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DOI

[10.1016/j.oceaneng.2019.106448](https://doi.org/10.1016/j.oceaneng.2019.106448)

Publication date

2019

Document Version

Accepted author manuscript

Published in

Ocean Engineering

Citation (APA)

Habben Jansen, A. C., Kana, A. A., & Hopman, J. J. (2019). A Markov-based vulnerability assessment for the design of on-board distributed systems in the concept phase. *Ocean Engineering*, 190, Article 106448. <https://doi.org/10.1016/j.oceaneng.2019.106448>

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A Markov-based vulnerability assessment for the design of on-board distributed systems in the concept phase

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Abstract

Naval ships are designed to operate in a hostile environment. As such, vulnerability is an important aspect that needs to be assessed during the design. With the increased interest in electrification and automation on board naval ships, the vulnerability of distributed systems has become a major topic of interest. However, assessing this is not trivial, especially during the concept phase, where the level of detail is limited, but consequences of design decisions are large. Many existing vulnerability methods assess the vulnerability of pre-defined concepts, and focus on systems rather than capabilities. To address this, a new method for assessing the vulnerability of distributed systems in the concept phase has been developed. This method not only evaluates the vulnerability of a pre-defined concept, but also provides direction for finding other, potentially better solutions. This is done from a capabilities perspective. The method helps ship designers and naval staff in setting vulnerability requirements, developing new concepts, and identifying trade-offs in capabilities. The method uses a discrete Markov chain and the

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eigenvalues of the associated transition matrix. A test case considering vulnerability of a notional Ocean-going Patrol Vessel (OPV) with two different powering concepts illustrates the method.

Keywords:

Naval ship vulnerability, Distributed systems, Concept ship design, Markov chain, Eigenvalues

1 **1. Introduction**

2 Naval ships are designed to operate in a hostile environment, which ex-
3 poses them to an ever-present risk of getting hit by weapon deployment of an
4 enemy. A hit may result in damage, such as failed structures, flooded com-
5 partments, impaired systems, or personal injuries. Consequently, the ship
6 and its crew may no longer be able to perform the intended operations. In
7 order to mitigate the risk of damage, survivability is a major design driver
8 during the design of the ship, as explained by e.g. Ball and Calvano (1994).
9 Various definitions of survivability exist. A commonly used definition pro-
10 vided by Said (1995), who defines survivability specifically for ships as “the
11 capability of a ship and its shipboard systems to avoid and withstand a
12 weapons effects environment without sustaining impairment of their ability
13 to accomplish designated missions”. Survivability consists of three major
14 components: susceptibility, vulnerability, and recoverability. Susceptibility
15 refers to the inability of a ship to avoid damage, while vulnerability refers to
16 the inability to withstand damage. Recoverability is defined by Said (1995)
17 as “the ability of a ship and its crew to prevent loss and restore mission

18 essential functions given a hit by one or more threat weapons”. These three
19 major elements are usually considered with an external man-made hostile
20 environment in mind. However, other circumstances can also impose a need
21 to consider survivability, such as accidental fires, collisions, damage resulting
22 from heavy seas, or cascading failures that result from increasingly complex
23 system design. Examples of non-hostile environments that have resulted in
24 damage include the collision of the KNM Helge Ingstad (BBC (2018)) and
25 repeated power failures on board Type 45 Destroyers (Elgot (2016)).

26 Considering these three major elements, vulnerability is in particular gov-
27 erned by the design of the ship. As such, it is the primary focus of many
28 research efforts. Susceptibility can also be addressed during the design, but
29 it is observed that in some cases hits can not be avoided, even if susceptibility
30 reduction measures have been taken (Schulte (1994)), (Reese et al. (1998)),
31 (Duchateau et al. (2018)). Recoverability is mainly governed by active on
32 board response, and is therefore addressed to a lesser extent in ship design
33 research. However, some examples of dedicated recoverability research exist,
34 such as the work of Piperakis and Andrews (2012) and Janssen et al. (2016).
35 The present paper focusses on vulnerability.

36 Various ship design areas can contribute to reducing the vulnerability
37 during the design of the ship. Reese et al. (1998) have identified structural
38 integrity, seakeeping, floodable length, damage stability, and system separa-
39 tion as primary topics of interest. Most of the measures that can be taken
40 with respect to these topics are aimed at obtaining an “intelligent layout”,
41 which is deemed the most effective protective measure by Brown (1991).
42 Traditionally, vulnerability has mainly been addressed from a weapons effect

43 perspective, with a focus on fire, blast, and fragmentation for above water
44 hits, and damage stability for underwater hits. Such topics continue to be
45 relevant for recent research (e.g. Boulougouris et al. (2017)). However, devel-
46 opments in the field of naval ship design impose a need for a stronger focus on
47 the vulnerability from a systems perspective, as automation and electrifica-
48 tion are design drivers of today’s naval ships (Brefort et al. (2018)), (Dougal
49 and Langland (2016)). This trend commenced in the 1980s and has since be-
50 come more distinct as a result of growing electrical demands for existing and
51 future sensors and weapon systems (Clayton et al. (2000); Doerry (2015)).

52 Doerry (2015) identifies several advantages of an Integrated Power System
53 (IPS), where the ship’s propulsion and the electrical system are combined in
54 one power system. These advantages include an improved support of high-
55 power mission systems, higher efficiencies of prime movers and propulsors,
56 and more flexibility in the general arrangement. In order to enable an IPS,
57 complex networks for distributing vital commodities such as electricity, fluids,
58 air, and data are indispensable. The systems that provide those commodities
59 are known as either distributed systems, a term used by e.g. Doerry (2006)
60 or distribution systems, a term used by e.g. de Vos and Stapersma (2018).
61 There is a slight and subtle difference between these terms. Distributed
62 systems are systems that are distributed throughout the ship, where distri-
63 bution systems are systems that distribute vital commodities. In practice,
64 these systems usually cover both characteristics, and the terms can be re-
65 garded interchangeable. This also applies to the present paper, which uses
66 the term distributed systems.

67 With the increasing interest in IPSs, the distributed systems networks

68 become more complex and interdependent. This makes them more opaque
69 and difficult to understand during the design. As a result, latent design
70 errors may occur. These may result in cascading failures, which have a
71 negative influence on the vulnerability (Brefort et al. (2018)). To identify
72 and prevent such cascading failures, the vulnerability of distributed systems
73 needs to be addressed in the early design stage (Goodrum et al. (2018)).
74 Various terminologies exist for the early stage ship design. This paper uses
75 the terminology of Andrews (2018), which refers to the early design stage
76 as the concept phase. A further discussion on the concept phase is provided
77 in Section 2.1. The concept phase is associated with several challenges and
78 is often regarded as the most challenging in ship design, as discussed by
79 Andrews (2018), van Oers (2011), and Gillespie (2012), among others. This
80 is caused by several reasons, which include, but are not limited to the need for
81 creativity in exploring and defining solutions, the large number of potential
82 solutions, and the potential variability of the design requirements over time.
83 In addition to that, the problem knowledge and level of detail are limited in
84 the concept phase, while decisions made in this phase have a major influence
85 on the committed costs (Duchateau (2016)). These challenges apply to all
86 ship design areas, but are considered from a vulnerability perspective in the
87 present paper. More specifically, three challenges for assessing vulnerability
88 in the concept phase are identified:

- 89 • Limited level of detail: The level of detail of a vulnerability assessment
90 in the concept phase needs to be limited enough to be used in a short
91 time frame on a potential large number of concepts, but detailed enough
92 to provide useful estimations of the vulnerability of these concepts.

- 93 • Generating vs. analysing concepts: In order to investigate whether a
94 concept is likely to meet the requirements, a physically realisable model
95 needs to be developed and tested. However, an assessment of a pre-
96 defined concept usually provides results of which the applicability is
97 limited to that specific concept. Assessing a pre-defined concept may
98 therefore be of limited use for generating novel concepts, or design
99 space exploration. Hence, a need for a more generalised method for
100 vulnerability assessments arises.
- 101 • Systems vs. capabilities: Requirements for vulnerability usually are de-
102 veloped and formulated in terms of residual mission capability, in com-
103 bination with a pre-defined damage or weapon impact. In other words,
104 the vulnerability requirements are operationally oriented (Reese et al.
105 (1998)). Yet, concept designs are usually defined in terms of compart-
106 ments and systems. Though systems and capabilities are inextricably
107 connected, the availability of systems is not necessarily a metric for the
108 availability of residual capabilities. In addition to that, the required
109 residual capabilities may be dependent on the impact level of a hit. This
110 requires a vulnerability assessment from a capabilities perspective, in
111 addition to a systems perspective.

112 Various tools and methods exist for assessing the vulnerability of naval
113 ships. These are discussed in more detail in Section 2. It turns out that many
114 existing vulnerability tools - including some that are aimed at the concept
115 phase - require a significant level of detail, such as a general arrangement,
116 a structural plan, or a systems design. Though some tools with a lower
117 level of detail exist as well, none of them addresses both other challenges.

118 In order to address this gap, a new method for assessing vulnerability has
119 been developed. The method uses a basic definition of a ship concept, which
120 includes compartments, main systems, and their routings. The probability
121 of availability for various levels of residual capabilities are calculated on the
122 basis of a discrete Markov chain. Due to this mathematical set-up, it is not
123 only possible to evaluate the vulnerability of a specific concept, but also to
124 obtain guidance towards other, potentially better concepts. This is achieved
125 by an evaluation of the eigenvalues of the transition matrix of the discrete
126 Markov chain.

127 The remainder of this paper is organised as follows. First, a literature
128 overview is provided in Section 2, which evaluates existing tools for assess-
129 ing vulnerability of naval ships and other domains. Subsequently, the new
130 method is explained in Section 3, including the mathematical set-up of the
131 discrete Markov chain and the eigenvalues of the associated transition matrix.
132 The application of the method is demonstrated with a test case in Section
133 4. Section 5 provides the results of the test case. Conclusions are drawn in
134 Section 6. This section also provides recommendations for further research.

135 **2. Literature overview**

136 *2.1. Design process in the concept phase*

137 A commonly used approach for the design of a complex product or sys-
138 tem is Systems Engineering (Kossiakoff et al. (2011)). This approach has also
139 been adopted for naval ship design, and has previously been described as To-
140 tal Ship Systems Engineering (TSSE). This covers all topics of ship design,
141 and is not limited to vulnerability. The five stages in TSSE are require-

142 ment definition, requirement analysis, synthesis, verification, and validation
143 (Brouwer (2008)). In systems engineering theory, defining the requirements
144 is independent of the solution(s), i.e. the ship concept(s). However, the sec-
145 ond concept phase challenge that has been identified in Section 1 reflects that
146 the two are not strictly separated in the case of designing naval ships (and
147 several other types structures). This has been discussed in more detail by
148 Andrews (2011, 2018). As such, the concept phase of naval ship design bene-
149 fits from an approach where design requirements and concepts are developed
150 simultaneously, with the right level of detail at the right time.

151 To bring more structure into the concept phase of naval ship design, this
152 phase can be subdivided into three design activities: concept exploration,
153 concept studies, and concept design Andrews (2018). In concept exploration
154 a wide, exploratory investigation of all possible options for layouts, capa-
155 bilities, and technologies is executed. This is carried out at a limited level
156 of detail. Based on the results of concept exploration, a limited number of
157 alternatives (about 1-5) are investigated in more detail. During this stage,
158 design drivers and the impact of design decisions on performance and cost
159 are investigated in more detail. Subsequently, the concept design stage aims
160 at providing sufficient information on capability and cost for ensuring that
161 the further design process can be executed coherently. The end of this stage
162 usually leads to commitment to a more substantial design and acquisition ef-
163 fort. Though these three activities are described as subsequent to each other,
164 they may overlap in practice. The overall objective of the concept phase is
165 to elucidate what is wanted and what is affordable.

166 A key feature of the concept phase is that the focus lies on decision

167 making. Though this is inextricably connected with generating concepts,
168 these concepts are not generated for detailed design and production, but for
169 elucidating requirements. As such, the concept phase mostly benefits from
170 generalisations rather than specific information on performance characteris-
171 tics of individual concepts. This is not limited to vulnerability, but holds
172 for ship design in general. From a vulnerability perspective, however, most
173 methods carry out an analysis of a pre-defined concept, which relates to the
174 specific perspective. Further research into the generalised perspective may
175 contribute to developing methods that are more suitable assessing vulnera-
176 bility in the concept phase, to feed into the concept phase of the ship as a
177 whole.

178 *2.2. Methods for assessing naval ship vulnerability*

179 Various vulnerability assessment methods and tools exist. Some of these
180 methods are aimed to be used in practical ship design by navies or shipyards,
181 while others are developed from a more fundamental research perspective.
182 Examples of the former type include the commercially developed tools RE-
183 SIST (TNO (2018)), SURVIVE (Schofield (2009)) and SURMA (Surma Ltd.
184 (2018)). These tools provide high fidelity assessments of a ship exposed to
185 one or more hits. They include damage effects such as pressure, flooding, and
186 fragmentation. The results of these tools comprise overviews of the damage
187 stability, availability of critical systems, and structural integrity after one or
188 more hits. The computations in these tools are based on detailed techniques.
189 RESIST, for example, uses algorithms that hold an intermediate position
190 between Finite Element Methods (FEM) and Computational Fluid Dynam-
191 ics (CFD), in addition to analytical and empirical formulas. Because of this

192 level of fidelity, detailed plans such as a general arrangement, a structural
193 arrangement, and a systems design are needed as input for these tools. This
194 makes them highly useful for detailed design stages. For the concept phase
195 they are of limited use, due to the required level of detail. For the con-
196 cept phase a simplified version of SURVIVE exists, known as SURVIVE Lite
197 (Schofield (2009)). This version can be used for more generic layouts and a
198 reduced level of subdivision. Another tool, called PREVENT Heywood and
199 Lear (2006) applies a similar level of detail.

200 Methods for assessing vulnerability in the concept phase exist as well.
201 Many of these have a more fundamental or scientific background. Piperakis
202 (2013) has developed a method that is specifically aimed at the concept
203 phase. It integrates susceptibility, vulnerability, and recoverability in an
204 method for assessing overall survivability. The method is layout-based. It
205 combines existing tools with a newly developed recoverability method. The
206 method is suitable for assessing a relatively low number of alternatives, but
207 at a relatively high level of detail. This fits well in the concept definition
208 phase. A comparable level of detail is considered by Goodfriend and Brown
209 (2017). They only consider vulnerability, with a specific focus on distributed
210 systems. Their method uses a multi-objective genetic algorithm to explore
211 the design space, with high effectiveness, low cost, and low risk as objectives.
212 The method has an exploratory nature, though it still requires a level of
213 detail that may be more suitable for later design stages.

214 An method with a lower level of detail has been developed by van Oers
215 et al. (2012). Their method uses an genetic optimisation algorithm that
216 generates routings of distributed systems, where low vulnerability is one of

217 the objective functions, quantified by minimising the loss of capability. The
218 method only considers variations on the shortest path. In a follow-up study,
219 Duchateau et al. (2018) also consider routings that may be longer, but po-
220 tentially less vulnerable. They also use a genetic optimisation algorithm. On
221 a similar level of detail, the vulnerability of distributed systems is considered
222 by Kim and Lee (2012). However, their aim is not to generate routings, but
223 to evaluate the availability of critical systems after one or more hits in a prob-
224 abilistic fashion. They investigate a binomial method, a Poisson method, a
225 tree diagram, and a Markov chain. Their method can be used with a lim-
226 ited level of detail, but the mathematical set-up becomes complex when the
227 number of redundant components is increased. Furthermore, their method is
228 well suited for evaluating pre-defined concepts, but does not provide guidance
229 towards other - potentially better - concepts.

230 In addition to genetic algorithms and probabilistic models, networks are
231 used as well for vulnerability assessments of distributed systems in the con-
232 cept phase. Goodrum et al. (2018) combine two networks, one describing the
233 compartments of the ship, and one describing systems design, to compute
234 an operability score for damaged compartments. All compartments are con-
235 sidered individually. The translation from their operability score to residual
236 capabilities is not addressed. However, since their method is network-based,
237 it is very robust and quick, allowing large numbers of layouts and damage
238 scenarios to be considered. Networks are also applied by de Vos and Sta-
239 persma (2018). They specifically focus on the logical connections between
240 the components of distributed systems, and do not consider physical com-
241 partments or routings. Similar to van Oers et al. (2012) and Duchateau et al.

242 (2018), they use a genetic optimisation algorithm. Trapp (2015) also uses
243 networks to model the logical connections between components of distributed
244 systems, optimising for network flow.

245 Brefort et al. (2018) have developed an architectural framework in order
246 to structure all these topics. They define the design of distributed systems in
247 terms of the physical, logical, and operational architecture, and their over-
248 laps. The framework is not a tool in itself, but aids in describing and un-
249 derstanding the various aspects and relationships of the design of distributed
250 systems. The method of Shields et al. (2016) has a similar background. While
251 not a design tool in itself, it provides an estimation of the complexity of a
252 design with respect to survivability. Doerry (2007) proposes survivability
253 metrics that enable better definition of power system requirements, from the
254 perspective of the operational needs of the ship. This is also not a tool in
255 itself, but aims to enable a better understanding of the link between design
256 requirements and operational needs.

257 *2.3. Methods for assessing vulnerability in other fields*

258 Vulnerability assessments are also carried out in other fields of study.
259 They are especially relevant for applications with flows through infrastruc-
260 tures, analogous with the flow through distributed naval ship systems. The
261 number of applications is extensive, but three examples are discussed here in
262 more detail.

263 A typical example of a non-naval vulnerability assessment is is the design
264 of land power grids. Liu et al. (2012) have defined an operational vulnera-
265 bility index to investigate the possible benefits of decentralised power gener-
266 ation. In terms of this index, a good network with respect to vulnerability

267 is one in which the long-distance large-capacity power transmission is mini-
268 mal. A major difference with naval ship applications is that land power grids
269 consider only one type of flow (electricity), while for naval ships interdependen-
270 cies with other types of flow, e.g. chilled water, data, and fuels, need to
271 be considered. Furthermore, the operational vulnerability index is not based
272 on damage or loss of systems or compartments, but on the efficiency of the
273 transmission.

274 Another non-naval ship design example of a vulnerability assessment is
275 the work of El-Rashidy and Grant-Muller (2014), who have performed a vul-
276 nerability assessment on a highway network. This example also considers one
277 type of flow (cars), but they have taken into account that the vulnerability
278 depends on various operational and external factors, such as different threats
279 or traffic speeds. This is done by defining vulnerability attributes that are
280 calculated based on basic road traffic parameters, such as the number of
281 lanes, the speed of the cars, and the congestion density.

282 A third example is the assessment of a health care facility. Arboleda
283 et al. (2009) have developed a methodology for assessing the operational
284 vulnerability of a health care facility during disaster events. In contrast to
285 the two methods mentioned earlier, this method takes into account that the
286 system, in this case a health care facility, is dependent on different types
287 of flow, such as water, power, and the transportation of medical supplies.
288 However, it takes into account only one default operational scenario.

289 *2.4. Gap analysis*

290 In Section 1 three challenges for assessing the vulnerability of distributed
291 systems in the concept phase have been identified. The first one concerns

292 the level of detail. Based of the review in Paragraph 2.2 it can be stated
293 that many of the methods require a considerable level of detail, which makes
294 them less suited for the concept phase. This also holds for some of the meth-
295 ods and tools that are specifically aimed at the concept phase. Though less
296 detailed methods exist as well, none of them address both other challenges,
297 concerning generating vs. analysing concepts, and systems vs. capabilities.
298 It is not uncommon to assess vulnerability at the capability level by describ-
299 ing a capability as a hierarchy of systems. Yet, the higher the level of such
300 hierarchies becomes, the more challenging it is to attribute their vulnerability
301 to specific parts of the ship concept, especially in the generalised perspective
302 that is needed during the concept phase. The examples of vulnerability as-
303 sessments in different fields of study are not directly applicable, since they
304 consider only one type of flow or one default operational scenario. Hence, a
305 vulnerability method that specifically links capabilities to the layout of a con-
306 cept, with the generalised perspective needed for the concept phase, is still
307 lacking in literature. In order to address this, a new method is introduced in
308 this paper.

309 During the concept phase, relevant, feasible, and affordable design re-
310 quirements are set, and design drivers and trade-offs are identified. In order
311 to match with these activities, the vulnerability method gives insight on how
312 the design of distributed systems influences the vulnerability. This is realised
313 by assessing concepts, deliberately at a low level of detail. Due to the math-
314 ematical set-up of the method, the results have a generalised nature, and are
315 not limited to the concepts that are defined upfront. In other words, specific
316 concepts are used to develop generalised knowledge. Therefore, these con-

317 cepts are meant to be used for creating insights and requirements, and are
318 not necessarily meant to be worked out in more detail during later design
319 stages.

320 **3. Method**

321 In order to assess the vulnerability of distributed systems on board naval
322 ships, there is a need to describe the availability of (parts of) these systems,
323 and the probability that the availability changes after one or more hits. To
324 enable this, a discrete time Markov chain has been selected as an appropriate
325 mathematical technique that forms the basis of the method. A significant
326 benefit of a discrete time Markov chain is that it is based on probability. In
327 terms of vulnerability this means that all damage scenarios can inherently be
328 addressed at once, which reduces the need for modelling individual damage
329 scenarios. The probabilistic nature of this technique is deemed appropriate,
330 as it gives an overall indication of the ability of a concept to withstand dam-
331 age. This fits well into the concept phase, where the focus is on comparing
332 alternatives rather than working out individual concepts. Furthermore, the
333 probabilistic nature can represent the real-life uncertainty as to whether and
334 where hits will occur. Nevertheless, modelling individual damage cases, such
335 as worst-case scenarios, remains indispensable during later design stages.

336 The base elements of a discrete Markov chain are a state vector \mathbf{s} and a
337 transition matrix T . These are now discussed in more detail by means of a
338 simple illustrative layout, which has been introduced previously in Habben
339 Jansen et al. (2018b). This layout comprises 9 compartments, positioned
340 as a 3×3 grid. The layout contains two systems. System A is located in

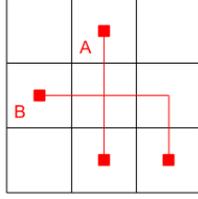


Figure 1: Graphical representation of the illustrative layout

341 3 compartments and system B is located in 4 compartments. The systems
 342 overlap in the central compartment. Figure 1 gives a graphical representation
 343 of this layout. It is assumed that both systems can individually be on or off.
 344 ‘On’ is defined as functioning, and ‘off’ is defined as not functioning due to
 345 a hit. Hence, the state vector becomes

$$\mathbf{s} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \end{bmatrix} \quad (1)$$

346 where

- 347 • s_1 is the probability for system A and B both being on
- 348 • s_2 is the probability for only system A being on
- 349 • s_3 is the probability for only system B being on
- 350 • s_4 is the probability for system A and B both being off

351 As a result of this definition, \mathbf{s} is a stochastic vector, meaning its ele-
 352 ments sum to 1. This is a requisite for a state vector of a discrete Markov
 353 chain. The transition matrix T describes the probability that \mathbf{s} changes over
 354 time. For the set-up of this method, time is defined in number of hits, and
 355 is not related to a physical time scale. It is assumed that one hit occurs

356 at each time step, disabling one of the compartments. The hit probability
 357 is uniform, regardless of the number or location of previous hits. Hence,
 358 compartments can be hit multiple times. If one or more systems are located
 359 in a compartment, they become unavailable. Repair of systems is not con-
 360 sidered. Hence, T is dependent on the layout, and is row stochastic. With
 361 this information, the elements in T can be calculated. For the illustrative
 362 layout, the probability for s_1 to s_1 , which is element $T_{1,1}$ is $3/9$, as three of
 363 the nine compartments (the empty ones) can be hit without losing system
 364 A or system B. The probability for s_1 to s_2 , which is element $T_{1,2}$ is $3/9$,
 365 as three compartments can be hit that result in loss of system B, while sys-
 366 tem A remains on. Similarly, elements $T_{1,3}$ and $T_{1,4}$ become $2/9$ and $1/9$,
 367 respectively. The same procedure can be followed for other elements in the
 368 transition matrix. For example, $T_{2,2}$ is the probability that, given system A
 369 is on and system B is off, the situation remains like that after a subsequent
 370 hit. This probability is $6/9$, as six compartments can be hit that do not
 371 disable system A (the three empty compartments and all compartments of
 372 system B, except for the central compartment that is shared with system A).
 373 Following this procedure, T becomes as follows for the illustrative layout:

$$T = \begin{bmatrix} 3/9 & 3/9 & 2/9 & 1/9 \\ 0 & 6/9 & 0 & 3/9 \\ 0 & 0 & 5/9 & 4/9 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

374 For the illustrative layout, the size of T is limited, and its elements were
 375 calculated by hand. However, the size of T quickly increases if more systems
 376 are considered. Hence, a script has been made for automatic computation

377 of T for any layout. The input for the script is a $n_s \times n_c$ matrix, where
 378 n_s is the number of systems and n_c is the number of compartments. If
 379 system x is located in compartment y , element $\{x, y\}$ of the input matrix
 380 equals 1. Otherwise, it equals zero. Following the same procedure as for the
 381 manually derived T , the transition matrix is computed. By definition, its size
 382 is $2^{n_s} \times 2^{n_s}$. Subsequently, \mathbf{s} and T can be used to calculate the probability
 383 for any state after any number of hits, using Equation 3:

$$\mathbf{s}(h) = \mathbf{s}(0) \cdot T^h \quad (3)$$

384 where h denotes the number of hits, and $\mathbf{s}(0)$ is the initial state vector.
 385 It is assumed that both systems are initially on, so the initial state vector
 386 becomes:

$$\mathbf{s}(0) = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

387 The probabilities of the four states can be plotted for an increasing num-
 388 ber of hits, which is presented in Figure 2. As explained in more detail in
 389 Habben Jansen et al. (2018b), the fact that the two systems are located in
 390 one layout already makes them interdependent from a vulnerability perspec-
 391 tive. This also holds in situations where there is no physical or logical overlap
 392 between the two systems. The results of Figure 2 are obtained by the matrix-
 393 vector multiplication of Equation 3. These results give information on what
 394 the shapes of the curves are, but not on why the curves are shaped that way.
 395 An explicit formulation of the curves can contribute to understanding the
 396 latter, and is one of the key contributions of this paper.

397 As the transition matrix is raised to higher powers of h , the explicit for-

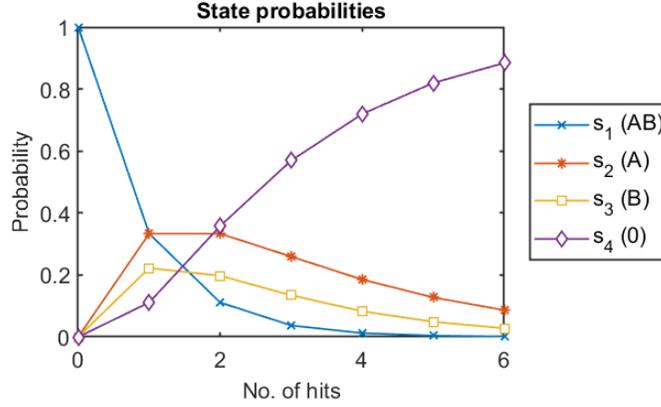


Figure 2: State probabilities for an increasing number of hits, associated with the illustrative layout

398 mulation can be obtained by applying matrix diagonalisation. By definition,
 399 the associated equation is:

$$T^h = PD^hP^{-1} \quad (5)$$

400 where D is a diagonal matrix with the eigenvalues of T on the diago-
 401 nal, and P contains the respective eigenvectors. This holds if and only if
 402 all eigenvectors of T , i.e. all columns of P , are linearly independent (Lay
 403 (2006)). This paper does not contain a proof that this universally holds for
 404 the transition matrix of any layout in general. However, the authors are not
 405 aware of any layout, either conceptual or more advanced, where the columns
 406 of P are not linearly independent. This indicates - but does not proof - that
 407 linear independence occurs for any layout. The linear independence of the
 408 columns of P can be confirmed by computing the rank of P . In this study
 409 MATLAB is used for this, and for all other computations described in this
 410 paper. If the rank of P equals the number of columns in P , its columns are

411 linearly independent. In addition to P , the diagonal matrix D needs to be
 412 constructed as well. This requires the eigenvalues of T . Since the vulnerabil-
 413 ity assessment only considers damage of systems, and not repairs, T is always
 414 an upper triangular matrix. Hence, the eigenvalues of T are the entries on
 415 its diagonal. As a result, the diagonal of D contains the same values as the
 416 diagonal of T . For the illustrative layout, this leads to:

$$D = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 \\ 0 & 0 & 0 & \lambda_4 \end{bmatrix} = \begin{bmatrix} 3/9 & 0 & 0 & 0 \\ 0 & 6/9 & 0 & 0 \\ 0 & 0 & 5/9 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

417 The associated eigenvectors are the columns of P :

$$P = \begin{bmatrix} 1 & -1 & -1 & 1 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

418 The rank of P is 4, so the columns of P are linearly independent. As
 419 such, matrix diagonalisation is indeed possible for this case, so the state
 420 probabilities can indeed be expressed explicitly. For the illustrative layout,
 421 this leads to:

$$Pr(s_1) = \lambda_1^h = (3/9)^h \quad (8a)$$

$$Pr(s_2) = -\lambda_1^h + \lambda_2^h = -(3/9)^h + (6/9)^h \quad (8b)$$

$$Pr(s_3) = -\lambda_1^h + \lambda_3^h = -(3/9)^h + (5/9)^h \quad (8c)$$

$$Pr(s_4) = \lambda_1^h - \lambda_2^h - \lambda_3^h + \lambda_4^h = (3/9)^h - (6/9)^h - (5/9)^h + 1 \quad (8d)$$

422 These equations show that the state probabilities are only dependent on
 423 eigenvalues of T . A major advantage is that this holds for any layout with two
 424 systems, regardless of the number of compartments or the physical location
 425 of the systems in the compartments. Thus, a specific, pre-defined concept is
 426 used to generate generalized knowledge. This can be used to search for alter-
 427 native solutions, and to evaluate the interdependencies between the states.
 428 Consider for example the situation where there is a desire to maximise the
 429 probability that both systems are on, i.e. to maximise $Pr(s_1)$. This probabil-
 430 ity is dependent on λ_1 only. This is element $(1, 1)$ of the transition matrix, i.e.
 431 the probability to remain in s_1 given that the previous state was s_1 already.
 432 In this example, this probability is $3/9$, corresponding to the number of com-
 433 partments where no systems are located. To increase the probability, this
 434 value needs to be increased. This implies that more compartments need to be
 435 empty, i.e. systems A and B need to be concentrated more, which is sensible
 436 from a physical perspective. However, this comes at a cost, as increasing λ_1
 437 has a negative effect on the probabilities for s_2 and s_3 . Hence, this leads
 438 to a high probability that both systems are on after one or more hits, but
 439 the probability that at least one of the systems is on, reduces. Though this
 440 result seems trivial for this illustrative layout, this method can be extended

441 to larger, more complex concepts as well, enabling a better understanding of
442 the trade-off between different levels of residual capabilities.

443 To scale up this method to layouts that can be used during the concept
444 phase, several additional issues need to be addressed. These have previ-
445 ously been introduced in Habben Jansen et al. (2018a). Contrary to the
446 systems in the illustrative layout, that contained only two components and
447 a routing between them, distributed systems on board naval ships are part
448 of multi-layered networks with one or more hub layers between suppliers
449 and consumers (de Vos and Stapersma (2018)). In addition to that, these
450 networks are often multiplex, resulting in interdependencies between the dif-
451 ferent commodities that flow through the network. For example, a chilled
452 water unit is represented by a single node, while it is a consumer of elec-
453 trical energy and a supplier of chilled water at the same time. As a result,
454 it is not possible to simply state that a system is on or off. This depends
455 on the availability of multiple components that may provide different types
456 of commodities. Within the Markov chain this is addressed by describing
457 the states as the availability of individual connections. These connections
458 contain edges of the distributed systems network, including the start node
459 and end node. Consider Figure 3 for an example, where it is assumed that
460 Consumer 1 and Consumer 2 provide the same capability. The table at the
461 right shows how the states for this example are defined. The capability is
462 available if the network is in State 1, 2, or 3. If the network is in State 4,
463 5, 6, 7, or 8, the capability is not available. Note that this is independent of
464 the transition matrix. Hence, the distributed systems network is subdivided
465 in individual connections, and subsequently the Markov chain is calculated.

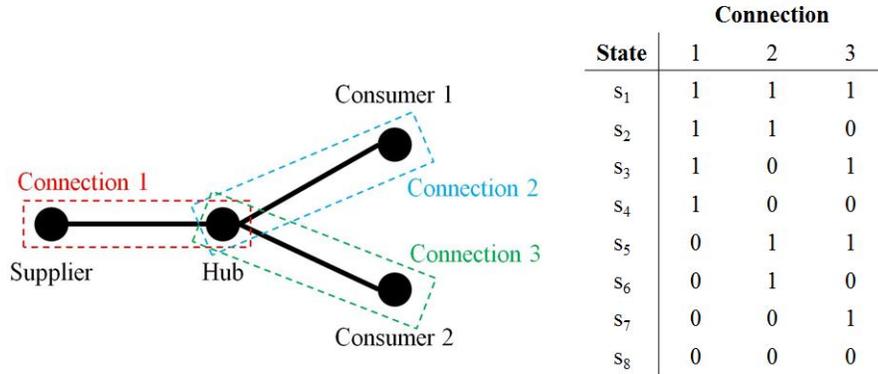


Figure 3: Definition of connections and states of the Markov chain of an example network, adapted from Habben Jansen et al. (2018a)

466 The interdependencies between connections (i.e. the fact that capabilities
 467 require a combination of certain edges) is accounted for after the Markov
 468 chain has been calculated. In the case of this example, the probability for
 469 having the capability available is found by adding the state probabilities of
 470 State 1, 2, and 3 together, as only they represent states where the capability
 471 is available.

472 The states, that describe the availability of individual connections, can be
 473 used to calculate the probability that certain levels of residual capability are
 474 available after one or more hits. These levels could for example be expressed
 475 as the ship’s ability to perform the main functions ‘fight’, ‘move’ and ‘float’,
 476 where full residual capability includes all three functions, medium residual
 477 capability only contains ‘move’ and ‘float’, and minimal residual capability
 478 only includes ‘float’. However, other definitions of residual capabilities can
 479 be applied as well. It is not possible to express the states directly as the
 480 availability of the capabilities, as multiple connections may contribute to a

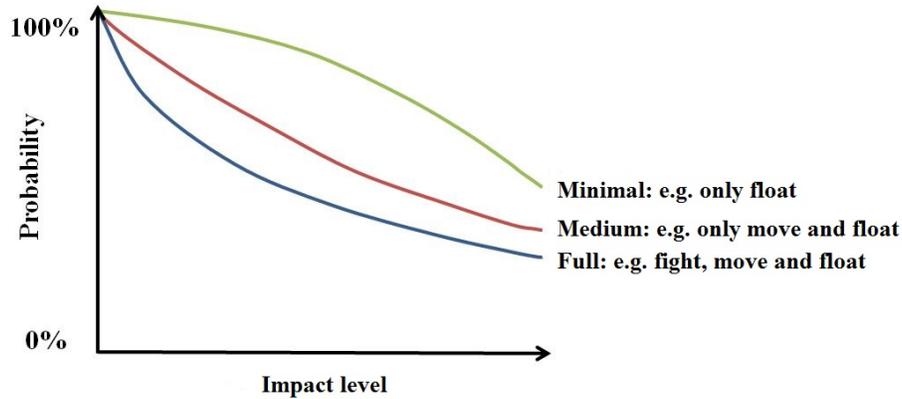


Figure 4: Qualitative example of the result provided by the capability-based vulnerability assessment. The probability for having full residual capability after a certain number of hits is smaller than the probability for having medium or minimal residual capability.

481 single capability. Likewise, a single connection may contribute to multiple
 482 capabilities. To obtain the probability that a certain level of residual capabil-
 483 ity is available, all states that contribute to that capability need to be added
 484 together, which provides a result that resembles the curves of Figure 4. As
 485 each state can be expressed as an explicit function of only the eigenvalues of
 486 T , this also holds for the explicit formulation of the capability curves of Fig-
 487 ure 4. Hence, eigenvalues of T are the direct link between the ship concept
 488 (consisting of the compartments and the routed distributed systems network)
 489 and the shape of the curves, and can be used to study the interdependencies
 490 between the different levels of capability.

491 4. Test case

492 This section provides a test case to illustrate the application and con-
 493 tributions of the method. This is an extension of the test case that has

494 previously been introduced in Habben Jansen et al. (2018a). It considers a
495 notional Ocean-going Patrol Vessel (OPV) with an offensive weapon system,
496 a defensive weapon system, and two propellers. Two powering concepts are
497 considered:

- 498 1. Conventional: The propulsion system is mechanical, and is separated
499 from the electrical distribution system, which powers both weapon sys-
500 tems. A forward and aft chilled water unit provide chilled water to the
501 weapon systems.
- 502 2. IPS: Both the propulsion system and the weapon systems are powered
503 by electrical power. The chilled water units for the weapon systems are
504 located in the vicinity of the weapon systems.

505 The distributed systems networks and the physical location of the net-
506 works in the ship are presented in Figure 5 and Figure 6, respectively.
507 Both concepts contain 12 connections. As a result, the number of states
508 is $2^{12} = 4096$. The Markov chain has been set up according to the method
509 described in Section 3, using the script for automatic generation of the tran-
510 sition matrix. The probability for each state has been calculated for up to
511 8 hits, meaning that up to 8 compartments are disabled. Subsequently, the
512 states are combined to four levels of residual capability, as specified in Table
513 1. For each individual state it is checked whether it contributes one or more
514 levels of residual capability. If so, the probability for that state is assigned to
515 that residual capability. If not, the probability for that state is ignored. The
516 result is a sum of contributing state probabilities for each level of residual ca-
517 pability, which is a quantitative version of the example result shown in Figure
518 4. For this test case, the result is presented in Figure 7. The horizontal axis

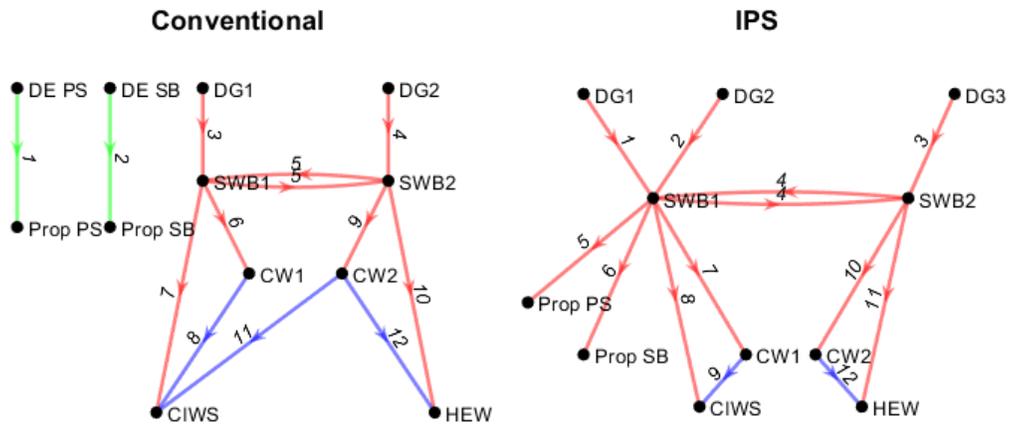


Figure 5: Distributed systems networks of the conventional and IPS concepts, adapted from Habben Jansen et al. (2018a). DE PS / SB = diesel engine port side / starboard, Prop = propeller, DG = diesel generator, SWB = switchboard, CW = chilled water plant, CIWS = close-in weapon system (defensive), HEW = high energy weapon (offensive). The edges are numbered 1-12, as denoted by the edge labels. Red edges denote electrical power connections, blue edges denote chilled water connections, and green power denotes mechanical energy connections. Between the SWBs there is only one connection, but it is directed both ways.

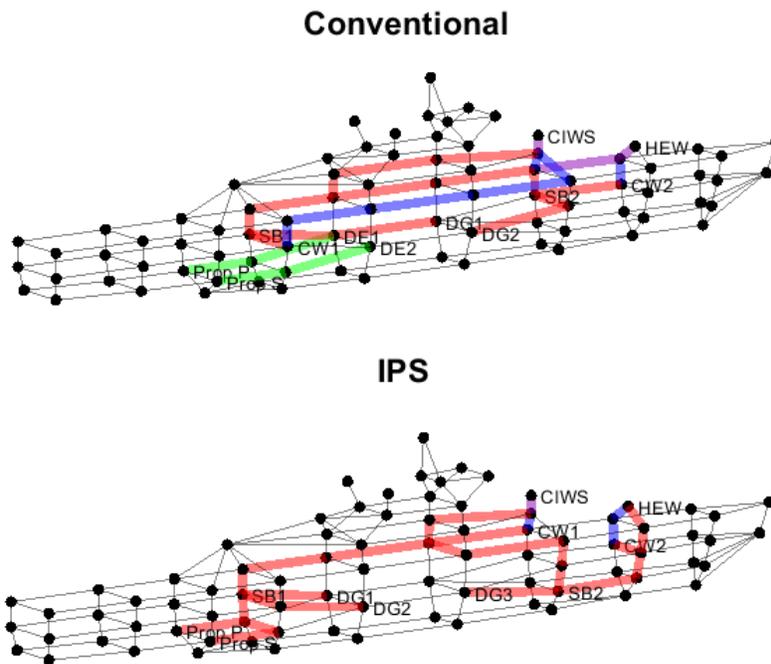


Figure 6: Physical location of the distributed systems networks in the ship, adapted from Habben Jansen et al. (2018a). A purple line denotes routings of both the electrical and chilled water network through the same compartments.

519 of this figure denotes the number of hits. The vertical axis is the probability
520 that at least the level of required residual capability is met. For example,
521 the probability to have at least minimal residual capability is higher for the
522 conventional concept (solid purple line) than for the IPS concept (dashed
523 purple line). The higher the number of hits, the bigger this difference be-
524 comes. This indicates that the conventional concept performs better than
525 the IPS concept for this level of residual capability (i.e. at least propulsion
526 at one side). For the level of considerable residual capability, i.e. at least
527 full propulsion and the defensive weapon, the IPS concept performs better.
528 This illustrates a trade-off in residual capabilities that needs to be made for
529 these two particular concepts. It should be kept in mind, though, that the
530 differences between the conventional concept and IPS concept are based on
531 ship concepts with a limited level of detail. If one concept performs better
532 than another concept at this stage, there is no definite guarantee that this
533 also holds when both concepts are developed in more detail. However, the
534 purpose of this assessment is not to select the best concept, but to identify
535 the underlying rationale that leads to these levels of vulnerability.

536 The results, including the associated trade-off, have previously been in-
537 terpreted in a qualitative fashion only. With the observation that the curves
538 can be written as a function of the eigenvalues of the transition matrix, a
539 formal mathematical description can be obtained, and is presented in this
540 paper. This gives insight into why the curves are shaped in this particu-
541 lar fashion. The resulting knowledge can be used to search for alternative,
542 potentially better concepts, and to identify and quantify interdependencies
543 between the different levels of residual capability.

Table 1: Levels and specification of residual capability, adapted from Habben Jansen et al. (2018a)

Residual capability	Description
Full	Offensive and defensive weapons, two-shaft propulsion
Considerable	Defensive weapon, two-shaft propulsion
Moderate	Defensive weapon, one-shaft propulsion
Minimal	One-shaft propulsion

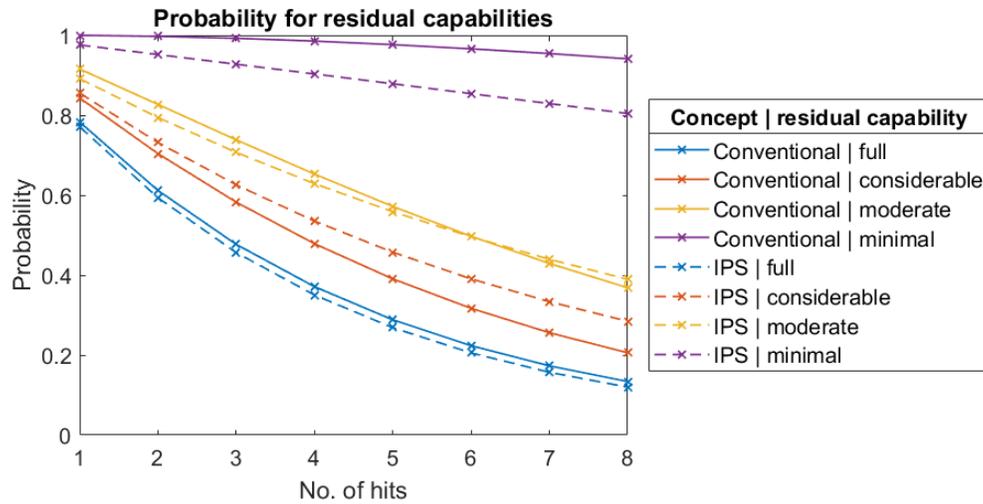


Figure 7: Probabilities for the four levels of residual capability for the conventional and IPS concept, adapted from Habben Jansen et al. (2018a)

544 **5. Results**

545 In order to formulate the probability curves for the states explicitly, ma-
 546 trix diagonalisation needs to be applied. This is only possible if the rank
 547 of P equals its size. In this case, this means that matrix diagonalisation is
 548 possible if the rank of P is 4096. Using MATLAB, this is found to be the case
 549 for both the conventional concept and the IPS concept. Hence, the curves of
 550 the different levels of residual capability can be expressed as:

$$Pr(c_i) = \sum_{k=1}^n f_k \cdot \lambda_k^h \quad (9)$$

551 where c_i denotes the i^{th} capability level (in this test case i runs from 1 to
 552 4), λ_k denotes the k^{th} eigenvalue of the transition matrix (in this test case k
 553 runs from 1 to 4096, which is n , the number of states), h is the number of
 554 hits, and f_k is an integer factor that states how strong λ_k contributes to the
 555 curve, and which sign it has.

556 The expression of Equation 9 can be set up for each individual vulner-
 557 ability curve. Table 2 gives the eigenvalues and factors for the curve that
 558 represents the probability for full residual capability of the conventional con-
 559 cept, as presented in Figure 7. The first column provides the state numbers
 560 of the eigenvalues that contribute to the curve (between 1 and 4096). The
 561 second column gives the actual value of these eigenvalues, as provided by
 562 the transition matrix. The third column states whether the eigenvalue cor-
 563 responds positively or negatively to the curve, and how strong. The corre-
 564 sponding state definitions are included as well, where the numbers 1-12 relate
 565 to the individual connections in the concept, as defined in Figure 5. Several
 566 observations can be made:

Table 2: The eigenvalues, and their corresponding factors and state definitions, that contribute to the curve of full residual capability for the conventional concept. The numbers 1-12 in the state definitions relate to the individual connections in the concept, as defined in Figure 5

k	λ_k	f_k	1	2	3	4	5	6	7	8	9	10	11	12
1	0.6747	2	1	1	1	1	1	1	1	1	1	1	1	1
3	0.6747	-2	1	1	1	1	1	1	1	1	1	1	0	1
81	0.7349	-2	1	1	1	1	1	0	1	0	1	1	1	1
129	0.6867	-1	1	1	1	1	0	1	1	1	1	1	1	1
131	0.6867	1	1	1	1	1	0	1	1	1	1	1	0	1
209	0.7470	1	1	1	1	1	0	0	1	0	1	1	1	1
257	0.6988	-1	1	1	1	0	1	1	1	1	1	1	1	1
259	0.6988	1	1	1	1	0	1	1	1	1	1	1	0	1
337	0.7590	1	1	1	1	0	1	0	1	0	1	1	1	1
513	0.6867	-1	1	1	0	1	1	1	1	1	1	1	1	1
515	0.6867	1	1	1	0	1	1	1	1	1	1	1	0	1
593	0.7470	1	1	1	0	1	1	0	1	0	1	1	1	1

- 567 • Though there is a total of 4096 states, only 12 states have eigenvalues
568 that contribute to the probability for full residual capability of the
569 conventional concept.

- 570 • Some eigenvalues have a positive contribution, while others have a neg-
571 ative contribution. Many of these eigenvalues occur in pairs that cancel
572 each other out. For each pair, connection 11 is off in one of the cor-
573 responding states, while connections 7, 10, and 12 are on. This state
574 is physically not possible, as connection 11 shares routings with these
575 other connections through the same compartments. The meaning of the
576 corresponding eigenvalues is strictly mathematical in this case. Nev-
577 ertheless, they should not be ignored. If modifications to connection
578 11 are made in such way that it no longer routed together with other
579 connections, the pair-wise cancellation may no longer be present.

- 580 • For every eigenvalue, the corresponding state includes the availability
581 of at least connections 1, 2, 7, 9, 10, and 12. Relating this back to the
582 distributed systems network of Figure 5, it turns out that these are all
583 non-redundant connections.

- 584 • For some states, connections 6 and 8 are off. Their unavailability is
585 related; individual availability of either connection 6 or connection 8
586 does not occur. For every state where connections 6 and 8 are off, there
587 is a fellow state where connection 11 is off.

- 588 • For most states, either connection 3, 4, or 5 is off, but no combinations
589 of these states.

590 These observations are the result of assessing this specific concept, but are
591 not restricted to the physical routings of the concept. Therefore they provide
592 valuable information that can be used to better understand and improve the
593 existing concept. The following procedure is proposed for this:

- 594 1. From all curves representing the various levels of residual capability,
595 select one to study in more detail. For this test case, the curve of full
596 residual capability for the conventional concept is investigated.
- 597 2. Check how many eigenvalues contribute to the shape of that curve.
598 This may be decisive for how the further assessment is carried out. In
599 this case, 12 eigenvalues contribute to the curve. The number of con-
600 tributing eigenvalues is no metric for the vulnerability - it can therefore
601 not be stated that either more or less eigenvalues is 'better'. However,
602 a smaller number of eigenvalues allows the designer to do a manually-
603 oriented assessment, while for a larger number of contributing eigenval-
604 ues the assessment may require a more computational approach. This
605 test case illustrates a manual approach. Assessment methods for larger
606 numbers of eigenvalues are still subject of further research.
- 607 3. Check for repetitions or pairs in the contributing eigenvalues. For this
608 test case, four pairs with connection 11 occur, leading to eigenvalues
609 that cancel each other out. As such, only four eigenvalues contribute
610 to the shape of the curve. They will be addressed in this test case.
- 611 4. Change the remaining connections in such way that the eigenvalues
612 with positive factors increase and the eigenvalues with negative factors
613 decrease. In order to increase an eigenvalue with a positive factor,
614 the connections that are on in that state need to be reduced in size or

615 concentrated. In order to decrease an eigenvalue with a negative factor,
616 the connections that are off in that state need to be reduced in size or
617 concentrated. From a mathematical point of view it could also be an
618 option to increase the size of the routings of the other connections, but
619 that would lead to increased vulnerability of those connections for the
620 sake of a lower relative vulnerability of the other connections. As such,
621 recommendations of size reduction and concentration of routings are
622 preferred.

623 This can be applied to this test case. Consider the situation where there is
624 a desire to increase the probability that there is full residual capability after
625 one or more hits. The eigenvalues λ_{81} , λ_{209} , λ_{337} and λ_{593} have the strongest
626 influence on this, as they are not cancelled out by other eigenvalues. More
627 specifically, λ_{81} needs to be decreased, and λ_{209} , λ_{337} and λ_{593} need to be
628 increased. For all these eigenvalues, connections 6 and 8 are off. In order
629 to decrease λ_{81} , the routings of these connections should be made smaller or
630 more concentrated. However, in order to increase λ_{209} , λ_{337} and λ_{593} , it is
631 the other way around. This is a mathematical representation of conflicting
632 requirements that result from interdependencies between the connections.
633 However, a closer look at λ_{209} , λ_{337} and λ_{593} shows that either connection 3,
634 4 or 5 is off in their associated states. In order to increase these eigenvalues,
635 the probability to remain in any of these states should be increased. This
636 indicates that all routings related to connections other than 3, 4, 5, 6 or
637 8 need to be made smaller, or more concentrated. Connections 1 and 2
638 are related to propulsion, and are not easy to modify for the conventional
639 concept. However, for connections 7, 9, 10, 11 and 12, two modifications are

640 proposed:

- 641 1. Bring CW2 above SWB2, closer to the CIWS. This concentrates the
642 routings of connections 9, 10 and 12, and reduces the routing length of
643 connection 11.
- 644 2. Concentrate the routing from SWB1 to the CIWS (connection 7) with
645 the routing between SWB1 and SWB2 (connection 5). This reduces the
646 number of compartments solely occupied by the routing of connection
647 7.

648 The concept is adjusted accordingly, such as presented in Figure 8. The
649 results of this adjustment are given in Figure 9. It can be observed that the
650 adjustments have the desired effect, as the curve for full residual capability
651 lies higher, indicating a higher probability for having this level of residual
652 capability after one or more hits. At the same time the curves for moderate
653 and considerable residual capability have increased as well. Hence, the pos-
654 itive effect of the modification goes beyond the level of residual capability
655 that was originally considered. In this case this effect is positive. However,
656 for other cases the residual capability of other levels may drop if the resid-
657 ual capability of the level that was originally considered is increased. This
658 method elucidates and quantifies these interdependencies.

659 The same method can be applied to the IPS concept. Figure 7 shows that
660 the probability for minimal residual capability, i.e. at least propulsion at one
661 side, is significantly lower for the IPS concept (purple dashed curve) than
662 for the conventional concept. Consider the situation where there is a desire
663 to increase this probability. The eigenvalues and factors that determine the
664 shape of this curve are presented in Table 3. For this case all factors are

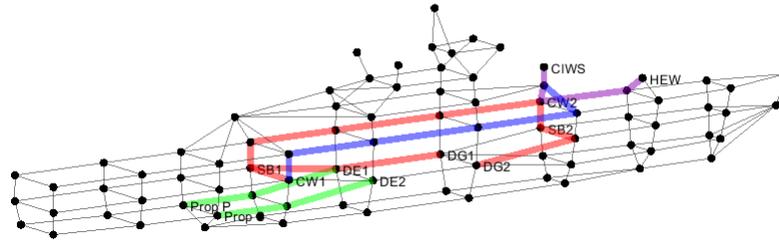


Figure 8: Physical location of the distributed systems networks in the adjusted conventional concept

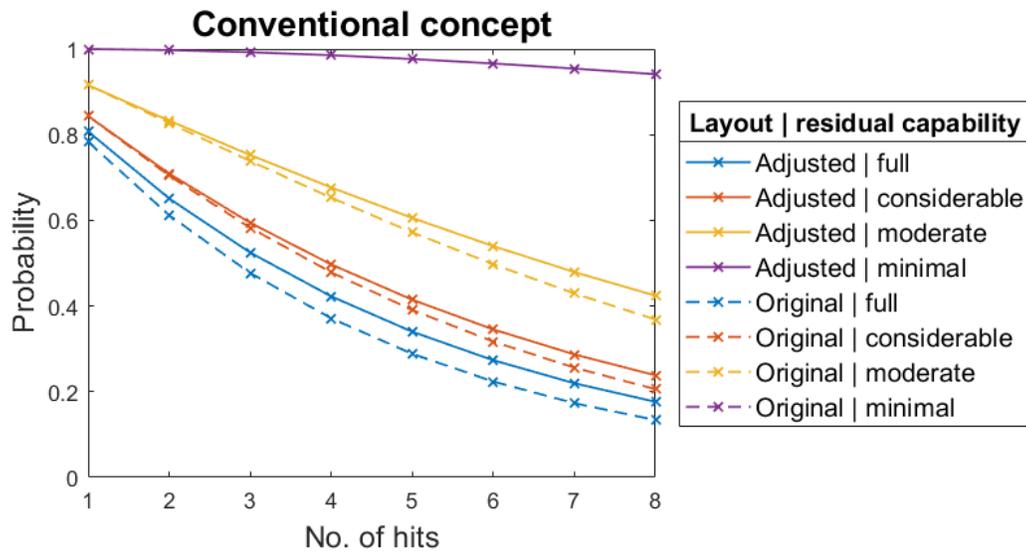


Figure 9: Probabilities for the four levels of residual capability for the adjusted conventional concept

665 either 1 or -1, so in order to determine the eigenvalues with the largest in-
666 fluence, the magnitude of the eigenvalues need to be considered. The largest
667 eigenvalues, i.e. the eigenvalues with the largest influence on the curve, are
668 λ_{1920} , λ_{1984} and λ_{2944} . The corresponding factor is 1 for all these eigenvalues,
669 so they make a positive contribution to the curve. Hence, the probability
670 for minimal residual capability increases when the magnitude of these eigen-
671 values increase. The state definitions associated with these eigenvalues show
672 that connections 1, 2, 5, and 6 are on, while the other connections are off.
673 In order to increase the probability for minimal residual capability, the num-
674 ber of compartments associated with these connections needs to be reduced,
675 and concentration and/or separation of the associated system components
676 and routings may be beneficial. To that end, SWB1 is relocated one com-
677 partment lower compared to the original IPS concept that was presented in
678 Figure 6. As a result, the distance between SWB1 and both propellers re-
679 duces. In addition of that, only one compartment is a single point of failure,
680 instead of two compartments for the previous situation. Since SWB1 has
681 been relocated, the routings from DG1 and DG2 need to be adjusted as well.
682 As a result, the routing from DG2 to SWB1 now has a partial overlap with
683 the routing between SWB1 and the starboard propeller. However, this does
684 not affect the power supply to the port side propeller, so the requirement
685 to have a large probability for propulsion at one side at least is still met.
686 Propulsion power can also be supplied via DG3 and SWB2, i.e. connections
687 3 and 4. However, the results of the eigenvalue assessment shows that these
688 connections have a smaller influence on the shape of the curve. These con-
689 nections are therefore left unchanged. The adjusted layout is presented in

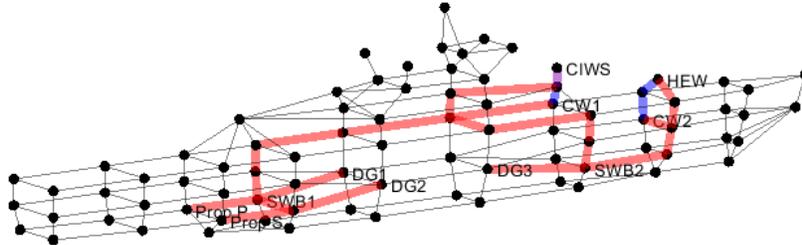


Figure 10: Physical location of the distributed systems networks in the adjusted IPS concept

690 Figure 10. The associated result is given in Figure 11. It can be seen that
 691 the probability for having at least minimal residual capability has increased
 692 significantly. Hence, the proposed solution has the desired effect. For the
 693 other levels of residual capability, the curves remain unchanged, so no trade-
 694 off needs to be made. This is because the capability that is considered, i.e.
 695 propulsion at one side at least, does not include components or routings of
 696 other systems.

697 6. Conclusions and recommendations

698 In this paper a method for assessing vulnerability of naval distributed
 699 ship systems is presented and illustrated. This method assesses the vulnera-
 700 bility in a quantitative fashion, from a capabilities perspective, in the concept
 701 phase. A major benefit of the method is that it does not only evaluate the
 702 vulnerability of an existing, pre-defined concept, but also provides direction
 703 for finding other, potentially better solutions. This is done from a capabilities
 704 perspective rather than from a systems perspective. The method accounts for
 705 the fact that the relation between individual connections and higher-level ca-

Table 3: The eigenvalues, and their corresponding factors and state definitions, that contribute to the curve of minimal residual capability for the IPS concept

k	λ_k	f_k	1	2	3	4	5	6	7	8	9	10	11	12
64	0.8072	-1	1	1	1	1	1	1	0	0	0	0	0	0
128	0.8313	1	1	1	1	1	1	0	0	0	0	0	0	0
192	0.8193	1	1	1	1	1	0	1	0	0	0	0	0	0
832	0.9036	1	1	1	0	0	1	1	0	0	0	0	0	0
896	0.9277	-1	1	1	0	0	1	0	0	0	0	0	0	0
960	0.9157	-1	1	1	0	0	0	1	0	0	0	0	0	0
1088	0.8313	1	1	0	1	1	1	1	0	0	0	0	0	0
1152	0.8554	-1	1	0	1	1	1	0	0	0	0	0	0	0
1216	0.8434	-1	1	0	1	1	0	1	0	0	0	0	0	0
1856	0.9277	-1	1	0	0	0	1	1	0	0	0	0	0	0
1920	0.9518	1	1	0	0	0	1	0	0	0	0	0	0	0
1984	0.9398	1	1	0	0	0	0	1	0	0	0	0	0	0
2112	0.8193	1	0	1	1	1	1	1	0	0	0	0	0	0
2176	0.8434	-1	0	1	1	1	1	0	0	0	0	0	0	0
2240	0.8313	-1	0	1	1	1	0	1	0	0	0	0	0	0
2880	0.9157	-1	0	1	0	0	1	1	0	0	0	0	0	0
2944	0.9398	1	0	1	0	0	1	0	0	0	0	0	0	0
3008	0.9277	1	0	1	0	0	0	1	0	0	0	0	0	0
3136	0.8434	-1	0	0	1	1	1	1	0	0	0	0	0	0
3200	0.8675	1	0	0	1	1	1	0	0	0	0	0	0	0
3264	0.8554	1	0	0	1	1	0	1	0	0	0	0	0	0

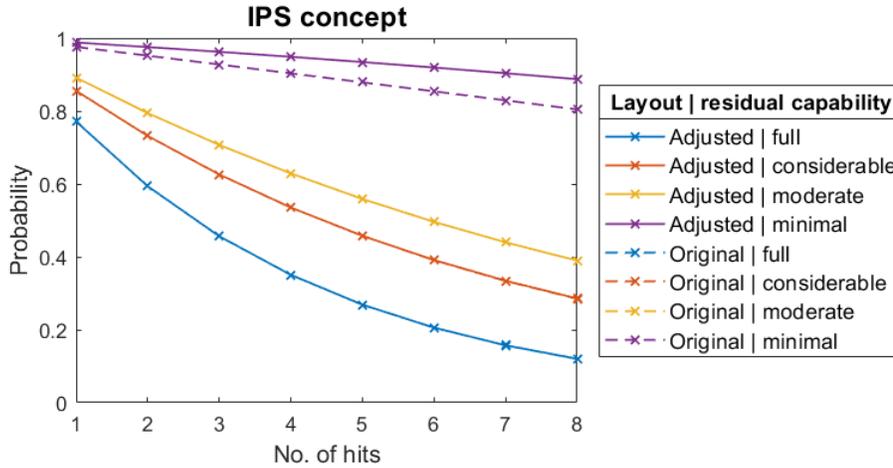


Figure 11: Probabilities for the four levels of residual capability for the adjusted IPS concept. The curves for considerable, moderate, and minimal residual capability are similar for the adjusted and the original concept.

706 probabilities is not necessarily one-to-one, and that potential trade-offs between
 707 various levels of capability may exist. An explicit mathematical formulation
 708 relates the availability of higher-level capabilities to specific connections in
 709 the distributed systems network that are decisive for this availability.

710 In addition to these general contributions, several specific conclusions can
 711 be drawn from the test case, where the vulnerability of a conventional power-
 712 ing concept and an IPS concept for a notional OPV has been assessed at
 713 various levels of required residual capability. It differs per level whether the
 714 conventional or IPS concept performs better. Though some of the differ-
 715 ences are subtle, there is a major difference in the probability for minimal
 716 residual capability, i.e. having propulsion at one side at least. For this level
 717 of residual capability, the conventional concept performs significantly better
 718 than the IPS concept. This is because the number of compartments that

719 is equipped with propulsion components and routings is larger for the IPS
720 concept, making it more likely to get hit. Nevertheless, the method has suc-
721 cessfully provided directions to modify the concept such that this improves,
722 without compromising the performance for other levels of residual capabil-
723 ity. The conventional concept has also been modified, with a goal to obtain a
724 higher probability for full residual capability. This has indeed been achieved,
725 also without compromising other levels of residual capability. It should be
726 kept in mind that these results are based on an assessment with uniform
727 hit probability. In earlier work of the authors it has been shown that other
728 (user-defined) hit probability distributions can be applied as well (Habben
729 Jansen et al., 2018b). These other types of distributions have not yet been
730 applied for obtaining design recommendations, such as done in this paper.
731 Opportunities arise for combining these two aspects, but the mathematical
732 set-up and design implications are still subject of ongoing research. The same
733 holds for scaling up the method to higher numbers of systems and routings.
734 As discussed in Section 3, the size of the transition matrix increases expo-
735 nentially with the number of connections that is considered. Currently this
736 limits the size and complexity of the method to distributed systems compa-
737 rable to the test case of this paper. Since this paper aimed to explain how
738 design recommendations for reduced vulnerability can be obtained, rather
739 than mimicking an actual design effort, this limited complexity is considered
740 appropriate. However, opportunities for scaling the method and including
741 more representative ship concepts are under consideration in ongoing work.

742 The vulnerability method presented in this paper considers system com-
743 ponents and routings that can be either on or off. In other words, the method

744 checks whether the power sources and sinks in the network are connected.
745 However, in order to meet the various level of residual capabilities, there also
746 needs to be sufficient effort and flow of the different commodities. Adding
747 a network flow assessment to this method would increase the fidelity. Such
748 an assessment can also evaluate in which damage cases an operational deci-
749 sion needs to be taken because there is a higher power demand than power
750 supply. However, the design stage for which this method is meant should be
751 taken into consideration while doing this, as the concept phase deliberately
752 is associated with a low level of detail.

753 **Acknowledgements**

754 Funding for this research is provided by Ms. Kelly Cooper from the
755 United States Office of Naval Research (ONR) under grant no. N00014-15-
756 1-2752, and is gratefully acknowledged. Furthermore, the authors would like
757 to thank the Defence Materiel Organisation of the Netherlands Ministry of
758 Defence for their in-kind contribution to this research.

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