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From Functional Arrangement to Vulnerability Assessment: Automating Naval Ship Design for Enhanced Survivability Analysis

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ABSTRACT

A novel method has been developed to rapidly assess vulnerability of a new platform which has been generated through a packing approach. This method quickly transforms a volumetric packing model into a surface model that includes ship structure including doors and hatches, mission critical systems and the crew. A weapon model was developed taking into account the unpredictability of a threat by generating multiple scenarios with the Monte Carlo method. Based on this set of simulations vulnerability measures can be introduced in a weight efficient manner. This in turn will allow the naval architects to design safer naval ships in balance with other requirements. This paper describes the process of vulnerability analysis in early ship designs and the feedback loop of conclusions to the designers

KEY WORDS

Design; Vulnerability assessment; Naval ship; Internal Explosion; Fragmentation; Early ship design; Survivability.

INTRODUCTION

Command Materiel and IT (COMMIT) is responsible for the procurement and sustainment of the navy ships (van Oers et al. (2018)). The FIDES tool has been developed by COMMIT to facilitate the process of procurement, in which initial optimizations are performed with respect to layout and weight (Takken (2008)). Once a set of concept designs have been deemed acceptable, it becomes more important to test these designs on the aspect of ship vulnerability with the potential threats which this new navy ship can face. This analysis is directly performed after the initial early design process and should give insight on the ship design when it is still possible to alter the layout and component placement. The purpose of the paper is to demonstrate tooling and methodology in which TNO supports COMMIT with ship vulnerability assessment against damage from threat weapons. The tool entails the process of transforming the volumetric FIDES model that COMMIT produces into a model suitable for TNO's software RESIST (RESilience of Ship Targets), as well as the tooling used for developing the threat information and threat detonation locations. The tooling will be demonstrated in the following order: the model transformation of a volumetric model to surface model process by means of ShipMATe (Ship Modelling through Automated Technology) is demonstrated. Manual steps are performed to rapidly setup a RESIST model which includes both structural and systems information. Secondly the fragment distribution model of the threat weapon is explained. In-house developed tooling is used for determining the threat detonation locations. Lastly the RESIST tool is showcased in which the weapon effects are made visible for a specific case study. In this case study an initial ship layout is used with

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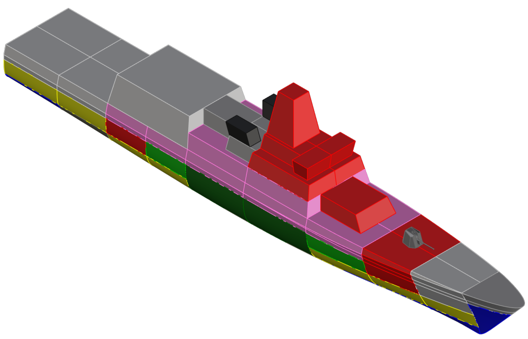
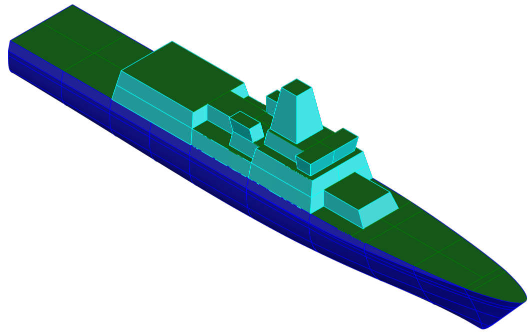
specific conservative demands through which vulnerability improvements can be showcased. Various vulnerability reduction measures are applied to the ship and their effectiveness is determined based on the ship system state, after which a set of combined vulnerability measures are synthesized. These results are then communicated with the naval architects which concludes the vulnerability analysis process.

SHIP MODEL DEVELOPMENT PROCESS

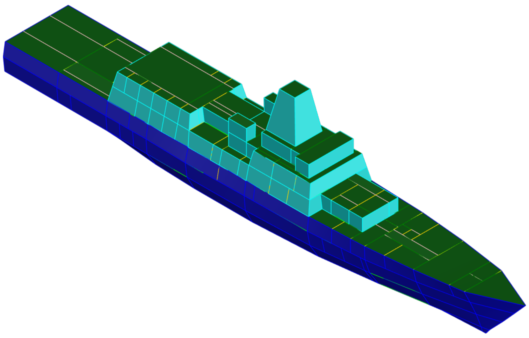
As mentioned in van Oers et al. (2018) the Netherlands Defence Material Organisation (present day COMMIT) is responsible for the procurement of new navy ships. This includes the exploration of the naval ship design during the early stages of such a procurement process. During the exploration of the initial ship design, several different volumetric functional arrangement models are built with the tool FIDES (Functional Integrated Design Exploration of Ships), see Takken (2008). With the help of this tool various design routes are explored in which each route undergoes their own design loop in which stability, weight, costs and other requirements are assessed. Once such a design seems feasible, the model is shared so that more detailed analysis can be performed. Vulnerability requires more detail since it is influenced by a broad set of parameters: the ship structure, the placement and robustness of components, the routing of cables and pipes and the location of crew members. The threat definition based on the ship's mission is important for the assessment of vulnerability, which requires a different type of modelling effort. To quickly deliver a vulnerability assessment, the model building process from Figure 1 should be automated as much as possible.



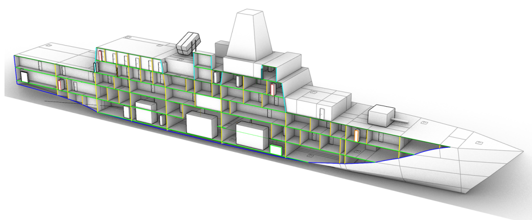
(a) The volumetric packing model in FIDES



(b) The surface model that is automatically generated from FIDES model



(c) The surface model transformed and simplified to a RESIST structural model



(d) RESIST model including passageways, components and systems

Figure 1: The process of model development through ShipMATe

During the early design stages, designers at COMMIT require an evaluation of design iterations within weeks. Next to the development of the initial arrangement, the designers also develop an initial plan of the routing and make an initial estimate of the primary component placement, see van Diessen et al. (2022). ShipMATe (Ship Modelling through Automated Technology) was developed to quickly prepare these initial ship arrangements into a model suitable for vulnerability assessment. The process is illustrated in Figure 1 and works in three distinct steps; The first step transforms the volume based FIDES model, portrayed in Figure 1a, into a surface model, shown in Figure 1b. The FIDES model that has been used for this paper is the same as the one developed for the automatic routing paper of COMMIT (Duchateau et al. (2018)). The reason for this surface model creation step is that most of the vulnerability analyses uses either a quadrangular surface with a specific thickness or shell elements in the case of FEM (Finite Element Method) model. This process is nearly completely automated while it allows the naval architect to make changes in the layout during the transformation process.

The second step in the process is to turn this surface model into a simplified surface model that only consists of quadrangular surfaces which is portrayed in Figure 1c. The reason for this simplification is that the current blast response model within RESIST requires a panel with two distinctive bending directions. This simplification affects the ship hull and panels that are in connection with the hull. These include: watertight bulkheads, transverse bulkheads and the hull panels. After this process is finished, the following steps will focus on including the structural data of the ship. Structural data is allocated to the various panels with the help of a ’scantling sheet’. This sheet appends the longitudinal and transverse stiffeners to various panels based on their type (deck, hull, longitudinal, watertight bulkheads and regular bulkheads) and their location (zonal position and deck level). The values for each of these properties are discussed with a naval architect specialised in the field of structural engineering. The inclusion of structural properties are essential for this type of vulnerability analysis since a more realistic approach for damage is used in this stage, which is where the analysis differs from other early design studies (Goodfriend and Brown (2018); Cramer et al. (2011)). The final structural properties of the panels can be modified if required. This allows the naval architect to add the necessary details to compartments which differ greatly in structural properties compared to the standard ship layout such as the ammunition storage rooms, the helicopter deck and the diesel generator room.

Once the structural model of the ship is completed, the systems on board of the ship can be created. Systems are included in a simplified manner because only limited information is available during the early design stages. Firstly the major components are approximated as filled bars, which include a skin material, skin thickness an internal material and a filling grade. This methodology is applicable to components ranging from small sensors to large components like diesel generators. The second step is to make an initial routing between the major components. Cable or pipe routing is often the more vulnerable part of the overall system. This process is currently performed manually, however tooling is in development to automate this process. The final step, see Figure 1d, in this process is to add the system logic to the model. The primary system logic is represented in a directed-graph, the requirements which check the ship state are represented in a tree structure. With all the necessary elements of the ship prepared an xml is generated by ShipMATe which allows for a direct transfer of the model into the RESIST software.

The ship has the following systems on board:

- The ship has a CODLAD (Combined diesel-electric and diesel) propulsion system
- The ship has a single anti surface weapon system and a single anti air system
- The ship has a single radar mast
- The ship includes for this study only the chilled water distribution and electrical distribution as auxiliary systems

THREAT MODEL

Where system studies commonly simplify the damage extend to compartment based rules , see (Duchateau et al. (2018); Jansen et al. (2020)), the damage extend for this systems study is based on physics-based model in which the threat consists of a blast and fragmenting warhead. A missile carries the warhead to the target and the fuse mechanism determines the detonation location, which could be either inside or outside the ship. The warhead is commonly a high explosive contained in a metal casing. The metal casing can be smooth resulting in natural breakup of the casing in fragments, or the casing can contain pre-formed fragments of most any shape. In this paper we have assumed an anti-ship missile with a naturally fragmenting casing. There are several models available to describe the fragment distribution from such casings, one of which is given in ANEP43 (NATO Standardisation Office (NSO) (2014)). This describes a generic approach based on the warhead geometry and a mathematical mass distribution. For the current study, we have made use of the SPLIT-X tool from Numerics GmbH. SPLIT-X includes an elegant approach to natural fragmentation where the Hoop strain of the expanding metal is compared to the material tensile strength. SPLIT-X results in a spatial distribution and mass distribution of fragments. These stochastic distributions have a certain level of randomness, which is also witnessed in testing of shells or warheads. The break up process results in a unique distribution for each and every test. This requires a probabilistic approach when dealing with natural fragmentation, every run will yield in different fragment loading on the construction (although RESIST includes the option to fix the random seed, so that identical runs can be performed). Ejection velocities of the fragments are based on the Gurney velocity (Gurney (1943)).

The blast module in RESIST is deterministic in its approach. Every run of the same scenario will yield the same blast loading results on the structure. Reflected blast waves are determined using the mirror approach; the detonation charge is mirrored with identical charges in the plane where the reflection takes place. A target panel is divided in discrete loading areas and reflections up to first or second order from all other panels in the compartment are taken into account. Quasi-static pressure level is determined using a TNO-developed model for the rise time. Isentropic venting is based on leakage through failed decks, panels and doors. The response of the blast loaded panel is based on an advanced Single Degree of Freedom (SDOF) model (van Erkel (1992)) that is solved by time step integration. Failure is based on empirical strain values at the rim of the panels. RESIST combines the effects of fragments and blast: panels are weakened when fragments perforate before the blast wave arrives.

Threat physics definition

The threat considered in this case study is a sea skimming anti-ship missile. Sea-skimmers approach the ship a few meters above sea-level. Sea-skimmers have a circular error probability (CEP Webb (2012)) that is significantly smaller than the ships dimensions, and therefore can hit the ship at a specific spot. Weapon system ballistic performance is often expressed in CEP. In statistics the standard deviation is often used for expressing Gaussian distributions.

Here the assumption is made that the aim-point of the missile is selected near the bridge of the ship. This likely improves weapon effectiveness, because the centre of the ship contains more valuable compartments than the bow and the stern. The current model assumes no special manoeuvres. For optimal probability of hitting a target, a sea skimmer should hit the target from the side, with enough margin to miss the water, and low enough to not miss the freeboard. For users of the derived detonation point clouds it is recommended to check if the aim-point aligns well with the ship most important compartments. The model assumes an average impact altitude above sea-level, with a standard deviation. A dive angle is drawn from a uniform distribution, which corresponds to a slight dive in the terminal trajectory. Although not fully representative, the relative bearing of the missile with respect to the ship is chosen with a uniform distribution. For the fusing mechanism an impact delay fuse is chosen, with a delay that aims for a detonation near the centreline of the ship.

Uncertainty of the detonation location

The impact location of a threat on a naval vessel depends on a number of parameters in the flight trajectory of the missile, the seeker head, the fuse mechanism and the signature of the vessel. Therefore, a Monte Carlo Method is used to account for multiple scenarios. The Monte Carlo method that is used for the points distribution operates in the following manner: the impact location of the warhead on the ship is determined which can be achieved by either pulling a location from an uniform distribution (mostly applied for shells) or by using a Gaussian distribution. Limitations can be applied for the impact locations for threat, for instance the height range is limited for the sea-skimmer whereas the impact locations of the grenade threat is limited to impacts on the decks.

The other properties of the threat that are determined with a Monte-Carlo method are the elevation and azimuth angle. The

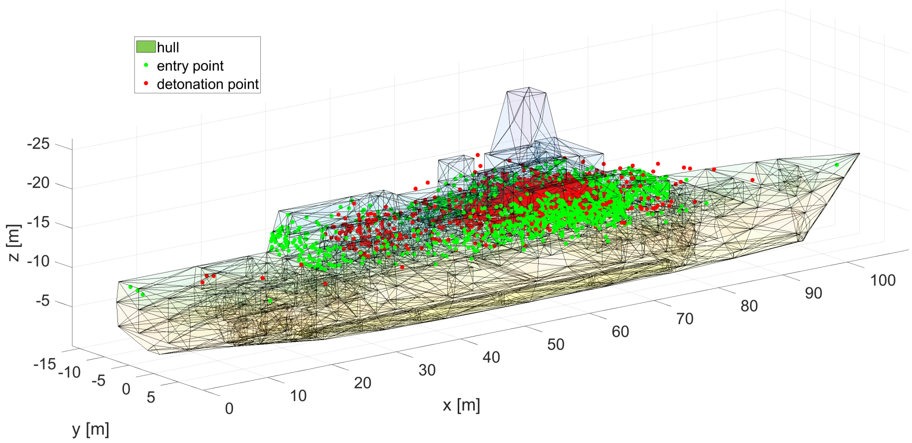


Figure 2: The impact and detonation points generated by the Monte Carlo detonation generator

velocity of the threat is fixed in this set of simulations since no distance based assumption is included for the determination of the threat properties. Finally the detonation mechanism of the threat needs to be defined, this can either be a deck counter or a proximity (delay) timer. With all these properties included a set of detonation locations are determined, similar to the example in Figure 2. The number of impact locations that is required for the analysis is dependent on both the type of analysis and the required confidence interval. As an example when we investigate the binary state of the ship with a confidence interval of 95% then about 1200 simulations are required to limit the error band to 5.7% (Clopper and Pearson (1934)).

CASE STUDY

With the ship model prepared and the threat impact points generated a set of Monte Carlo runs can be performed. The first results are the indicator to find improvements in the design. This ship model has been made so that it is not fully optimized with respect to vulnerability a priori. By performing an initial run of the Monte Carlo simulations on this baseline ship, the effectiveness of measures are demonstrated. The vulnerability is tested on the baseline ship by checking if the ”Mission Capability” state of the ship is still met. The ”Mission Capability” state is defined by the following conditions:

- Power must be available in each of the zones of the ship
- The SeWaCo (Sensor Weapons Communication) system must be active

  The mast must available

  Chilled Water must be available

  2 out of the 3 servers must be available and cooled

  Either the anti-air or anti-surface weapon system must be available
- The ship must remain mobile

  One of the propulsion lines must be operational

  One of the propulsion machinery (diesel-electric or diesel) must be available

  One of the steering gears must be available

The vulnerability of the ship can be minimized by intelligently combining the different measures. The second step of proposing effective vulnerability measures is to assess how effective various vulnerability measures are. To assess the effectiveness of the vulnerability measures three variations of the ship have been made. Once a model is setup, it becomes easy to update the model with new additions to the design.

The first modified ship model has all its transverse bulkheads upgraded to blast and fragment resistant bulkheads (HARNESS bulkheads in this case , see van der Wal et al. (2018)). The outcomes of the simulations, visualized in Figure 3b demonstrate two areas in which the HARNESS bulkheads prove to be particularly effective when compared to the unprotected state. The first point is allocated at deck C underneath the bridge and close to a chilled water riser and a server room. The original 40 runs that take place in this compartment are rendered harmless due to the bulkhead taking more dynamic load of the blast wave and while also reducing the amount of fragments that would normally hit the servers. Similar effects are seen at deck D at the compartment second left to the furthest right bulkhead of the main superstructure. In this case a chilled water riser is protected significantly increasing the survivability of the local systems that require cooling like the server and the distribution board nearby.

The second vulnerability measure that is explored is increasing system redundancy. The ship design was improved with the redundancy of the electrical system of the ship, whereas the chilled water system remained unchanged. The chilled water system was not altered in this model since it required to add piping, whereas the electrical system does not require extra cable trays. The redundancy is increased by linking a load centre to two different distribution boards. The difference between the regular layout (Figure 4a) and redundant layout (Figure 4b) is the interconnection of the main switch board and that each load center is linked to two distribution boards.

Aside from the Monte-Carlo distribution, which is shown in Figure 3c, the actual performance of the systems can also deliver insight which parts of the systems benefit from the redundancy. For this case-study the system based comparison are made for the “Power to all zones” requirement of the ship and to investigate the performance of the mast which is a single point of failure within this ship design. Figure 5 shows how the overall “Power to all zones” criteria is met in more cases. It should be mentioned that the increased redundancy measure seems to be having the most effect in zone 3, whereas for example improving zone 2 does not increase the performance by much. The mast increases in survivability significantly as well, as shown in Figure 6. The load centre of the mast is in zone 3, meaning that increasing redundancy is a worthwhile effort.

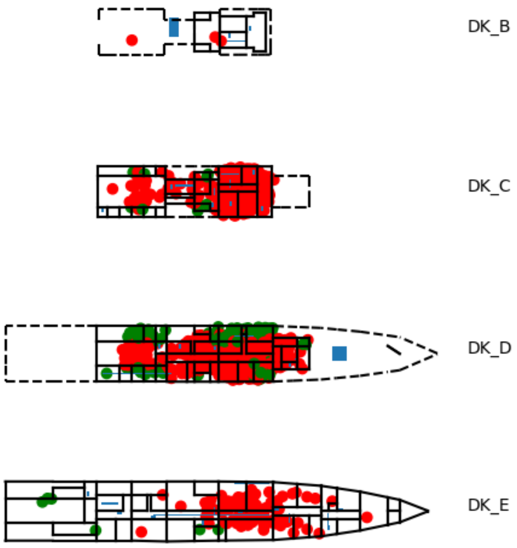
The third vulnerability measure that has been investigated is that of hardening the components within ship. The ship model has been altered in such a manner that all the kill criteria of the components have been tripled. The kill criteria include the maximum pressure and maximum amount of kinetic energy that a component can withstand. Based on the results of this set of simulations, illustrated by Figure 3d it can be concluded that increasing the strength of the components is the most effective solutions. An analysis tool is used to see which hardened components improve the resilience the ship the most. This is done by correlating the increased “Mission Capable” states and see which components did not fail in these specific runs. The conclusion of this analysis is to harden the components that are close to the single points of failure like the chilled water piping close to the mast and the cables to the load centre of the mast.

By combining the lessons of the three sets simulations with different vulnerability measures, the following adaptations have been made to a final model:

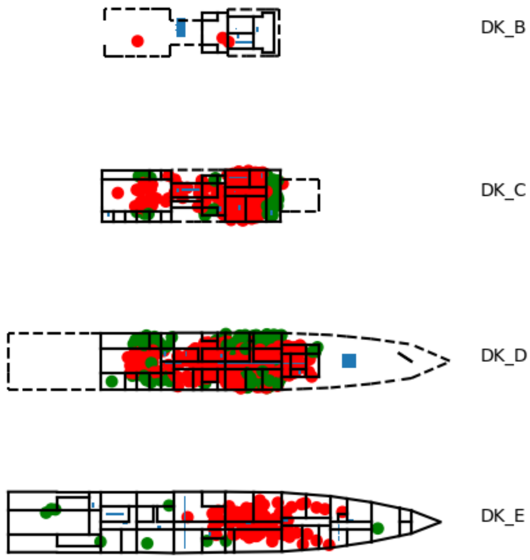
- The HARNESS bulkheads will be placed in the areas where they caused reduction in vulnerability, this is highlighted in blue in the results
- Zone 3 and zone 4 will have redundant cables to significantly increase performance of the zonal power requirement
- The components with respect to the single point of failure (the mast and its subsystems) will be hardened

Each of these measures have been selectively chosen and the weight of the ship is only marginally increased by the adjustments:

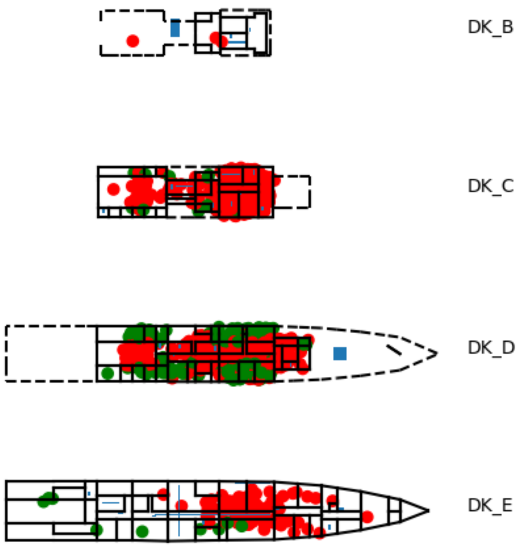
- The cables and piping that have been strengthen has been limited to 100 meters. This is realised with an armoured



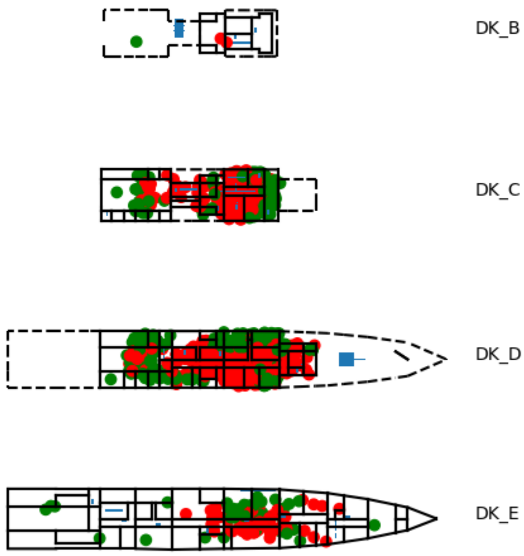
(a) The vulnerability of the unprotected ship



(b) The vulnerability of the ship with HARNESS bulkheads



(c) The vulnerability of the ship with extra redundancy



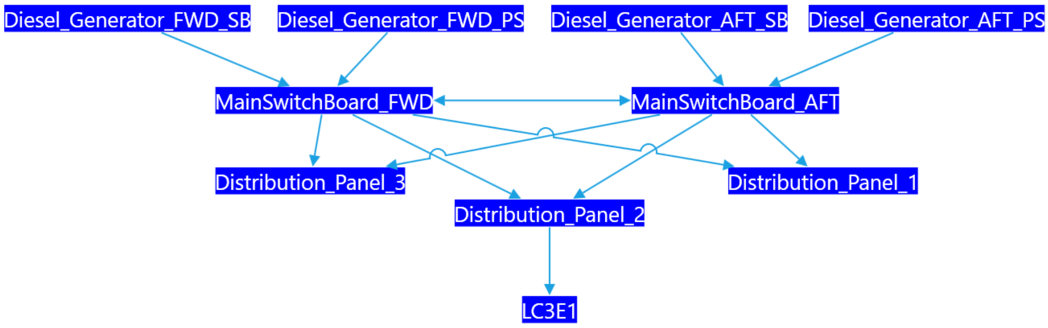
(d) The vulnerability of the ship with stronger components

Figure 3: Monte Carlo results with a sea-skimmer threat, showing when the ship is "Mission Capable" in the colour green after impact

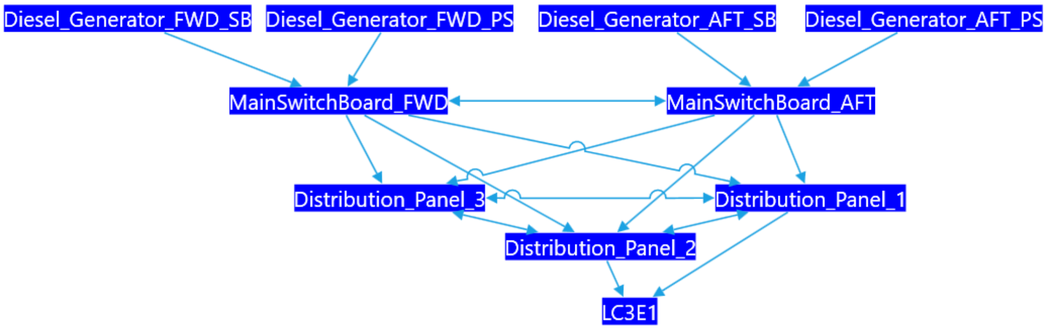
tray of about 0.1 m tall and 0.4 m wide, in which both cables and pipes can be protected. This would result in a weight increase of about 3 tonne

- The area of panels that have been turned into HARNESS bulkheads is about 100 square metre which results in a weight increase of about 9 tonne
- The increased weight increase of the redundancy is hard to estimate since the cable trays were already in the model. Extra cables would have to be introduced but this is more complicated to give insight in.

By performing a new set of Monte Carlo calculations there is a clear decrease in vulnerability as shown in Figure 7. The to-

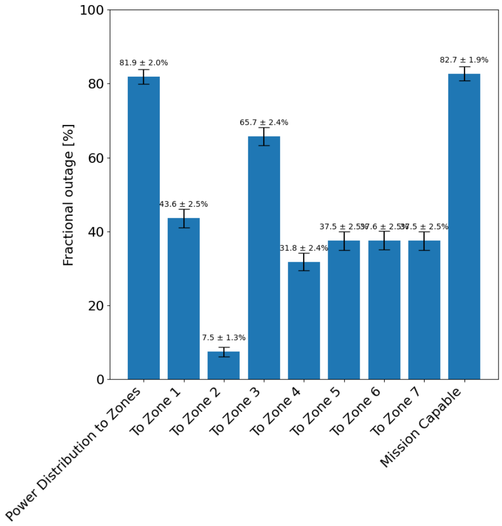


(a) Regular layout electrical system to a single load center

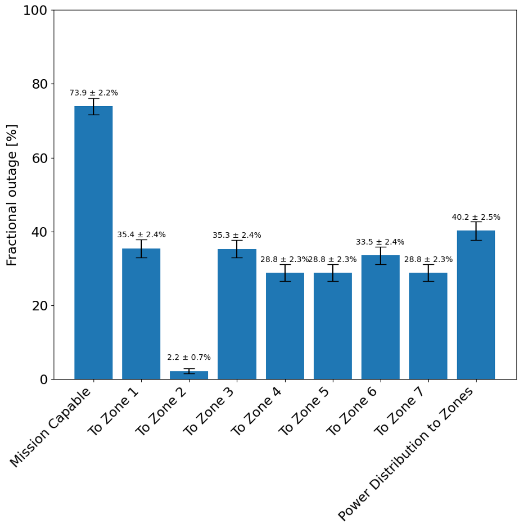


(b) Redundant layout electrical system to a single load center

Figure 4: Comparison of the system layout between the regular and redundant system



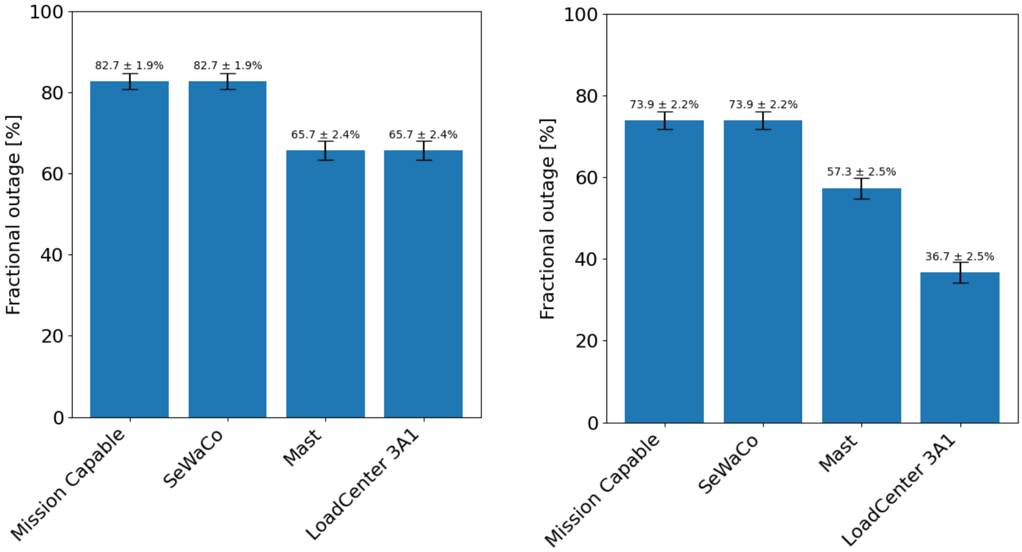
(a) System outage of the unprotected ship



(b) System outage of the redundant ship

Figure 5: ”Power to each of zones” requirement in relation to the ”Mission Capable” state of the ship

tal availability, that is the 100% minus he percentage outage, of the mast increases from 34% to 43% , the availability of the power in zones from 18% to 60% and the overall ”Mission Capability” has been met from 18% to 33%. It does demonstrate that a ship with a lot of single points of failure it is impossible to retain the ”Mission Capability” state for all the impacts. However, using a smart selection of measures a great deal of vulnerability can be reduced. These upgrades to the ship de-



(a) System outage of the unprotected ship **(b)** System outage of the redundant ship

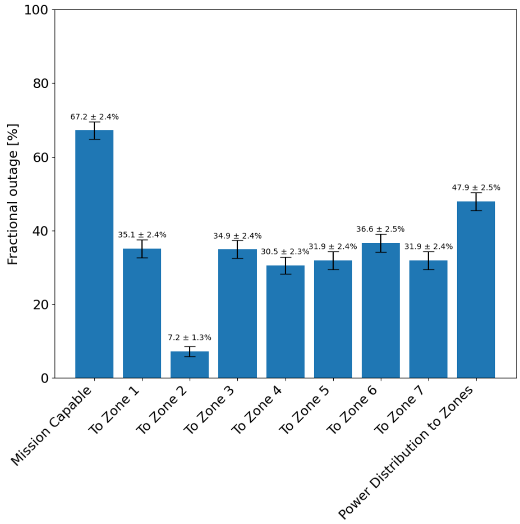
Figure 6: Mast availability requirement in relation to the ”Mission Capable” state of the ship

sign were verified and could be advised to the naval architects in the design department of COMMIT to include in the next iteration of the design. The naval architects review whether the vulnerability reducing measures can be accommodated taking into account volume, weight, estimated cost and other requirements. This review is based on a balance between the penalty on a specific requirement and the gain in survivability of the ship.

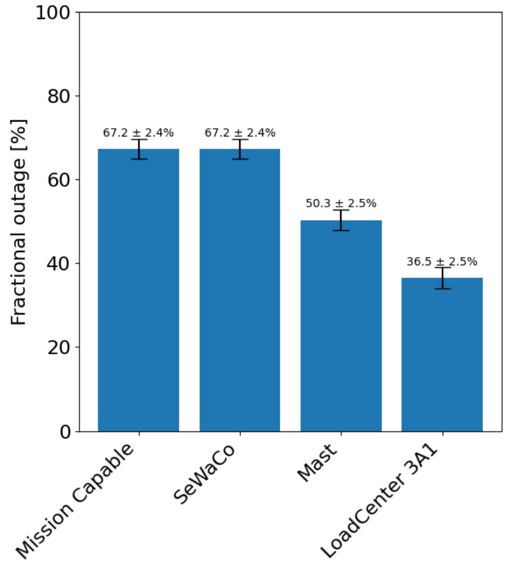
CONCLUSIONS

Through an automated process of model conversion it is now possible to evaluate an early stage ship design with respect to vulnerability. While the process requires the knowledge of a naval architect with respect to the structure and the component placement, quick simulation can aid the further improve the arrangement design. The threat modelling methodology demonstrates the need for the inclusion of both fragmentation and blast damage. Following from the probabilistic and non-uniform behaviour of the fragmentation model it is necessary to determine the detonation locations in a probabilistic manner. The detonation location tooling is based on specifics of a missile, such as the final flight trajectory, seeker head and fuse mechanism. When accounting for the variability of both the threat and threat detonation location a baseline for the assessment of the ship can be produced and weak points of the ship arrangement can be identified.

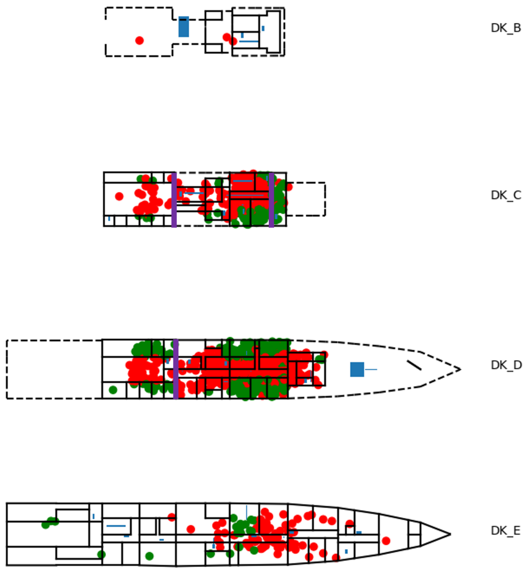
Based on the ship design variations the effectiveness of the vulnerability reduction measures could be determined and a smart selection of measures was made. This complete process shows how rapidly vulnerability of primary damage can be reduced, however for the inclusion of secondary damage and damage control, further model development and tooling should be developed. TNO and COMMIT continue to work closely together to further shorten the feedback loop of consequences by design choices on the vessel’s vulnerability. This allows for participation in concurrent design sessions, in which several disciplines work together on the design of a new vessel. Such sessions require on the spot answers to questions relating to vulnerability, or at least within weeks between subsequent sessions. Based on the work described in this paper COMMIT and TNO are able to iterate early ship designs to achieve a ”first time right” design that is compliant with the vulnerability requirements.



(a) Zonal system outage of the ship with survivability measures



(b) Mast outage of the ship with survivability measures



(c) The vulnerability of the ship survivability measures

Figure 7: Mast availability requirement in relation to the ”Mission Capable” state of the ship

FUTURE WORK

Further work focusses on combining the disciplines of susceptibility and recoverability, so that the entire chain of survivability of a naval vessel is covered. Vulnerability experts and experts on signatures (susceptibility) can for example work on technologies to predict and manipulate hit locations of particular missiles. When all countermeasures fail, the hit location may be steered to a spot with minimal crew attendance at that particular moment or to a spot with minimal consequences on operational availability of systems. A priori RESIST simulations can populate lists of such locations for a number of threats.

The future work could also aim to combine the routing optimisation that is performed by the designers with the a better definition of the damage extend that is defined by the analysts. This would bring the topic of vulnerability in a more realistic manner earlier into the design process.

CONTRIBUTION STATEMENT

H.J. den Ouden: Conceptualization, methodology investigation; writing – original draft. **R. van der Wal:** supervision; writing – review and editing.

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