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PROBABILISTIC RISK ASSESSMENT FOR INTERGRATING SURVIVABILITY AND SAFETY MEASURES ON NAVAL SHIPS

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SUMMARY

Conflicts of today are characterized by both traditional and irregular tactics and non-state actors making innovative use of modern technologies. These conditions set new demands on naval ships. The aim of this investigation is to describe how, based on probabilistic risk assessment, the concept of operation for a naval ship can be turned into safety scenarios to be used in the evaluation of risk. In this investigation, civilian state-of-the-art methods for probabilistic risk assessment are merged with the specific demands of naval ships. Relevant aspects of safety culture, codes, regulations and rules are analysed with respect to requirements on safety scenarios, and military operational research with respect to modelling military systems. The results show that the scenarios must have calculable probability and must be adapted to the vessel in question. Results from simulations show that modelling operational tasks is a way to support experts in the definition of safety scenarios.

1. INTRODUCTION

Probabilistic risk assessment is used in civilian shipping as a tool to formulate regulations and to assist in ship design (1). For naval ships, other approaches are used which do not have to follow the same rules and regulations for approval. It is, however, reasonable to assume that if probabilistic risk assessment procedure were to be applied to naval vessels, their safety and survivability performance would be enhanced.

The current investigation examines how the civilian practise of probabilistic risk assessment can be applied to naval ships and what positive effects this could have on safety measures. In this context, safety is defined as including all measures covered by the IMO publications, maritime safety, as well as measures specifically designed to address the effects of military attack, survivability and security. In this investigation, survivability is seen as a function of the susceptibility, vulnerability and recoverability of the naval ship under study. Security is achieved when the ship is protected from external threats.

Total safety of a ship can never be achieved (2). Hence, safety efforts focus on reducing possible risks that affect safety- Here, risk is defined as the probability of the occurrence of an unexpected/unwanted event times the consequence of it happening. Different measures to reduce risks are often interconnected with each other and it is not possible to change these measures without affecting other aspects of the ships safety.

Safety is a matter of compromise. How to systematically enhance the safety of naval ships is an important issue both for defence executives involved in technology development and for tactical commanders at sea. Probabilistic risk assessment (1) offers a framework for a more structured approach that includes risk, or safety, throughout the ship design, operation and decision support processes.

The safety of naval ships under attack is a national issue, i.e. it is not governed by international regulations. Naval warships are excluded from the IMO conventions. SOLAS states that "the present regulations, unless expressly provided otherwise, do not apply to ... ships of war and troopships" (3). Nevertheless, a naval ship often operates under non-military conditions and under such conditions that civilian maritime safety regulations apply to many parts of the ship (4). However, for some tasks, civilian regulations are inadequate (5): military success cannot be achieved at sea without great risks (2) and risk awareness for those situations cannot depend solely on civilian maritime safety methods.

In the current study, probabilistic risk assessment is used as a method for quantification of risks. The method includes "risk analysis" as well as the methodology used in traditional "risk-based ship design". Risk is used here as a way to quantify safety. The aim is to investigate and describe how, based on probabilistic risk assessment procedure, the concept of operation for a ship can be turned into relevant safety scenarios. It should be possible to use such scenarios in the evaluation of consequences and probabilities as a decision support tool in the design of naval ships.

In this investigation, civilian state-of-the-art methods for probabilistic risk assessment are merged with the specific demands of naval ships. In Section 2, important elements of probabilistic risk assessment are described in order to define the process and a framework in the following sections. In Section 3, relevant aspects of safety culture, codes, regulations and rules are analysed with respect to the requirements of safety scenarios. The analysis focuses on requirements, which ensure that the result can be used to improve the design process and enhance design decision making. Military operational research, focussing on modelling military systems, are described in Section 4 in order to ensure that safety scenarios model military operations effectively. Section 5 presents an example of a numerical simulation for event probability estimation. It demonstrates how probability-based scenarios can be derived, based on the requirements discussed in the previous sections of this investigation. Finally, Section 6 discusses the achievements made during the current investigation, followed by the conclusions, which are presented in Section 7.

2. PROBABILISTIC RISK ASSESSMENT

Risk analysis is a tool for identifying and assessing possible unwanted events and finding effective measures to minimise the risk (6). The purpose of introducing probabilistic risk assessment into the design process analysis of naval ships is to meet safety goals more effectively through a well-balanced combination of proactive and reactive measures. This could then be used as input to a systems engineering process for concept development, new-builds and midlife upgrades, as well as operational planning. The aim is to get ships more fitted to their intended use.

2.1 RISK-BASED SHIP DESIGN

Considerable research effort has been devoted to the area of risk-based ship design. In this section an overview and some results, relevant to safety scenarios for naval ships, are presented.

The IMO code of safety for high-speed craft (7) states that, for civilian commercial ships, it is possible to use a prescriptive code to ensure a suitable level of safety. However, for novel or specialised types of ship, a prescriptive safety code is often too restrictive. Consequently, probabilistic methods (or risk-based methods) need to be used to ensure that the risks for different incidents are kept acceptably low.

Risk-based ship design requires, according to Vassalos (1): (i) a consistent measure of safety and a formalised procedure of its quantification (risk analysis), (ii) risk analysis to be integrated into the design process to allow for tradeoffs between safety and other design factors, and (iii) a parametric model of the ship, access to fast and accurate first-principle tools and a common ship design model in an integrated design environment.

Based on these requirements, risk-based ship design analysis can be performed with different tools and methods in order to meet the requirements for the design project at hand. When selecting the assessment procedure, the following aspects must be considered:

- **Design stage flexibility:** at the concept stage, flexibility for major changes but lesser knowledge about the ship, use coarser methods.
- **Major hazard potential:** greater potential for total loss or multiple fatalities, less desirable to use rule-based approaches. Focus the procedure on major ship accident categories.
- **Risk decision context:** novelty, uncertainty or stakeholder concern calls for more thorough risk assessment (1).

The result of a risk analysis should be used with other ship performance data in design decision making, see figure 2.

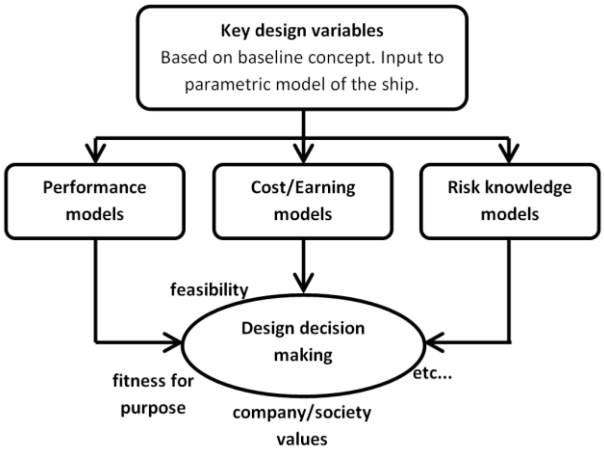

Figure 2: Design decision making in risk-based ship design. Redrawn from Vassalos (1).

2.2 HAZARD AND SCENARIO IDENTIFICATION

The first step of a risk analysis is the identification of hazards where both creative and analytical techniques are used. The “what can go wrong” question must be explored systematically, usually based on expert judgment; see (8) and (9).

Critical design scenarios must be created based on the identified hazards. The design scenarios should have calculable probability and consequences that could collectively quantify the life-cycle risk of a ship at sea. They relate to accidents categories with major hazard potential. When generic design scenarios are available, they must be adapted and customised to the specific design features and expected performance of the vessel in question (1).

Kaneko (10) states that the use of experts in risk analysis must be supported by analysis methods and simulations of plausible risks in order to increase the reliability of the total analysis. It is important to evaluate the process by which hazards occur and lead to accidents. Special focus should be put on disaster escalation scenarios.

Tam and Bucknall (11) describe how rules for evasive manoeuvres affect the actions taken when there is another ship at close range. These rules have an effect on the probability of, for example, a collision or the type of collision (scenario). Such rules for actions must therefore be included in the scenario definition or simulation. For naval ships, this means that the rules for conducting a tactical task (tactics) must be used when designing the scenarios as well as assessing the probability and consequence of each of the scenarios.

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2.3 CONSEQUENCES AND PROBABILITIES

After hazard identification and scenario definition, the scenarios must be analysed in detail. The purpose of this analysis is to investigate the consequences of the identified hazards and to calculate their probabilities. This can, for example, be carried out by a combination of event and fault trees (6).

2.4 RISK CRITERIA

Assessment of the risk associated with a specific maritime operation should be used to ensure involved parties that the risk is acceptable low. At the same time the accepted risk level should allow for operation of the ship at feasible cost level. Ship owners are responsible for weighing the risk against the cost of implementing controls and measures and the impact on operational gain. But organizations and the society also set limitations on allowed risks, risk criteria.

Risk criteria have been discussed within the IMO as a result of the risk-based approaches. Agreed individual risk criteria targets for new ships are 10-4 annually probability of loss of crew member and 10-5 annually probability of loss of passenger and public ashore. Probabilities above these level limits should be reduced no matter what the consequences (12). According to Pedersen (13) the risk criteria must generally be established for the following types of risk:

- Fatalities
- Pollution of the environment
- Loss of property or financial exposure

Different principles must be used to formulate acceptance criteria dependent on the consequence and special focus must be on events with several fatalities. This because society is more concerned about single events with many fatalities, societal risk, than several incidents with few fatalities per incidents (13). It is therefore reasonable to assume that the risk associated with naval operations needs specific acceptance criteria as the consequence is not comparable with traditional operational risks for shipping.

NATO defines force protection as “measures and means to minimize the vulnerability of personnel, facilities, materiel, operations and activities from threats and hazards in order to preserve freedom of action and operational effectiveness thereby contributing to mission success” (14). Based on the definition the following types of risk criteria are in this study suggested for naval operations:

- Fatalities
- Loss of technical systems and materiel
- Impact on operational effectiveness and freedom of action

The first two, fatalities and loss of technical systems and materiel are important of their own, but does also combine to affect impact on operational effectiveness and freedom of action.

2.5 NAVAL SHIPS AND RISK

Security is regarded as one of the Principles of War; these principles are crucial to successful military planning and actions. Security is achieved when you take measures to protect your forces. Appropriate security allows for freedom of action by reducing your vulnerability to your enemy’s actions (15) and ((14).

Safety as it is defined in this study (see section 1) is therefore an important measure of success for naval ships. Survivability of a naval ship is not only a question of having the right weapon systems or armour, it can, as the Naval Ship Code (NSC) defines it, be described in terms of the susceptibility, vulnerability, and recoverability of the ship (16):

- **Susceptibility** includes technical and tactical measures and describes how easily the ship can be detected.
- **Vulnerability** is the inherent ability of the ship to resist damage.
- **Recoverability** is the ability of the ship and its crew to sustain operational capability.

All three aspects are functions of technology, tactics and efforts carried out onboard. Survivability can also be described and analysed by layers of protection, see the “survivability onion” in figure 3. Different layers have different characteristics depending on the type of vessel in question.

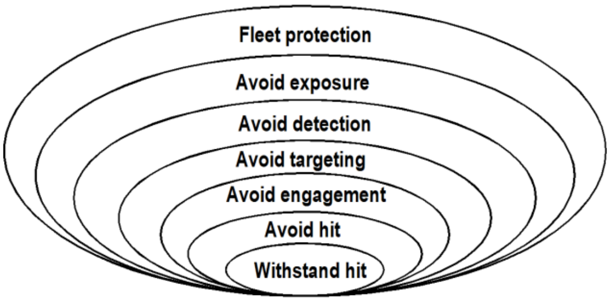

Figure 3: The survivability onion.

Probabilistic risk assessment needs relevant safety scenarios based on the concept of operation of the ship in question in order to be a suitable tool in the design decision making regarding compromises between different safety measures. The scenarios should be able to be used in all aspects of the design of the ship. The typical top level structural links of safety scenarios for naval ships, as displayed in figure 4, must be broken down into scenarios specific for the ship in question.

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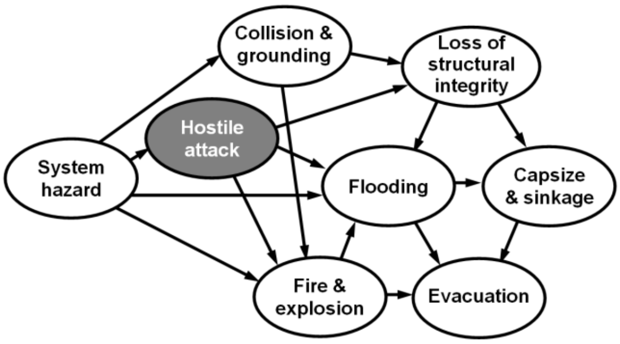

Figure 4: Typical top level structural links of safety scenarios for naval ships. Redrawn from Vassalos (1) and specific system hazard for naval ships added.

In conclusion, scenario-based analyses of a naval ship are, to a great extent, dependent on the characteristics of the ship itself. They also depend on the ship's concept of operation, the intended area of operation, the measures that constitutes the layers *cooperative protection* through *avoid hit* of the survivability onion, and characteristics of the foreseeable threats.

3. REQUIREMENTS OF SAFETY SCENARIOS

In this section, relevant aspects of safety culture, codes, regulations and classification rules are analysed with respect to the requirements of safety scenarios in order to ensure that the results can be used to improve the design process and enhance design decision making. In Section 4, the field of military operational research is analysed in terms of the simulation of military systems.

3.1 SAFETY CULTURE

Reason (17) defines safety as the "ability of individuals or organisations to deal with risks and hazards so as to avoid damage or losses yet still achieve their goals". Reason also states that effective safety work needs experienced and educated participants that can navigate close to the limits of acceptable danger, without passing over the edge.

Safety is, as discussed in section 2.3, not only a function of technical measures in the design and construction of the ship. From Reason's description, it is clear that many proactive measures are dependent on the knowledge of the crew and on the human factors onboard such as man-machine interfaces and watch systems.

According to Parker et al. (18), a desirable safety culture does not just emerge; it is a result of many aspects. As part of their work, the key organisational aspects (concrete as well as abstract) of safety culture are described. These aspects of safety culture are summarised here to define three basic areas of safety culture:

- **Formal regulations and processes** including, for example, methods for benchmarking, audit systems, and risk analysis.
- **Competence and training** including work quality and safety observations.
- **Shared risk awareness** throughout the organisation.

It is important to consider these basic areas of safety culture when defining and using safety scenarios. This should ensure that the safety scenarios are consistent with the safety culture in the intended organisation and that the use of safety scenarios can also support the development of the culture itself.

3.2 CODES, REGULATIONS AND RULES

By their very nature regulations, codes and rules are prescriptive. Prescriptive standards are generally formulated as a result of accidents and therefore suitable for routine activities. But, they devolve responsibility and may restrict innovation and be unsuitable for new and future developments (8).

3.2 (a) International Maritime Organisation (IMO)

Risk-based approaches have been developed by the IMO since the 1960's. The first risk-based regulation was the Safety of Life at Sea from 1974 (SOLAS74) with probabilistic damage stability (19). In 1997, the IMO adopted the Formal Safety Assessment (FSA) as a risk-based approach to rule making (12).

In 2002, the new SOLAS Chapter II-2 on fire safety came into force; this includes Regulation 17 on alternative design and arrangements based on safety equivalence to the prescriptive regulations. Similar regulations regarding alternative arrangements for machinery, electric installations and for life-saving appliances and arrangements were introduced in 2010 (20).

IMO has, however, no specific regulation regarding the use of probabilistic risk assessment in the design of ships. There is no working description on how to carry out a fully risk-based ship design process in the regulatory framework. The introduction of FSA is, however, a clear indication that the IMO will in future require the use of probabilistic risk assessment in decisions regarding maritime safety. Some IMO comments on probabilities and safety scenarios are presented below.

Risk criteria have been discussed within the IMO as a result of the risk-based approaches. Agreed individual risk criteria targets for new ships are 10^{-4} annually probability of loss of crew member and 10^{-5} annually probability of loss of passenger and public ashore. Probabilities above these level limits should be reduced no matter what the consequences (12). Furthermore, according to the IMO, the safety scenarios used in the FSA must be ranked with probabilities and consequences with clearly defined indices on a logarithmic scale. The combination of probabilities and consequence indices represents a risk level (9).

According to the HSC Code (7), the probability assessment in a Failure Mode and Effect Analysis (FMEA) should be based on the operational life of the particular craft, or crafts of the same type. Numerical values of probabilities should be on a per hour or per journey basis.

3.2 (b) Naval Ship Code (NSC)

The Naval Ship Code (NSC) is a new naval code proposed by the NATO Standardization Agency that may be applied to surface naval vessels and to other vessels operated by the armed forces or agencies of a state. The NSC is optional and is both based on and benchmarked against the IMO's conventions and resolutions. The NSC is goal-based and the ship should be verified against the goals during the design and construction stages as well as during operation. The goals are however not risk-based. The code does not include measures specifically designed to address the effects of a military attack. Six tiers are defined in the code with an increasing level of detail: tier 0 - Aim, Tier 1 - Goal, Tier 2 - Functional areas, Tier 3 - Performance requirements, Tier 4 - Verification method, and Tier 5 - Justification (16).

In Tier 0 the overall objectives are stated as follows. "*Through the effective assurance that essential safety functions will be available […] with the intention of: 1.1 Safeguarding life in all foreseeable operating conditions throughout the lifetime of the ship; 1.2 Offering a level of safety to which embarked persons are exposed that is no less than the level of safety to which persons embarked on a merchant ship are exposed. 2 For hazards occurring under extreme threat conditions, the code permits an appropriate level of safety as determined by the Naval Administration."* (16).

Tier 4 should be defined in one of three ways: prescriptive requirements, a performance based solution or through delegation to a recognised organisation for confirmation. The verification methods should be selected so that they are appropriate to the concept of operations and the safety goal outlined in Regulation 0 Goal of Chapter 1. The naval administration agrees to the verification methods with the ship owner and the organisation conducting the verification.

Even though the code does not include measures to address hostile attacks, Annex A, "Guide to the naval ship code", describes how required survivability should be defined as a result of the specific operational profile of the ship. The Annex states that potential damage caused by hostile acts, required post-damage ship capability and a philosophy for recovery from the damage state, must be defined for effective application of the code. This should be defined as scenarios in the ship's concept of operation. The concept of operation should also include ship attributes, intended environment and operating, survey, maintenance and disposal philosophy. Note, however, that the NSC does not discuss the possibility of introducing probabilities and risk in the scenarios and analysis except for structural limit states where the use of probability-based margins of safety are encouraged (16).

3.2 (c) Rules for classification of naval ships

There are a number of classification societies that have rules for the classification of naval ships, see for example (5) and (21). Det Norske Veritas (DNV) "Rules for classification of high speed, light craft and naval surface craft" (21) is used in the current study as an example.

In the DNV rules, a definition of basic parameters and the method of analysis regarding the physical effect of weapons are presented in Part 6, Chapter 18, Combat survivability. The parameters and method defined should be used to analyse the system's redundancy for damage to an extent set by the owner. There is, however, no guidance regarding how to employ and use probabilities in the survivability analysis. The probability concept can be used to support the FMEA in accordance with the IMO HSC Code (21).

4. MILITARY OPERATIONAL RESEARCH

Within military operational research (MOR), scientific methods are used to quantify aspects of military operations in order to support decision. However, the techniques and tools used are, to a large extent, common with those used for other sectors such as economic and social activities (22).

4.1 MEASURES OF EFFECTIVENESS

Here effectiveness will be defined as "a measure of how successful an organization is in producing a desired or intended result" (23) and as a function of operational gain and operational effort according to Morse and Kimball (24), see equation 3.

$$effectiveness = \frac{unit\ of\ operational\ gain}{unit\ of\ operational\ effort} \qquad \text{Equation 3}$$

How to define measures of effectiveness, choose a unit of gain and a unit of effort, for naval ships depends on the task and is a national matter governed by doctrine. There is no specific measure of effectiveness for safety, but the operational gain and effort will be directly or indirectly dependent on the level of safety. Indirectly, a high level of safety allows freedom of action and consequently a higher probability of operational gain, if the effort is kept constant. A high level of safety will reduce the demand on operational effort when executing a specific task (gain kept constant). More direct operational gain can for some tasks, such as escort and air defence, be measured in terms of maritime security delivered, which according to Perry et al. (25) is a direct function of the safety of the naval ship in question.

An objective study of the different aspects of safety is a complex task. Introducing one or more measures of comparative effectiveness will allow an objective and quantitative comparison of measures with no obvious common unit of measure (24). Therefore, in theory, a well-defined measure of effectiveness could be the link between different evaluation methods and constitute a basis for a design decision support tool (24).

4.2 MODELLING MILITARY OPERATIONS

Modelling of military systems and military operations is often a part of the development of systems in for example the systems engineering process. The aim is then most often to test how different technical performances of the system interact and affect the system effectiveness and efficiency. These models often have probabilistic characteristics, but the aim is seldom to calculate the risk for the system.

A safety scenario is a model of reality to be used when analysing risks associated with the modelled operations. MOR often deals with requirements for models of military operations and the process to develop such models (22).

In problem formulation the variables that affect the problem must be defined as well as the constraints and limitations. There must be particular focus on the measures of effectiveness, as they will give guidance on how the modelled system will be used and how different alternatives are prioritized (22).

Statistical analysis, such as analysis of variance, test for goodness of fit, regression and correlation analysis, plays an important role in model validation if results of the system operation are available. Military system studies, however, suffer from a lack of historical data and realistic experiments can be impossible to perform because they may lead to destruction or casualties. Often, military system model validation is limited to sub-model validation based on statistical data and model validation by expert opinion, sensitivity analysis and hypothesis validity (22).

In most military systems, events occur at isolated points in time. These are called discrete systems. An event-driven simulation is appropriate as a numerical approach if the inter-event intervals are random; a time-driven simulation is appropriate if the intervals are equal (26).

In MOR literature, different techniques for modelling military technical systems are described and validated (26). Such research serves as good input when deciding what factors are important when modelling naval tasks and scenarios.

5. ASSESSING SCENARIO PROBABILITY WITH NUMERICAL SIMULATION OF TACTICAL TASKS

The definition of concept of operation, areas of operation, threats, and the basic technical concept for a ship are normally formulated during the design phase. However, the causal relationships that link the characteristics of the ship and its intended use to the operational risks are not easily understood. (ta med till disk?)

Safety scenarios for commercial ships are often based on accident statistics combined with expert judgment, but for military operations, statistical data is rare. In this section, a model for probability-based numerical simulation is presented. The objective of the model is to use the concept of operation to identify scenarios that relate to accident categories with major hazard potential and to assess the scenario probability. The model is a formalised procedure of incident quantification to support definition of probability-based safety scenarios. The resulting scenarios could then be used in risk analysis.

The inputs to the simulation model are typical design parameters such as ship speed, sensor characteristics and intended fleet composition. Based on the concept of operation, the relevant types of naval operation are divided into tactical tasks defined with measures of effectiveness, environmental data and threat characteristics. These kinds of simulations are in there structure and model characteristics not new, but the result must be aggregated and handled so that it is consistent with probabilistic risk assessment.

Figure 5 shows a generic structure for simulations of tactical tasks were the aim is to evaluate and indentify event and hazard probabilities for a large number of events. As indicated in the figure multiple tasks must be calculated for a ship.

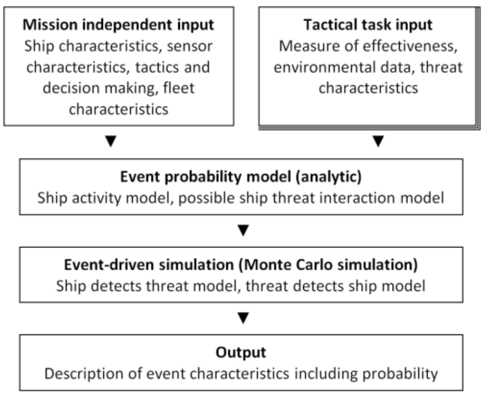

Figure 5: Top level description of numerical simulation code.

5.1 EXAMPLE NUMERICAL SIMULATION

In the current investigation the simulation model is intended as a demonstration example of a tactical task. The chosen tactical task is ship transit through an area where there is a mine threat; this task is selected because of a mine's well-defined behaviour. The task could be a part of an amphibious or special force operation. The measure of operational gain is distance travelled and the measure of operational effort is ship days, the measure of effectiveness is subsequently ship average speed. To manage the task the ship must detect, localise and identify mines and take countermeasures such as evasive manoeuvre to avoid the threat. Note that the task of clearing mines, which could also be a part of an amphibious operation, would have other measures of effectiveness. False alarms are not considered here, although false alarms would affect the measure of operational effectiveness as it is defined above and there is an important trade-off between high probability of detection and false alarms (27).

The simulation scheme, presented in figure 5, adopted for this specific task is presented in figure 6.

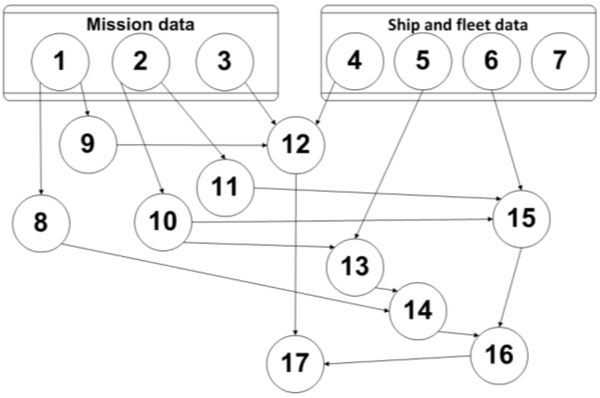

Figure 6. Influence diagram of example numerical simulation. The diagram displays direct influences on probabilities of the parameters, unless the parameter is displayed with a circle with a thick line; then the value is given deterministically based on the values of the influences.

The input includes information about how the ship performance is affected by environmental parameters, e.g. sensor range and probability of detection as a function of weather – and sensor operator alertness as a function of weather and part of watch. Table 1 presents the parameters and the statistical data that constitute the simulation model. References are given, where such are used, and the values and dependencies are assumed if no reference is given.

Table 1: Simulated parameters and simulated dependencies.

Parameter	**Dependency (the value of the parameter for each event given by)**
Environmental factors	
Mine density [discrete: high/low]	Stochastic. P=0.3/0.7. High 6×10^{-4} mines/m^2 and low 6×10^{-6} mines/m^2, estimated from (28).
Part of watch [discrete: beginning/end]	Stochastic. P=0.08/0.92, based on 6 h watches.
Sea state [discrete: no waves/waves]	Stochastic. P=0.88/0.12, based on $H_{s,mean}\geq$1.8m (29).
Threat characteristics	
Dangerous distance [m]	65
Ship and sensor characteristics	
Event, definition	Mine passing inside area observed by operator.
Max speed [knots]	22
Operator alertness, identifying mine in sensor data [s]	Evenly distributed between $t_{min}=1$ and $t_{max}=3$. t_{max} increased with 400% if part of watch is *end* (30). t_{max} increased with 300% if *sea state* is *waves.*
Sensor, area observed by operator [deg, m]	±25 deg. from ship course, distance 500 m, see also figure 7.
Sensor, hull mounted sonar, detection distance [m]	Defined by $P_{detection}=k((R_{max}-R)/R_{max})^4$ (27) where $k=0.95$ (31).
Sensor, max detection distance, R_{max} [m]	480 estimated from (31). Reduced by 30% if *sea state* is *waves.*
Decision making	
Definition, needed time for countermeasures [s]	>30 (less time available for countermeasures defined as critical)
Operating speed [knots]	3.3 when high mine threat and 5.5 when low mine threat.

In order to detect a mine the sensor must detect and localise the mine and the operator identify it as a mine. Both probability of detection and operator alertness is influenced by environmental parameters and the result of the simulations shows that the a change in the parameters drastically changes the available time for counter measures. In figure 6 the available time for countermeasures for 1 000 000 events are used to present cumulative frequencies for four different situation types. The figure shows for example that all mine encounters that happens in an area with low mine density, waves and in the end a watch and will result in less than 100 seconds available for countermeasures compared with only 10% of all encounters in a high mine density area, this due to the combination of higher ship speed, shorter average sensor range and lower operator alertness.

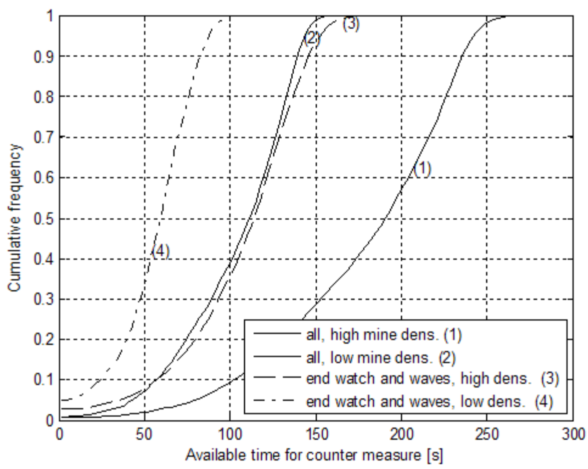

Figure 6: Cumulative frequency of available time for counter measure. 1 000 000 simulated events.

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The combination of wave-induced ship motions and higher probability of personnel fatigue during end of watch drastically influences the probability of critical time for counter measures. A simulation of 1 000 000 events equals 2 488 years of continuous operation for one ship on this task. Of the 1 000 000 events about 3 200 are classified as critical. From all critical events, 49% occur at night and when the sea state is waves, even though these circumstances only represent 11% of all events.

The result can also be analysed in regards to geometrical considerations compiled in cumulative plots or figures such as figure 7 were each mine encounter is plotted relative the ship. This information can then be used to design scenarios for further risk analysis.

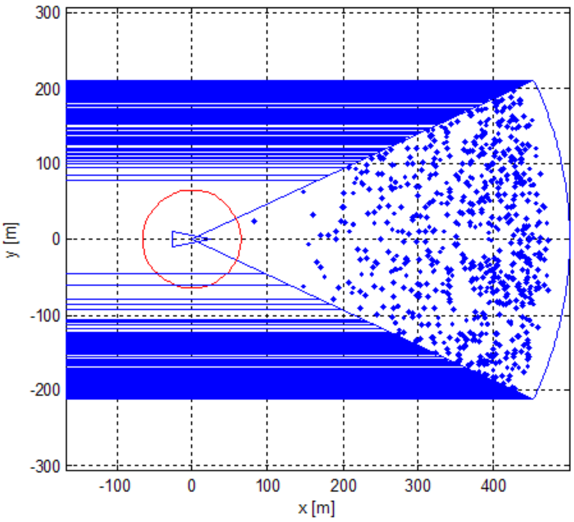

Figure 7: Simulation output with the ship and area observed by operator. Each event (mine encounter) represented by a dot (mine position relative ship when detected) or a horisontal line (mine passes by not detected). Distance in meters. 1 000 simulated events.

5.2 CONCLUSIONS FROM EXAMPLE SIMULATION

The simple simulation example show that the simulation does not only identify critical circumstances, it also actually quantifies how and to what extent the circumstances combine to create hazards. The definition of a safety scenario by experts can therefore be based on simulation results for the critical events with data such as mine position relative, ship weather and information about distribution of available time for counter measure. The output also allows for probability assessment of the scenario. These disaster escalation scenarios then relate to an accident category with quantified hazard potential and are customised to the specific design features and expected performance of the vessel in question.

Based on the defined safety scenario a detailed risk analysis can be carried out to calculate or assess the probabilities of different possible consequences of the identified critical events.

6. DISCUSSION

For civilian ships there are limitations on how far the concept of operation can be used in the design of the ship. This because of commercial reasons, but also because the control of such things as crew training is not fully under the auspices of the ship-owner. For naval vessels and other vessels operated by the armed forces or agencies of a state, these commercial reasons are less evident and crew training is normally well governed.

For naval ships there are close links between effectiveness, freedom of action and the allowable risk levels, but without a measure to assess the risks the relations cannot be fully understood and analysed. This is also stated in the Allied joint doctrine for force protection were it is stated that ”a comprehensive risk assessment process is essential to guide risk management decision-making and prioritization” (14).

All the three risk criteria here suggested for naval operations can then in combination with probabilistic risk assessment be used to create risk knowledge models. Such models will then allow for comparing different alternatives more thoroughly and include operational risk, this to create a balance between risk and capability.

Defining the concept of operation and the analysis of events that lead to major degradation of safety are omitted from the NSC and are left to the naval administration to deal with. These events can, in general, be classified as unlikely, but at the same time can be very likely for a specific ship when it is performing the task for which it is designed. How the concept of operation should be described and quantified is central to how safety can be implemented. The NSC is goal-based and the ship should be verified against goals during the design and construction stages as well as during operation. Although the goals are not risk-based, a risk-based verification method is not contradictory to the NSC’s definition of performance based verification.

The calculations in the simulation are a model of the ship and its operation. Many aspects of naval operations can never be included in the model. Specific numerical output must be used cautiously. Here it is suggested that results be used to assist experts in identifying critical scenarios and estimating their probability. This would assist in a process that otherwise relies completely on expert judgment. After risk analysis and assessment, the naval administration must also decide on additional safety factors when basing design decisions on risk analysis and acceptable risk. These safety factors must be decided upon, using the reliability of the risk analysis as a basis.

The scenarios defined by a risk-based scenario definition with the help of ship operation simulations allow risk analysis of both traditional maritime safety areas and military survivability areas. The risk for different areas is therefore comparable and can be assessed specifically for a particular ship. The process also allows for the structural documentation of scenarios and the resulting risks. Furthermore, this documentation can be used throughout the design and operation of the ship. This would also show which scenarios were not considered, which is also important when taking decisions regarding issues such as deployment. The proposed methods also allow the introduction of risks associated with new tactical tasks, such as anti-piracy, counter-terrorism operations in ice, into generic design scenarios.

The defined scenarios also serve as a basis for discussions on how safety is achieved and maintained in different situations with those involved in the process, for example crew or engineers.

From above it can be argued that probabilistic risk assessment with safety scenarios can support all three areas of basic safety culture: formal regulations and processes, competence and training and shared risk awareness throughout the organisation. Probabilistic risk assessment also allows for a continuous safety work where the scenarios also can be validated and further developed based on new experiences and data throughout the ship life.

Risk is a well-defined measure of effectiveness, which for naval ships, is a link between different evaluation methods and can constitute a basis for a design decision support tool, see figure 8.

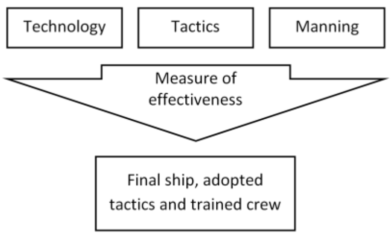

Figure 8. Measure of effectiveness to support decisions in design, construction and during operation. Adoption of figure 2 in to a military context and extension to include operation of the ship.

7. CONCLUSIONS

The aim of this investigation is to investigate and describe how, based on probabilistic risk assessment, the concept of operation for a naval ship can be turned into relevant safety scenarios. It should be possible to use these scenarios in evaluating consequences and probabilities as a design decision support tool in the design of naval ships.

The investigation shows that the scenarios must have calculable probability and must be adapted and customised to the specific design features and expected performance of the vessel in question with an emphasis on disaster escalation scenarios. Results from simulations show that modelling tactical tasks in military operations is a possible way of supporting experts in the definition of safety scenarios.

The use of safety scenarios supports risk analysis of both traditional maritime safety areas as well as military survivability areas and the key aspects of safety culture throughout the design, construction and operation of the ship.

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