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A Framework for Vulnerability Reduction in Early Stage Design of Naval Ship Systems

ABSTRACT

Naval ships are designed to operate and survive in hostile environments. As such, vulnerability reduction is a major topic of interest during the design of a naval ship. For modern naval ships the vulnerability is largely determined by the design and layout of distributed systems. The vulnerability of these systems needs to be assessed early on, as design decisions made in this stage are decisive for the vulnerability of the final ship. Various early stage methods for assessing vulnerability exist, but a clear structure on when to use what types of methods, how these methods relate to each other, and how these methods provide relevant answers, is still lacking. To address this gap, this paper introduces a framework for early stage design of distributed systems, in the context of vulnerability reduction. This framework supports in choosing the right vulnerability method at the right design stage. The framework considers an operationally oriented systems perspective on vulnerability, and a physically oriented ship perspective. In addition to that, early stage design is subdivided in concept exploration and concept definition, which have different purposes and contributions in the design process. The framework provides examples of methods that can be used to investigate vulnerability for the various perspectives and design stages. These examples consider methods that have been developed by joint Delft University of Technology (TU Delft) and the Netherlands Defence Materiel Organisation (DMO) research efforts, as well as other methods. Opportunities and challenges for integrating these methods between themselves and in the design process in general are discussed.

1. INTRODUCTION

1.1. Vulnerability of distributed systems

Naval ships are designed to operate, survive, and win in a hostile environment. As such, the design of a naval ship as a whole, including its crew, weapons, sensors, and supporting systems must be designed to cope with and to be survivable in man-made harsh circumstances. In a military context this specifically relates to threats resulting from intentional warfare. However, surviving in harsh circumstances also includes non-hostile aspects, such as being able to avoid or withstand collisions, groundings, or fires. This feature is known as survivability, and is considered a major design driver in naval ship design.

Survivability is expressed as the product of three key aspects: susceptibility, vulnerability, and recoverability (Said, 1995). Susceptibility focusses on avoiding damage, for example by reducing noise and heat signatures. Vulnerability concerns resisting the effects of damage, for example by an intelligent general arrangement or ballistic protection. Recoverability focusses on repairing and recovering from damage, such as fire-fighting and reconfiguring systems. All aspects are a function of the design of the ship, though recoverability is also largely determined by active response on board (of which the effectiveness is a function of the design of the ship again, amongst others). This paper focusses on vulnerability, as weapon hits or other damage cannot always be avoided (Duchateau et al., 2018; Reese et al., 1998).

The layout of a naval ship has a major influence on the vulnerability. An intelligent subdivision of watertight compartments, and appropriate structural integrity of the bulkheads separating them, can decrease the consequences of damage significantly. This perspective on vulnerability, consisting of the more traditional naval architecture disciplines such as hydromechanics and structures, has long been applied and continues to be relevant in modern naval ship design (Boulougouris and Papanikolaou, 2013). However, the vulnerability of modern naval ships is increasingly being governed by developments in automation, electrification (Doerry, 2015), and digital transformation (Bolton et al., 2018). Systems that are associated with these developments, such as high energy weapons or advanced radar systems, heavily rely on vital resources such as electricity, chilled water, and data. The systems that distribute the supply of these resources are known as distributed systems, since they tend to extend to all parts of the ship and therefore are strongly related to the arrangement of all components in the ship. These distributed systems are becoming more and more interdependent and vital for on-board naval operations. Hence, the design and layout of distributed systems has become equally important as the more traditional naval architecture disciplines, especially from a vulnerability perspective. For that reason, this paper focusses on the vulnerability of distributed systems. In the remainder of this paper, this is simply referred to as 'vulnerability'.

1.2. Vulnerability in early stage design

The vulnerability is largely determined by the way in which the distributed systems are designed and integrated into the ship. Especially decisions made in the early design stages, such as the number and location of major equipment items and the routing of connections between these components, are decisive for the vulnerability of the final ship. While early stage design decisions influence the vulnerability, this relation also holds the other way around: early consideration of vulnerability influences design decisions. A practical example is the application of redundancy of critical systems, such as the propulsion system. If this is desired due to vulnerability reduction reasons, it implies duplication and separation of e.g. generators, engine rooms, switchboards and other elements in all layers of the distribution system, possibly including zoning. This is a major size driver for the design. Hence, early stage design decisions and vulnerability considerations are highly interdependent. Though this paper limits itself to vulnerability, this also holds for other aspects, such as cost and operational performance. At the same time, the available problem knowledge, design data, and time to make these decisions are limited in the early stages. In other words, the decisions with the largest influence on the final ship need to be made with very limited data and details. To overcome this difficulty, caused by a lag in information, various tools and methods can be used to assess or estimate the vulnerability during various phases in early stage design. These tools need to match the design phase for which they are meant, i.e. the results that they provide should be producible with the design data available at that stage, and capable of answering the typical design questions asked at that stage. In order to support this, there needs to be a clear understanding of which questions are asked during early stage design, and how the different vulnerability tools and methods can provide answers to those questions.

Though descriptions of early stage vulnerability methods and explanations of the early stage design process are available in literature, a clear structure on when to use what types of methods, how these methods relate to each other, and how these methods provide relevant answers, is still lacking. To address this gap, this paper introduces a framework for early stage design of distributed systems, in the context of vulnerability. The goal of this framework is to provide guidance on how to assess vulnerability during the various phases of early stage design. First, relevant background on the nature of early stage ship design and on distributed systems is provided in Section 2. Subsequently, the framework is presented in Section 3. This framework contains methods that have been developed by joint research efforts of the Delft University of Technology (TU Delft) and the Netherlands Defence Materiel Organisation (DMO), as well as other methods. These methods are discussed in Section 3 as well. Section 4 explains how these methods can be integrated in order to complement each other, both from a design process perspective and a more specific mathematical perspective. A brief higher-level reflection on the naval ship design process is given in Section 5. Section 6 contains a conclusion. Recommendations are provided in Section 7.

2. EARLY STAGE DESIGN METHODS AND SYSTEM MODELS

2.1. Nature of early stage naval ship design

Early stage design is the first part of the design process. The goal of early stage design can be either to define a single concept design that is worked out in more detail in later design stages, or to define and validate feasible, affordable and relevant design requirements. In a naval ship design context, the early design stage usually starts with an explorative study in which many concepts are generated and assessed. Based on the explorative study, a lower number of concepts is considered in more detail, working towards a validated set of requirements that will eventually be used for developing the solution. These two stages are known as concept exploration and concept definition. There are various views on how the goals of these stages are exactly defined (see (Kossiakoff et al., 2011) for a discussion). The naval ship design context of concept exploration and concept definition are discussed by (van Oers et al., 2018):

1. <u>Concept exploration</u>. In this phase it is investigated which design requirements are needed, and how various solutions affect these requirements. The result of this phase is a set of feasible, relevant, and affordable requirements. In addition to that, important trade-offs and driving factors for performance, effectiveness and cost are identified. In this phase, the focus is on global ship characteristics at a low level of detail, and the number of concepts that is investigated, generally is large.
2. <u>Concept definition</u>. In this phase it is investigated whether the most promising solutions are likely to meet the requirements that have previously been defined. The focus is on de-risking the solution by incorporating a significantly higher level of

detail, both of the concepts and of the performance assessments. The number of concepts that is investigated, is considerably smaller.

The concept exploration and concept definition phase, which together form the early design stage, fit into the systems engineering approach. System engineering is a proven design approach that is commonly followed within naval ship design (Brouwer, 2008). A key element in systems engineering is the V-diagram, that describes the relationships between missions, at a high level of abstractness, down to the solution, which has a specific and physical nature. Various versions of the V-diagram exist. This paper uses the V-diagram as defined by (Duchateau, 2016), presented in Figure 1.

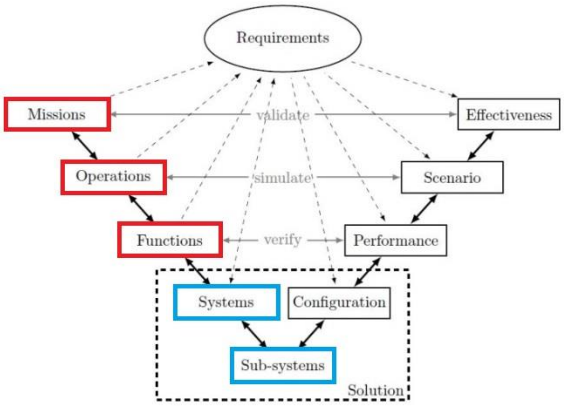


Figure 1: Systems engineering V-diagram for naval ship design, adapted from (Duchateau, 2016)

The overall purpose of a naval ship is described in the mission statement, at an abstract and generic level. Subsequently, the mission statement is made more specific by defining a concept of operations and functions. The mission, operations, and functions are input for the technical requirements of the ship. These requirements are used as input for designing systems and subsystems, which form the solution, i.e. the actual ship. If a solution has been developed, the quality of the solution can be evaluated at various levels by verification, simulation, and validation. Following the definitions of (Pedersen et al., 2000), this paper uses the term verification for internal consistency, and validation for product justification. In other words: verification considers: “Have we designed the ship right?” and validation considers: “Have we designed the right ship?”.

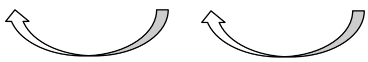
The V-diagram has a strong relation to the various steps in the design process. Defining high-level mission requirements, which is done during concept exploration, has a strong relation to the top left, more abstract blocks of the V-diagram, denoted in red. This effort is known as requirements elucidation, and is discussed in more detail by (Andrews, 2011). For defining appropriate requirements, the validation step is essential. As indicated by the V-diagram, validation can only be carried out if a solution is realized. However, due to limited design data and time, and the large number of potentially interesting solutions, developing detailed solutions is unrealistic at this stage. Instead, solutions from a generic perspective at a low – but not too low – level of detail are needed. These solutions need to elucidate overall performance and trends, and should support explorative studies. The purpose these studies is to understand which trends and trade-offs exists, and especially why these exist, in order to be able to define a set of operationally relevant, technically feasible, and affordable requirements. In other words: the solutions that are generated in concept exploration support defining the requirements, rather than that they serve as actual starting points for detailed engineering. Probabilistic methods can support these efforts. From a vulnerability perspective, typical questions to ask at this stage are “Does an all-electric powering concept increase the survival probability compared to a conventional concept with separate mechanical propulsion?” or “How many engines and generators are needed to ensure robust power generation, given any hit of any size at any location?”.

For the concept definition stage, there is a shift in design focus and types of questions that are asked. This stage is more aimed at the bottom left blocks of the V-diagram, denoted in blue. This stage has a more specific nature, focusing on actual engineering solutions, i.e. systems and sub-systems. A solution is still required to consider the whole V-diagram, but at this stage the solution and validation become more detailed. The focus is on de-risking the solutions that have been explored during concept exploration. To that end, the overall performance that was assessed in concept exploration is now again considered in more detail. In addition to that, the local performance of individual systems and potential bottlenecks are identified. Less solutions are considered, but at a higher level of detail. Where probabilistic methods were suited for concept exploration, concept definition may benefit from deterministic methods that can identify bottlenecks or other local design aspects that need to be further addressed. Contrary to the solutions of concept exploration, which were rather explorative, the solutions of concept definition can be used as an actual starting point for further design and acquisition efforts. From a vulnerability perspective, typical questions asked at this stage are “Does an additional cross-connection between two load centers reduce the vulnerability?” or “Does relocating a switchboard reduce the consequences of a specific hit scenario?”

Concept exploration and concept definition are both part of early stage design. The set of requirements that results from this stage is worked out further during detailed design and engineering, eventually leading to a single solution that is ready for production. Both concept exploration and concept definition again consider the whole V-diagram, but now the focus is on checking and confirming performances. Again, the earlier design stages are revisited. If requirements are not met, they are usually solved at local level, without costly modifications that affect the overall design. The main design activities and level of detail of all design stages are summarized in **Error! Reference source not found.**.

Table 1: Main design activities and area of focus for various design stages. Each design stage has its specific areas of focus. In addition to that, each design stage also revisits the area of focus from earlier design stages.

Design stage	**Concept exploration**	**Concept definition**	**Detailed design & Engineering**
Main activity	Exploring	De-risking	Detailing, checking, confirming
Area of focus	Overall performance and trends	Local perform-ance and bottlenecks	Detailed plans and performance analyses



Revisiting

2.2. Nature of distributed systems models

In order to design a distributed system, there needs to be at least a basic approach for modelling these systems. Only by modelling them, their vulnerability and other relevant characteristics can be evaluated. Two ways for describing distributed systems can be distinguished: a system perspective and a ship perspective. Both have been applied in joint TU Delft and DMO research efforts. Both perspectives consider different components of distribution systems, and how they are connected. The system perspective does this from an operationally oriented perspective, while the ship perspective focusses more on physical aspects and layout. Hence, the perspectives together provide logical, operational, and physical descriptions of distributed systems, which are all needed for a comprehensive design effort of distributed systems (Brefort et al., 2018). The system perspective and ship perspective are discussed now in more detail.

2.2.1. System perspective

The system perspective focusses on the marine engineering aspects of distributed systems design, such as capacity, flow, and (thermo)dynamics aspects. In order to support this perspective, a description of the logical connections between various components of the distributed systems is needed. This is described by means of a topology. The word ‘topology’ is used in various contexts. Its definition is: “the way in which constituent parts are interrelated or arranged” (Oxford University Press, 2019). Within a distributed systems context, a topology is usually described as a mathematical network with nodes and edges (de Vos and Stapersma, 2018). The nodes represent different components in the network, such as generators, switchboards, and chilled water plants. Edges between these nodes represent a logical relationship between the respective system components. For example, if a generator supplies electrical power to a switchboard, there is an edge between the nodes for that generator and switchboard. The nodes and edges can be categorized according to their functions. There are different types of nodes: suppliers and consumers of a commodity on the one hand, and hubs on the other hand. The hubs perform the distribution function. Hubs are not necessarily associated with one compartment or location in the ship. For example, a main pipeline has the function of a hub, but is runs through multiple compartments (see Section 3.2.3 of (de Vos, 2018) for the authors’ definition of hubs). Similarly, there are different types of edges, corresponding to the commodity that flows through them. For example, an edge between a generator and a switchboard represents transport of electrical power, while an edge between a chilled water plant and a weapon system represents transport of liquids, i.e. chilled water. An example of a topology for a notional naval ship is presented in Figure 2**.** Note that this topology contains multiple types of distributed systems, such as 440V power, 690V power, chilled water, and data. These different types of distributed systems are interdependent, because several components belong to multiple types. For example, a chilled water plant is a consumer of 440V power, but a supplier of chilled water. Due to this interdependency, it is infeasible to design the different types of distributed systems separately, and combine them afterwards. Hence, the topologies in this paper all contain multiple types of distributed systems – be it with a limited number of components due to the intended early design stages.

Topologies are particularly useful for addressing operationally oriented design aspects, such as load balancing and selecting the appropriate number and capacities of various components. This type of operationally oriented design aspects involves specialist knowledge of marine engineering related topics, such as thermodynamics and heat transfer. This marine engineering perspective is a key aspect of the system perspective. A topology may also contain information on physical aspects, for example on zoning, the size and location of components, or the location of routings. However, due to the operationally oriented types of assessments that topologies are used for, the primary focus remains with the logical relations and visualization of relative positions in the ship is of minor importance.

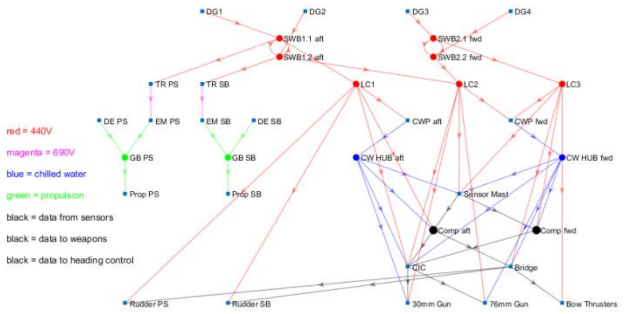


Figure 2: Example of a simplified topology of a notional naval ship, as published in (de Vos et al., 2018). Note the resemblance with system block diagrams or single line diagrams.

System topologies can be defined either by hand or by automatic generation. The former is applicable for few nodes and edges or for few different topologies, while the latter applies to many nodes and edges or many different solutions. The latter has been investigated by the authors. This encompasses an automatic topology generation method with an optimization algorithm for obtaining topologies, for example by optimizing for low system vulnerability and low system 'claim', i.e. low weight, space, and cost (de Vos and Stapersma, 2018). A pseudo-result of such an assessment is provided in Figure 3, where a trade-off between vulnerability and system claim is highlighted, and an example of a rudimentary design solution is presented.

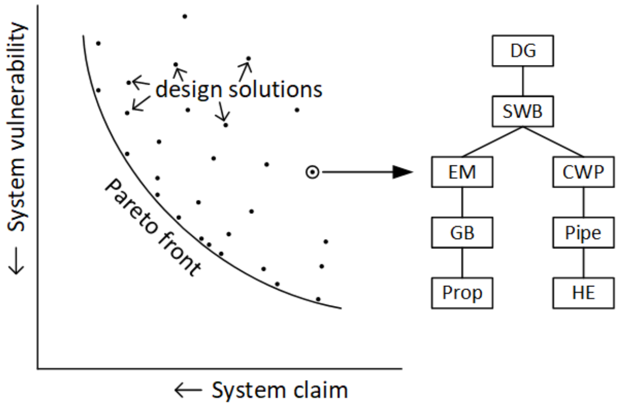


Figure 3: Example of automatic topology generation, including a trade-off and an example of a rudimentary design solution, as published in (de Vos and Stapersma, 2018).

Section 2.4 of (de Vos, 2018) describes a design procedure for the integrated design of distributed systems in naval ships in fourteen steps. The first steps, that lead up to the possibility of defining / generating a system topology, are given below in an adjusted version of the procedure that was tailor-made for this article:

1. Define vital, mission-related components, i.e. end-users.
2. Define support components (suppliers) and distributed systems that the end-users require to function.
3. Define hubs in each distributed system.
4. Generate or define by hand topologies that provide the logical relations in the distributed systems, i.e. the connections between the components.
5. Assess performance of topologies (design solutions for interdependent distributed systems) w.r.t. different design objectives including vulnerability.

Though the first five steps consider the possibility to generate topologies, which could intuitively be associated with the systems perspective, they are independent of the marine engineering fundamentals that are a key factor of the systems perspective. Similarly, generating a topology is independent of weight and volume fundamentals that are a key factor of the ship perspective. As such, the four five steps precede any assessment and / or further development of the ship / system design. In other words: they form a starting point that is independent of the perspectives that are applied later in the design process. The entire procedure, including the first five steps above, will be discussed in Section **Error! Reference source not found.**.1. The next steps in the procedure will be treated in Section 2.2.2.

2.2.2. Ship perspective

Once a topology is available, distributed systems can also be modelled from a ship perspective. This perspective focusses on physical integration of the distributed systems within the ship. In essence, the ship perspective builds upon the same information of the distributed systems that is included in the topology. It may contain information on logical relationships, load balancing, sizing, and physical placement of components and routings. However, where the topology is primarily suited for addressing operationally oriented design aspects (such as energy balances), the ship perspective is relevant for physical integration (such as mass and volume balances). For example, the ship perspective for distributed systems is used for determining in which compartments vital system components and routings can best be located, and how these components can be integrated into the ship without violating other design aspects, such as logistics or stability. In other words, the focus for the ship perspective is with physical relations. A key aspect for modelling this are routings of system connections. This is highly important, as a good topology does not guarantee a good systems design. If vital and/or redundant connections in a topology are routed through the same compartments, the topology remains vulnerable, even if the topology itself is feasible. The routing is based on the systems topology, which is known from the first four or five steps of the design procedure as introduced in the previous section. Whether the fifth step is part of the design procedure depends on the choice to automatically generate many topologies (which then requires a first selection methodology) versus defining topologies by hand. The nodes and edges in the topology are now assigned to specific parts of the ship, usually at compartment level. The design procedure of (de Vos, 2018) thus continues with:

6. Define the location of nodes in the ship.
7. Generate or define by hand the routing of edges through the ship compartments.
8. Assess performance of routed design solutions of interdependent distributed systems with respect to. different design objectives including vulnerability.

An example of a system design modelled with the routing approach is provided in Figure 4. This figure also provides the topology that forms the basis of the routings.

Similar to system topologies, routings can be defined either by hand or by automatic generation. Again, the latter has been investigated by the authors. This includes a k-shortest path algorithm combined with a genetic algorithm to search for shortest and least vulnerable routing combinations (Duchateau et al., 2018). Possible routings are identified using a k-shortest path algorithm (Yen, 1971). This algorithm not only identifies the shortest possible path for each connection, but also the k-1 other shortest paths in increasing order of path length (where k is an integer number to be chosen by the user). Most importantly, this algorithm allows for exploring slight detours to the absolute shortest path, possibly identifying routings that are longer, but less vulnerable.

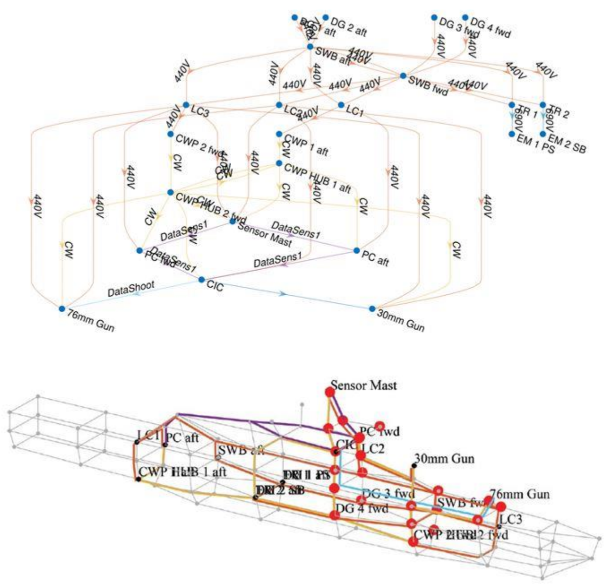


Figure 4: Example of a system design of a notional Oceangoing Patrol Vessel, including a topology (top) as well as the routing (bottom), as published in (Duchateau et al., 2018).

3. FRAMEWORK FOR VULNER-ABILITY REDUCTION

3.1. Framework layout

In Section 2 the various stages of naval ship design have been explained, from a perspective of vulnerability. Section 2 has also described the need for two complimentary perspectives on modelling distributed systems. To enable effective and efficient vulnerability assessments throughout the design process, it is highly important that the assessment methods match with the types of questions asked and level of detail available at the various design stages. To that end, a framework has been developed that matches various methods for vulnerability assessments to the various ship design stages and distributed systems perspectives. The framework is presented in Table 2.

For concept exploration and concept definition, the framework contains methods that have been developed by joint TU Delft and DMO research efforts. The development of these methods has resulted from the observation that many existing methods are mostly suited for later, more detailed design stages. The framework also contains examples of these methods. The methods included in this framework are explained in more detail in the subsequent paragraphs of this section. It must be noted, however, that the methods included in the framework are not exclusive. The purpose of the framework is to link the right vulnerability methods to the right design stage and distributed system perspective. As such, the framework may also be used for including other vulnerability methods, or even for other naval architecture disciplines.

Table 2: Framework for matching vulnerability methods and design stages

		Design stage		
		Concept exploration	Concept definition	Detailed design & Engineering
Perspective	System (topology)	Max-flow-between-hubs	Hurt state percolation / topology	GES, MVFP models
	Ship (routings)	Markov	Hurt state percolation / routings	RESIST, SURVIVE, SURMA
		Tools developed by joint TU Delft / DMO research efforts, described in this paper		Examples of other tools

3.2. Max-flow-between-hubs

The max-flow-between-hubs approach aims to improve reconfigurability of system designs. This approach requires only a topology. No routing or location information is required. System topologies are thus analogous to e.g. system block diagrams or single line diagrams that are used in practice. The idea behind focusing on system topology first, before addressing the actual location of components and connections in the ship, is to filter the design space from the perspective of operational performance of the systems; i.e. an energy flow perspective. It makes little sense to place and route systems that are deemed infeasible or inoperable as such a system will never be realized. Theoretically, the actual lay-out of connections (length, diameter, nr. of bends, etc.) has an effect on operational performance of the systems, but in ship systems this effect is typically very small and can be neglected. This is the reason the idea of focusing on system topology first holds and why max-flow-between-hubs is particularly useful for concept exploration.

The mathematical definition and explanation of max-flow-between-hubs are given in (de Vos and Stapersma, 2018). Note that this vulnerability metric is fundamentally different from probabilistic methods to assess vulnerability. The metric is designed to focus on a specific aspect of vulnerability which is considered the most elusive aspect from a topological point-of-view. As such, max-flow-between-hubs is more like a designers' rule-of-thumb; it does not require the "simulation" of the ship / system being hit and therefore does not require as much computational capacity than the other vulnerability assessment methods discussed in this paper. In (de Vos, 2018) three robustness measures were identified that are used in practice to decrease the vulnerability of systems from an operationally oriented perspective:

1 Increasing redundancy by duplicating functionally similar components, either as full back-up or with performance degradation, or by different type of components (similar function, different working principle) such as accumulators.
2 Introducing separate "islands" in the system topology (i.e. zoning). The islands are able to operate as stand-alone systems in critical operations (islands should then also be physically separated; i.e. located in different zones in the ship separated by blast-resistant and watertight bulkheads).
3 Increasing reconfigurability of the distribution systems by increasing the number of paths between suppliers and users. This is achieved by additional supply lines to vital users and by interconnecting the afore-mentioned islands by cross-overs.

Max-flow-between-hubs focusses on the last measure: reconfigurability of distributed systems as arguably the most important and elusive aspect of system vulnerability. It is assumed that reconfigurability of distributed systems is improved by increasing the interconnectivity between the

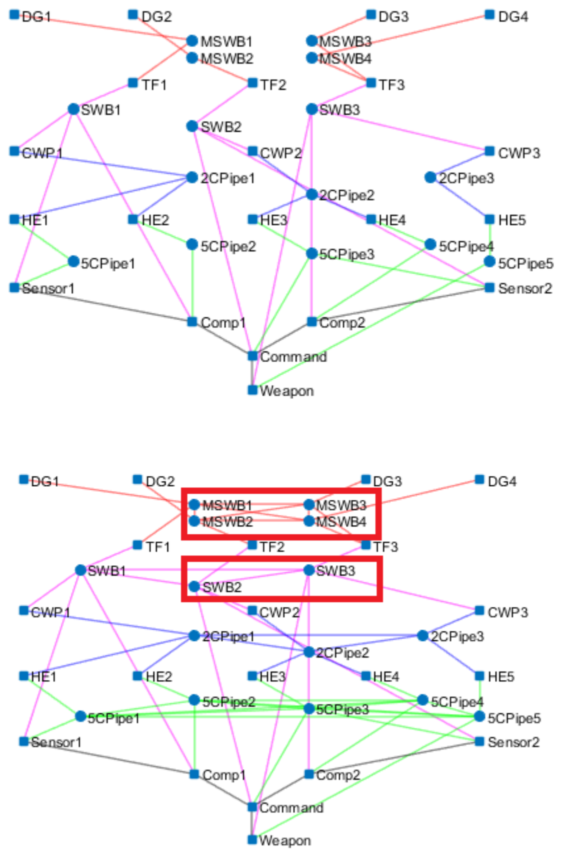


Figure 5: Two possible system design solutions; the bottom solution is preferred by max-flow-between-hubs due to additional switchboard connectivity (shown in red boxes). Pictures source: (de Vos and Stapersma, 2018)

(most) central distribution points of the systems; i.e. the hubs. By improving the maximum flow between hubs specific connection patterns, like ring distributions, are preferred in conceptual system design solutions as depicted in Figure 5.

3.3. Hurt state percolation

With this approach, described in (Duchateau et al., 2018), the consequences of a hit are determined by systematically removing parts of the system design, which represents damage cases. For each of these individual damage cases it is checked which system components are still connected, and whether these connections can provide the required resources to (vital) users. A hit is defined as an occasion where a compartment, bounded by bulkheads and decks, is disabled. A hit in one compartment also affects the adjacent compartment in transverse direction (i.e. port side or starboard), if applicable. It is user-defined whether the compartments above, below, before, and aft of the hit compartment are affected as well. For small hits this is not the case, while for large hits it is included. The damage of such a hit is assumed not to propagate through blast-resistant bulkheads. An example of a hit scenario with one small hit is provided in Figure. It comprises both the port side and starboard compartment, but the damage does not propagate through decks of transverse bulkheads. All compartments have equal hit probability, so the method does not account for signatures such as hot spots at this stage. Nonetheless, the method can account for this, if desired. The deterministic hit simulating approach makes the method suitable for the concept definition stage. The approach can be used both on a system topology or a fully routed topology throughout the ship. The difference between these two is the hit-state information. If a topology is used as the system design, nodes or edges will be hit and removed accordingly. If a routed topology is used, one or more compartments will be hit, and thereby the associated nodes and edges of the topology. A depth-first tree search algorithm on the damaged system topology forms the basis of this approach. Each node in the network is checked for their individual supply requirements. The results give insight into where bottlenecks in the system design occur once hit.

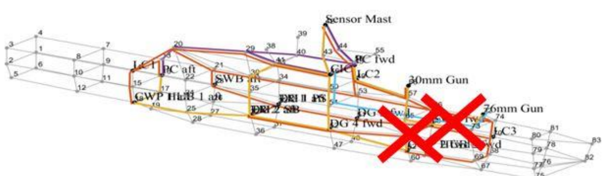


Figure 6: Example of a deterministic hit scenario with one hit covering two compartments, as used in the hurt state percolation method.

For single or dual hit cases it is possible to simulate all possible hit cases within the order of seconds for a concept comparable to the one presented in Figure 4. For more than two hits a combinatorial explosion of possible hit location combinations occurs. Assessing such scenarios requires a finite number of random cases. The vital users that are assessed can also be grouped into capabilities, such as Anti-Air Warfare (AAW) or Anti-Surface Warfare (ASuW). This comes at the cost of adding more simulations, as multiple combinations of systems may exist for a single function. The hurt state percolation approach does not take into account remaining network capacity. Hence, a connected network in this method does not necessarily imply a working network in reality – it is a necessary but not sufficient condition.

3.4. Markov

This approach provides the likelihood that certain levels of residual capability can be met after one or more hits (Habben Jansen et al., 2018). A discrete Markov chain forms the basis of this approach. The approach uses a system topology that is routed throughout the ship and is tested as such, though it can also be applied on a topology without routings. The availability of individual edges in the topology is expressed in a state vector. The probability to transfer to another state after one or more hits results from the physical location of the routings, and is expressed in the transition matrix. These two elements form the basis of the Markov chain. The probability for each state after any number of hits can be calculated by matrix-vector multiplications. In the Markov method, a hit is assumed to encompass one single compartment. Adjacent compartments in all three dimensions are assumed to be unaffected. Scenarios up to 8 hits are calculated. In other words: an increasing damage level is represented by numerous small hits, rather than one hit with a large damage extent. This way of modelling hits is primarily meant as a representation of increasing damage level, and is not necessarily related to the probability that such scenarios will actually occur. Yet, due to the increasing attention for asymmetric warfare (Wilson, 2010), the way in which the hits are modelled also relates to actual potential damage scenarios. Subsequently, the probability for individual states is converted to the probability for different levels of residual capability. By definition this approach has a probabilistic nature. Hence, all damage scenarios are considered together, all at once. Figure gives a notional example of a result that can be obtained with this approach. Though the figure in this example is qualitative, a real-world application of this method provides quantitative probabilities for discrete numbers of hits. The levels of required residual capability can be specified according to the requirements set by the designer or other decision-makers.

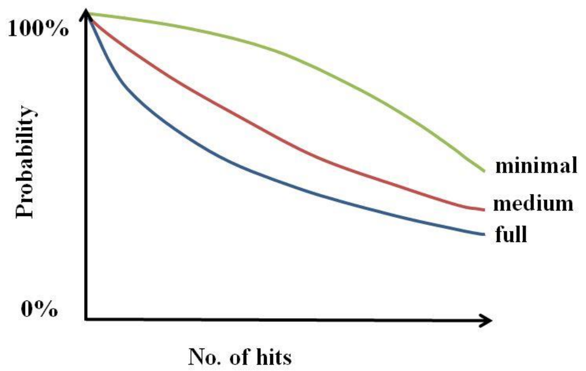


Figure 7: Pseudo-result of a vulnerability assessment using the Markov approach for various levels of residual capability. The more residual capability is required, the lower the probability for compliance is.

Due to the probabilistic nature, a key aspect of this approach is that it gives a global estimation of vulnerability. This fits well with the assessments carried out in the concept exploration stage. It does not specify the consequences of individual hit scenarios, such as a worst-case scenario. These are usually addressed in later stages. The approach can easily handle large numbers of hits. However, for large number of edges a combinatorial explosion occurs, which limits the usability of this method in such cases.

3.5. Other methods

The methods that are described in this paper have been developed for concept exploration and concept definition. They can theoretically also be applied in more detailed design and engineering stages, though this requires additional efforts to keep the computational effort to a manageable level. However, they are not meant to be high fidelity methods for later design stages. At these stages, vulnerability reduction may encompass detailed analyses of the structural, logistical, and operational consequences of blast, fragmentation, and fire spread, amongst others. This requires more detailed modelling and simulation approaches, such as CAD-models and analyses of structures, fluids and gasses, potentially using FEM or CFD methods. Examples of vulnerability tools that support this are RESIST (TNO, 2018), SURVIVE (Schofield, 2009), or SURMA (Surma Ltd., 2018). The results of such tools can be used for checking and confirmation, usually at a stage where significant modifications to the design are no longer realizable or desired. In addition to that, they can be used for obtaining input information for early stage methods, such as damage extent scenarios for different weapons. These tools assess vulnerability from the ship perspective. For the more operationally oriented systems perspective, an example of a more detailed tool is GES (TNO, 2013) or Mean Value First Principles models using a lumped-parameters approach as often used by marine engineering researchers of TU Delft, see e.g. (Grimmelius and Stapersma, 2000) and (Geertsma et al., 2017). GES can be used to set up load balances for various operational conditions of systems, using the Bond graph method. The tool includes a capacity analysis. In addition to the concept exploration and concept definition tools, that checked whether a network is connected, GES uses the capacity analysis to check whether a network is working after a certain damage scenario. Similar to the ship-oriented high fidelity tools, this is usually done at a stage that is used for checking and confirmation, rather than for making major early stage design decisions.

4. INTEGRATION

4.1. Integration in design process

The methods for concept exploration and concept definition that have been explained in Section 3 have been developed as individual, self-contained methods. Yet, they are meant to be integrated in the design process as a whole. Figure 8 presents the authors' vision on this integration. Distributed systems design starts with defining a topology (step 1-4, see Section 2.2.1), as the topology forms the common basis of both the systems perspective and the ship perspective. Note, however, that the amount of topologies, or the level of detail of the topology is not necessarily prescribed. As this step takes place in concept definition, the amount of topologies may be large, and the level of detail may be small. Before the topology is used in the ship and system perspectives, a performance assessment needs to be carried out if the number of topologies considered is indeed large (step 5). This paper considers vulnerability, but this can also encompass other measures of performance.

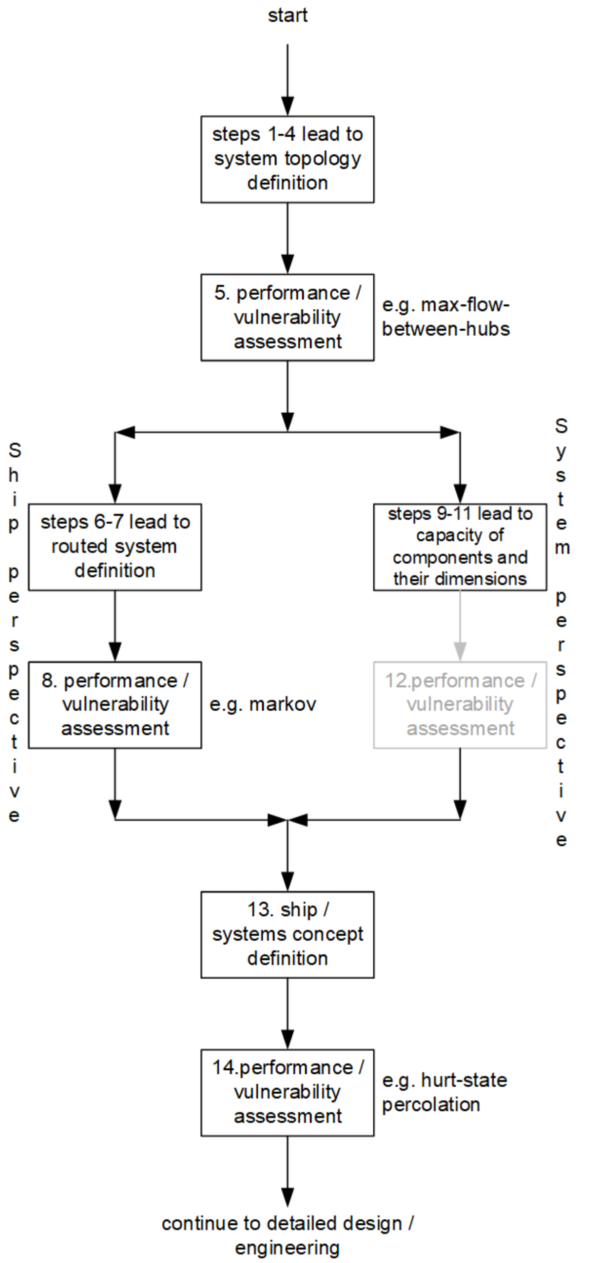


Figure 8: Proposed integration of methods in ship and systems design process

The vulnerability assessment of the topology can for example – but not necessarily – be carried out with the max-flow-between-hubs method. After the topology has been generated, two parallel tracks are envisioned. The first track is the ship perspective, and encompasses the routing of the topology, and the associated vulnerability assessment, e.g. Markov (steps 6-8, see Section 2.2.2). All steps up to step 8 can be carried out using methods described in this paper. It has however already been noted that a connected network is not necessarily a working network. To ensure sufficient power supply within the topology, additional steps are needed, that considers the operationally oriented aspect of distributed systems design:

9. Determine the amount of power (effort and flow) the users need in the operational conditions of interest.
10. Determine the individual capacity of the suppliers in order to balance total power supply and demand.
11. Determine the principle dimensions and weights of all components.

Though steps 9-11 are allocated to the system perspective, they are not strictly isolated from the ship perspective. Determining the dimensions and weights of components, for example, needs to be carried out in close cooperation with the more physically oriented ship perspective. However, the two tracks have deliberately been separated because of the fundamentally different goals of the tracks. Similar to the ship perspective, the system perspective needs a vulnerability assessment (step 12). This assessment needs to include capacity and load balancing. The methods described in this paper do not yet support this. Section 7 gives several brief recommendations for this gap. After step 12 the ship perspective and system perspective are brought together to ensure adequate integration of these perspectives (step 13: concept definition). At this stage the concepts (one or multiple) have grown to a considerable level of detail, and a more detailed vulnerability assessment is required (step 14), such as hurt state percolation.

4.2. Computational integration

The methods described in Section 3 are not only envisioned to be integrated in the design process in general, but also on a more specific, computational level. A basic form of compatibility between the methods can support this computational integration. Though the methods are currently still self-contained, it can be observed that all three methods rely on the same type of information: a system topology with nodes and edges, either or not including a physical routing. This common feature may offer opportunities for integration of these methods. An important consideration for method integration is the size of the system model, i.e. the number of nodes and edges in the topology or routing. The max-flow-between-hubs method requires a certain minimum number of nodes (especially hubs) to provide a meaningful result, and has been applied for a test case with 36 nodes (de Vos and Stapersma, 2018). For the Markov method the number of edges is determinative for the computational effort. Test cases with 12 edges and 12 nodes have been carried out (Habben Jansen et al., 2018). In its current status, the method allows up to 13 edges. For the hurt state percolation the number of nodes and edges is less relevant. A test case considers 23 nodes (Duchateau et al., 2018), but the method has been applied with up to 100 nodes, such as presented in Figure 9. The computational effort is determined by the number of hits, which is currently limited to two. Larger numbers of hits require a random selection of representative hits.

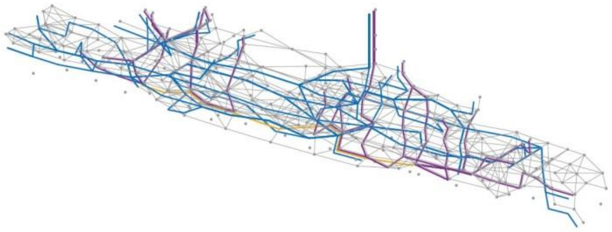


Figure 9: Example of a scaled-up test case of the hurt state percolation method with routings

Table 3: Overview of main characteristics of the vulnerability methods

Method	Typical no. of nodes/edges	Design stage	System model type
Markov	< 13	Concept exploration	Routing
Max-flow-between-hubs	> 36	Concept exploration	Topology
Hurt state percolation	20-100	Concept definition	Topology or routing

The typical number of nodes and edges for these methods are summarized in Table 3, along with the earlier discussed design stages and system modelling types. In general it can be stated that the earlier an assessment is carried out, the less information it should consider. The vulnerability methods of this paper follow this statement. Markov and max-flow-between-hubs, which are meant for concept exploration, require indeed less nodes and edges than hurt state percolation, which is meant for concept definition. However, it is also important to consider the two types of modelling systems. Though the system perspective (topology) and the ship perspective (routings) on distributed systems may contain the same type of information, as discussed in Paragraphs 2.2.1 and 2.2.2, a clear sequential approach can be identified: there needs to be a topology before it can be routed through the ship. Hence, in the ideal situation, the topology that has been assessed with max-flow-between-hubs can be used to make the routing that can be assessed with Markov. However, in their current status, the methods do not support the ideal situation because of a difference in their required number of nodes and edges. For a full integration of assessing both the topology and the topology routed through the ship in concept exploration, the number of nodes and edges for Markov needs to be increased, or the number of nodes for max-flow-between-hubs should be decreased. For concept definition this issue is less relevant, as hurt state percolation is not limited by the number of nodes and edges, but by the number of hits.

The discrepancy in required number of nodes and edges for Markov and max-flow-between-hubs may be addressed by considering the way in which the codes and algorithms have been written. This has not yet extensively been addressed, as there was little need to do so when the methods were developed as to be self-contained. However, several computational improvements may support further integration of the Markov and max-flow-between-hubs method. However, computational integration is not a goal in itself, and needs to be carried out with the design process context of Figure 8 in mind.

5. REFLECTION

This paper has advocated for the need to allocate the right vulnerability methods to the right design stages, and has provided several examples of methods and challenges for realizing this. Though these methods are meant to support practical naval ship design efforts, they also relate to more fundamental naval ship design theory. This mainly involves the design process, i.e. the order in which various tasks are carried out. As described in Section 4.1, the common procedure is to first generate a concept, and then analyze the performance of that concept. In this paper this process is described for vulnerability reduction, but this procedure also holds for other naval architecture disciplines. An important restriction of this procedure is that the designer can only analyze concepts that he or she has thought of upfront – concepts that have not been defined, can inherently not be analyzed. This approach may therefore constrain concept exploration efforts, as the explorative nature of this stage is associated with generating (potentially many) concepts. Hence, an analysis method may therefore not inherently be suited as a design aid. Though pre-defining concepts is inevitable for obtaining design knowledge, it may be interesting to investigate whether *specific* concepts can lead to *generic* knowledge, either in vulnerability reduction or other naval architecture disciplines.

The same argumentation holds for the relation between requirements and concepts. Concept exploration is meant to find feasible requirements. These requirements are eventually used to find a feasible solution. Yet, in order to find feasible requirements, concepts are generated, which in fact are solutions itself. In other words: finding a solution needs requirements, while finding requirements needs solutions. Though the starting point does in fact not matter that much, as this is an iterative process, the question remains for the designer of how to undo himself or herself from potential restrictions of pre-conceived ideas on the design problem. Again, *generic* methods may offer solutions. They are widely applicable, re-usable, and hardly limited by prior assumptions, supporting fast requirement setting, design, and analysis.

6. CONCLUSIONS

A clear understanding of the design process and the associated design methods is of vital importance for efficient and effective ship design. This paper has presented a framework to structure these aspects from a perspective of vulnerability reduction of on-board distributed systems. Examples of generic, low fidelity methods that support concept exploration are provided, as well as examples of more detailed and deterministic methods for concept definition. These methods, which are the result of joint TU Delft and DMO research, were originally developed as self-contained methods, but are now being brought together to ensure adequate knowledge capturing and modelling throughout early stage naval ship design. The tools vary in their perspective on system modelling (topology or routings) and the number of nodes and edges that are considered.

It is acknowledged that some gaps remain, especially in terms of a capacity assessment. As such, additional efforts are needed for fully integrating the methods. Yet, also in their current status, the methods provide a meaningful contribution. The more detail added in a vulnerability assessment, the more likely it is that infeasibilities are found. However, if the fundamental set-up of a topology or routing is infeasible for a certain design problem, there is no need to perform such detailed assessments. Hence, a rough, early indication of the feasibility of a topology or routings remains necessary as well. The methods in this paper provide these simplified assessments. As such, the methods discussed in this paper are helpful, but not sufficient.

The framework in this paper can help in applying the right method or tool at the right design stage. The framework has been developed with a systems engineering perspective in mind. As such, it matches with existing naval ship design procedures. At the same time it is acknowledged that existing ship design procedures have the risk of being limited by past design experience or pre-conceived ideas. Though the framework does not directly provide a solution to this challenge, it helps the designer in evaluating the naval ship system design process and the suitability of his or her design methods. This is not limited to the field of vulnerability reduction. As such, the applicability of this framework goes beyond its form as presented in this paper.

7. RECOMMENDATIONS

Several recommendations for further development of the framework and its individual methods can be made. Some are of a very practical nature. These are discussed first. The first recommendation considers the computational integration of the methods. As explained in Section 4.2, the vulnerability methods are not yet entirely compatible from a computational perspective, which mainly manifests itself in the number of nodes and edges required for the methods. If this issue is resolved, the transitions between the methods become easier and more smooth, enabling faster concept design. Secondly, it is recommended that the methods presented in this paper are tested for existing ships in order to provide verification for the methods. The third re-commendation considers the way in which the hurt state percolation and Markov methods define vulnerability. Currently this has a binary nature, a system or capability is either on or off, based on whether the associated connections in the topology are damaged or not. However, as mentioned in Section 3.3, a connected network does not imply a working network. Previous research has shown that this limitation may result in too optimistic vulnerability estimations (Goodrum et al., 2018). As presented in Figure 8, this issue is not yet addressed by a method that is specifically aimed at concept exploration or concept definition. Including a capacity or flow analysis may overcome this limitation. However, it comes at the cost of increased complexity. It can either be done at a basic level by comparing the sum of supply and demand of the sources and sinks, or at a more detailed level by a network flow analysis that checks whether the associated edges are still available, and have sufficient capacity in terms of effort and flow.

It should be kept in mind, that all efforts to improve the methods do not become too detailed for the design stage for which these methods are meant. For example, an analysis of transient behavior of systems that are hit is for now considered “a bridge too far” in concept exploration or definition.

The final recommendation is of a more fundamental nature, and considers a re-evaluation of the naval ship design process in general. This framework has shown that existing methods may be incompatible with the standard design-analyze procedure. This procedure, in turn, may limit an explorative study of concepts that have yet to be defined. Hence, a need for new design methods, or even a new perspective on the ship design process arises. The subtle balance between generality and specificity should be a major key aspect in these future efforts.

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REFERENCES

Andrews, D.J., 2011. Marine requirements elucidation and the nature of preliminary ship design. Int. J. Marit. Eng. 153.

Bolton, M., Waterworth, S., McClurg, R., 2018. Enabling, Equipping and Empowering the Support Enteprise through Digital Transformation, in: Proceedings of the 14th International Naval Engineering Conference. Glasgow, pp. 607–613.

Boulougouris, E., Papanikolaou, A., 2013. Risk-based design of naval combatants. Ocean Eng. 65, 49–61.

Brefort, D.C., Shields, C.P.F., Habben Jansen, A.C., Duchateau, E.A.E., Pawling, R.J., Droste, K., Jaspers, T., Sypniewski, M., Goodrum, C., Parsons, M., Yasin Kara, M., Roth, M., Singer, D.J., Andrews, D.J., Hopman, J.J., Brown, A., Kana, A.A., 2018. An Architectural Framework for Distributed Naval Ship Systems. Ocean Eng. 147, 375–385.

Brouwer, R., 2008. A Framework for Systems Engineering in Ship Design from a NATO Specialist Team Perspective, in: Engineering the Total Ship Symposium. American Society of Naval Engineers, Falls Church.

de Vos, P., 2018. On early-stage design of vital distribution systems on board ships. Delft University of Technology.

de Vos, P., Stapersma, D., 2018. Automatic topology generation for early design of on-board energy distribution systems. Ocean Eng. 170, 55–73. https://doi.org/10.1016/j.oceaneng.2018.09.023

de Vos, P., Stapersma, D., Duchateau, E.A.E., van Oers, B.J., 2018. Design Space Exploration for on-board Energy Distribution Systems: A New Case Study, in: Proceedings of the 17th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT ’18). Pavone, pp. 463–481.

Doerry, N., 2015. Naval Power Systems: Integrated power systems for the continuity of the electrical power supply. IEEE Electrif. Mag. 12–21. https://doi.org/10.1109/MELE.2015.2413434

Duchateau, E.A.E., 2016. Interactive evolutionary concept exploration in preliminary ship design. Delft University of Technology, Delft.

Duchateau, E.A.E., de Vos, P., van Leeuwen, S., 2018. Early stage routing of distributed ship service systems for vulnerability reduction, in: 13th International Marine Design Conference. Helsinki.

Geertsma, R.D., Negenborn, R.R., Visser, K., Hopman, J.J., 2017. Pitch control for ships with mechanical and hybrid propulsion: modelling, validation and performance quantification. Appl. Energy 206, 1609–1631. https://doi.org/10.1016/j.apenergy.2017.09.103

Goodrum, C.J., Shields, C.P.F., Singer, D.J., 2018. Understanding cascading failures through a vulnerability analysis of interdependent ship-centric distributed systems using networks. Ocean Eng. 150, 36–47.

Grimmelius, H.T., Stapersma, D., 2000. Control optimisation and load prediction for marine diesel engines using a mean value first principle model, in: Proceedings of MS&TES. Newcastle upon Tyne.

Habben Jansen, A.C., Duchateau, E.A.E., Kana, A.A., 2018. Towards a novel design perspective for system vulnerability using a Markov chain, in: Proceedings of the 14th International Naval Engineering Conference. Glasgow.

Kossiakoff, A., Sweet, W.N., Seymour, S.J., Biember, S.M., 2011. Systems Engineering Principles and Practice, 2nd ed. Wiley, Hoboken, New Jersey.

Oxford University Press, 2019. topology [WWW Document]. Oxford English Dict. URL https://en.oxforddictionaries.com/definition/topology (accessed 1.18.19).

Pedersen, K., Emblemsvag, J., Bailey, R., Allen, J., Mistree, F., 2000. Validating design methods & research: the validation square, in: Proceedings of DETC '00. Maryland.

Reese, R.M., Calvano, C.N., Hopkins, T.M., 1998. Operationally Oriented Vulnerabiliity Requirements in the Ship Design Process. Nav. Eng. J. 110, 19–34. https://doi.org/10.1111/j.1559-3584.1998.tb02383.x

Said, M.O., 1995. Theory and Practice of Total Ship Survivability for Ship Design. Nav. Eng. J. 107, 191–203. https://doi.org/10.1111/j.1559-3584.1995.tb03085.x

Schofield, J., 2009. SURVIVE and SURVIVE Lite - survivability assessment from concept to operational support, in: Proceedings of the American Society of Naval Engineers Day. Maryland.

Surma Ltd., 2018. SURMA survivability analysis [WWW Document]. URL http://survivability.fi/surma/demo/ (accessed 1.29.19).

TNO, 2018. RESIST Lite [WWW Document]. URL https://www.tno.nl/media/1644/resist_lite.pdf (accessed 11.26.18).

TNO, 2013. General Energy Systems.

van Oers, B.J., Takken, E., Duchateau, E.A.E., Zandstra, R., Cieraad, S., van den Broek - de Bruijn, W., Janssen, M., 2018. Warship Concept Exploration and Definition at The Netherlands Defence Materiel Organisation. Nav. Eng. J. 130, 61–82.

Wilson, B., 2010. Responding to Asymmetric Threats in the Maritime Domain: Diplomacy, Law and Naval Operations. Marit. Aff. J. Natl. Marit. Found. India 5, 68–85. https://doi.org/10.1080/09733150903429551

Yen, J.Y., 1971. Finding the K Shortest Loopless Paths in a Network. Manage. Sci. 17, 661–786. https://doi.org/10.1287/mnsc.17.11.712

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