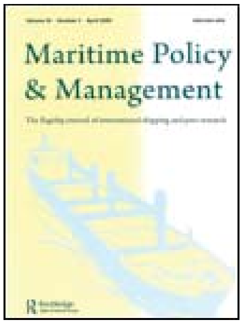

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Common patterns in aggregated accident analysis charts from human fatigue-related groundings and collisions at sea

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Research has shown that there are potentially disastrous outcomes of human fatigue at sea. The conditions in which the seafarers have to operate are becoming more and more demanding. The study in this article attempts to aggregate accident charts derived from in-depth studies of human fatigue-related accidents to determine common patterns of interlinked fatigue factors. The accidents are analyzed by means of the Cognitive Reliability and Error Analysis Method (CREAM), which in the article has been modified for maritime accidents. The main fatigue factors identified are ‘shift work’, ‘irregular working hours’, ‘inadequate task allocation’, and ‘excessive demands’. The study reveals several differences between ship collision and grounding accidents and their corresponding fatigue factors. Human fatigue-related collision accidents are characterized by wrong/badly timed decisions, misconceptions, and poor communication between the vessels. Right before the collision the crew is often panicking and mistakes are easily made. In human fatigue-related groundings, the conditions are often monotonous and the navigating officer has either overlooked the upcoming seabed or simply fallen asleep. Safety climate issues are also identified as important contributors to human fatigue.

1. Introduction

Measuring safety performance has become increasingly important in many high-risk industries, such as nuclear power, the chemical industry, the offshore oil and gas industry, and air traffic control. Much work has been done to study the factors that shape the safety climate in these industries, but little research has focused on shipping (Hollnagel 2004; Håvold and Nesset 2009).

Maritime transportation has a long history of accidents. The shipping industry has spent a lot of resources on improving ship structures and the reliability of ship systems. The ships today are technologically advanced and highly reliable (Rothblum et al. 2002; Stoop 2003). Still, statistics are indicating that not only is the number of shipping accidents increasing but also the reason may well be the advanced technology, as well as human factors (Nilsson, Gärling, and Lützhöft 2009; Bambulyak and Frantzen 2011). In Norwegian waters, at least 8 out of 88 groundings in 2006 were influenced by watchkeepers falling asleep (Gould and Koefoed 2007). The conditions that the seafarers have to operate in are becoming increasingly demanding. There are, for instance, shorter sea passages, higher traffic density coupled with reduced manning, and rapid crew turnaround

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(Hetherington, Flin, and Mearns 2006). In general, seafarers are reported to experience more accidents than the onshore population (Roberts and Hansen 2002).

Surveys show that about 75–96% of marine casualties are fully or partially caused by human and organizational errors (Ren et al. 2008). The technical systems are getting more and more reliable (Arslan and Turan 2009). As a result, the number of accidents related to human actions have risen from around 30 % in 1960–1980 to around 70–80% in the 1990s (Hollnagel 1998). Technical advances have also contributed to decreasing the manning level. Today, a Very Large Crude Carrier may have a crew of 22 seafarers, whereas 25 years ago a similar vessel would have been manned with a crew of in between 40 to 50 people. The reduced manning levels and improved automation systems have revealed the underlying level of influence of human error in accident causations (Hetherington, Flin, and Mearns 2006). The Marine Accident Investigation Branch (MAIB) summarized the accident causes from 66 investigation reports. They concluded that watchkeeper manning levels, human fatigue, and a master's ability to discharge their duties are major causal factors in ship collisions and groundings, and poor lookout is a major factor in collisions (MAIB 2004).

The problem one faces when performing research on human fatigue is the lack of any clearly defined and agreed-upon definition. It is difficult to compare research results since the definitions of human fatigue (henceforth only denoted as fatigue) often are vague. There is also a general agreement that any percentages based on accident data underestimate the true magnitude of the problem, because of underreporting and not prioritizing the fatigue problem (Williamson et al. 2011). In addition, conducting pure statistical analysis is problematic due to underreporting of accidents in the maritime community and the poor details in the various databases (Li and Wonham 2001; Hassel, Asbjørnslett, and Hole 2011). Fatigue is a multidimensional construct and its effects on cognitive performance are complex. Thus, the true extent of fatigue in transportation is unclear and unknown.

The purpose of this article is to analyze maritime collision and grounding accidents to identify human fatigue factors involved and their interconnections. An in-depth study method called Cognitive Reliability and Error Analysis Method (CREAM) is used and modified to the maritime domain because it provides a systematic approach to classifying fatigue factors and their relationship. The results are compared and validated with general findings from the literature.

The analysis of maritime accidents may reveal valuable information regarding the impact of fatigue on risk. In general, the literature on fatigue identifies a number of fatigue factors, but to prevent accidents one needs to understand their causes and how they come together to create fatigue. To our knowledge, no studies have attempted to aggregate accident charts so that common patterns of interlinked fatigue factors can be determined in the maritime bridge's navigational teams. Macrae (2009) successfully applied CREAM for maritime accidents, but his focus was on human factors in general and not specifically on fatigue.

The remainder of this article is structured as follows: Section 1.1 explains fatigue factors at sea and Section 1.2 discusses the various types of accident models available. Section 2 presents the research method and the data material used in the study, Section 3 presents the accidents' results, and Section 4 gives the conclusions.

1.1. *Human fatigue factors*

The abstractness and complexity of fatigue is the reason why the term fatigue factor is used in this article, instead of, for example, fatigue *causing* factors or fatigue *consequences*. Fatigue factors are defined as being physical or cognitive properties with interdependencies to fatigue. The interdependencies mean that there is a unidirectional or bidirectional relationship between fatigue and the fatigue factors so that the state of one fatigue factor is affected by or correlated with the state of another fatigue factor, including fatigue itself. In other words, the term 'fatigue factor' implies that there is a relationship between the fatigue factors or between those factors and fatigue itself. There may even exist 'loops' in terms of one factor influencing another factor, which again causes additional impact of the first one.

Extensive literature exists on fatigue within the medical, transportation, and psychology fields of research. Summed up, fatigue can be classified into physical and cognitive (mental) categories. Mental fatigue is believed to be psychological in nature, whereas physical fatigue is considered synonymous with muscle fatigue (Grandjean 1979; Lal and Craig 2001). Both physical and mental fatigues cause decline in alertness, mental concentration, and motivation. The major symptom of mental fatigue is a general sensation of weariness and disinclination for any kind of activity (ibid). The use of one's focus shifts to the tasks in the present or in the immediate future, and the more peripheral tasks and warnings are overlooked (Lovell 1999). Operating at a very high level of concentration combined with heavy workload over time can result in high levels of mental fatigue. Fatigue was identified as an important contributor to maritime environmental disasters like the Exxon Valdez and Peacock on Pipers Reef in Australia (Lovell 1999).

A suitable definition of fatigue in maritime working environments is 'a *biological drive for recuperative rest*' (Desmond and Hancock 2001; Noy et al. 2011; Williamson et al. 2011). A broader definition of fatigue is '*subjective experience of someone who is obliged to continue working beyond the point at which they feel confident of performing a task efficiently*' (Smith, Lane, and Bloor 2001). The latter definition is used in this study.

An important fatigue factor is the safety climate which reflects the attitudes, beliefs, perception, and values that persons share in relation to safety at all levels of the organization (Cooper 2000). Safety climate is the only one aspect of the safety culture in an organization. Safety culture can be defined as a constructed system of meaning through which the hazards of the world are understood. (Pidgeon 1991). There is, however, a lack of universal consensus regarding the term safety culture and safety climate. Often the terms are used interchangeably in the literature (Health & Safety Executive 2005). A useful framework was provided by Cooper (2000), where he defines the safety culture as a set of attitudes, perceptions, competencies, and patterns of behavior in an organization which encompasses 'how people feel' about safety and safety management systems. This feeling *is* the safety climate, which can be measured subjectively through the use of, for example, questionnaires. These questionnaires uncover the attitudes and perceptions of safety climate at a given point of time (Cooper 2000). The level of employee empowerment, higher management involvement and interest, the rewarding system, safety information, investment in safety, safety-oriented procedures, training, and the reporting system all reflect safety climate onboard ships.

Management should frame the working environment so that safety is focused on at all times. Tolerance of letting the employees get exhausted, overworked, or if task allocations are not properly managed are indications that the safety climate is not of a high standard. Higher fatigue levels are therefore assumed to be associated with less than adequate safety climate. Further on, the safety culture, which influences the safety climate, is not only about the management commitment to safety, its communication style, and the overt rules of reporting errors but also about the employees' motivation, morale, perception of errors, and attitudes toward management and factors that impact safety on board, such as fatigue (Itoh, Andersen, and Seki 2004). Work environments in which differences are attempted to be resolved with dialogue and discussions are least likely to report stress, poor general health, exhaustion, or sickness absence (Hyde et al. 2006).

In general, safety culture in maritime transport can be grouped into three levels, of which the third level is the highest. The first level is a culture of punishment where the essential theme is to identify and then frequently blame the last person in the chain. The second level reflects a culture of compliance to external rules with no real commitment or motivation from the organization itself. The third level is the culture of self-regulation where the organization is continuously and actively seeking to improve safety and learn from the mistakes made (Kristiansen 2001). In several studies (Havold 2000; Kristiansen 2001; Anderson et al. 2003), good communication between the personnel and management, between persons onboard and onshore, and between the different departments of the company has been recognized as a key success element in terms of a safety culture. However, since the safety culture is not easily measured or assessed, we therefore limit our attention to safety climate in this study.

Another fatigue factor is the sleep homeostatic effect (sleep deprived or time awake). It must be accounted for when interpreting circadian (biological 24 hours rhythm) influences on human performance (Williamson et al. 2011). Disruption in the circadian rhythm can upset the body temperature, blood pressure, work performance, and sleep/wakefulness (Lal and Craig 2001). At sea, noise, motion, vibration, fumes, and even the anticipation itself of getting woken up frequently disturb rest periods. Studies suggest that there is higher accident risk at times when human beings are normally asleep (Smith, Lane, and Bloor 2001).

Communication between seafarers, between vessels, and between ships and the vessel traffic services is also vulnerable to fatigue. Accurate communication skills are especially important because of the many cultures and nationalities that work together (Macrae 2009; Manuel 2011). This creates language barriers and can increase the stress level on board (Rothblum et al. 2002). In a study dealing with the problems and practices of maritime English usage, it was found that those with language problems had lower perceptions of all aspects of life on board. The study suggested that it may be a result from increased level of stress arising from communication problems (European Union-DG VII 1999).

In regard to falling asleep, humans can operate relatively unaffected by sleep disturbances when performing active tasks with low mental demands, but the opposite is not true (Gould and Koefoed 2007). When the ships are in open waters with little or no traffic, the officer in charge on a modern bridge with navigational equipment like GPS and ECDIS only needs to monitor the ship's location in relation to the passage plan, which is a low mental activity. Nighttime, rolling movements, warm wheelhouse/bridge, solitude on watch, and shortage of sleep can lead to the officer falling asleep. In simple words, automation could lead to lowering the probability of an accident, but coupled with a perception of better control and the effect of behavioral adaption, for instance, lowered alertness or an increase in risk-taking, automation may decrease the positive effects and even reverse them (Elvik, Høye, and Sørensen 2009).

An extensive study published in 2006 by the Centre for Occupational and Health Psychology in Cardiff concluded that the potential for fatigue at sea is high due to seafarers' exposure to a large number of recognizable risk factors, operational, organizational, and environmental (Smith, Allen, and Wadsworth 2006). Seafarers work in shift patterns, which may contribute to fatigue and poorer health (Phillips and Sagberg 2010).

Onshore studies show that working in excess of 50 hours per week increases occupational stress (Smith, Lane, and Bloor 2001). Seafarers' situation is that at least half of them work more than 80 hours per week. In addition, noise, motion, vibration, fumes, and the anticipation of getting woken up frequently disturb rest periods. In a self-reporting study of sleep quality, 70% of the seafarers reported poor sleep at sea (ibid). The work regulations limit the exposure somewhat, but do typically not take into account the circadian rhythm, nor the rate of accumulation of sleep debt, the frequency of opportunities for full recovery from sleep debt, and they do not take into consideration non-work-related time (Gander et al. 2011).

A Swedish study on fatigue at work measured 30 participants in two different watch systems: the two watch system 6 on/6 off and the three watch system 4 on/8 off (Lützhöft et al. 2007). The participants answered a questionnaire measuring health. The participants also underwent medical tests like measuring activity and reaction time. The main result, although not statistically significant, was that there seemed to be a higher level of fatigue among the workers in the two-watch shift system. Another multipartner research study (Horizon 2012) was conducted aiming to investigate the impact of watchkeeping patterns on the cognitive performance of seafarers. Among other things, the study used simulators to investigate the effects of the 6 on/6 off and 4 on/8 off watch system. In total a total of 87 men and three women participated. On the whole, the former watch system had a higher fatigue (sleepiness) levels than the latter. Further on, the sleepiness levels also was found to have a peak between 0400 and 0800 hours.

It is also important to note that boredom, which is not classified as a type of fatigue, can lead to feelings of weariness and sleepiness, decreased vigilance, and disinclination for tasks involved, and decline in alertness. Boredom is caused by low level of stimulation, by a regular repetition of identical stimuli, or by having few mental or physical demands (Grandjean 1979). However, in practice it is hard to distinguish boredom from fatigue caused by, for instance, long hours of monotonous work. Fatigue can be seen as a transitory period between awake and asleep and if uninterrupted by recovery, it can lead to sleep (Lal and Craig 2001). Below is a short summary list of the main fatigue factors generally identified in the literature:

- Company culture and management style
- Sleep and rest
    - Quantity and quality of sleep/rest
- Biological clock and circadian rhythm
- Monotony and boredom
- Level of automation
- Indoor environment on bridge (comfortable chairs, temperature, noise, etc)
- Shift work and work schedules

1.2. *Accident models*

An accident can be defined as a sudden, unwanted, and unplanned event or event sequence that leads to harm to people, the environment, or other assets (Rausand 2011). Accidents in complex socio-technological systems rarely happen because of a single unexpected event or a single failure. Even an unexpected event may not be unwanted. Some unexpected events are labelled 'good fortunes', while other events less fortunate are called 'near misses' or 'mishaps'. More serious events are called incidents, accidents, and disasters. In brief, to be able to call an event an accident, it has to be unexpected *and* have an unwanted outcome (Hollnagel 2004).

Accident models try to explain why accidents happen and causality is an important concept. In general, there are three main paradigms accident models can be grouped into sequential, epidemiological, and systemic accident models. The understanding of the various accident models is important for choosing the right method to analyze an abstract phenomenon like fatigue among the navigating crew of a ship.

The sequential models are the earliest and simplest accident models (Kjellén 2000). The accident is described as a result of events occurring in a specific order, sequential in time. An early example is the Domino theory (Heinrich 1959). In the domino theory model, a link in the chain is an unsafe act or unsafe condition, and by preventing it, the accident is avoided. Event tree analysis is a technique which is suitable for Domino-based methods. However, an accident at sea is rarely the result of a single event; rather it may be a product of a long chain of events and rare events occurring together.

The sequential models were early criticized for being too simple, and the possibility to work with multiple causality was limited (Hollnagel 2004; Reinach and Viale 2006). Sequential models imply that there is one single main cause in the beginning of the sequential chain, called the root cause. However, the analysis can always be taken one or more steps further back in search of a new root cause. The sequential models have therefore introduced certain stop rules, which are more or less subjective and made dependent on constraints of time and resources. The whole concept of one single root cause is therefore misleading and should be used with care (Griffith and Mahadevan 2011).

The second-generation accident models, often termed ‘epidemiological’ models, had their analogy with the spreading of a disease, that is, that the outcome was a result of a combination of factors, some manifest and some latent that happen to exist together in space and time. Examples of epidemiological models are the Swiss cheese model (Reason 1990) and models of sharp end–blunt end interaction (Woods et al. 1994). In the epidemiological models, the search is for latent failure conditions. The investigators are not to look for only *one* main root cause. The models admit the complexity and the fact that the analysis must account for complex interactions among different factors. Yet the epidemiological models are still sequential in their core; they follow a sequence of events from a beginning to an end in the direction of causality (Nygren 2006).

The systemic accident model takes into account the socio-technological system that shapes the conditions for the people and equipment performance rather than only focusing on human or mechanical error (Flohberger 2010). The Functional Resonance Accident Model (FRAM) is an example of a systemic model. FRAM shows how the various functions of a system’s component may resonate and create hazards that can run out of control. In systemic models, the whole system is looked at as one entity, not as being made up of several components (Hollnagel 2004). Accidents happen when the system’s ability to control the events no longer is sufficient. The systematic models have their origin in control theory, chaos theory, and the idea of stochastic resonance. Epidemiological or systemic accident models should be used when analyzing systems involving human actions. Sequential models may still be used where simple machines are involved. However, human actions and organizational factors require more comprehensive modelling.

2. Methodology and material

2.1. *The Cognitive Reliability and Error Analysis Method (CREAM)*

CREAM was developed by Erik Hollnagel (1998) for the analysis of safety related errors in socio-technological systems to determine the human, technological, and organizational factors that may be involved in error causation (Akhtar et al. 2010). CREAM has been based on the principles of cognitive system engineering. It was originally developed for the nuclear power industry, but is a generic technique which can be used in various areas involving complex and dynamic systems. In-depth case studies, like maritime accident investigation reports provide detailed data that are otherwise unattainable from statistics. The main purpose of converting case studies (i.e., the accident investigation reports) into CREAM charts that are aggregated is to identify common patterns which in turn give birth to various hypotheses and relationship theories. The patterns are possible to identify because the charts are consistent and because the classification schemes compel the analyst to think through the accident in the same systematic way for each case.

Even though CREAM generates accident charts in a timeline, its underlying model and technique is not sequential. CREAM is therefore claimed by some to be a systemic method because of its non-linear reasoning (Hollnagel 2004; Qureshi 2008). However, the end result of a CREAM analysis, that is, the aggregated charts, points to cause–effect relationships because of the timeline involved, and thus, it could also be argued that CREAM is not fully systemic. Still, the method produces valuable insights into the system being studied.

For road traffic accident analysis the Driving Reliability and Error Analysis Method (DREAM) has been developed, which is basically an adapted version of CREAM (Warner et al. 2008). There are many parallels between road traffic accidents and maritime accidents; however, the maritime accidents are more complex in their human cognitive nature. There are also stronger influences of organizational and technological factors compared to road traffic accidents where the driver is often the only human being in charge. In maritime accidents there may be complex interactions between the bridge's team members. Human performance over time, as required on a ship's bridge, usually demands great cognitive effort, including sustained vigilance, selective attention, complex decision-making, and automatized perceptual skills. In light of these cognitive elements and the research literature on fatigue, CREAM was selected as a suitable method for analyzing the interaction of the fatigue factors and human performance on a ship's bridge.

The approach in CREAM requires three necessary parts: a model, a classification scheme, and a classification method (Sandin 2008). Figure 1 shows how CREAM can be used as a tool to generalize causes and relationships from maritime accidents.

CREAM has a comprehensive classification scheme for accidents. The classification scheme groups and classifies the actions, causes, and the outcomes of events. The biggest distinction is made between the effects/manifestations which are termed phenotypes and the causes termed genotypes. Phenotypes refer to observable effects, that is, human (observable) actions, as well as system events, such as release of matter and changes in speed, direction etc. The genotypes (the non-observables) can be classified into three groups: man, technology, and organization. The challenge with a classification scheme (taxonomy) is that it must contain a large number of details to be useful. On the other hand, if the taxonomy is too detailed, the number of categories becomes too large, making it difficult to classify events. In addition, each category becomes too narrow in scope. Therefore, the taxonomy is seen as a flexible tool which needs to be renewed and updated

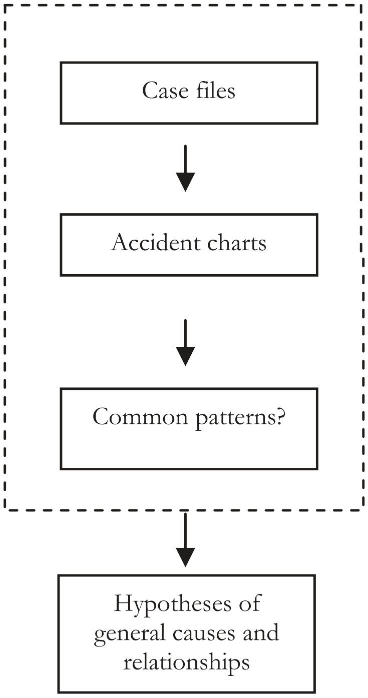

Figure 1. Aggregated causation charts are based on case studies from in-depth accident investigations. The dotted rectangle indicates CREAM's application area (Sandin (2008)).

regularly (Sandin 2008). CREAM does not define the factors in the taxonomy in detail (see Table 1). It is up to the analyst to make use of them as he or she interprets them. A relatively high degree of subjectivity is therefore involved in the analysis of each accident. However, when several charts are combined (aggregated charts), the method yields common patterns which are interpreted as disclosing cause–effect relationships. The degree of subjectivity is further lowered if the same accidents are analyzed by different persons in teamwork or individually. CREAM's taxonomy is not organized in a strict hierarchical way; thus, several pathways can lead to any particular consequence. A genotype coming before another genotype in one accident chart can well change places in another accident chart. Therefore, in accordance with the systemic view, the single accidents charts created are not considered to be causation charts, as is the case with sequential models; rather they should be interpreted as signifying relationships and interactions between the various factors.

The flexible way of organizing the taxonomy is important in order to model complex socio-technological systems. The results are highly dependent on the structure of the taxonomy and one may therefore question the objectivity of the CREAM taxonomy. However, even with a non-linear taxonomy and high reliance on the analyst, the CREAM results are shown to be reproducible by other researchers.

To strengthen the validity of research using CREAM, the aggregation charts may be conducted by a different set of researchers than the individual accidents charts. Double set of researchers may work as a quality check of the total analysis. To validate a version of CREAM developed for road accidents (DREAM), a study was done on how different researchers understand and use the taxonomy for same accident (Sandin 2008). The

Table 1. Explanations of CREAM genotypes adopted from (Hollnagel 1998).

Genotype	Explanation
Wrong direction	Movement in the wrong direction or the wrong kind of movement of the vessel.
Timing	An action started too early or too late (delayed action).
Observation missed	A signal or an event that should have been the start of an action is missed.
Inattention/distraction	The performance of a task is not completed because of a shift in attention or an event was missed due to inattention that can be explained by cognitive function.
Fatigue/performance variability	The person's response and precision of actions are reduced due to fatigue.
Communication failure	Movement in the wrong direction or the wrong kind of movement of the vessel.
Inadequate procedure	An action started too early or too late (delayed action).
Inadequate plan	A signal or an event that should have been the start of an action is missed.
Irregular working hours	The performance of a task is not completed because of a shift in attention or an event was missed due to inattention that can be explained by cognitive function.
Inadequate quality control	The person's response and precision of actions are reduced due to fatigue.
Shift work	Movement in the wrong direction or the wrong kind of movement of the vessel.
Inadequate task allocation	An action started too early or too late (delayed action).
Excessive demands	A signal or an event that should have been the start of an action is missed.

Source: (Sandin 2008).

results showed that on average 83% genotypes and 78% of the phenotypes were identical. Although DREAM is different from CREAM the methodology and the technique for analyzing the accidents are the same. The CREAM taxonomy was originally designed for the nuclear power industry. When analyzing fatigue-related maritime accidents with CREAM, the challenge is to translate the event of accident, including the fatigue factors, into genotypes found in the CREAM taxonomy. Table 1 contains explanations of the CREAM genotypes, for brevity only those genotypes are listed which were picked at least five times or more during the analysis of the accidents in the current study.

Summing up CREAM, when analyzing an event or accident one must find suitable genotypes in the taxonomy to choose from. Each of these genotypes is then looked up in the taxonomy which guides in finding further suitable matches (genotypes) until the taxonomy options are exhausted. We have used CREAM to search for interdependencies and common conditions that can be associated with fatigue-related accidents. The CREAM version 0.6.1 was used which can be downloaded directly from the internet (CREAM v.0.6.1 2012). For further reading about CREAM, we refer to (Hollnagel 1998, 2004; Sandin 2008).

2.2. *Fatigue-related maritime accidents*

The accidents in the present study were collected from 98 collision/contact accidents and 56 groundings from the MAIB in the UK (MAIB 2004). In addition, 22 maritime accident reports from the Accident Investigation Board Norway were included. From all of these accident investigation reports, 33 fatigue-related accidents were identified: 16 collisions and 17 groundings from 1999 to 2011. If the accident investigation report explicitly suspected fatigue at the time of the accident, or two or more of the fatigue factors described in Section 1.1 were judged to be present, the accident was regarded as being fatigue related. Consequently, all of the accidents in our sample were assumed to involve fatigue. The accidents were not limited to any specific ship type; however, vessels with at least four crewmembers were included so that the interaction and communication between the personnel could be taken into account when analyzing fatigue. See Annex 1 for a detailed overview of the accidents included in the current study.

2.3. *Classification and aggregation of CREAM charts*

Each individual fatigue-related maritime accident was classified by means of CREAM version 0.1.6 (CREAM v.0.6.1 2012). In order to identify patterns of genotypes and links, the CREAM charts for the collision and grounding accidents were first aggregated as two separate groups. Then, all charts were aggregated together in order to view the overall picture and identify differences and/or similarities between the charts from the collision and grounding accidents.

CREAM aggregation charts point out the factors most often occurring and identify interdependencies and common conditions that can be associated together. The CREAM taxonomy is somewhat limited so several factors are commonly interlinked. Aggregation charts space out these interlinks. In the charts, the accident is placed to the right and then the factors closest to it in the timeline are placed to its left side. Thus, causation can be inferred. However, as mentioned in Section 1.2, in accordance with the systemic view, a line in the chart should be interpreted with care, even though causation can be inferred, they primarily signify relationships and interactions between the various factors. Straight lines are therefore used instead of arrows to indicate this fact. For instance, in Figure 2, ‘observation missed’ can be inferred as being the effect or consequence of ‘fatigue’. However, the aggregation of the CREAM charts in our analysis places ‘observation missed’ closer to the accident, thus indicating it to be a cause of fatigue.

3. Results

3.1. *Collision accidents*

Figure 2 illustrates the aggregation of the collision accidents. Collision is defined here as two vessels unintentionally being in physical contact with each other. In the collision accidents, ‘observations missed’ was tightly linked to ‘fatigue’. Fatigue also influenced ‘timing’ which in a turn led to a collision. Examples of bad timing include initiating a turn too late or misjudging the other vessel’s speed.

‘Communication failure’ and especially ‘irregular working hours’ are also tightly linked to ‘fatigue’. In the accidents examined, there was often no communication between the personnel on board. Even when other members of the bridge team noticed too high speed or a turn not being conducted properly, there was a lack of whistle blowers. Communication often initiated when it was already too late, and when the environment got panicky and mistakes easily were made. ‘Communication failure’ may be a cause or an effect of fatigue, but is in either way linked to ‘fatigue’. Even though CREAM’s taxonomy places one genotype before the other, the interpretation of the CREAM diagrams is that there is a connection between these two genotypes which one should be aware of. In light of the systemic view, as discussed above, one should be careful to determine a genotype as an absolute cause or an effect to another genotype. However, CREAM does point out patterns in accidents from which typical influences of the various genotypes are highlighted. ‘Irregular working hours’ is used when the personnel had to

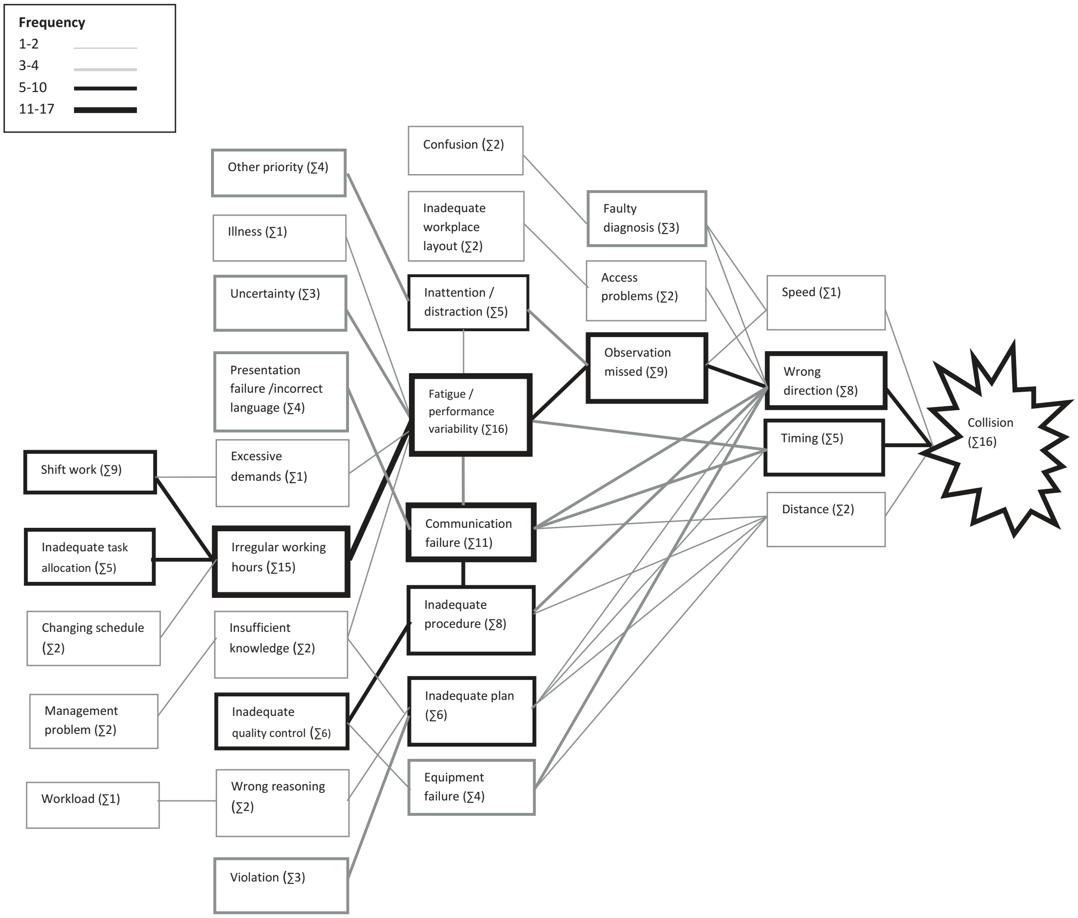

Figure 2. Aggregation of CREAM accident charts of fatigue-related collisions. The sum denotes the frequency of the factors in the accidents.

work whenever they were needed even outside their watch. 'Irregular working hours' is linked with 'shift work' and 'bad allocation of the tasks', like for instance, sending the lookout to do lower priority work and leaving the officer alone in the bridge. The masters, for instance, frequently worked outside their shifts when the ship was on harbor loading and unloading and when the ship was navigating out from the port.

The aggregation shows that 'Communication failure' is linked with 'inadequate procedures'. The interpretation of this must be that 'inadequate procedures' may lead to communication failures and not the other way around. In one accident, for example, the pilot was busy finding the right radio channel to communicate with the other vessel instead of maneuvering the vessel by sight even when the collision had become imminent. Inadequate or misguided communication and planning between the boarding pilot and the master is another example. When the pilot is navigating the vessel, the master is still the main responsible person on board and should therefore be critical to the pilot's choices and ask questions. Ideally the master and the pilot should cooperate in navigating the vessel. However, the master often goes into a passive state, not adjusting the orders of the pilot when it is obviously evident to do so (Lovell 1999).

Finally, two collision accidents resulted from the officer falling asleep and in one of them the officer was under the influence of alcohol. However, no genotypes were available in our CREAM version to include ‘asleep’ or ‘alcohol abuse’ in our analysis.

3.2. *Groundings*

Figure 3 illustrates the aggregation of the grounding accidents. Grounding is defined here as the vessel’s impact on the seabed causing damage to the hull; 17 accidents were classified as groundings.

The main finding is that ‘fatigue’, ‘inattention’, and ‘inadequate procedure’ together influence ‘observation missed’ which in turn lead to groundings. Shallow waters or submerged rocks were overlooked even if they were clearly marked on the radar screens and charts.

Fatigue is linked to ‘excessive demands’ and ‘irregular working hours’. ‘Inadequate procedures’ are tightly linked with ‘inadequate quality control’. ‘Inadequate procedure’ includes incomplete, or in some cases, total lack of the navigational planning. In three accidents the navigational equipment was not working properly.

In general, groundings occurred when the vessel for some reason missed a turn. The overwhelming majority (14 accidents) had ‘wrong direction’ (i.e., the maneuver is made in the wrong direction) as the direct reason for grounding, as shown in Figure 3.

Although not managed by the CREAM taxonomy, the high levels of inattention and fatigue may be related to the time pressure the bridge personnel are exposed to. Often, passage planning is absent because it is actively omitted, especially by masters and pilots who feel familiar with port approaches. Still, poor planning alone is often not enough to

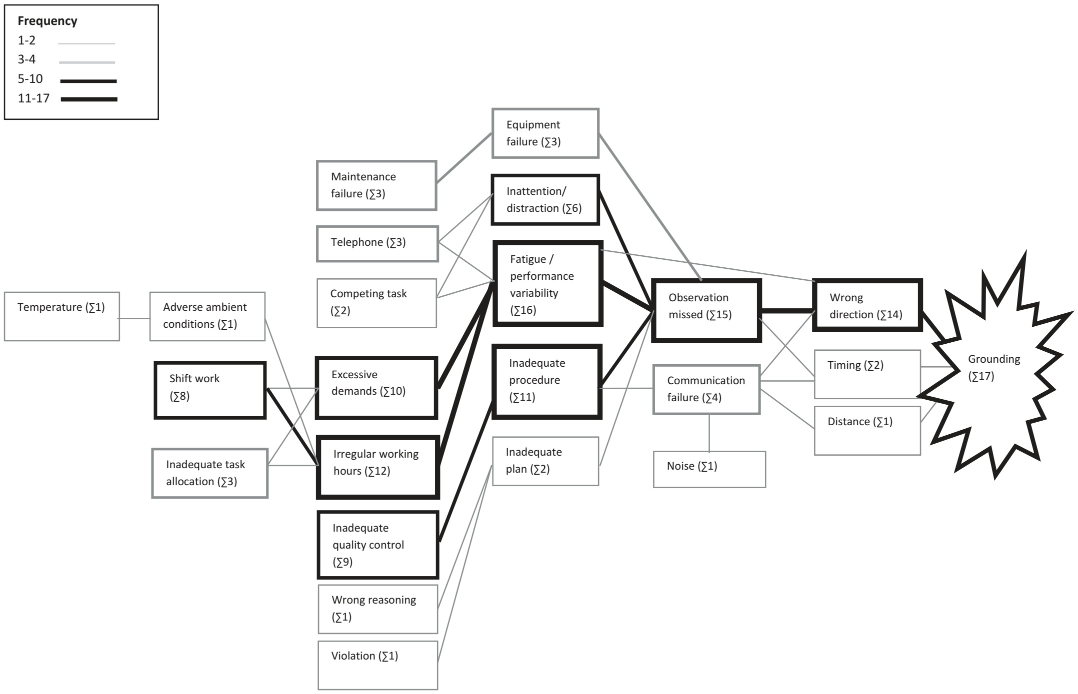

Figure 3. Aggregation of CREAM accident charts of fatigue-related groundings. The sum denotes the frequency of the factors in the accidents.

lead to grounding, but coupled with fatigue, inattention, and omitting passage plan may turn out to be crucial.

3.3. *The overall picture*

Figure 4 illustrates the aggregation of both collision and grounding accidents (note that only genotypes with frequency five or higher are included to emphasize the patterns). In general, ‘observation missed’ and ‘timing’ are closely related to ‘fatigue’. ‘Fatigue’ is mostly linked to three genotypes: ‘excessive demands’, ‘irregular working hours’, and ‘Observation missed’. ‘Irregular working hours’ is closely linked to ‘shift work’ and ‘inadequate task allocation’; 27 out of 33 accidents had irregular working hour schemes for the personnel. ‘Communication failure’ is not directly connected to ‘fatigue’, but it is however noticeably present and contributes to ‘observation missed’.

In 22 accidents the navigating officer did not use a ‘lookout’. Lookout duties are easily given a lower priority to other waiting tasks like maintenance, catching up with sleep, etc. Lookout duties are also thought of as unnecessary redundancy, especially when the traffic is low. When fatigued, the risk of missing observations increases when the lookout is omitted or assigned other tasks (MAIB 2004). A strong and direct link between ‘fatigue’ and ‘inadequate procedures’ was not found, even though they both influenced ‘observation missed’.

Figure 5 shows the percentage of a genotype being included in the analysis. The blue columns represent the collision accidents and the red columns represent the grounding accidents. It is clear that some genotypes are overrepresented in grounding while others are overrepresented in collision. ‘Observation missed’ and ‘excessive demands’ stand out in grounding accidents, while ‘communication failure’ seems to be central in collision accidents.

Figure 6 shows the circumstances at the time of the accident. In about 21% of all the accidents the navigating officer was under the influence of alcohol, and in about 40% of

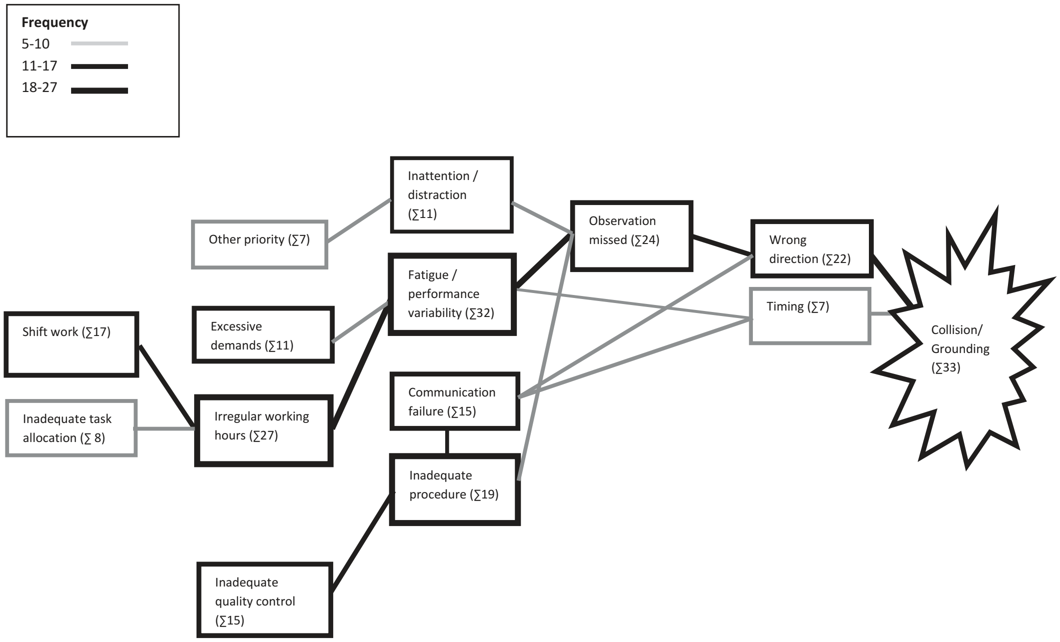

Figure 4. Aggregation of CREAM accident charts of fatigue-related collision and groundings. The sum denotes the frequency of the factor.

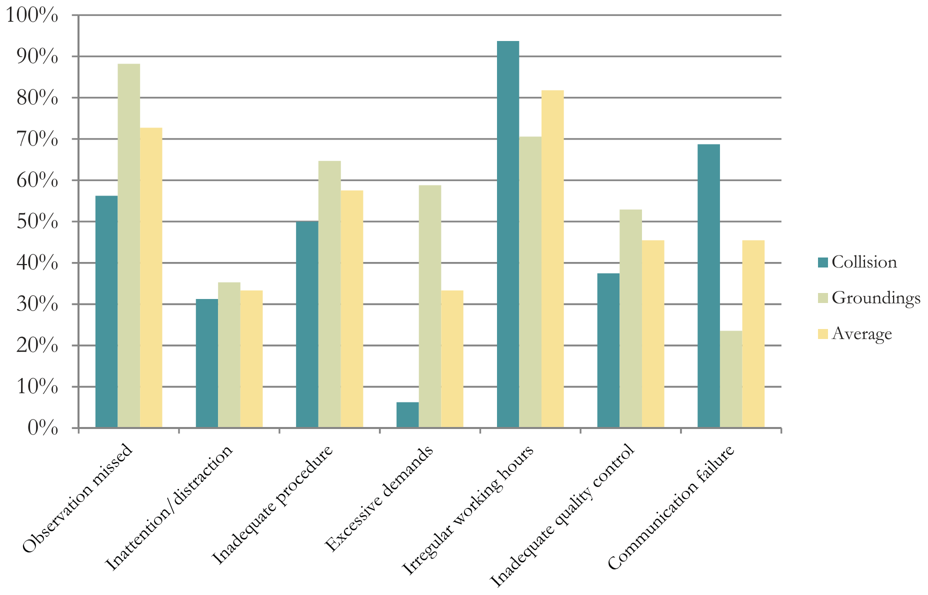

Figure 5. Frequently used causal factors from the CREAM taxonomy for the 33 fatigue-related accidents.

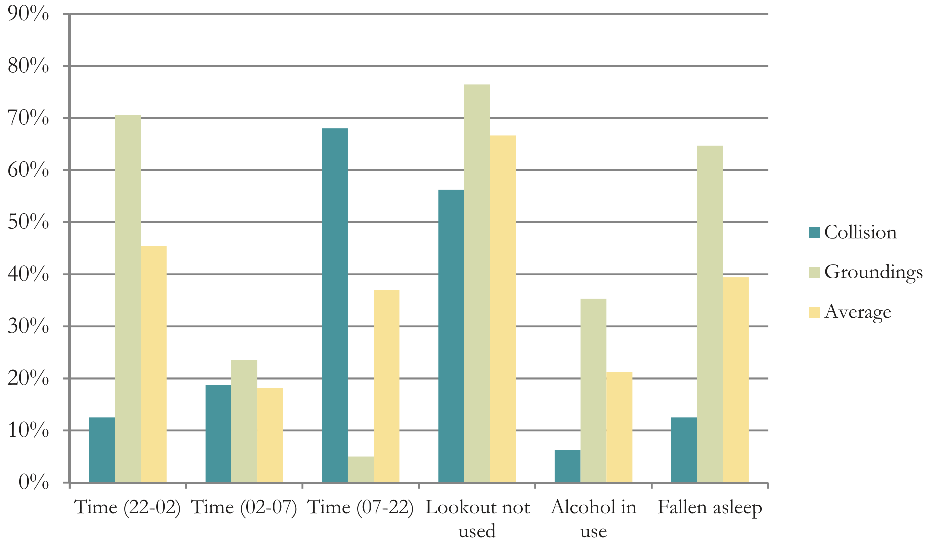

Figure 6. Various circumstances in the 33 fatigue-related accidents in the study.

the accidents the officer had fallen asleep. As previously mentioned, misuse of alcohol and drugs could unfortunately not be included in the analysis as no genotypes are available from the CREAM taxonomy.

The circadian effect also seems important: all groundings, with the exception of one, happened between 22–02 hours (4 accidents) and 02–07 hours (12 accidents). Collisions, on the other hand, mostly occurred during the daytime and in the evening. The lack of lookout was high in both collision and grounding accidents. Studies show somewhat different results on exactly when the risk of collisions is at its highest between 0600 and 0700 (Folkard 1997), and

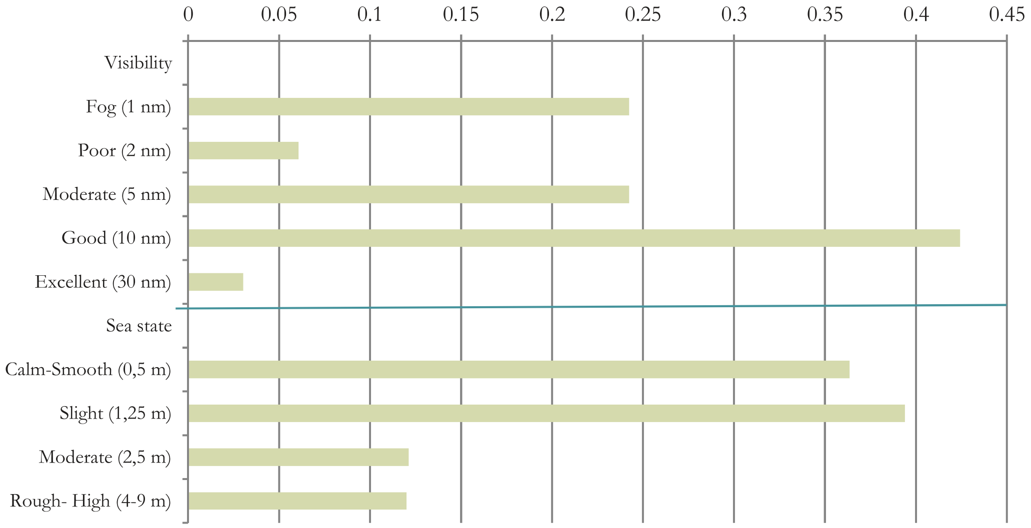

Figure 7. Sea state level and visibility level ratios at the time of accident. The sea states indicate the wave lengths in meters at sea (Douglas sea scale). The definition of the range of the visibility is from (Pick (1932)).

in general, collision accidents are associated with the start of a shift. The collisions between ships at sea are more likely to occur during the early hours of the day, and while they are *under way*, that is, when the crew is finished with anchoring or berthing, but when they have not yet reached open waters (Smith, Lane, and Bloor 2001).

Figure 7 illustrates the sea state at the time of accident. The majority of accidents happened when the sea state and the visibility were considered relatively good. One officer fell asleep in moderate sea when the vessels were subject to waves, while all other similar accidents happened in calm–smooth or slight sea state. Apart from one accident, the visibility levels were good when the officers fell asleep. This seems to support the theory that monotonous weather conditions, coupled with fatigue can lead to reduced vigilance and sleep, as discussed by (Allen, Wadsworth, and Smith 2008; Williamson et al. 2011; Phillips and Sagberg 2010).

The age of the ships was not a significant factor in the accidents. The average age of the ship in the collision accident was 14.3 years and 17 years old for groundings. The ships were all well equipped with the necessary navigational instruments. Man–machine interface problems when fatigued were generally not mentioned in the accident investigation reports.

A particular hazardous situation is when circadian and sleep homeostasis is coupled with alcohol and monotonous conditions. Even low alcohol exposure significantly impairs the performance of maritime pilots (Howland et al. 2001). A period of sustained wakefulness of 18 hours can be comparable to a Blood Alcohol Concentration (BAC) of 0.05%. If sleep deprivation continues for 24 hours, the effect of fatigue is equal to a BAC level of 0.10%. Use of alcohol also significantly impairs the visual search and the solving of navigational problems (Marsden and Leach 2000). Prolonged watches in combination with abuse of alcohol are a major cause to fatigue-related accidents (IMO 2001). Almost 35% of the grounding accidents analyzed in our study involved alcohol abuse.

The above findings indicate that fatigue in grounding accidents is different from fatigue in collision accidents. The groundings were less complex accidents than collisions. In groundings, the bridge team either had an officer asleep or missed vital observations, which eventually led to grounding of the vessel. In collisions, the events had several aspects and were more complicated to analyze in CREAM. More genotypes had to be chosen from the taxonomy for collision accidents than groundings in order to describe the accident in a satisfactory manner.

4. Discussion and conclusions

The study in this article reveals several differences between collision and groundings accidents and their corresponding fatigue factors. The general nature of collisions is that the vessels spot each other, but badly timed decisions are made and misconceptions are formed due to fatigue. Right before the collision the atmosphere is often panicking and mistakes are easily made. Genotypes like ‘communication failure’, ‘inadequate plan’, and ‘inadequate procedure’ play a bigger role in collisions than in groundings.

A typical grounding accident in the present study happened in monotonous conditions, with good visibility and calm sea, the navigating officer being fatigued and therefore missing vital observations or badly timing a turn. The fatigue might be generated from poor organizational culture.

‘Communication failure’ was an important element in both types of accidents. Bad communication indicates a poor safety climate where team support and whistle blowing are not encouraged. Several collisions could have been avoided if the whole team was actively involved instead of being spectators to the master’s or to the embarking pilot’s actions. Pilots had most of the time written passage plans brought with them to the bridge, but they were not discussed with the rest of the crew. In practice they were only superficial plans. However, this practice was seemed to be accepted from both parties: the master and the pilot.

In the overall picture (groundings and collisions), fatigue is tightly coupled with ‘observation missed’ which in turn leads to ‘wrong direction’. Other genotypes were ‘shift work’, ‘inadequate task allocation’, ‘irregular working hours’, and ‘excessive demands’. All of these latter-mentioned genotypes point to a deteriorated safety climate, with a high tolerance for long hours of work. More alarmingly the poor safety climate did not seem to be limited to the shipping companies. Also, the attitudes of the embarking pilots toward safety issues were surprisingly poor. Good communication is essential for a healthy safety climate. The present study suggests that lack of communication seems to be one of the main problems in the collision accidents. The communication between the pilot, the master, and the rest of the team was often at the bare minimum.

In the accidents examined, it can be concluded that the core of the ISM Code (IMO 2010) was not followed, which is to constantly be thinking about safety and recognizing that accidents are preventable through following correct procedures and established best practices, like having a proper lookout which is well rested and motivated for the job. Overall, there was also a lack of human resources, time pressure, and relatively frequent staff turnover in the bridge’s navigational team. This makes it difficult to implement a good safety management system.

Even though CREAM is generic, it was originally not developed for maritime accidents, and as such, it does not include all the fatigue factors which are generally recognized as being important for the bridge management team at sea, for instance 'homeostatic sleep' or 'circadian effect'.

The actual links between the genotypes in the taxonomy are not well documented in CREAM. Thus, even though the results call attention to important fatigue factors and the interaction between them, one cannot say that the results are derived independently from CREAM. In theory, other methods may therefore highlight other fatigue factors and their interdependencies. Still, the existing taxonomy in CREAM, even if not precisely defined and accounted for, is built up of well-recognized elements in cognitive engineering adaption and adjustments of the taxonomy is encouraged. Therefore, the CREAM taxonomy can and should be adjusted to better suit maritime accidents. In the maritime version, the genotypes could be further categorized and more precisely defined. 'Irregular working hours', for instance, could be divided into three more factors like 'shift work scheme 4–8–4', '6–6', or '12–12'. We have already seen one example in our study of how the taxonomy needs to be adjusted. All of the 17 groundings were fatigue related; hence, we know that fatigue was an element in all of the groundings. Nevertheless, fatigue was only picked as a genotype 16 times. This is because in one grounding accident, the genotypes were chosen in such an order that fatigue never showed up as an available genotype to choose from in the taxonomy. Use of drugs and abuse of alcohol could not be included either.

In the present form of CREAM, the taxonomy does not include the possibility of choosing genotypes for incorrect use of the various maritime navigational equipment available on the ship's bridge. Other fatigue factors, like those mentioned in the IMO fatigue guidance manual (IMO 2001), should also be integrated in an upgraded CREAM version for maritime accidents. Examples are frequency of port calls, time between ports, weather conditions, ship design, and location of quarters. By doing so, one could go a step further in the analysis and define more genotypes, such as vessel's maintenance, the automation level, the number of different nationalities on board, poor bridge design, etc. An attempt was made in a master thesis (Nygren 2006); however, a more profound and documented work is needed for research work.

A possible weakness of the current study is that the same researchers were used to produce the individual accident charts and the aggregated charts. A different set of researchers for the aggregation charts may have worked as an extra quality assurance. However, this may be an important point to consider whether the charts become more extensive and complicated. In this study the aggregations were considered to be straightforward and not wide-ranging.

In-depth analysis has the privilege to go deep into each accident and look for explanations. However, the maritime industry should pay attention to the lack of consistencies in the accident reports. Even within the same accident investigation organization, the reports do not follow one single template, making it difficult to draw statistics without including subjective interpretations. The accidents analyzed in this study are purposely fatigue related. General conclusions must therefore be drawn with care. Nevertheless, a vital lesson learned from this study is that more effort is needed to improve the knowledge of how fatigue factors contribute to accidents.

Macrae (2009) showed in his study, focusing on human factors in general, that 'planning', 'interpretation', 'communication failure', and 'team work' were the major grounding accident contributing genotypes. For collision accidents 'inadequate plan', 'missed observation', and 'poor interpretation' were the main accident contributing genotypes. Our aggregation charts, derived from fatigue-related accidents, highlight slightly different genotypes. For groundings 'inattention', 'inadequate procedures', and 'observation missed', and for collisions 'communication failure', 'inadequate procedures', and 'observation missed', were the major contributing genotypes. This indicates that fatigue influences the human cognitive processes in such a way that specific precaution and measures should be prioritized and applied when fatigue could be in the picture. The bridge team should be trained to recognize and admit fatigue and exercise caution related to the fatigue factors discovered in our study.

Accident analysis implies use of theoretical accident models. Most of them are not fit to model complex phenomena; they simulate sequential chains which assume little or no interaction between the various chains of events leading to an accident. In complex socio-technical systems one needs models which can take into account the complexity and the correlations between the various causal chains. Bayesian Belief Networks (BBN) are able to deal with this complexity (Rausand 2011), but they require an underlying theoretical accident model to build upon. In-depth analysis of accidents using CREAM can assist in identifying and arranging the fatigue factors to be used in building a BBN network.

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Annex 1

	Name of the vessel	Place of accident	Report	Year of the accident	Accident type
1	Pride of Canterbury	England	MAIB report nr 2/2009	2008	Grounding
2	Kivalina	Norway	AIBN report nr:9 205 885	2008	Grounding
3	Antari	Ireland	MAIB report nr 7/2009	2008	Grounding
4	Aqua -boy	Scotland	MAIB report nr 14/2007	2006	Grounding
5	Harvest Caroline	Scotland	MAIB report nr 13/2007	2006	Grounding
6	Kathrin	England	MAIB report nr 24/2006	2006	Grounding
7	Berit	Denmark	MAIB report nr 17/2006	2006	Grounding
8	Lerrix	Germany	MAIB report nr 14/2006	2005	Grounding
9	Jackie Moon	Scotland	MAIB report nr 5/2005	2004	Grounding
10	Jambo	Scotland	MAIB report nr 27/2003	2003	Grounding
11	Nedlloyd Mangellan	England	MAIB report nr 18/2002	2001	Grounding
12	Brothers	England	MAIB report nr 1/2007	2006	Grounding
13	Primrose	Scotland	MAIB report nr 13/2002	2001	Grounding
14	Resplendent	Shetland	MAIB report nr 10/2002	2001	Grounding
15	Lomur	Shetland	MAIB report nr 7/2002	2001	Grounding
16	Betty James	Scotland	MAIB report nr 34/2002	2000	Grounding
17	Choise	England	MAIB report nr 33/2002	2001	Grounding
1	Boxford	England	MAIB report nr 17/2011	2011	Collision
2	Skagern	England	MAIB report nr 6/2007	2006	Collision
3	Samskip Courier	England	MAIB report nr 6/2007	2006	Collision
4	Maritime Lady	Germany	MAIB report nr 2/2007	2005	Collision
5	Lykes Voyager	Hong Kong	MAIB report nr 4/2006	2005	Collision
6	Orade	England	MAIB report nr 23/2005	2005	Collision
7	Hyundai Dominion	China	MAIB report nr 17/2005	2004	Collision
8	Sky Hope	China	MAIB report nr 17/2005	2004	Collision
9	Dorthe Dalsoe	Sweden	MAIB report nr 10/2005	2004	Collision
10	Saint Jacques II	Germany	MAIB report nr 5/2002	2002	Collision
15	Celtic King	Wales	MAIB report nr 2/2001	2001	Collision
11	Atlantic Marmaid	Germany	MAIB report nr 12/2002	2001	Collision
12	Highland Pioneer	England	MAIB report nr 15/2001	2001	Collision
13	De Bounty	Wales	MAIB report nr 2/2001	2000	Collision
14	Bruce Stone	England	MAIB report nr 31/2001	2000	Collision
16	Dole America	England	MAIB report nr 32/2000	1999	Collision

MAIB: Marine Accident Investigation Branch. Website: www.maib.gov.uk
AIBN: Accident Investigation Board Norway. Website: www.aibn.no