Proceedings of 15th International Marine Design Conference (IMDC-2024)
June 2-6, 2024
Amsterdam, the Netherlands

Capability driven vulnerability analysis of a naval combatant

Czop, Michal[1,*]; Megen, Demi van[1]; Droste, Koen[1]

ABSTRACT

This paper presents a fine-tuned approach to vulnerability assessment, focusing on protecting capabilities instead of individual systems and their components. The foundation of this method is a system model which uses functional chains to identify the contribution of individual systems towards to fulfilment of the ships capabilities. The key advantage of using functional chains is that by showing that individual functions can still be fulfilled, it is demonstrated that the vital capability containing those functions remains available. This paper first explains the theory behind the methodology and then demonstrates its working principles using a generalized case study for a single capability.

KEY WORDS

ship vulnerability; ship survivability; model-based system engineering; functional chains; naval design.

INTRODUCTION

In naval design, survivability is a set of measures aimed at reducing the likelihood of being hit by a hostile effector and limiting the consequences of such damage. It can be divided into two sub-disciplines: susceptibility and vulnerability. The former includes managing the asset's signatures (radar, infra-red, acoustic, etc.) to prevent detection, confusing the weapon's homing systems (for example using decoys), or ultimately destroying the incoming threat. The latter i.e., vulnerability reduction, which is the focus of this paper, includes the measures which reduce weapon effects with the assumption that the vessel has already been hit.

There are multiple reasons to implement the vulnerability aspect in a modern naval combatant design. The overarching goal is to reduce the potential death toll amongst the crew, following the philosophy that while ships are replaceable, people are not. However, replaceable does not equal disposable, thus the second objective is to limit the extent of damage and decrease the risk of the loss of the asset. An additional benefit is that reduced vulnerability increases the availability of ship's systems in a damaged state, thus improving the prospects of completing mission objectives. It is worth noting, that the approach discussed in this paper is only relevant to threats on or above the waterline, resulting in kinetic damage, blast, and fragments emission. The underwater threats, such as mines and torpedoes, usually lead to a shock event affecting the entire vessel, which requires a fundamentally different approach.

ESTABLISHED APPROACH TO VULNERABILITY REDUCTION

Physical protection measures

Vulnerability reduction includes multiple distinct solutions which need to be considered at consecutive design stages. In the age of battleships, for the most part, this objective was fulfilled by heavily armouring the ships, which made them more resistant to (naval) gunfire. However, the technological landscape has completely changed; modern, more powerful weapons have

[1] Damen Naval (Vlissingen, Netherlands)
* Corresponding Author: m.czop@damennaval.com

Submitted: 14 February 2024, Revised: 1 May 2024, Accepted: 3 May 2024, Published: 19 May 2024

Conference paper, DOI: https://doi.org/10.59490/imdc.2024.835 e-ISSN: 3050-4864

rendered this strategy ineffective and impractical. Additionally, the heavy armour comes with a major penalty to other design aspects, primarily signatures, weight, and space, thus increasing cost of construction and operation (due to increased fuel requirement). Nonetheless, certain impact protection measures continue to play a key role in limiting the extent of damage to the ship. Blast-, Fragment and/or fire retaining bulkheads and reinforced decks are applied in strategic locations to contain the effects of a hit to a limited part of the vessel. With increasing prevalence of asymmetric scenarios, it is becoming more common to additionally protect high value and/or heavily manned compartments with the aim of stopping the penetration of the ship's hull by smaller weapons fire. Similarly, sections of reinforced bulwarks as well as bulletproof vests serve to protect the personnel on the open decks against small-calibre gunfire.

System architecture measures

In addition to shielding and containment, system architecture measures are implemented to improve resilience of the vital systems of the ship. This strategy drives the arrangement of systems by acknowledging that they may be partially damaged, therefore single points of failure must be avoided to reduce the impact of weapon effects. The established approach to this issue is designating a set of ship's systems as vital and ensuring there are multiple instances of each in the vessel with sufficient physical separation. This is the key distinction between availability and vulnerability analysis – two systems located in the same compartment are redundant from the availability standpoint, however they can be damaged by a single weapon hit. When selecting the locations of the vulnerability-redundant systems, longitudinal separation is preferred over vertical. This is not only because ships are usually longer than they are tall, but also due to the fact that that bulkheads tend to offer more resistance to blast effects than decks do. For most support systems (providing consumables, control, cooling, etc.) the distribution infrastructure must also follow a redundant design to be able to service the dependent vital systems outside of the damaged section. This is achieved either by routing the main line through compartments well under the waterline with riser pipes extending upwards or by developing a ring arrangement for cabling and piping. Switchboards and valves are placed at selected boundaries allowing to isolate the damaged section and continue servicing the remainder of the vessel.

A ship contains multiple interconnected systems, very few of which are capable of functioning fully independently. The measures described above are effective at providing redundancy of individual systems, however on their own they fail to capture the interdependencies amongst them. For example, let us assume a vessel with a redundant electric propulsion system, powered by a ring-shaped distribution network with two generator sets in different areas of the ship. These generator sets have independent cooling circuits, which require uninterrupted supply of freshwater, delivered from either of two pumps located in a single machinery space, halfway between the generator rooms. In this case a single weapon hit can damage both pumps, not only indirectly disabling the propulsion system but also leading to a complete blackout. This is only an illustrative example – in complex naval platforms these interdependencies are often obscured by the sheer amount of complexity and interconnectivity of all systems on board.

Based on the arguments above, simply doubling and separating all the systems on the vessel may seem like the optimal solution, however the redundancy measures come with a severe penalty to weight, space, and cost. Consequently, a more in-depth analysis is needed to accurately select the systems and components to protect and develop a resilient design without compromising other design aspects.

CAPABILITY DRIVEN APPROACH

The defining feature of capability-driven approach is that it shifts the focus of the analysis from protecting individual system components to protecting high-level (vital) capabilities of the ship. This chapter explains how these capabilities are described in a system model and mapped to the relevant systems, followed by the assumptions of the analysis and the principles of evaluating system performance.

System model as the foundation of analysis

This paper presents an approach to the issues described above by basing vulnerability analysis on functional chains created with ARCADIA – a model-based systems engineering method developed by THALES (Voirin, 2017). The system model describes the capabilities of the vessel represented using functional chains. A functional chain consists of several functions which interact with each other, in essence describing the sequence of events/actions which need to happen in order to achieve a given desired capability. These functions are then assigned to (or allocated to) systems which execute them. This makes the interactions between functions become a representation of interactions (or interfaces) between systems. These interfaces are modelled as functional exchanges, showing both the functional and physical interdependencies between systems (Roques, 2017). This approach makes it possible to analyse the systems one-by-one and ensure a functionally resilient design regardless of its complexity. The fundamental assumption is that if all functions in the relevant chain can be fulfilled, the capability in question is secured.

The vulnerability analysis is focused on the overall design philosophy of a system and location of components. The system model is constructed on an even higher level where each system as a black box with allocated functions. Generic representation of systems, functions, and functional exchanges is shown in Figure 1. In this diagram the crew is modelled as a logical actor (external to the system but interacting with it), whereas the ship is acting as a container for the systems being analysed. Both the logical actors and systems have functions allocated to them and interact with each other by the means of functional exchanges (shown as arrows), which represent an interaction (e.g., exchange of matter or information) between two functions.

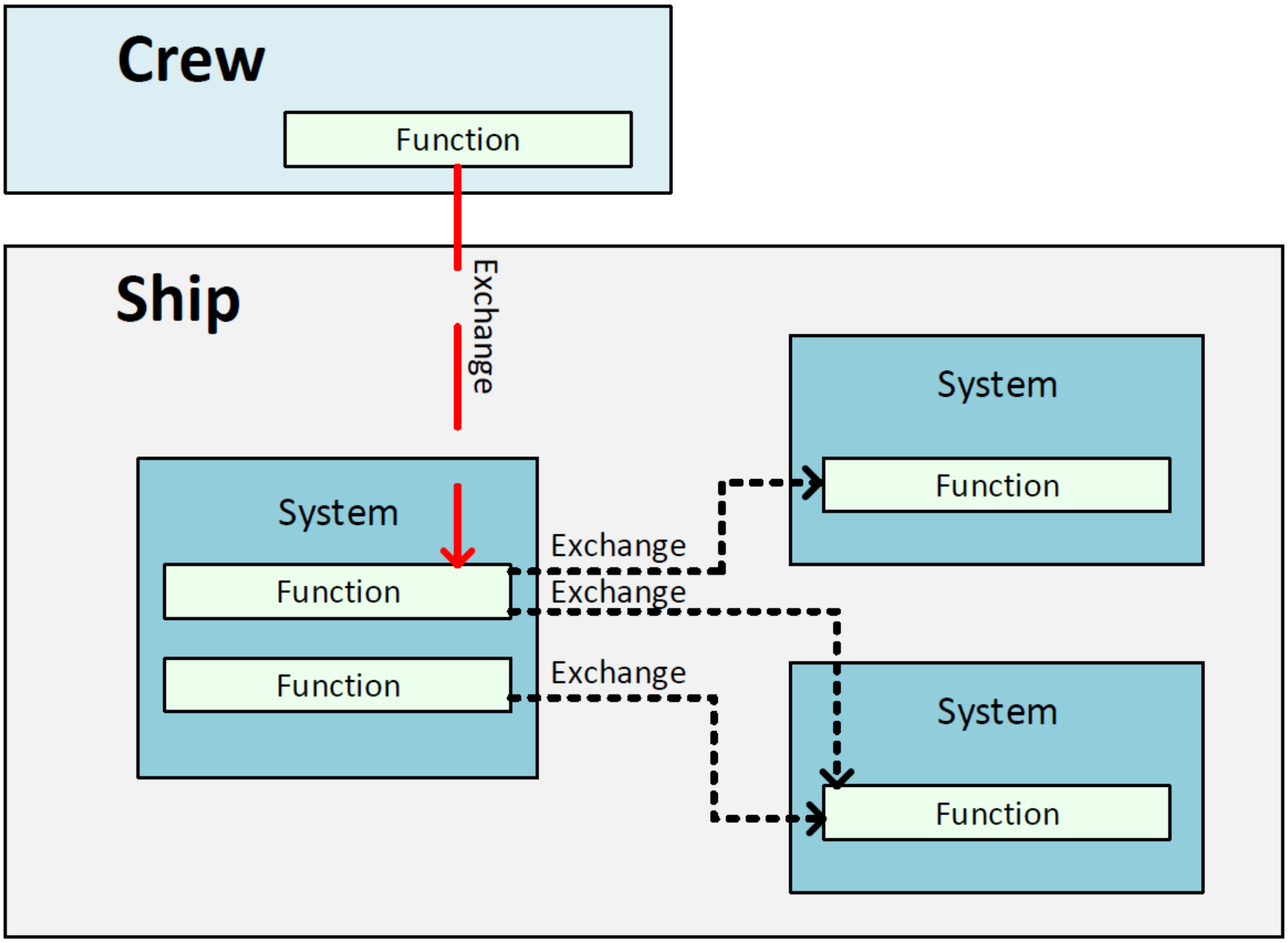

Figure 1. Generic representation of systems, functions, and functional exchanges

Definition of residual capability

It can be expected a damaged ship will not have the same capabilities as an intact one. Thus, vulnerability reduction effort should start by defining the minimum required residual capabilities after a damage event. These residual capabilities describe which functionalities of the vessel must remain available even after sustaining damage. Normally, several capability levels will be specified, with fewer functionalities required for increasing severity of damage. In this paper, two levels will be used, corresponding to arbitrarily defined small hit and large hit. The assumptions relating to threats are discussed in the next section.

Based on the system model, the functional chains contributing to the specified residual capabilities are evaluated and the functions which need to be preserved are classified as vital. By extension, the systems fulfilling these functions are also classified as fully or partially vital, i.e., only the parts of the systems supporting the residual capabilities are considered vital. The degree to which a system can fulfil its function after damage (in degraded state) is referred to as residual performance.

At the initial design stages, the residual capability may be stated as simply as "The vessel shall be able to propel itself and control its heading after a small hit". As the design matures and trade-offs are better understood, more precise level of residual performance can be specified, e.g., that the speed of 5kn must still be achievable after a small hit. As such, the capability-driven approach does not force a specific arrangement, instead giving system designers freedom to choose the best solution. As long as the residual capability objective can be met in the damaged state, the outcome of the analysis would be considered satisfactory.

Assumptions of damage effects

As mentioned in the previous section, the residual capability levels correspond to threat levels, i.e., the assumed weapon threats from which the ship needs to be protected. The selection of these design threats and calculation of their effects is beyond the scope of this paper. To demonstrate the following stages of the analysis, two threat levels are specified: a small hit is defined as damage to one compartment (volume between two consecutive decks and two consecutive watertight bulkheads), whereas a large hit includes multiple compartments. The weapon impact can occur in any location above the waterline, resulting in an array of damage cases to be calculated and evaluated in the analysis.

Due to inherently unpredictable nature of explosions, it is infeasible to predict, which equipment in the damaged compartments will be affected. While there are methods which can provide a finer estimate of failure, they are overly time-consuming to be applied for every investigated damage scenario. Therefore, a conservative assumption is that all the equipment, cabling, and piping located in these spaces may be destroyed, reflecting the worst-case scenario. It is worth noting that less pessimistic assumptions can be made for small-calibre ballistic threats, but these are not considered in this paper.

Effects of damage on residual capability

The damage effect analysis is used to determine the residual performance of the ship after battle damage and, if it is not satisfactory, the measures required to increase the survivability of the ship. All the vital systems are individually analysed for the impact of each damage case. Two types of system degradation are considered after battle damage: through direct damage, when system components are located in an affected compartment, or degradation following a failure of a support system (providing an essential consumable or control to the system in question). The indirect cases are mentioned during an analysis, but mostly function as a quality check, since they will also be identified when the damage effects on the relevant system are evaluated. In certain cases, the loss of a function might be acceptable as long as it can be compensated by another system, thus avoiding a complete loss of the vital capability, since there is a functional back-up.

Vulnerability analysis generally focuses on the worst-case scenario for each system. In practice, residual performance after a hit is likely to be higher than the guaranteed minimum. Besides proving that the minimum required performance is met, the capability-driven approach gives the designer and the user comprehensive understanding of the consequences of damage in various areas and the potential impact on damage control and residual capability. To demonstrate the practical implications of this theory, the next part illustrates the strategies and principles listed above in a case study.

GENERIC CASE STUDY – FIRE FIGHTING

This example shows the analysis of a simplified firefighting case on a fictitious ship. The goal of the analysis performed in this case study is to demonstrate that the residual capability of firefighting remains available after battle damage by proving that all functions contributing to this capability can still be sufficiently fulfilled. A large hit damage case was chosen, as it affects a wider range of systems, therefore making the vulnerability analysis more complex. Both the damage case and the functional chain describing the capability are provided as an input and their development is not discussed in detail.
The following sub-sections correspond to the three steps of the process: functional chain analysis, damage extent analysis, and damage effect analysis.

Functional chain analysis

The functional chain analysis breaks down the process of firefighting into the contributions of the different systems and/or actors. Following the specification of residual performance level required, the system model describing the normal operation is adapted to only contain the functions required after battle damage. Figure 2 shows the functional chain describing firefighting during normal operation, with different line styles corresponding to different exchange media. The interactions between the crew and the functions assigned to the crew are outside of the scope of this paper and are therefore modelled in a very simplistic manner. The detailed explanation of contributing systems and functions if provided in the subsequent paragraphs.

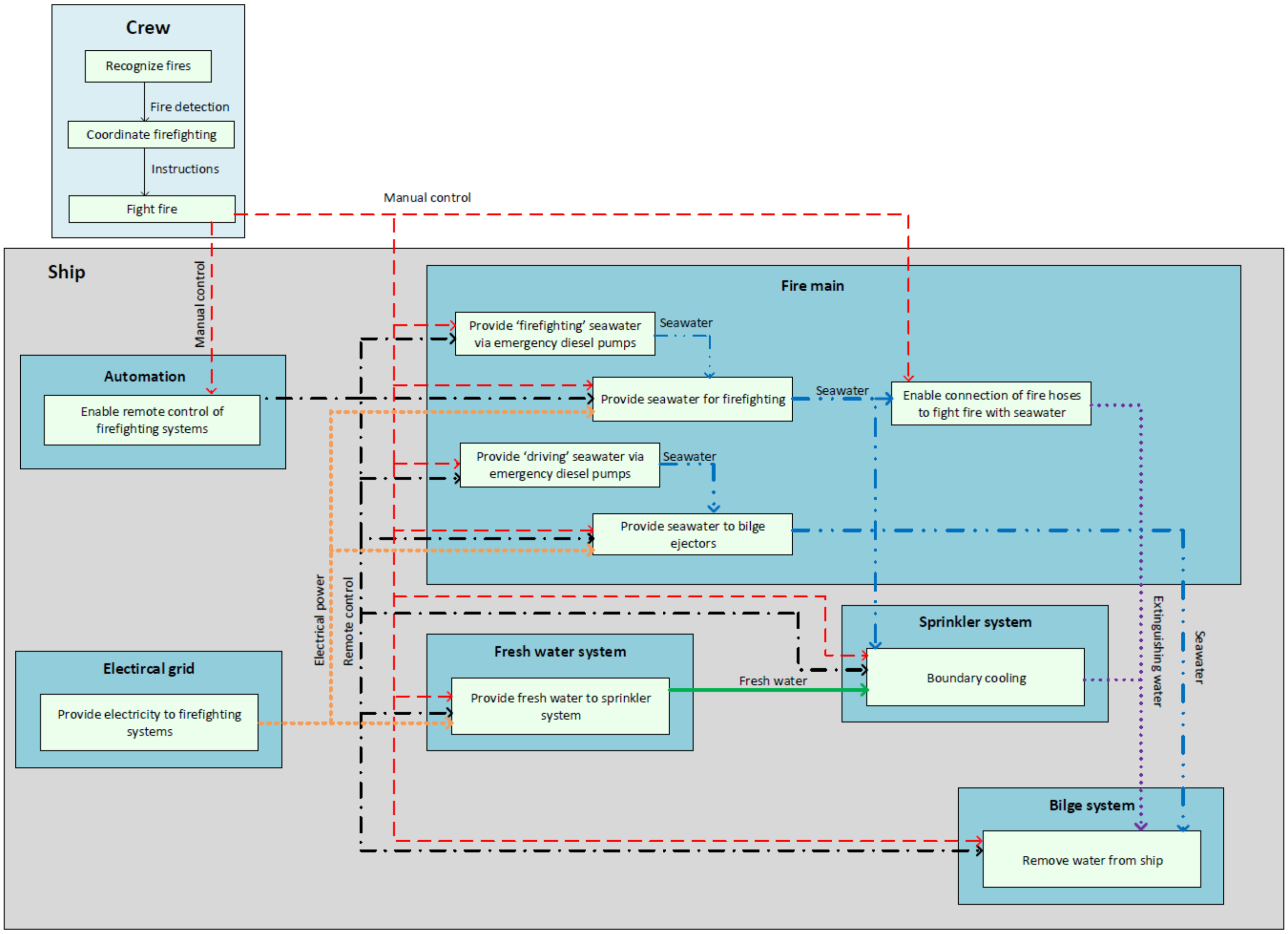

Figure 2. Simplified diagram of functional chain Firefighting

Firefighting during normal operation

In this scenario, the ship is sailing through friendly waters on the way to a deployment area. It is a quiet night and most of the crew are resting, except those on watch. During a routine patrol of the vessel, a petty officer smells a hint of smoke in the passageway and follows the scent to find that a fire had broken out inside an unmanned machinery space. The fire is clearly too big to put out with a fire extinguisher, so he immediately reports this to his superior officer. The alarm is raised and the officer gathers a firefighting team, coordinates a response strategy, and the crew promptly start firefighting using the onboard systems.

On this ship, fire hoses serve as the primary means of firefighting. The crew will normally use the hydrant located in the affected compartment or, if inaccessible, connect the fire hoses to the hydrants in adjacent compartments. The fire hoses are sufficiently long to span multiple compartments.

If fire is present in a compartment adjacent to an ammunition store, the store will require boundary cooling as a safety precaution to prevent an explosion. This is achieved with a sprinkler system which can cool the room using the fresh water supply or seawater as an emergency backup solution. Activation of the system is done either from one of the command spaces via the automation systems or by a local panel.

The build-up of extinguishing water, from both firefighting and boundary cooling, is removed from the ship via ejectors which are part of the bilge system. These bilge ejectors utilize the Venturi effect to enable the intake of water. To do so a driving medium is required, which in this case is seawater provided by the fire main.

During normal operation, the crew will activate all the electric pumps required for water supply via the integrated platform management system (IPMS), or alternatively every system can also be manually activated on the location. Two diesel-driven seawater pumps are available in case of a power outage.
Coming back to the firefighting crew, with all systems are available and functioning correctly, it only takes a few minutes for the personnel to take control and safely extinguish the fire. None of the crew suffered any injuries, but the damage is significant enough that the vessel will need to stop for emergency repairs at a friendly port. After a few weeks, she will be able to sail again and resume deployment.

Firefighting with a ship damaged in battle

Following the unscheduled maintenance due to the previous fire, the ship is back to full availability and continues the mission: protecting a vital trade route from pirates and other armed groups. Not long after the vessel and the crew arrive in the area, one of key countries in the region is shaken by a coup-d'état putting a hostile military dictatorship in power. The immediate collapse of diplomatic relations and escalation of the political conflict leads to something that would have been unthinkable just weeks prior. The hostile regime sends a barrage of anti-ship missiles towards the vessel. Three missiles are tracked and eliminated by the self-defence systems, but one gets through – the ship is hit.

After the initial impact, the crew promptly assess the severity of the situation. Again, a petty officer sees a fire inside the affected compartments and reports it to his superior. Clearly the blast has damaged most components, cabling, and piping in the affected compartments, so the performance of firefighting systems is now degraded. The question arises: will the crew be able to control and extinguish the fire?

To ensure that the vessel can fulfil the vital residual capability of firefighting, the relevant functions must be identified. They can be defined based on the normal operation, by determining which functions are considered essential after battle damage and, as such, require protective measures. This rationale causes several functions (from the 'normal' functional chain) to be labelled as non-essential. In this case, the loss of electrical power is acceptable thanks to the diesel-driven back-up for the electrical fire pumps. Similarly, remote control (provided by IPMS) is not essential since all required equipment can also be controlled manually.

The freshwater system has also been marked as non-vital, but for a different reason. The preferred medium for boundary cooling is indeed freshwater as it is less corrosive than seawater. Freshwater is however considered a limited resource as it takes time and energy to produce it, therefore the sprinkler system is also connected to the fire main as a backup, since seawater can be supplied virtually indefinitely. Marking the freshwater system as a vital system would imply that protective measures need to be provided to the system. This would likely entail either a redundant system layout or local protection. Both options would come with severe penalty to weight and space. The fire main is already designated as a vital system due to the seawater requirement of the hydrants and of the bilge system. Adding another consumer to the list will not result in a dramatic increase of the weight of the ship nor will it take significant space within. The preferred solution is to prioritize protection of one system instead of two.

All systems that are allocated a vital function are now considered vital systems. Therefore, the vital systems are the fire main, the sprinkler system and the bilge system. The remaining functions are considered required for the residual capability and are summarized (together with the systems they are assigned to) in Table 1.

Table 1. Functions forming the residual capability Firefighting

Vital System	Function
Fire main	Provide 'firefighting' seawater via emergency diesel pumps
Fire main	Provide seawater for firefighting
Fire main	Enable connection of the fire hoses to fight fire with seawater
Fire main	Provide 'driving' seawater via emergency diesel pumps
Fire main	Provide seawater to bilge ejectors
Sprinkler system	Room cooling
Bilge system	Remove water from ship

Damage extent analysis

During the damage extent analysis, the areas that are affected by weapon impact are determined, based on the specified design threat, vessel arrangement, and a set of assumptions. Only one battle damage event is considered at a time and the secondary effects, in this case fire, will only affect the damaged area.

In the scenario being analysed, a single damage case is evaluated; a missile hit in compartment C IV. This is considered a large hit affecting multiple compartments. The damaged area of the fictitious ship used in this case study is shown in Figure 3.

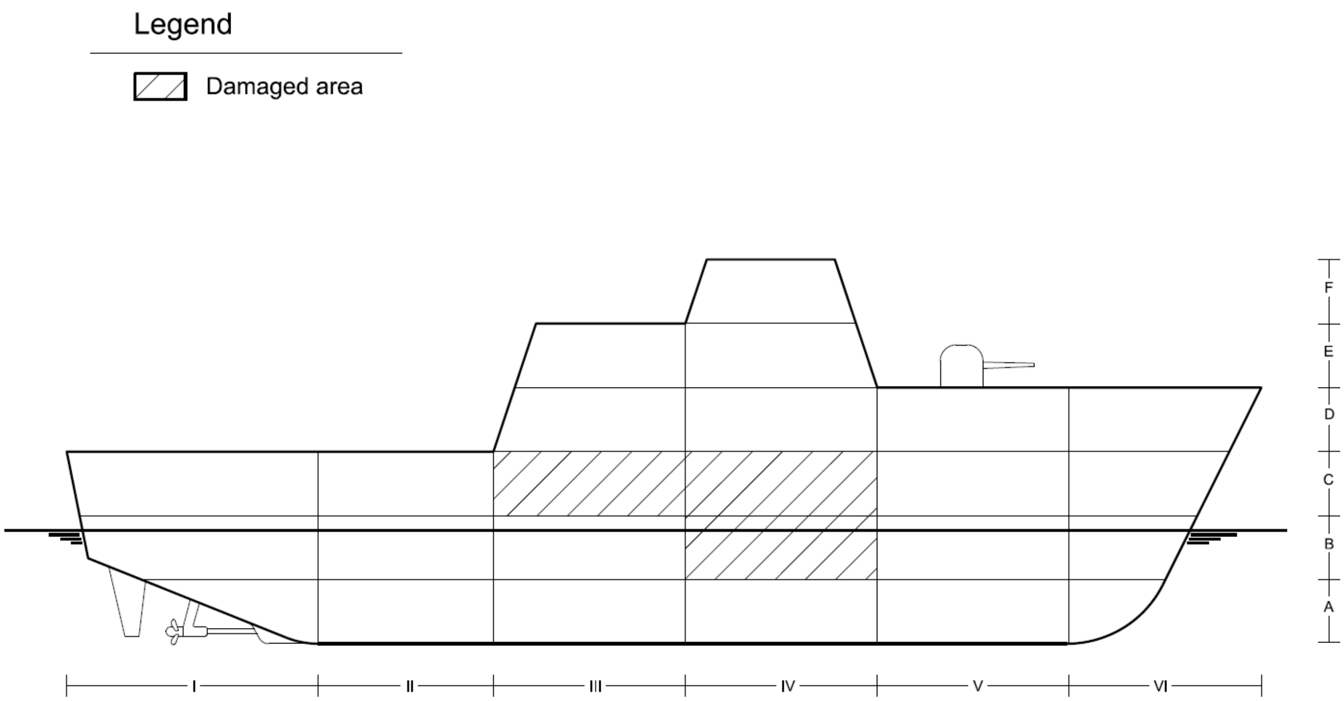

Figure 3. Side view of a vessel showing large hit damage

Damage effect analysis

All the vital systems are individually analysed for the selected damage case. Firstly, a brief description of the functions allocated to the system and the minimum expected performance of the system is provided, followed by description of the system layout and dependencies, and lastly performance after damage is discussed. The systems are discussed in the order of increasing complexity and the number of dependent systems: the sprinkler and the bilge systems are analysed first, followed by the evaluation of the supporting system fire main.

Sprinkler system

The sprinkler system only has one function which is to cool the ammunition room in case of fire in an adjacent space. This is also considered to be the minimum required functionality.
The layout of the system is given in Figure 4. To fulfil this function the system consists of branches with open nozzles (modelled as black bulbs) within the ammunition store. A valve is opened to allow seawater to enter the branches from the fire main (red flag).

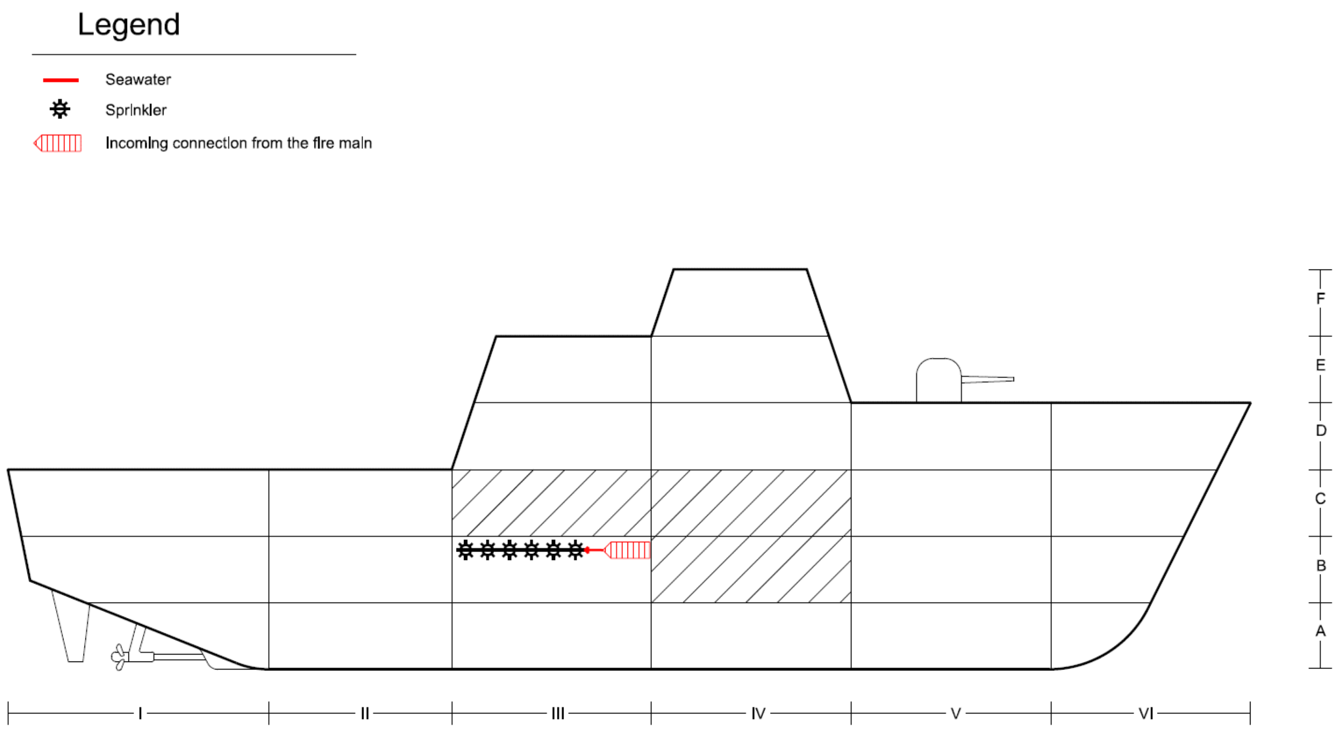

Figure 4. Layout of the sprinkler system

According to the system model, the sprinkler system is dependent on the crew, the automation system, the freshwater system, and the fire main. The sprinkler system requires the crew to activate the system and the fire main to provide a cooling medium to function properly. Automation, the electrical grid, and the freshwater system have been marked as non-vital and thus should be assumed to no longer provide any support towards the sprinkler system, i.e., full degradation is allowed. The dependencies of the system have been summarized in Table 2.

Table 2. Dependencies of the sprinkler system on other systems

System	Provision towards the sprinkler system	Allowable degradation	Effect of full degradation
IPMS (Automation)	Means of starting/stopping the boundary cooling.	Full degradation allowed	The crew will have to start and stop the system locally.
Crew	Means of starting/stopping the boundary cooling.	No degradation allowed	No means of starting or stopping the system.
Freshwater system	Provision of fresh water as a cooling medium.	Full degradation allowed	The sprinkler system will use seawater as a cooling medium.
Fire main	Provision of seawater as a cooling medium.	No degradation allowed	The sprinkler system no longer receives a cooling medium.

The system itself is located outside of the damaged area and therefore remains intact. This damage case does not prevent the system from fulfilling its function and therefore the performance is sufficient.

Bilge system

According to the system model, the bilge system is required to remove the water that has collected on A-deck from the ship. After battle damage, the source of this water will be from both boundary cooling and firefighting. The minimal required performance after any damage case is the ability to remove water from every watertight zone. The system layout of the bilge system is shown in Figure 5.

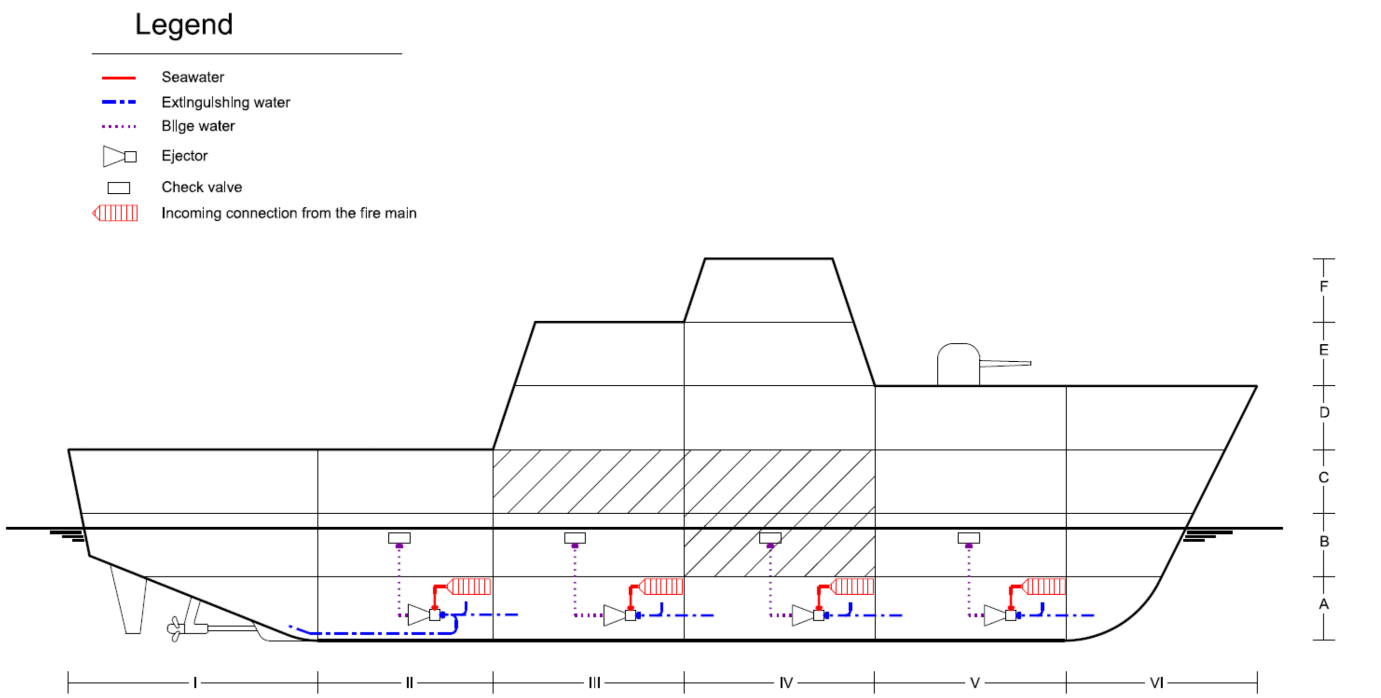

Figure 5. Layout of the bilge system

The system consists of four bilge ejectors which remove water from their corresponding compartment via suction lines (marked blue). Additionally, each ejector can drain the adjacent compartment forwards of the one it is placed in via an emergency suction line. The ejector located in compartment A II also has a suction line connecting to the aftmost compartment. When a valve is opened, the driving seawater (marked red) flows through the bilge ejector which starts removing water from the compartment. The mix of removed and driving water (marked purple) is then ejected from the ship via check valves in the decks directly above the bilge ejectors.

The bilge system depends on the crew to activate the system and on the fire main to provide a driving medium. Similarly to the sprinkler system, the IPMS is not required thanks to the back-up local control. Table 3 gives an overview of the system dependencies.

Table 3. Dependencies of the bilge system on other systems

System	Provision towards the sprinkler system	Allowable degradation	Effect of full degradation
Automation	Means of starting/stopping the bilge system.	Full degradation allowed	The crew will have to start and stop the system locally.
Crew	Means of starting/stopping the bilge system.	No degradation allowed	No means of starting or stopping the system.
Fire main	Provision of seawater as a driving medium.	No degradation allowed	The bilge system will not be able to remove water without a driving medium.

One of the check valves and its connected piping is damaged in this example. Thus, water cannot be removed via that compartment. However, the emergency connection is still available to remove water from compartment A IV.

The system can still remove water from every watertight compartment. The minimum performance is thus met, and the degraded state is considered acceptable.

Fire main

Most functions for this residual capability are assigned to the fire main. These functions can be summarized as providing seawater to the firefighting systems and allowing the connection of fire hoses. The minimum performance of this system is more complicated than the previous two systems as the fire main is a support system. The layout of the fire main is shown in Figure 6.

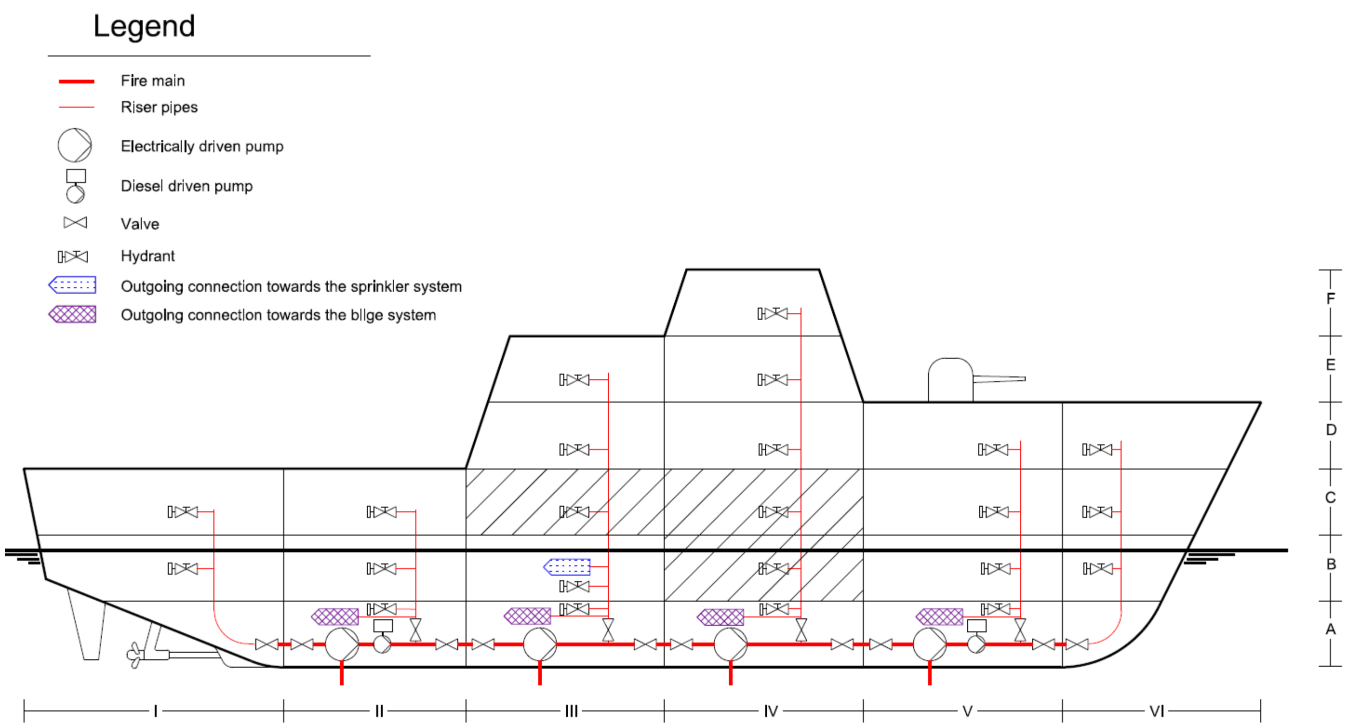

Figure 6. Layout of the fire main

Fire hoses are the primary means of firefighting, the minimum performance for the fire main is therefore the availability of a functioning fire hydrant in at least one compartment adjacent to every damaged compartment.

The bilge system needs a driving medium and is required to remove water from every zone, however that does not imply that seawater must be available in all zones. For this damage case, the minimum performance of the fire main is the availability of seawater in zone II, III, and V, so that water can be removed from every zone. Lastly, the minimum requirement derived from the sprinkler system is the availability of seawater in compartment B III.

The system consists of four electrically driven pumps and two emergency diesel driven pumps. To fight fire, boundary cool one room, and remove water from the ship, a single pump (electrically or diesel-driven) is required.
A valve is provided whenever the fire main penetrates a bulkhead and all riser pipes are fitted with a valve at A-deck. A little flag is added to signify when a riser pipe is connected to a different system. Hydrants are provided in every compartment. Table 4 gives an overview of the dependencies of the fire main.

Table 4. Dependencies of the fire main on other systems

System	Provision towards the sprinkler system	Allowable degradation	Effect of full degradation
Automation	Means of starting/stopping the (emergency) pumps.	Full degradation allowed	The crew will have to start and stop the system locally.
Crew	Means of starting/stopping the (emergency) pumps.	No degradation allowed	No means of starting or stopping the system.
Crew	Manual connection of the fire hoses and firefighting.	No degradation allowed	No means of fighting fire.
Electrical grid	Provision of power towards electrical firefighting pumps.	Full degradation allowed	Emergency diesel driven pumps will provide seawater for firefighting.

The system requires electrical power for its four main pumps. The generation of power is not guaranteed as it is not marked as a vital system for firefighting, as such it should be assumed that the main pumps are not available. The crew will therefore activate the emergency diesel-powered pumps.

Two riser pipes are located in the damaged area, so these riser pipes will be closed off to isolate the damaged part of the system. The function to fight fire with hoses remains available as the compartments adjacent to the damaged area are equipped with working hydrants that can provide seawater. However, seawater cannot be supplied to the sprinkler system in compartment B III or the bilge system in compartments A III & A IV, since they are connected to the closed-off riser pipe. The functions "Provide seawater to bilge ejectors" and "Provide seawater for firefighting" are not fulfilled. This is not an acceptable performance, thus adjustments to the system are required to improve the availability of seawater.

The supply of seawater towards the bilge system must be evaluated. As discussed before, part of the bilge system is located in the damaged area, therefore the bilge ejector located in compartment A IV will remain unavailable even if seawater is supplied. However, the ejector located in compartment A III has an emergency suction line to compartment IV. Both compartments A III and A IV can thus be emptied if the bilge ejector in compartment A III is supplied with seawater. An additional valve could increase the availability of the seawater supply.

The supply of seawater to the sprinkler system must not be compromised. A solution could be either a second pipeline routed to the sprinkler system or smart placement of an additional valve. The pipeline is not the preferred solution as it adds additional weight, takes up space and further adds to the complexity of the system. The recommended solution would be placing an additional valve in the riser pipe located in compartment B III above the connection to the sprinkler system, as shown in Figure 7. This would ensure the availability of seawater to both the bilge system and the sprinkler system. With the additional valve implemented all functions assigned to the fire main can be fulfilled to an acceptable standard.

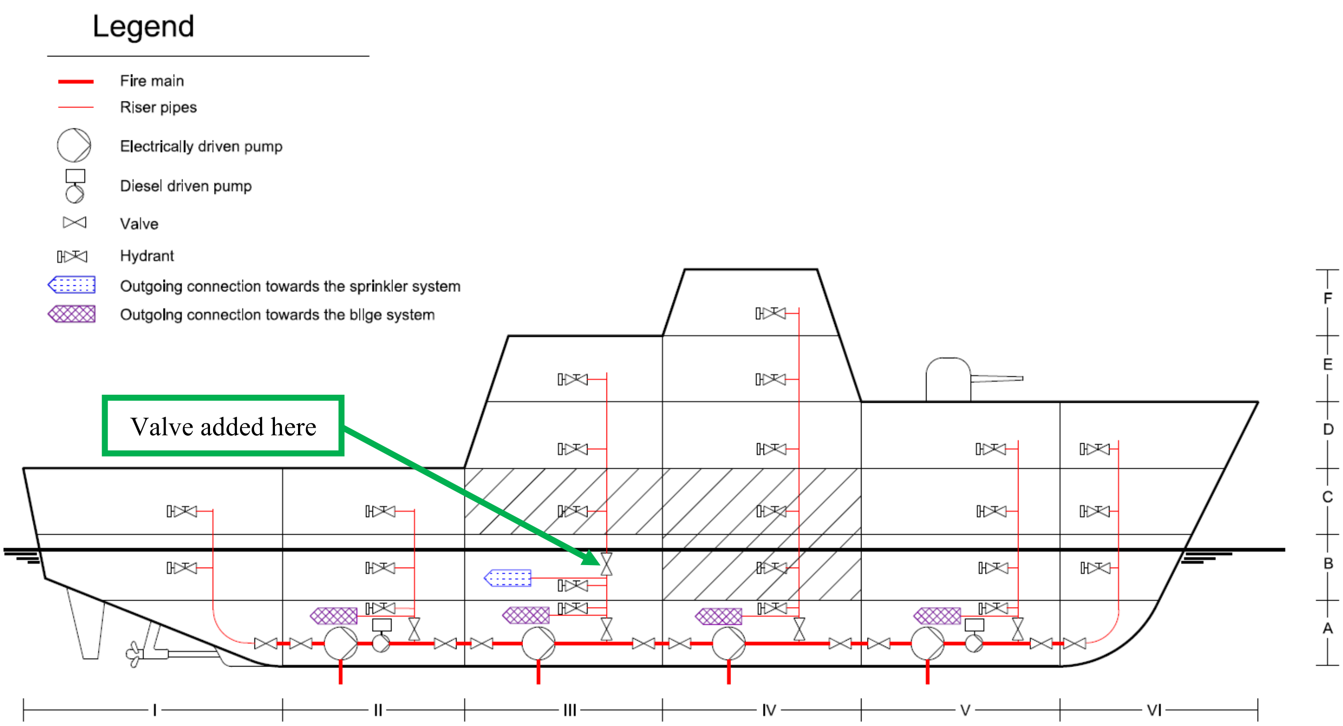

Figure 7. Placement of the additional valve based on vulnerability analysis

Firefighting after battle damage

Luckily for the crew, this comprehensive system vulnerability assessment had been completed on the design stage and the additional valve is present. The commanding officer leading the firefighting operation is well-aware of the design of the vessel and the damage control response required to ensure the performance of the firefighting systems.
The officer orders one of his crewmates to close the valve in the riser pipe located in compartment B III and open the valve connected to the sprinkler system located in the same compartment. He directs another crewmate to open the valve connected

to the bilge ejector located in A III. Two people are sent to start the diesel-powered pumps and the remaining firefighting crew are set to fight the fire within the compartment using the fire hoses. Even with fewer systems available, the crew are able to extinguish the fire successfully, keeping the ammunition store intact.

Since the ship sustained severe structural damage from the missile impact, she will require major repairs before returning to service. The important thing is that the platform was salvaged and the crew members are able to make it home safe and sound and live to sail another day.

CONCLUSIONS

The example showed that with minimal changes to the design, the survivability of the ship could be significantly increased, whilst avoiding unnecessary penalties to other design aspects. It is worth stressing, that the example only considers one capability, a small selection of systems and a single damage case. Naturally, the complexity of the analysis increases as more vital capabilities, systems, and damage cases are included. Nonetheless, by employing the approach presented in this paper, it is possible to break up the analysis into manageable parts and evaluate ship's resilience in a logical and structured manner. The functional model serves as an excellent tool to determine how degradation of individual functions is detrimental to the required residual capability. Overlaying this information with the calculated damage extents results in an analysis that focuses on the protecting the functionality of the ship rather than individual components. This fine-tuned approach to vulnerability analysis makes it possible to deliver more resilient and better optimised designs in a cost-efficient manner.

CONTRIBUTION STATEMENT

Michal Czop: investigation; methodology; writing – original draft; writing – review and editing.
Demi van Megen: conceptualization; investigation; methodology; writing – original draft; visualisation.
Koen Droste: conceptualization; investigation; methodology; supervision.

ACKNOWLEDGEMENTS

We extend our heartfelt gratitude to the following colleagues who played pivotal roles in the development and success of this work:

Jitte van Dijk and **Marijn Hage**: Their invaluable expertise in system modelling elevated the quality of the theoretical foundations of the paper. Furthermore, their dedication and insightful feedback significantly contributed to the overall quality of the work.

Rob de Gaaij and **Sander Allefs**: On the discipline front, Rob and Sander provided encouragement, guidance, and institutional support which made the creation of this paper possible. We appreciate their commitment to our shared vision.

Additionally, we would like to recognise **Damen Naval** for providing the time and resources necessary to complete and present this work to the IMDC.

REFERENCES

Voirin, J.-L. (2017). Model-based System and Architecture Engineering with the Arcadia Method. Elsevier.

Roques, P. (2017). Systems Architecture Modeling with the Arcadia Method: A Practical Guide to Capella. ISTE Press.