risk, not the absolute level of risk. They cover a portion of the total risk.

Input of data based on literature dealing with BBN quantification, is often not possible due to uncertainties how these values were gathered and which rating/weight was given to the individual nodes.

Indicators cannot model the whole complexity of real-world problems. Therefore a testing and verification process is necessary, which is not a part of this study. The RIFs and indicators framework leaves always room for interpretations due to a subjective and context-specific understanding and due to various approaches.

6.3 Recommendations for Further Work

The recommendations may be classified as:

- **Short-term**
  - Further research on possible quantification by using accident data, incident data, performance measuring tools including expert judgement to weigh the different RIFs.
  - Performing a sensitivity analysis gives the information on which factors of the BBN contribute the most to the risk of grounding. Based on that targeted measures to prevent grounding accidents can be developed.
- **Long-term**
  - Validation of possible indicators based on an indicator testing. This could be performed in cooperation with a shipping company. Investigations on changeability, measureability and other criteria can be done in practice. Based on that the most suitable indicators can be identified. However, the safety attitude and willingness of the company can influence the validity of the risk indicators.
  - Implementation of indicators as a tool for risk control. Indicators can give data about the safety performance on board of the ship in a practical way.

Appendix A

Acronyms

AIS Automatic Identification Systems

ARPA Automatic Radar Plotting Aid

BBN Bayesian Belief Network

BRM Bridge Resource Management

CCTV Closed Circuit Television

CPT Conditional Probability Table

DAG Directed Acyclic Graph

DGPS Differential GPS

DNV Det Norske Veritas

DSB Directorate for Civil Protection

ECDIS Electronic Chart Display and Information Systems

ECS Electronic Chart System

ENSI Enhanced Navigation Support Information

GPS Global Positioning System

GeNie Graphical Network Interface

GT Gross Tonnage

HCD Human-Centred Design

HELCOM Helsinki Commission

IBS Integrated Bridge System

IEC International Ergonomics Association

IMO International Maritime Organization

INS Integrated Navigation System

NASA TLX NASA Task Load Index

NCA Norwegian Costal Administration (Kystverket)

NMA Norwegian Maritime Authority (Sjøfartsdirektoratet)

NSRM National Ship Risk Model

NTNU Norwegian University of Science and Technology

OOW Officer of Watch

ORIM Organizational Risk Influence Model

PSA Petroleum Safety Authority

QRA Quantitative Risk Analysis

RADAR Radio Detection And Ranging

RIF Risk influencing factor

SAGAT Situation Awareness Global Assessment Technique

SOLAS International Convention for the Safety of Life at Sea

STCW Standards of Training Certification and Watchkeeping for Seafarers

SWAT Subjective Workload Assessment Technique

UCD User-Centred Design

VTMIS Vessel Traffic Management and Information Services

VTS Vessel Traffic Service

WMO World Meteorological Organization

Appendix B

BBN Grounding Model

The next following figure represents the Ship Grounding Model from the *National Ship Risk Model* project (Studio Apertura, 2016) with all suggested adjustments based on this study. The model is implemented in GeNie (Graphical Network Interface), a software to model Bayesian Belief Networks (`https://dslpitt.org/genie/`).

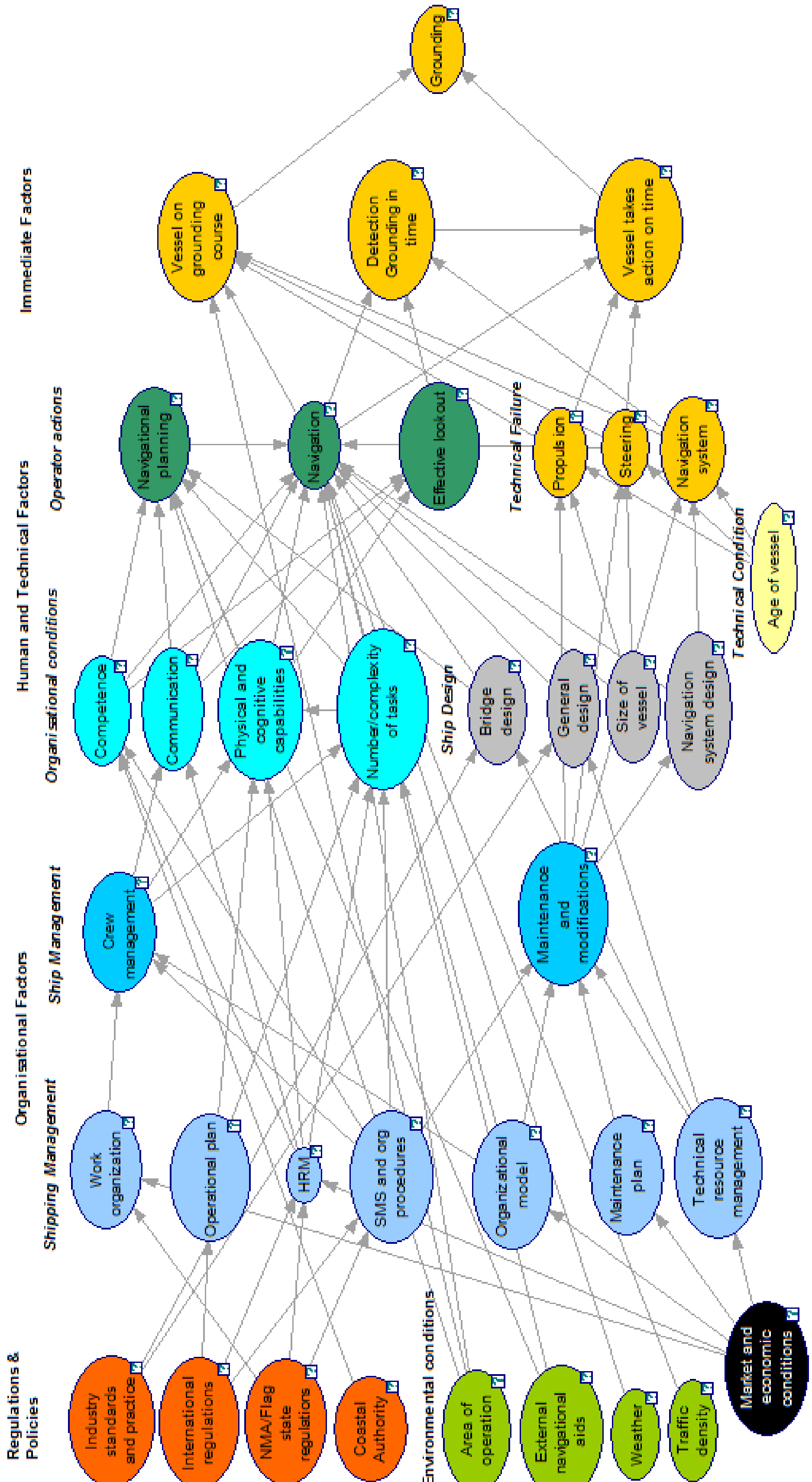


Figure B.1: Bayesian Belief Network of ship grounding accidents

Appendix C

Working practice indicators

Core task model of sea piloting and used the following working practice indicators based on (Nuutinen and Norros, 2009, p.135)

1. Creating knowledge of a particular sea area
2. Creating a situational orientation
3. Anticipation and waiting for results
4. Testing ship's controllability
5. Maintaining orientation in the moving vessel
6. Controlling the movements of a vessel
7. Taking account of the whole traffic situation
8. Information formation on a cumulative interpretation of the situation and location
9. Integrating information from different representations
10. Shifting from one representation to another
11. Formation of and up-dating shared plans
12. Formation of shared interpretation of the situation

13. Following norms and common practices
14. Exercising control over performance through monitoring and rechecking
15. Integrating expertise regarding the environment, routes and the vessel
16. Constructing and maintaining an ad-hoc team
17. Taking account of the work demands in timing of changes in division of work
18. Continuous attempt reflect on one's own conception of the core task
19. Focusing on the core task in demanding situations
20. Balancing between contradicting goals
21. Courage to make decisions in demanding situations
22. Constructing an understanding of a bridge crew's competence
23. Balance between "proving" own expertise and submitting it to monitoring
24. Reflectivity, attempt to learn and analyse own competence and its restrictions
25. Balance between acting according to plan-situation
26. Seeking different sources for feedback
27. Preparedness for possible difficulties and high demands

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