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# Survivability of an Ocean Patrol Vessel – Analysis approach and uncertainty treatment

## Abstract

Military Ocean Patrol Vessels (OPVs) are today an increasingly common type of naval ship. To facilitate the wide range of tasks with small crews, OPVs represent several ship design compromises between, for example, survivability, redundancy and technical endurance, and some of these compromises are new to military ships.

The aim of this study is to examine how the design risk control-options in relation to survivability, redundancy and technical endurance can be linked to the operational risk in a patrol and surveillance scenario. The ship operation for a generic OPV, including the actions of the threat, is modelled with a Bayesian network describing the scenario and the dependency among different influences.

The scenario is described with expert data collected from subject matter experts. The approach includes an analysis of uncertainty using Monte Carlo analysis and numerical derivative analysis.

The results show that it is possible to link the performance of specific ship design features to the operational risk. Being able to propagate the epistemic uncertainties through the model is important to understand how the uncertainty in the input affects the output and the output uncertainty for the studied case is small relative to the input uncertainty. The study shows that linking different ship design features for aspects such as survivability, redundancy and technical endurance to the operational risk gives important information for the ship design decision-making process.

*Keywords: risk control options; ocean patrol vessel; survivability; uncertainty analysis; influence diagram*

## 1. Introduction

The risk control options for achieving security and survivability for naval ships are aspects that are often connected to central aspects of the ship design, such as damage stability and system redundancy. When the basic design is set, the possibility of changing the ship's survivability is limited. Therefore, there is a need to assess the level of survivability at early stages of the ship design to provide input to the decision process regarding risk control options. Such an assessment is especially challenging when the threats envisioned are new and the survivability design of older ships is not a relevant benchmark. This work presents a framework for decision analyses where both the operational risk and the uncertainty of the assessment are studied.

Comprehensive studies on ship security risk analysis are rare [1, 2], and the systematic handling of the uncertainties needed to create rational input for the decision-making process is even rarer. There is a need for a deeper understanding of ship security analysis and how ship security analysis can incorporate uncertainties as an important part of the risk picture. In a study of risk analysis for a piracy case, Liwång and Ringsberg [2] document expert uncertainty and how it can be reduced in relation to threat analysis.

Risk is not constant and is subject to considerable degrees of uncertainty. The rarer the event, if predictable at all, the less reliable the historical data and the estimates based on them will be [3]. To enable the results of an analysis to reflect the uncertainties and the possibility of surprises occurring, there is a need for a risk-informed approach that is more than calculated probabilities and expected values [4]. To include uncertainties in the phenomena and processes will open up a broader context where the uncertainties and possible surprises are considered to be an important part of the risk picture. This context would then provide a rational input to the decision-making process [4] and increase the credibility of the security risk analysis [5]. To be able to handle risk as more than merely expected values, this work discusses both aleatory and epistemic uncertainties where:

- Aleatory uncertainty is defined as a stochastic uncertainty that describes randomness and that can, given a perfect controllable and probabilistic world, be captured with frequencies; typical variables that often are probabilistically modelled include the wave height on an ocean or the fail frequency for a pump.
- Epistemic uncertainty is defined as a knowledge-based uncertainty that represents a lack of knowledge regarding how a phenomenon affects the output of a process, such as how an antagonistic threat will act in a specific situation. In this work, epistemic uncertainty is conceptualized as the difference in estimates and beliefs between different experts.

In this study, the case of an antagonistic threat against a military ocean patrol vessel (OPV) is investigated. The risk is assessed and the uncertainties examined with a focus on how the uncertainties:

- affect the output,
- can be propagated through the analysis, and
- can be described to the decision maker.

The chosen case involves a common type of modern naval vessel and one of the most frequent types of incidents involving naval vessels in recent years. The case includes technical systems, but also strategies and priorities made on board. This because incorporating organizational or procedural factors and effects is important to really be able to examine the strength of a security system [6].

Section 2 discusses the theory and methodology of the study. The methodology is based on an influence diagram approach and uncertainties analysis. Section 3 presents the case. Section 4 presents the model, data and uncertainties. Section 5 calculates the probabilities for the three studied consequences and the uncertainties of the result. Section 6 discusses the implications of the result, and Section 7 states the conclusions.

## 2. Theory and methodology

### 2.1 Ship security

In relation to ship security and military survivability the design process includes several aspects not covered in the traditional naval architectural scope, such aspects range from the magnetic properties of the machinery and equipment [7] and the infrared properties of the paint scheme [8] to the layout of the bridge [9]. Given a security incident these design aspects will affect the likelihood of different consequences. For these aspects, the behaviour and probability as well as the uncertainties are studied in different research fields and disciplines, as presented in Table 1. Typically that means that approaches, models, and tools from the fields described in Table 1 are needed to transform the design alternatives investigated in a design process to the conditional probabilities, including uncertainties, used in the model in Section 4.

**Table 1.** Research fields that are needed as input to the studied analysis of operational risk.

| Research field | Influence types | Example of references |
|---|---|---|
| Naval Architecture | Damage stability, ship and wave interaction | Schreuder, Hogstrom [10]; and Pedersen [11]. |
| Meteorology | Weather effects | Grasso, Cococcioni [12]; and Jedrasik, Cieslikiewicz [13]. |
| Operational analysis | Naval ship operations, damage assessment | Jaiswal [14]; Morse and Kimball [15]; and NATO [16] Vaitekunas and Kim [8]. |
| Ship protection and | Effects of weapons on ships vulnerability | Boulougouris and Papanikolaou [17]; Det Norske Veritas [18]; NATO [16]; and Pelo and Alvå [19]. |
| Human factors | Human actions, effects of organizational structure | Musharraf, Khan [6]; and Lützhöft, Nyce [20]. |

The areas described in Table 1 are crucial for obtaining input for the model under study but will not be discussed further except in relation to the model validation in Section 5.2.

In ”Principles of engineering safety: Risk and uncertainty reduction”, Möller and Hansson [21] discuss the principles of engineering safety and suggest the following four principles [21]:

(1) *Inherently safe design,* which means that potential hazards or threats are excluded.
(2) *Safety reserves* with safety factors or safety margins.
(3) *Safe fail* systems so that if it fails, it does so safely.
(4) *Procedural safeguards* were procedures and training is used to enhance safety.

Often, systems are designed with a combination of the principles above, and some applied approaches can be said to belong to more than one principle [21]. The list can also be seen as arranging the principles from straightforward to complex or from low uncertainty to high uncertainty. Therefore, the requirements on the decision process are increased if the later safety principles from the list above are used.

By analysing suggested ship security measures (risk control options) in the “Survivability of small warship and auxiliary naval vessels” [16]; Det Norske Veritas “Rules for Classification of High Speed, Light Craft and Naval Surface Craft” [18]; Lloyd’s Register “Rules and regulations for the classification of naval ships” [22]; the “Best management practice for protection against Somalia based piracy” [23]; and the appendix to the “International Ship and Port facilities Security” (ISPS) code [24], it is found that the focus is on *safe fail* and *procedural safeguards*. In regards to safe fail this means that the ship must be built to be operational, with constraints, even if there is an attack. Möller and Hansson [21] classify these principles as fail operational, often applied as physical or immaterial barriers but also as redundancy, segregation and diversity.

Procedural safeguards in regard to ship security can be exemplified by, but are not limited to, prepared procedures for the crew if the ship is under attack and special emergency organizations onboard to handle the effects of an attack such as personal injuries, fire and flooding.

The fact that ship security relies so heavily on safe fail and procedural safety increases the epistemic uncertainty about the function or effectiveness of the security system. This increased uncertainty leads to an increased need to handle and understand the uncertainties throughout the decision process.

## 2.2 Uncertainties in ship security modelling

In the early stages (project initiation, planning, analysis and alternative generation) of a ship development project, the need to understand the intended system and its limitations is crucial [25]. At the same time, the uncertainties are large at the early stages. Therefore, understanding the uncertainties is a part of understanding the system. Because the classic risk analysis approach does not provide for displaying how uncertainties affect the result, this work will apply the highest level of uncertainty treatment described by Paté-Cornell in "Uncertainties in risk analysis: Six levels of treatment", where the uncertainty is displayed as a family of risk estimates in the output [26]. This level requires propagating the uncertainties throughout the analysis.

In "Uncertainty in quantitative risk analysis – Characterisation and methods of treatment" Abrahamsson [27] groups uncertainty into three classes:

- parameter uncertainty as a result of the value parameters being unknown or varying,
- model uncertainty that arises from the fact that any model is a simplification of reality, and
- completeness uncertainty because not all contributions to risk are addressed [27].

Knowing the class of uncertainty is important because the class defines the treatment and how and whether the uncertainty can be reduced [27]. This work focuses on parameter uncertainty but also to some extent discusses model uncertainty. The model uncertainty is exemplified by three different model alternatives representing competing phenomenal explanations.

Completeness uncertainty is also important but will not be addressed here, and the case and hazard analysed will therefore in this study be assumed to be important and relevant but also complete, i.e., including the only relevant issues. For a ship development project several different types of incidents must be considered so that they together can form a reasonable representation of the life of the ship.

Aleatory uncertainty can be treated with frequentist classical risk analysis methods, but the challenge is the epistemic uncertainty, which can be approached only through Bayesian probability and expert opinions [26]. How to measure epistemic uncertainty depends on the class of uncertainty [27] and is in this study defined as expert disagreement (see Liwång, Ringsberg [2] for examples of how epistemic parameter uncertainty can be quantified as the result of expert disagreement).

## 2.3 Ship security and influence diagrams

In this study, the risk (probability for three consequences) is assessed with influence diagrams and the sensitivity analysis is performed according to the description in Sections 2.4 and 2.5. An influence diagram is a graphical and mathematical representation of a network of influences on an event. The methodology of influence diagrams is derived from decision analysis and, according to the International Maritime Organization (IMO), it is particularly useful in situations for which there may be little or no empirical data available, and the approach is capable of identifying the influences and therefore the underlying causal information [28]. However, many real-world problems have complex relationships, and the underlying information may be difficult to determine [29].

According to Tatman and Shachter [30], the power of influence diagrams derives from their ability to represent the probabilistic aspects and also show functional dependencies and the information flow as a graph. The graphical representation is natural and intuitive for the decision maker and aid in communication between decisions makers and experts. The general statements above on influence diagrams have been shown to be valid in maritime safety in general [6, 31, 32] and more specifically to be a promising tool for ship security [2, 33]. At the same time, large influence diagrams can be complex and hard to visualize [29].

The influence diagram approach is chosen here because it allows for a clear illustration and communication of the influences and topology which is a prerequisite for being able to develop the model in cooperation with subject matter experts (to eliminate misunderstandings). The influence diagram, at the same time allows for more versatile definitions of relations than fault and event trees and is fully mathematical defined [31]. Without these quantitative aspects the uncertainty analysis cannot be performed. Therefore, this combination of qualitative and quantitative aspects presented by the influence diagram is a critical component of the methodology. For the methodology it is also important that the uncertainty analysis can take use of the scenarios mathematical definition and capture the different aspects of the input uncertainty as described in Section 2.4 and 2.5.

The example influence diagram in Figure 1, with the data in Table 2, will be used throughout Section 2 to describe the proposed method. The value for $s_5$, in Figure 1 is calculated using the expected probabilities for $x_1$ to $x_4$ and the mode probability for $x_5$, according to Table 2. This value (probability) for the target influence (consequence under study) calculated without including epistemic uncertainty is in this study referred to as the target node's *expected value* and ignores any effect as a result of the input uncertainty.

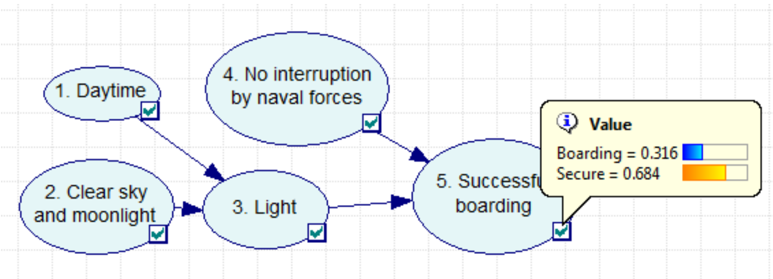


**Figure 1.** Influence diagram for simplified example system used in Section 2 to describe the analysis of uncertainties. This influence diagram is visualized using GeNIe by the Decision Systems Laboratory of the University of Pittsburgh [34].

**Table 2.** Example system, influences, probabilities and uncertainties. $\veebar$: exclusive disjunction (XOR).

| Influence | States | Conditions | Variable (or constant) name | Value incl. epistemic uncertainty (for first state if not otherwise stated) [min;max alt. min;mode;max] |
|---|---|---|---|---|
| $s_1$ Daytime | yes; no | NA | $x_1$ | 0.55;0.65 |
| $s_2$ Clear sky… | yes; no | NA | $x_2$ | 0.1;0.3 |
| $s_3$ Light | yes; no | $\|s_1$=yes$\|s_2$=yes | ($k_1$) | 1 |
| | | $\|s_1 \veebar s_2$=no | ($k_2$) | 1 |
| | | $\|s_1$=no$\|s_2$=no | ($k_3$) | 0 |
| $s_4$ No interruption… | yes; no | NA | $x_3$ | 0.8;1 |
| $s_5$ Successful boarding | yes; no | $\|s_3$=yes$\|s_4$=yes | $x_4$ | 0.3;0.7 |
| | | $\|s_3$=yes$\|s_4$=no | $x_5$ | 0;0.15;0.2 |
| | | $\|s_3$=no | ($k_4$) | 0 |

## 2.4 Epistemic parameter uncertainty

There is often a need to collect information about the studied system from experts [26, 27, 30, 35]. There is often also a need for different experts types for different submodels [26]. The use of experts is also very much needed for the case studied here, and different competence profiles will be used for different aspects of the model. The experts used are described in Section 4.2. The experts are, in this study, primarily used to quantitatively and qualitatively discuss what type of data are available, whether there are competing theories, how expert opinions could be aggregated (see Paté-Cornell [26] for different methods) and how these circumstances affect the epistemic parameter and model uncertainty.

In the model, the aleatory parameter uncertainty is described as probabilities for the discrete states of the parameters and the epistemic parameter uncertainty as a distribution around the aleatory probabilities, as shown in the rightmost column in Table 2. This description is a simplification of the general case, where the parameters can be continuous, and the aleatory uncertainties are then described with a probability density function and the epistemic parameter uncertainty as a family of probability density functions [26].

There are several methods available for the analysis of parameter uncertainty and uncertainty propagation [27]. In this study, Monte Carlo analysis and numerical derivative analysis are used to examine the uncertainties, because these two approaches are well documented and feasible to implement in a real ship security analysis and, because they are based on different principles and therefore answer to different needs. Monte Carlo and two-phase Monte Carlo analysis are fairly simple to implement and at the same time make it possible to distinguish between different uncertainties, but require the probability distributions of the uncertainties [27]. Numerical derivative analysis investigates the sensitivity for each input, but the approach works best for relatively small uncertainties.

In the Monte Carlo analysis, the epistemic uncertainty of each variable is sampled *n* times according to Latin hypercube sampling which uses "stratified sampling without replacement" as described by Vose [36]. The output of the model is calculated *n* times, where each calculation represents a unique stochastically chosen combination of values for the uncertain variables [27].

The numerical derivative analysis is derived from the Taylor series

$$y = f(x_i = b) \approx f(a) + \frac{\partial y/\partial x_i}{1!}(b-a) + \frac{\partial^2 y/\partial {x_i}^2}{2!}(b-a)^2 + \cdots \quad \textbf{Equation 1}$$

of the function $f(x_{i=1..N})$ defining the model under study, where $y$ is the model output and $x_i$ are the model parameters. From Figure 1 and Table 2, it can be derived that the function $f(x_{i=1..N})$ for the probability ($y$) of the state *yes* for successful boarding is given by

$$y = f(x_i) = k_{1.1}x_{1.1}x_{2.1}x_{3.1}x_{4.1} + k_{1.1}x_{1.1}x_{2.1}x_{3.2}x_{5.1} + \cdots + k_{1.2}x_{1.2}x_{2.1}x_{3.1}x_{4.1} + \cdots$$

**Equation 2**

where the value of all terms (here 16 terms in total, each representing a unique combination of the states for influences 1 through 4) are between zero and one. The variable $x_{1.2}$ can be substituted for $(1-x_{1.1})$ because the sum of the states for an influence is always one. Therefore, Equation 2 also can be written as

$$y = k_{1.1}x_{1.1}x_{2.1}x_{3.1}x_{4.1} + k_{1.1}x_{1.1}x_{2.1}x_{3.2}x_{5.1} + \cdots + k_{1.2}(1-x_{1.1})x_{2.1}x_{3.1}x_{4.1} + \cdots.$$

**Equation 3**

The function $f(x_{i=1..N})$ is therefore a linear system with respect to $x_{i=1..N}$ and the second derivative is zero. Therefore, according to the Taylor series, given a small change in $x_i$ ($x_{i2}$-$x_{i1}$), the change in $y$ ($y_2$-$y_1$) will be given by

$$y_2 - y_1 = \partial y/\partial x_i\,(x_{i2} - x_{i1}). \quad \textbf{Equation 4}$$

Based on Equation 4, this study uses the term $\partial y/\partial x_i$ as a measure of how an uncertainty in $x_i$ will affect the output. In this study, the term $\partial y/\partial x_i$ is numerically calculated for each variable with uncertainty (such as $x_1$-$x_5$, according to Table 2).

To perform the Monte Carlo analysis and the numerical derivative analysis, a specific calculation code is here developed to create a rational calculation process for the multiple influence diagram outputs needed. The output for the example system is presented in Figure 2 for the Monte Carlo analysis and Table 3 for the numerical derivative analysis. In the boxplot in Figure 2 and all boxplots in Section 5.1, an outlier is defined as an observation that falls beyond the:

lower limit: Q1-1.5(Q3-Q1), or the **Equation 5**

upper limit: Q3+1.5(Q3-Q1) **Equation 6**

where Q1 and Q3 are the first and third quartiles displayed by the box. The outliers are depicted using circles and the whiskers in the box plot represent the lowest and highest values not classified as outliers.

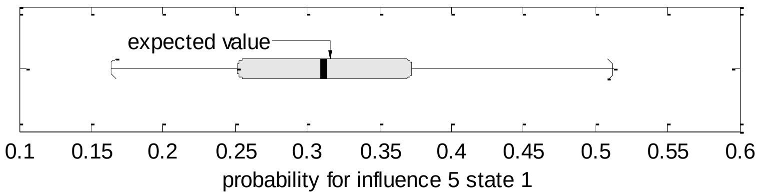


**Figure 2.** Results of the Monte Carlo analysis of the example system presented in Figure 1 and Table 2, showing the resulting epistemic uncertainty for the probability of successful boarding, calculated with n = 100 000.

**Table 3.** Results of the numerical derivative analysis of the example system presented in Figure 1 and Table 2, showing the term $\partial y/\partial x_i$ for each uncertain variable and state. Variables with two states are only displayed ones in the list.

| Pos | Var. | $\lvert\partial y/\partial x_i\rvert$ |
|---|---|---|
| 1 | $x_{4.1}$ | 0.61 |
| 2 | $x_{1.1}$ | 0.37 |
| 3 | $x_{3.1}$ | 0.24 |
| 4 | $x_{2.1}$ | 0.19 |
| 5 | $x_{5.1}$ | 0.07 |

According to Figure 2 the probability of a successful boarding is asymmetrically distributed around the median value 0.31. Note that the expected value 0.32, displayed in Figure 1, does not equal the median value from the Monte Carlo analysis. From Table 3 it can be seen that the system is most sensitive to uncertainty in variable $x_{4.1}$ (i.e., the probability for state 1 for influence 5 given influence light and no interruptions) and least sensitive to uncertainty in variable $x_{5.2}$. The sum of $\partial y/\partial x_i$ for the states of a variable is zero, as the sum of the probabilities for an influence (and variable) is always one, and a change in the probability of one state will have to be accompanied by an opposite change in the other states. Therefore, variables with two states are only displayed ones in Table 3.

### 2.5 Model uncertainty

Central to being able to develop an appropriate computational model is a well-defined scenario and problem as well as a conceptual model. There exist structured approaches where a subjective uncertainty factor is calculated based on the relevance and validity of the model and the variability of the modelled phenomenon; however, this quantification of the uncertainty tends to be arbitrary [27].

An approach described by both Abrahamsson [27] and Paté-Cornell [26] is to use parallel models that represent different beliefs regarding how the studied phenomenon can lead to risk. This approach is used in this study, and the competing models (Alt. 0, Alt. 1, Alt. 2 and Alt. 3) are here presented in Section 5.1 and used to illustrate how model uncertainties can be described and analysed.

## 3. Scenario, threat and ship

Traditionally, naval ships are built for war and battle, and the type of war expected governs the protection and weapon systems [9]. Today, there are also naval ships built for situations other than war, including a wide range of tasks such as patrol and surveillance, force projection, command platforms, helicopter operations, special operations and maritime law enforcement, anti-drug and smuggling operations and search and rescue. These ships are sometimes built for low-level conflicts where there is no direct military threat.

### 3.1 Scenario and threat

The studied scenario is one of the most common situations performed by international coalitions in recent years, such as the naval part of the United Nations Interim Force in Lebanon (UNIFIL) and the anti-piracy efforts off Somalia. The ship has the role of controlling a specific area along a coast. The tasks are patrol and surveillance, force projection, command platform and helicopter operations. In the studied scenario, the ship is usually patrolling on open water, but it also makes short stops in a few selected harbours.

The threat studied in this work is an antagonistic organization (such as drug smugglers or terrorists) that aims to disrupt the military activity and thus decrease the military control of the coast and harbours in the area.

#### 3.1.1 Threat specification

In Table 4, the International Chamber of Commerce International Maritime Bureau (ICC IMB) statistics on maritime attacks show some attacks on ships in military roles, but the reports cannot be considered to be complete. The ICC IMB reports can therefore only be used to give a general overview of maritime attacks. In total according to the IMB statistics, there were 2386 attacks on ships during 7 years, or 340 attacks on average per year.

**Table 4.** ICC IMB reported attacks 2006-2012 worldwide. Figures in parentheses are the number of attacks on military ships. [37, 38]

| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Attacks | 239 (0) | 263 (0) | 293 (0) | 410 (0) | 445 (3) | 439 (0) | 297 (1) |
| Fatalities or missing | 18(0) | 8(0) | 32(0) | 18(0) | 8(0) | 8(0) | 6(0) |

In an incident report summary prepared by the security consultant Allen-Vanguard for NATO Allied Command Transformation (ACT), the counter improvised explosive device (C-IED) integrated project team (IPT) reports a total of 28 incidents (excluding piracy and drug related incidents) for the years 2000-2012 worldwide [39]. The report is not a complete list of attacks and focuses on attacks using improvised explosive devices. Combining the attacks on military vessels described by the ICC IMB and NATO, a total of 14 attacks are described, and another 3 attacks were interrupted or failed before they reached the target. In 6 incidents, the type of target was unconfirmed. In total, 61 persons were reported killed and 47 injured in the 14 attacks on military vessels. The attacks from 2000 to 2012 are listed in Table 5. The incidents are mostly reported from the Mediterranean, Bay of Aden, Red Sea and Persian Gulf (8 incidents with military target) but also other waters off Africa and Asia [39].

**Table 5.** Maritime attacks for the years 2000-2012, with the purpose of disrupting military supply chains and obstructing military aims (excluding piracy and drug related incidents that only involved civilian ships). Attacks described by NATO [39] or ICC IMB [37, 40].

| | **Military target** | **Civilian target** | **Type of target not known** | **Σ** |
|---|---|---|---|---|
| Ship attacked | 14 | 3 | 0 | **17** |
| Attacks on marine installations | 1 | 2 | 0 | **3** |
| Interrupted and failed attacks | 3 | 0 | 6 | **9** |
| **Consequences for crew** | | | | |
| Injured | 47 | 12 | NA | **59** |
| Killed | 61 | 117 | NA | **178** |
| **Methods and weapons** | | | | |
| Explosives | 12 | 5 | 5 | **27** |
| Improvised sea mines | 2 | 0 | 1 | **3** |
| Suicide bombers | 7 | 3 | 1 | **11** |
| Gunfire or rockets | 6 | 0 | 0 | **6** |

Neither of the two sources for Table 4 claim to be complete with regard to attacks on military vessels, and the total number attacks for the years 2000 to 2012 is most likely higher than 14.

The threat modelled in this study is attack with an explosive device concealed in a small boat or by underwater swimmers, which represents approximately 65% of the attacks described in Table 5. The size and reliability of the charge are limited by the organization's resources and the marine environment. The charge is designed to be set off in direct contact with the hull at the waterline at a position where there are assumed to be sensitive compartments inside. However, it is probable that due to difficulties with the attack, the charge will be set off at an arbitrary location along the waterline or at a distance from the ship. Based on recent years' attacks and disrupted planned attacks, NATO estimates that the probability of an attack increases in proximity to land and with low speed [39].

### 3.2 Ship

To avoid confidential material the ship studied in this work is a generic OPV; see Survivability of small warships and auxiliary naval vessels [16] for more information on the roles and survivability measures of OPV's. The ship is designed and equipped for a small crew compared to a traditional military ship. The ship is described in Table 6.

For the foreseen threats in the area, the ship and organization is designed to meet the following survivability requirements:

A. Severer injuries and casualties should be kept to a minimum in case of an attack.
B. The ship should remain floating after an attack.
C. The ship should, by its own power, be able to move to safer place after an attack.

The survivability measures introduced (risk control options) focus on increasing the ships technical ability to withstand a local hit. The measures therefore are to be defined as safe fail and focus on the two later survivability requirements (B and C). There is no specific protection for the crew other than typical restrictions on movements onboard and on where different tasks are performed. However, the crew's training and equipment for reorganization for recoverability tasks are procedural safeguard which affects the probability for all the consequences defined by the survivability requirements.

**Table 6.** Description of the generic ocean patrol vessel studied.

| **Dimensions and configuration** | | | |
|---|---|---|---|
| Length | 90 m | Draught | 3.5 m |
| Beam | 13 m | Speed, max | 25 knots |
| Displacement | 1.800 tons | Material | Steel with aluminium superstructure |
| Crew | 25 persons | Berths | 60 |
| Propulsion | 2 x 7 MW (diesel engines) | Autonomy | 25 days |
| Range | 5,000 nautical miles at 15 knots | | |
| **Main equipment** | | | |
| Small helicopter landing pad, command and control room with extra capacity for command tasks, a medium caliber dual-purpose naval gun and two fast boarding and rescue boats. | | | |
| **Survivability measures** | | | |
| The ship is built to civilian standards but with an increased number of watertight compartments; extra power supply redundancy with spatial separation of generators and main power distribution lines, and extra separation of critical systems for the ship navigational systems [16]. | | | |

## 4. Model

The model defines the system of study, the delimitations introduced and is specifically developed to calculate the probability for the consequences defined by the survivability requirements A – C stated in Section 3.2. The model used is a simplification of the real event. The included probabilities are collected from experts and derived from submodels based on experiments and calculations from the areas described in Table 1. Different design alternatives will via such submodels affected the probabilities in the model and therefore affect the probabilities for the three consequences under study. The studied ship is a generic OPV according to Section 3.2. Based on the specifications of the OPV typical values for the probabilities in the model are collected from experts. The specific numerical outputs can therefore not be verified or validated against operational data. A study on a specific ship would require a more rigorous method for collecting data to facilitate larger expert groups and a higher number of experts in each area studied.

The threat probability of exploiting vulnerability is here used to introduce a base rate (including the definition of the unit, for example, the probability of more than one attack per year) for attacks dependent on the area of operation (at sea or close to the coast). However, the calculations are here performed assuming an attack.

### 4.1 Model definition

When developing the model, it is important to define each influence clearly and to make sure the definition is understood by the experts involved [24]. The model is defined according to Figure 3, Table 7 and Tables A1-A3 in the appendix. The model has a base alternative (**Alt. 0**) and three competing alternatives as a result of model uncertainty:

- **Alt. 1** where the intent of the threat and not only the ship speed also affects the detonation position (affects the topology of the influence diagram and the definition of conditional probabilities for $s_7$, see Figure 3 and Table A2).

- **Alt. 2** where the reorganization onboard always prioritizes taking care of injured crew and casualties before trying to restore watertight integrity and systems for propulsion and/or navigational command and control (affects the definition of conditional probabilities for $s_{17}$, see Table A3). Therefore, Alt. 2 represents a more pessimistic view of the crew's ability to prioritize and actively contribute to the ships survivability.
- **Alt. 3,** which is a combination of Alt. 1 and Alt. 2.

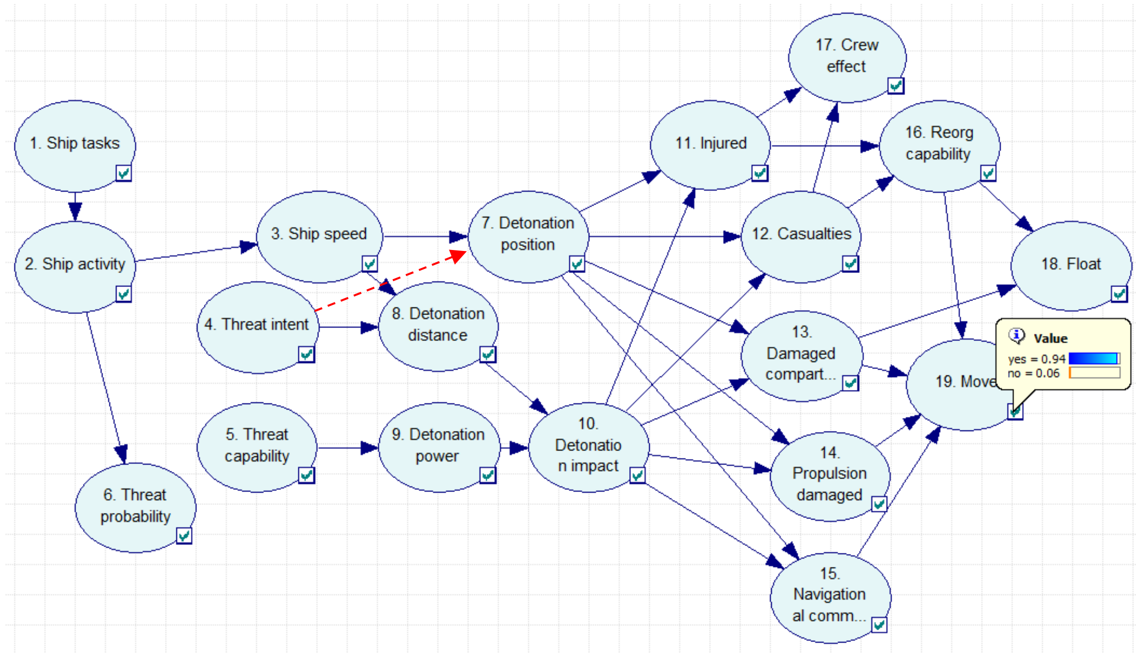


**Figure 3.** Influence diagram for assessing the probability of the consequences studied. Values calculated without epistemic uncertainties according to Table A1. The influences and solid arcs represent the base alternative (Alt. 0) and the dashed arch represents an alternative model (Alt. 1). This influence diagram was created using GeNIe by the Decision Systems Laboratory of the University of Pittsburgh [34].

The main design decisions in the model studied here are as follows:

- The threat probability does not affect the model output, i.e., the probabilities are calculated given the occurrence of an attack.
- The model analyses the effects on the ship 30 minutes after the attack; given more time, the crew can in most cases restore the functions with higher probability.
- Several influences are here defined by qualitative states. For a specific ship, these influences would be defined by quantitative (continuous) states; see for example $s_7$, $s_8$, $s_9$, $s_{10}$ and $s_{12}$. The probabilities for each state are here derived from continuous probability functions (see Boulougouris and Papanikolaou [17] for examples of such functions).
- Reorganization is here defined as restructuring the crew to concentrate on core survival activities. The values for reorganization include priorities made onboard (see for example Alt. 2).
- In the model (all model alternatives), restoring watertight integrity is prioritized before restoring propulsion and navigational command and control.
- Weather and degree of closed watertight doors are included in $s_{19}$.

- Some influences are known with high accuracy (low epistemic uncertainty) because they are technically defined, see for example $s_{13}$.
- Some parts of the influence diagram function as administrative bookkeeping and logic operators and do not introduce parameter uncertainty, see for example $s_{10}$ and $s_{16}$. These influences can however introduce model uncertainty, as in Alt. 2.

According to the model in Figure 3 calculated without epistemic uncertainties the probability of a low level of effects on the crew (state 2 of $s_{17}$) is 0.91, the probability of the ship floating (state 1 of $s_{18}$) is 0.99, and the probability of the ship being able to move (state 1 of $s_{20}$) is 0.94.

**Table 7**. Modelled system, influences, probabilities and uncertainties. See Table A1-A3 for values of the probabilities and epistemic uncertainties.

| Influence | | States | Variable | Probability incl. epistemic parameter uncertainty |
|---|---|---|---|---|
| $s_1$ | Ship tasks | patrol | - | Deterministic |
| $s_2$ | Ship activity | sea;coast | $x_1$ | Based on mission tasks, low uncertainty |
| $s_3$ | Ship speed [knots] | 0;5;15 | $x_2$- $x_3$ | Based on mission tasks, low uncertainty |
| $s_4$ | Threat intent | high;low | $x_4$ | Based on intelligence data/assessment, very high uncertainty |
| $s_5$ | Threat capability | high;low | $x_5$ | Based on intelligence data/assessment, high uncertainty |
| $s_6$ | Threat probability | high;low | $x_6$- $x_7$ | Based on intelligence data/assessment, high uncertainty (does not affect the output) |
| $s_7$ | Detonation position along ship | fore;mid;aft;miss | $x_8$- $x_{10}$ | Can be tested with full scale tests, uncertain |
| $s_8$ | Detonation distance from ship | at;close;far | $x_{11}$- $x_{16}$ | Can partly be tested with full scale tests, uncertain |
| $s_9$ | Detonation power | high;low | $x_{17}$- $x_{18}$ | Based on intelligence data/assessment, uncertain |
| $s_{10}$ | Detonation impact | high;med;low | - | Can be calculated using accurate models, low uncertainty |
| $s_{11}$ | Injured | high;low | $x_{19}$- $x_{25}$ | Can be partly simulated, uncertain |
| $s_{12}$ | Casualties | high;low | $x_{26}$- $x_{32}$ | Can be partly simulated, uncertain |
| $s_{13}$ | Damaged compartments | 0;1;2;3 | $x_{33}$- $x_{36}$ | Can be calculated with accurate models, low uncertainty |
| $s_{14}$ | Propulsion damaged | yes;no | $x_{37}$- $x_{45}$ | Can be partly simulated, uncertain |
| $s_{15}$ | Navigational command and control damaged | yes;no | $x_{46}$- $x_{53}$ | Can be partly simulated, uncertain |
| $s_{16}$ | Reorganization capability | 0;1;≥2 | - | Directly calculated from parents, no uncertainty |
| $s_{17}$ | Crew effect | high;low | - | Directly calculated from parents, no uncertainty |
| $s_{18}$ | Float | yes;no | $x_{54}$- $x_{59}$ | Based on weather and the probability of watertight doors being correctly closed, low uncertainty |
| $s_{19}$ | Move | yes;no | $x_{60}$- $x_{61}$ | Directly calculated from parents, no uncertainty |

According to Tables 7 and A1-A3 the input parameter uncertainty varies substantially. Influence 4 has the highest uncertainty, here estimated as an even distribution between 0 and 0.7 according to Table A1-A3.

### 4.2 Model validation

As described in section 2.4, each area of the model must be validated and developed by a group of experts with the relevant competence and experience for the phenomena discussed. In this study, semi-structured interviews were performed with experts to validate the level of epistemic and aleatory uncertainty for each influence (presented in Tables 7, A1, A2 and A3) and to build a wider knowledge base for the studied case. The epistemic uncertainty was conceptualized in the interviews as the typical level of disagreement between different international groups or studies. The selection of experts was made to cover the applied aspects of the areas presented in Table 1. In total, six experts from northern Europe were used in the study. The experts' profiles are summarized in Table 8.

**Table 8.** Expert profiles.

| Type of expert | Total | International experience military | International experience method develop. | Senior position | Commanding or executive position |
|---|---|---|---|---|---|
| Military | 3 | 3 | 3 | 2 | 2 |
| Civilian | 3 | 1 | 3 | 2 | 2 |
| Σ | 6 | 4 | 6 | 4 | 4 |

### 4.3 Dependency among influences

It is important to note that the calculation method handles the co-dependency between influences, such as the fact that $s_7$ and $s_{10}$ are dependent because both are affected by the state of $s_3$. This fact means that the probability for $s_{11}$-$s_{15}$ cannot be calculated from the probability of $s_7$ and $s_{10}$ as if they were independent; the calculation must be based on all the conditional probabilities for all ancestors of $s_{11}$-$s_{15}$. Ignoring this dependency will, for the probability of a high number of injuries ($s_{11}$ state 1), give an error of approximately 26%, i.e., a probability of 5.5% instead of 7.4%.

## 5. Analysis and results

In Sections 5.1 to 5.3 the output from the three different analysis approaches are presented. The output from the analysis is further discussed in relation to the aim of this study in Section 5.4.

### 5.1 Analysis of the Monte Carlo analysis

As seen in Figure 4, the median and the quartiles are not affected when the number of samples is decreased to 1 000. However, for influence 17, there is a small change in the tails and extreme values if the number of samples is decreased substantially below 10 000, although the relative number of calculations leading to an outlier is fairly constant for the three calculations. It ranges from 4.2‰ to 2.8‰ and the lowest is n = 10 000. The focus in this study is the general effect of the parameter uncertainties on the output uncertainty for the three consequences studied, as exemplified by the different uncertainties in Figure 5. In such a comparison the difference illustrated in Figure 4 between the number of samples does not affect the result and conclusions made. Therefore, in this study, 10 000 samples will be used in the calculations, except for analysing the effect of the model uncertainty on influence 19 (Figure 8). The important aspect is to always use the same number of samples in a comparison between outputs. When analysing the effect of model uncertainty on influence 19 only 1 000 samples are used in order to decrease the calculation time. This is possible because the different model alternatives do not affect the parameter uncertainty.

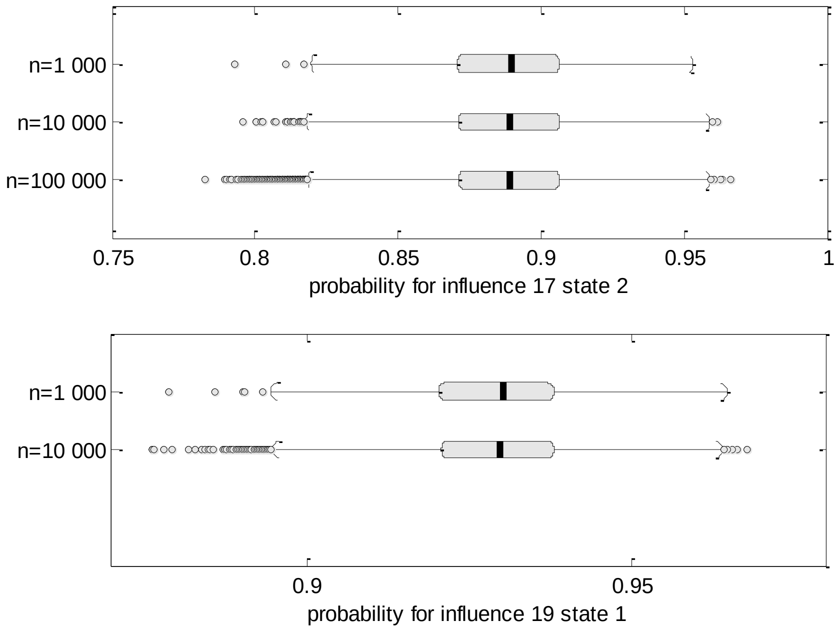


**Figure 4.** Analysis of convergence for the Monte Carlo analysis for the probability of low impact on crew (state 2 of influence 17) and for the probability for ships the ship being able to move (state 1 of influence 19).

In Figure 5, the uncertainty of the three target influences (the consequences under study) is displayed together with the expected value calculated with the mode and median values. The largest interquartile distance is for influence 17 and is 0.04. For all targets there is a more noticeable left tail and the distribution is otherwise fairly symmetrical around the median value. As observed, the expected values do not always represent a good approximation of the output.

Ignoring the epistemic uncertainties and using the most probable values for the input will not give the most probable output according to the Monte Carlo analysis. See especially the difference between the *expected value* and the boxplot median for influences 17 and 19 in Figure 5. Note that both calculations are based on the same expert input (but when calculating the *expected value,* the expert uncertainty is ignored).

It can also be observed that although some of the ancestor uncertainties are high, such as the threat intent and threat capability, the output uncertainty is reasonably lower. The interquartile distances are 0.04, 0.004 and 0.02 for influence 17 state 2, influence 18 state 1 and influence 19 state 1, respectively.

Figure 5 also shows that the consequence with highest probability is high effect on the crew (influence 17), the probability is about 10 percent. The effect on the crew is also the one assessed with the highest uncertainty. Therefore, in a situation where the three consequences studied are equally important it would be natural to start with developing controls that both decrease the probability for high effect on the crew as well as decreases the uncertainty for influence 17 (increases the robustness).

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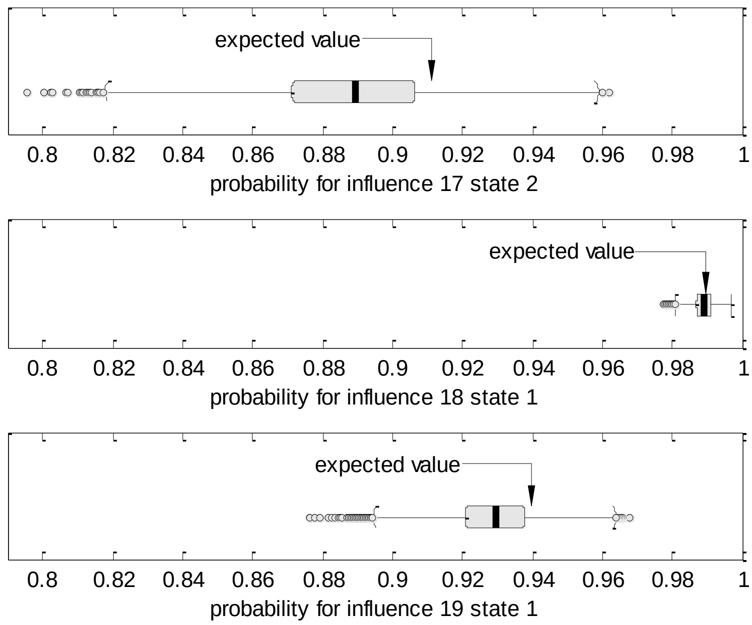


**Figure 5.** The output uncertainty for the consequences under study (influences 17, 18 and 19) as a result of the Monte Carlo analysis. The *expected value* is the value calculated without epistemic uncertainties according to Table A1, n = 10 000 for all three calculations.

### 5.2 Analysis of the numerical derivative analysis

Table 9 lists the ten highest $\partial y/\partial x_i$ for each examined output (target). As seen in Table 9, there are for each target a few variables of extra high importance. In particular, for influence 18, the derivative for the top three variables are all five times higher than the derivative for the fourth variable. However, the high effect variables (with high value for the derivative) are not the same for the three targets and are spread across the influence diagram. Only one variable ($x_1$) is in the top ten for all three influences.

It is also noteworthy that the variable with the second highest uncertainty (variable $x_5$, which describes the threat capability) is the variable with the highest effect on influence 17 and the fifth most important variable for influence 19.

Table 10 lists the ten highest estimated maximum uncertainty contributions ($\Delta y_{max,i}$) given by

$$\Delta y_{max,i} \approx |\partial y/\partial x_i\,| \cdot x_{unc,i}$$ **Equation 7**

where $x_{unc,i}$ is half the uncertainty range for variable *i* according to

$$x_{unc,i} = \left(x_{max,i} - x_{min,i}\right)/2.$$ **Equation 8**

$x_{unc,i}$ is calculated from Tables A1-A3. Given the high effect of $x_5$ on influence 17 and 19 and the high uncertainty for $x_5$, it is important to try to reduce the uncertainty of $x_5$, as doing so will have a substantial effect on the uncertainty for influences 17 and 19. However, for influence 18 the effect of the uncertainty of variable $x_{59}$ (describing the probability for the ship being able to float given a three compartment damage and high reorganization capability) is high, even though the uncertainty for $x_{59}$ is relatively small compared to other variables.

**Table 9.** The ten variables with the highest $|\partial y/\partial x_i|$. Variables with two states are only displayed ones in the list.

| | Influence 17 state 1 | | Influence 18 state 1 | | Influence 19 state 1 | |
|---|---|---|---|---|---|---|
| Pos | Var. | $\|\partial y/\partial x_i\|$ | Var. | $\|\partial y/\partial x_i\|$ | Var. | $\|\partial y/\partial x_i\|$ |
| 1 | $x_{5.1}$ | 0.13 | $x_{55.1}$ | 0.27 | $x_{61.1}$ | 0.16 |
| 2 | $x_{1.1}$ | 0.12 | $x_{57.1}$ | 0.14 | $x_{40.1}$ | 0.07 |
| 3 | $x_{18.1}$ | 0.12 | $x_{59.1}$ | 0.11 | $x_{50.1}$ | 0.06 |
| 4 | $x_{2.3}$ | 0.10 | $x_{35.4}$ | 0.02 | $x_{53.1}$ | 0.06 |
| 5 | $x_{2.1}$ | 0.10 | $x_{35.1}$ | 0.01 | $x_{5.1}$ | 0.06 |
| 6 | $x_{12.1}$ | 0.08 | $x_{56.1}$ | 0.01 | $x_{1.1}$ | 0.05 |
| 7 | $x_{16.1}$ | 0.08 | $x_{35.2}$ | 0.01 | $x_{18.1}$ | 0.05 |
| 8 | $x_{22.1}$ | 0.07 | $x_{10.4}$ | 0.01 | $x_{43.1}$ | 0.05 |
| 9 | $x_{3.3}$ | 0.07 | $x_{34.4}$ | 0.01 | $x_{2.3}$ | 0.05 |
| 10 | $x_{3.1}$ | 0.07 | $x_{1.2}$ | 0.01 | $x_{8.3}$ | 0.05 |

**Table 10.** The ten variables with the highest effect on the output uncertainty $\Delta y_i$. Variables with two states are only displayed ones in the list.

| | Influence 17 state 1 | | | Influence 18 state 1 | | | Influence 19 state 1 | | |
|---|---|---|---|---|---|---|---|---|---|
| Pos | Var. | $\Delta y_{max,i}$ | $x_{unc,i}$ | Var. | $\Delta y_{max,i}$ | $x_{unc,i}$ | Var. | $\Delta y_{max,i}$ | $x_{unc,i}$ |
| 1 | $x_{5.1}$ | 0.04 | 0.30 | $x_{59.1}$ | 0.003 | 0.03 | $x_{5.1}$ | 0.02 | 0.30 |
| 2 | $x_{18.1}$ | 0.03 | 0.25 | $x_{35.4}$ | 0.003 | 0.15 | $x_{18.1}$ | 0.01 | 0.25 |
| 3 | $x_{4.1}$ | 0.02 | 0.35 | $x_{57.2}$ | 0.003 | 0.02 | $x_{4.1}$ | 0.008 | 0.35 |
| 4 | $x_{12.3}$ | 0.01 | 0.25 | $x_{55.1}$ | 0.001 | 0.005 | $x_{50.1}$ | 0.006 | 0.09 |
| 5 | $x_{14.3}$ | 0.009 | 0.25 | $x_{5.1}$ | 0.0009 | 0.30 | $x_{12.3}$ | 0.005 | 0.25 |
| 6 | $x_{3.3}$ | 0.009 | 0.13 | $x_{34.4}$ | 0.0008 | 0.13 | $x_{3.3}$ | 0.004 | 0.13 |
| 7 | $x_{12.1}$ | 0.008 | 0.10 | $x_{18.1}$ | 0.0007 | 0.25 | $x_{61.1}$ | 0.004 | 0.03 |
| 8 | $x_{22.1}$ | 0.007 | 0.10 | $x_{10.4}$ | 0.0006 | 0.08 | $x_{52.1}$ | 0.004 | 0.14 |
| 9 | $x_{2.3}$ | 0.006 | 0.06 | $x_{3.3}$ | 0.0005 | 0.13 | $x_{40.1}$ | 0.004 | 0.05 |
| 10 | $x_{11.3}$ | 0.006 | 0.20 | $x_{4.1}$ | 0.0004 | 0.35 | $x_{14.3}$ | 0.004 | 0.25 |

### 5.3 Effects of the model uncertainty

Figures 6 through 8 displays the effect of the model alternatives as presented in Section 4.1 (influence 17 is not affected by Alt. 2 or 3). It can be observed that the competing models affect both the value of the target influences and the sensitivity to uncertainties. The greatest effect on the output lies in Alt. 1 and Alt. 2 for influence 19. For all the studied cases, the effect of the model uncertainty is similar to, or smaller than, the results of the parameter uncertainty.

Even though the expected value cannot be used to predict the median output from the Monte Carlo analysis it can, according to Figures 6 to 8, be used to predict the overall effect of a model change.

Given relatively small effect of the model uncertainty on influence 17 and 18, the competing models does not present a problem for assessing those risks. However, when assessing the operational risk the probability for the ship being able to move after an attack (influence 19) also must be considered. Then especially the uncertainty as a result of the model Alt. 2 must be further investigated and if possible reduced.

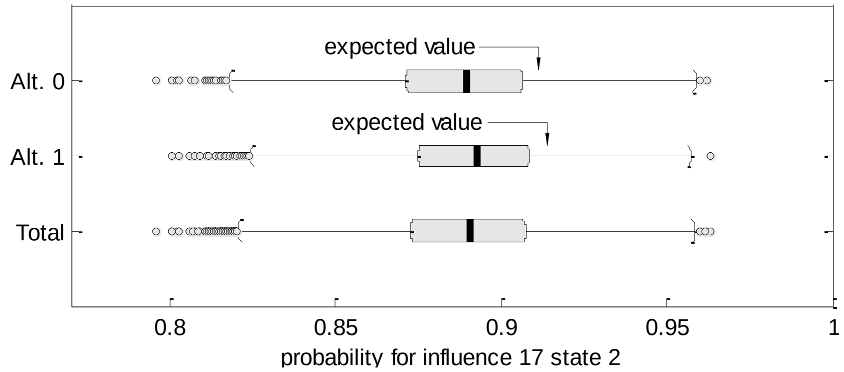


**Figure 6.** Model uncertainty for influence 17. The *expected value* is the value calculated without epistemic uncertainties. The total is a boxplot of all the results from the analysis of both Alt. 0 and Alt. 1.

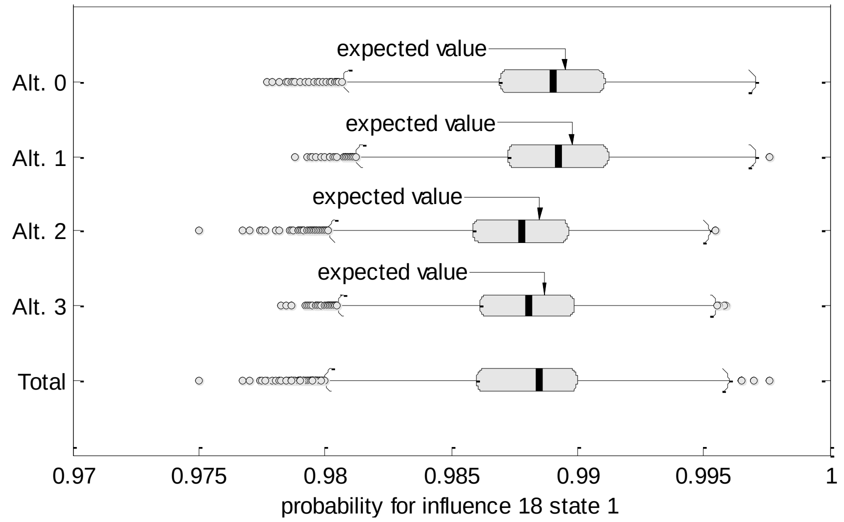


**Figure 7.** Model uncertainty for influence 18. The *expected value* is the value calculated without epistemic uncertainties. The total is a boxplot of all the results from the analysis of Alt. 0, Alt. 1, Alt. 2 and Alt. 3.

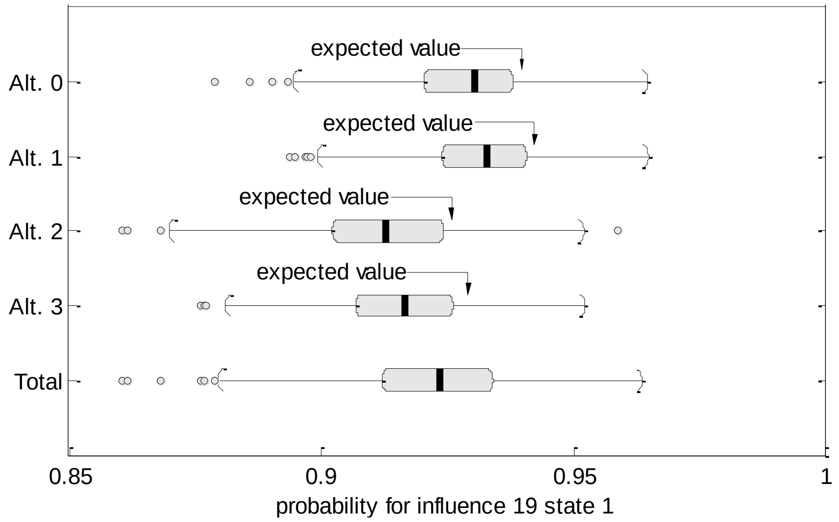


**Figure 8.** Model uncertainty for influence 19, n=1 000. The *expected value* is the value calculated without epistemic uncertainties. The total is a boxplot of all the results from the analysis of Alt. 0, Alt. 1, Alt. 2 and Alt. 3.

### 5.4 Results

The box plots for the three output parameters, in Figure 5, give a good understanding of how the uncertainties affect the output, including the most probable values as well as the tails. Such results give the analyst and the decision maker the information needed to take the total uncertainty into account and not only the expected probability and consequences.

The results are here presented with boxplots highlighting the quartiles, according to Equations 5 and 6. However, any limit could be used, depending on the needs of the decision-making process.

A high uncertainty can give rise to two different alternatives; one is the need to decrease the uncertainty in the analysis, and the other is to find a protection solution with a lower uncertainty. When the aim is to decrease the uncertainty, the parameter uncertainty must be revisited. To revisit the parameter uncertainty structurally requires knowledge of how the different input parameters contribute to the output uncertainty. This contribution is estimated by the numerical derivative analysis presented in Table 10. The results of the numerical derivative analysis very clearly indicate which input must be revisited. Deriving similar results from the Monte Carlo analysis is very time and calculation intensive.

From the results is clear that the proposed approach can assess the risk and examine the uncertainties and be described to the decision maker. However, the results also show that this kind of approach is needed for understanding which variables affect the output uncertainty. From the numerical derivative analysis, it can be observed that there are high effect variables all over the influence diagram, and the high effect variables differ for the three studied influences. It also seems that there is no easily identifiable system for finding the variables that affect an influence, other than doing a sensitivity analysis. The results also show that there are variables with considerable uncertainty that does not contribute substantially to the output uncertainty. It is also noteworthy that the output uncertainty is small relative to the input uncertainty, only about, or less, than four percentages compared to 10 to 20 percentages for many input variables. Therefore, high parameter uncertainty does not necessarily lead to high output uncertainty.

Figures 6 through 8 show how the different model alternatives affect output in terms of both median values and uncertainty. However, the figures also suggest that the expected value, even though it does not predict the Monte Carlo median, can be used to estimate how an alternative model will affect the median output compared to a previously analysed model alternative because, for all the studied cases, changing the model causes the changes in the expected value to follow the changes in the median.

Together, the three methods studied here give valuable information on the output uncertainty and also how the different input parameters and model contribute to the uncertainty. This information is very valuable for both the analyst and the decision maker.

**6. Discussion**

The chosen case represents a common modern naval vessel type and one of the most frequent types of incidents involving naval vessels in recent years. The case includes technical systems, but also strategies and priorities made on board. The studied ship is a generic OPV, and the result is therefore not representative for any specific OPV. The analysis of a specific OPV may give lower or higher probabilities depending on the choices made in design, tactics and manning. The specific numerical outputs can therefore not be verified or validated against operational data.

It must be noted that the studied model is a simplified model, especially as the included influences are described using discrete states to facilitate a transparent study where the results are easily understood. A study on a specific ship would require a more rigorous method for collecting data to facilitate larger expert groups and a higher number of experts in each area studied.

Is the uncertainty in the output too high for choosing risk control options? The answer to that question is up to the decision maker, not to the analyst. However, based on the type of results presented in this study, the question can actually be discussed, and there is a chance to work structurally with the uncertainties and reduce both the input uncertainty and the model uncertainty.

Decreasing the uncertainty below the values analysed here will require experiments, refinement of computer models and possibly full scale tests with similar ships. These approaches are all possible, though costly. It is therefore important to perform such investigations effectively in the most important areas; such decisions can be assisted by the type of analysis suggested here. Additionally, Equations 2 and 3 show that it is possible, if desired, to deepen the analytical analysis of the model to investigate such aspects as optimization and robustness.

According to the experts, the level of uncertainty used in this study is realistic, but can be decreased. For example, in the area of weapons effects and ship survivability, there are international benchmark studies comparing experiments and the results from different simulation software. Using such studies and refining the models used will decrease the uncertainty below the values displayed in Table A1.

The example studied here is manned with a relatively small crew compared to traditional war ships. However, compared to civilian ships, the crew is large, and the possibility for crew reorganization is therefore high compared to civilian ships. As shown in the output this potential for reorganization is an important safety and security measure that enables the ship and crew to respond to incidents and reduce their effects. The effect on crew reorganization can be seen in Alt. 2 for influence 18, which shows that the crew size and prioritizing on board can affect the probability of meeting the survivability requirements, where the median value for the probability of restoring navigational command and control is reduced by 2 percentages, from 93% to 91%.

The approach tested in this study provides essential knowledge for evaluating whether the knowledge at hand is sufficient for decision-making about appropriate risk control options. The approach can also test different control options and their sensitivity to the input uncertainties. This approach therefore offers a deeper understanding of the uncertainties and a better possibility of making decisions.

Ship security measures are mainly *safe fail* and *procedural safeguards*, as can also be observed in the model and in the output. The fail safe can be seen in the probabilistic values, where the probability of a severe consequence is relatively small even in the event of an attack, and the procedural safeguards in the topology, where the crew has the potential to reduce the effects of an attack.

## 7. Conclusions

The aim of this study is to present an approach for assessing operational risk and to show the effects of both aleatory and epistemic uncertainties throughout the analysis. In this study, the case of an antagonistic threat against a military OPV is used to assess the risk and examine the uncertainties. The studied ship is a generic OPV; the analysis of a specific OPV may give lower or higher probabilities depending on the choices made in design, tactics and manning.

Together, the three methods studied here give valuable information on the output uncertainty and on how the different input parameters' uncertainties and the model uncertainty contribute, the analysis also show that the output uncertainty is small relative to the input uncertainty.

The gained information is very valuable for both the analyst and the decision maker. The analyst can use this information to decide where to expend effort on decreasing input uncertainty. The decision maker obtains a broader understanding of the effectiveness of the risk control options and their sensitivity to uncertainties.

The results show that it is possible to link the performance of specific ship design features to the operational risk. Being able to propagate the epistemic uncertainties throughout the model is important to understand how the uncertainty regarding the input affects the output. The numerical derivative analysis effectively estimates the sensitivity of the output to each input parameter uncertainty. Therefore, the study shows that linking different ship design features regarding aspects such as survivability, redundancy and technical endurance to the operational risk provides important information for the ship design decision-making process.

## 8. Acknowledgments

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## Appendix A

As shown Table A1 it is natural for several different conditional probabilities for an influence to be described with the same values (see $x_{53}$ and $x_{60}$). If this is the case it is important to define this value as one variable in the Monte Carlo analysis and the numerical derivative analysis. If not the effect of uncertainty for these variables will be underestimated.

Throughout the appendix the following definition of logical operators are used:

- conjunction (AND): $\wedge$
- inclusive disjunction (AND/OR): $\vee$
- exclusive disjunction (XOR): $\veebar$

**Table A1.** Numerical values for probabilities and uncertainties in modelled system.

| Influence | States | Conditions | Var. | Probability incl. epistemic uncertainty (for first state if not otherwise stated) [min;max alt. min;mode;max] |
|---|---|---|---|---|
| **$s_1$ Ship tasks** | **patrol** | **NA** | **-** | **deterministic** |
| $s_2$ Ship activity | sea;coast | $\|s_1$=patrol | $x_1$ | 0.58;0.62 |
| $s_3$ Ship speed [knots] | 0;5;15 | $\|s_2$=sea | $x_2$ | state 0: 0.04;0.05;0.06; state 5: 0.15;0.2;0.25 |
| | | $\|s_2$=coast | $x_3$ | state 0: 0.55;0.6;0.7; state 5: 0.15;0.2;0.25 |
| $s_4$ Threat intent | high;low | NA | $x_4$ | 0;0.7 |
| $s_5$ Threat capability | high;low | NA | $x_5$ | 0;0.2;0.6 |
| $s_6$ Threat probability | high;low | $\|s_2$=sea | $x_6$ | 0.01;0.02 |
| | | $\|s_2$=coast | $x_7$ | 0.1;0.2 |
| $s_7$ Detonation position along ship | fore;mid;aft;miss | $\|s_3$=0 | $x_8$ | state fore: 0.13;0.18; state mid: 0.52;0.57 state aft: 0.25;0.31 |
| | | $\|s_3$=5 | $x_9$ | state fore: 0.09;0.14; state mid: 0.41;0.46 state aft: 0.33;0.38 |
| | | $\|s_3$=15 | $x_{10}$ | state fore: 0.02;0.07; state mid: 0.15;0.21 state aft: 0.18;0.23 |
| $s_8$ Detonation distance from ship side | at;close;far | $\|s_3=0\|s_4$=high | $x_{11}$ | state at: 0.5;0.7; state close: 0.1;0.3 |
| | | $\|s_3=0\|s_4$=low | $x_{12}$ | state at: 0.2;0.4; state close 0.2;0.5 |
| | | $\|s_3=5\|s_4$=high | $x_{13}$ | state at: 0.2;0.4; state close 0.3;0.6 |
| | | $\| s_3=5\|s_4$=low | $x_{14}$ | state at: 0.1;0.2; state close 0.2;0.6 |
| | | $\|s_3=15\|s_4$=high | $x_{15}$ | state at: 0.0;0.05; state close 0.05;0.15 |
| | | $\|s_3=15\|s_4$=low | $x_{16}$ | state at: 0.0;0.01; state close 0.0;0.06 |
| $s_9$ Detonation power | high;low | $\|s_5$=high | $x_{17}$ | 0.8;0.95;1 |
| | | $\|s_5$=low | $x_{18}$ | 0;0.05;0.5 |
| $s_{10}$ Detonation impact | high;med;low | $\|s_8$=at$\|s_9$=high | - | state high: 1 |
| | | $\|s_8$=at$\|s_9$=low | - | state med: 1 |
| | | $\|s_8$=close$\|s_9$=high | - | state med: 1 |
| | | $\|s_8$=close$\|s_9$=low | - | state low: 1 |
| | | $\|s_8$=far$\|s_9$=high | - | state low:1 |
| | | $\|s_8$=far$\|s_9$=low | - | state low:1 |
| $s_{11}$ Number of injured | high;low | $\|s_7$=fore$\|s_{10}$=high | $x_{19}$ | 0.7; 0.95 |
| | | $\|s_7$=fore$\|s_{10}$=med | $x_{20}$ | 0.2; 0.4 |
| | | $\|s_7$=mid$\|s_{10}$=high | $x_{21}$ | 0.75; 0.98 |
| | | $\|s_7$=mid$\|s_{10}$=med | $x_{22}$ | 0.25; 0.45 |
| | | $\|s_7$=aft$\|s_{10}$=high | $x_{23}$ | 0.5; 0.8 |
| | | $\|s_7$=aft$\|s_{10}$=med | $x_{24}$ | 0.2; 0.3 |
| | | $\|s_7$=miss$\|s_{10}$=high | $x_{25}$ | 0; 0.4 |
| | | $\|s_7$=miss$\|s_{10}$=med | - | 0 |
| | | $\|s_{10}$=low | - | 0 |

**Table A1.** Continued.

| Influence | States | Conditions | Var. | Probability incl. epistemic uncertainty (for first state if not otherwise stated) [min;max alt. min;mode;max] |
|---|---|---|---|---|
| $s_{12}$ Casualties | high;low | $\|s_7$=fore$\|s_{10}$=high | $x_{26}$ | 0.6;0.9 |
| | | $\|s_7$=fore$\|s_{10}$=med | $x_{27}$ | 0;0.3 |
| | | $\|s_7$=mid$\|s_{10}$=high | $x_{28}$ | 0.65;0.85 |
| | | $\|s_7$=mid$\|s_{10}$=med | $x_{29}$ | 0;0.2 |
| | | $\|s_7$=aft$\|s_{10}$=high | $x_{30}$ | 0.25;0.6 |
| | | $\|s_7$=aft$\|s_{10}$=med | $x_{31}$ | 0;0.15 |
| | | $\|s_7$=miss$\|s_{10}$=high | $x_{32}$ | 0.0;0.25 |
| | | $\|s_7$=miss$\|s_{10}$=med | - | 0 |
| | | $\|s_{10}$=low | - | 0 |
| $s_{13}$ No of damaged Compartments | 0;1;2;3 | $\|s_7$≠miss$\|s_{10}$=high | $x_{33}$ | state 0: 0;0.05; state 1: 0.2;0.26; state 2: 0.38;0.5 |
| | | $\|s_7$≠miss $\|s_{10}$=med | $x_{34}$ | state 0: 0;0.1; state 1: 0.34;0.42; state 2: 0.33;0.4 |
| | | $\|s_7$≠miss $\|s_{10}$=low | $x_{35}$ | state 0: 0.2;0.32; state 1: 0.4;0.47; state 2: 0.1;0.21 |
| | | $\|s_7$=miss$\|s_{10}$=high | $x_{36}$ | state 0: 0.8;0.91; state 1:0; 0.09 |
| | | $\|s_7$=miss$\|s_{10}$≠high | - | state 0: 1 |
| $s_{14}$ Propulsion damaged | yes;no | $\|s_7$=fore$\|s_{10}$=high | $x_{37}$ | 0;0.08 |
| | | $\|s_7$=fore$\|s_{10}$≠high | - | 0 |
| | | $\|s_7$=mid$\|s_{10}$=high | $x_{38}$ | 0.15;0.38 |
| | | $\|s_7$=mid$\|s_{10}$=med | $x_{39}$ | 0.07;0.22 |
| | | $\|s_7$=mid$\|s_{10}$=low | $x_{40}$ | 0;0.11 |
| | | $\|s_7$=aft$\|s_{10}$=high | $x_{41}$ | 0.82;1 |
| | | $\|s_7$=aft$\|s_{10}$=med | $x_{42}$ | 0.6;0.7 |
| | | $\|s_7$=aft$\|s_{10}$=low | $x_{43}$ | 0.11;0.24 |
| | | $\|s_7$=miss$\|s_{10}$=high | $x_{44}$ | 0;0.18 |
| | | $\|s_7$=miss$\|s_{10}$=med | $x_{45}$ | 0;0.08 |
| | | $\|s_7$=miss$\|s_{10}$=low | - | 0 |
| $s_{15}$ Navigational command and control damaged | yes;no | $\|s_7$=fore$\|s_{10}$=high | $x_{46}$ | 0.02;0.18 |
| | | $\|s_7$=fore$\|s_{10}$=med | $x_{47}$ | 0;0.12 |
| | | $\|s_7$=fore$\|s_{10}$=low | - | 0 |
| | | $\|s_7$=mid$\|s_{10}$=high | $x_{48}$ | 0.16;0.5 |
| | | $\|s_7$=mid$\|s_{10}$=med | $x_{49}$ | 0.07;0.3 |
| | | $\|s_7$=mid$\|s_{10}$=low | $x_{50}$ | 0;0.18 |
| | | $\|s_7$=aft$\|s_{10}$=high | $x_{51}$ | 0.15;0.65 |
| | | $\|s_7$=aft$\|s_{10}$=med | $x_{52}$ | 0.06;0.34 |
| | | $\|s_7$=aft$\|s_{10}$=low | $x_{53}$ | 0;0.08 |
| | | $\|s_7$=miss$\|s_{10}$=high | $x_{53}$ | 0;0.08 |
| | | $\|s_7$=miss$\|s_{10}$=med | - | 0 |
| | | $\|s_7$=miss$\|s_{10}$=low | - | 0 |
| $s_{16}$ Reorganization capability | 0;1;≥2 | $\|s_{11}$=high$\|s_{12}$=high | - | state 0: 1 |
| | | $\|s_{11}$=high$\|s_{12}$=low | - | state 2: 1 |
| | | $\|s_{11}$=low$\|s_{12}$=high | - | state 1: 1 |
| | | $\|s_{11}$=low$\|s_{12}$=low | - | state 2: 1 |
| $s_{17}$ Effect on crew | high;low | $\|s_{11}$=high∨$s_{12}$=high | - | state high: 1 |
| | | $\|s_{11}$=low$\|s_{12}$=low | - | state low: 1 |
| $s_{18}$ Float | yes;no | $\|s_{13}$=0$\|s_{16}$≥0 | - | 1 |
| | | $\|s_{13}$=1$\|s_{16}$=0 | $x_{54}$ | 0.97;1 |
| | | $\|s_{13}$=1$\|s_{16}$≥1 | $x_{55}$ | 0.99;1 |
| | | $\|s_{13}$=2$\|s_{16}$=0 | $x_{56}$ | 0.95;0.99 |
| | | $\|s_{13}$=2$\|s_{16}$≥1 | $x_{57}$ | 0.96;1 |
| | | $\|s_{13}$=3$\|s_{16}$=0 | $x_{58}$ | 0.86;0.96 |
| | | $\|s_{13}$=3$\|s_{16}$≥1 | $x_{59}$ | 0.92;0.98 |

**Table A1.** Continued.

| Influence | States | Conditions | Var. | Probability incl. epistemic uncertainty (for first state if not otherwise stated) [min;max alt. min;mode;max] |
|---|---|---|---|---|
| $s_{19}$ Move | yes;no | $\|s_{13}\geq0\|s_{14}\wedge s_{15}$=yes$\|s_{18}=0$ | - | 0 |
| | | $\|s_{13}\geq0\|s_{14}\wedge s_{15}$=yes$\|s_{18}=1$ | - | 0 |
| | | $\|s_{13}=0\|$ $s_{14}\wedge s_{15}$=yes$\|s_{18}=2$ | $x_{60}$ | 0.52;0.61 |
| | | $\|s_{13}\geq0\|s_{14}\underline{\vee}s_{15}$=yes$\|s_{18}=0$ | - | 0 |
| | | $\|s_{13}=0\|s_{14}\underline{\vee}s_{15}$=yes$\|s_{18}\geq1$ | $x_{61}$ | 0.72;0.78 |
| | | $\|s_{13}=0\|s_{14}\wedge s_{15}$=no$\|s_{18}=0$ | - | 1 |
| | | $\|s_{13}\geq0\|s_{14}\wedge s_{15}$=no$\|s_{18}\geq1$ | - | 1 |
| | | $\|s_{13}\geq1\|s_{14}\wedge s_{15}$=no$\|s_{18}=0$ | - | 0 |
| | | $\|s_{13}\geq1\|s_{14}\underline{\vee}s_{15}$=yes$\|s_{18}=1$ | - | 0 |
| | | $\|s_{13}\geq1\|$ $s_{14}\wedge s_{15}$=yes$\|s_{18}=2$ | - | 0 |

**Table A2.** Numerical values for probabilities and uncertainties in modelled system for Alternative 1.

| Influence | States | Conditions | Probability incl. epistemic uncertainty (for first state if not otherwise stated) [min;max alt. min;mode;max] |
|---|---|---|---|
| *$s_1$ - $s_6$ according to Table A1* | | | |
| $s_7$ Detonation position along ship | fore;mid;aft;miss | $\|s_3=0\|s_4$=high | state fore: 0.03;0.09; state mid: 0.6;0.7 state aft: 0.11;0.21 |
| | | $\|s_3=0\|s_4$=low | state fore: 0.13;0.18; state mid: 0.52;0.57 state aft: 0.25;0.31 |
| | | $\|s_3=5\|s_4$=high | state fore: 0.02;0.06; state mid: 0.51;0.65 state aft: 0.18;0.25 |
| | | $\|s_3=5\|s_4$=low | state fore: 0.09;0.14; state mid: 0.41;0.46 state aft: 0.33;0.38 |
| | | $\|s_3=15\|s_4$=high | state fore: 0.01;0.03; state mid: 0.21;0.3 state aft: 0.16;0.21 |
| | | $\|s_3=15\|s_4$=low | state fore: 0.02;0.07; state mid: 0.15;0.21 state aft: 0.18;0.23 |
| *$s_8$ - $s_{20}$ according to Table A1* | | | |

**Table A3.** Numerical values for probabilities and uncertainties in modeled system for Alternative 2.

| Influence | States | Conditions | Probability incl. epistemic uncertainty (for first state if not otherwise stated) [min;max alt. min;mode;max] |
|---|---|---|---|
| *$s_1$ - $s_{17}$ according to Table A1* | | | |
| $s_{18}$ Reorganization capability | 0;1;2 | $\|s_{11}$=high$\|s_{12}$=high | state 0: 1 |
| | | $\|s_{11}$=high$\|s_{12}$=low | state 0: 1 |
| | | $\|s_{11}$=low$\|s_{12}$=high | state 0: 1 |
| | | $\|s_{11}$=low$\|s_{12}$=low | state 2: 1 |
| *$s_{18}$ – $s_{20}$ according to Table A1* | | | |