Designing resilient fleets for maritime emergency response operations

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Abstract

In this paper, we investigate the problem of designing resilience into a fleet for maritime emergency response operations. A broad set of events can trigger emergency response, requiring that a fleet of vessels for this purpose must contain a diverse set of functionalities. We can obtain significant gains in fleet resilience by taking advantage of functional overlaps between equipment installed on, or refitted onto the vessels. Combining design structure matrices and tradespace analyses with failure modes, we evaluate the performance of fleets for emergency response operations. The approach is illustrated with a small, qualitative case.

Keywords: Maritime operations, Fleet design, Resilience

Introduction: The elements of the maritime environment

Humankind has been connected to the sea throughout recorded history and ocean-related activities we engage in are continually expanding. Globalization has spurred an amazing increase in trade, and has contributed to the emergence of complex maritime supply chains. The oil and gas industries have expanded further offshore in areas with deeper water since the first offshore wells were constructed, and similar trends are expected in the aquacultural industries. Coastal areas are home to most of the larger population centres, with ports providing easy access to global markets. The oceans also act as routes of escape. Today, we see how refugees use the Mediterranean Sea for this purpose, seeking security and a better life in Europe.

The wide range of applications for which the oceans are used hints at the diversity of possible needs during emergencies. Coastal environments are vulnerable to diverse threats and hazards as for instance oil spills, salmon lice, and invasive species. These are examples of unintended consequences of industrial activities at sea, which may hurt biodiversity. In addition, coastal communities are easily affected by disasters such as hurricanes and flooding. During land-based humanitarian crises, swift redirection of maritime logistics chains can save many lives. Maritime industries like shipping and offshore oil and gas also need emergency response systems that can increase safety of life and property by responding to undesired events, for example ship collisions, accidental blowouts from offshore oil installations, or a variety of other technical system failures. These examples show that there is significant uncertainty around the nature of the emergency, and thus the required response. Does the emergency relate to oil and gas production, for example an oil spill or accidental blowout? Do we need to rescue people from the sea after a capsizing?

A fleet for maritime emergency response and rescue operations should be able to respond to a wide range of alternative emergencies. This requires that the fleet is able to deliver a multitude of functionalities, while the need for each of these functionalities essentially is uncertain. To be able to deliver the functions required for some emergencies, we should facilitate the use of vessels for tasks not originally intended. This means that vessels can respond to situations that were outside the context of the fleet design originally. Such functional overlap may signify that creative use of equipment, through a careful functional analysis, may enhance the resilience of the fleet. The purpose of this paper is thus to investigate how to design for resilience in fleets for emergency response, protecting the maritime environment.

There is literature addressing the problem of designing a fleet for emergency response, or related applications. Mileski and Honeycutt (2013) argue for the use of a flexible pool of maritime assets coming together to respond to a disaster scenario, suggesting there is no optimal way to plan and arrange a fleet for emergency response. Chattopadhyay et al. (2009) apply tradespace exploration for evaluating the performance of surveillance systems for response during specific disaster scenarios. Mekdeci et al. (2012) discuss the connection between operational scenarios, capability requirements, and design choices in a fleet of systems for maritime security. Design aspects of resilience in maritime transportation are discussed by Berle et al. (2011a), Berle et al. (2011b), and Omer et al. (2012). A military perspective of engineering resilient systems is part of US Department of Defence research agenda (Goerger et al., 2014; Spero et al., 2014), showing that there is a need for research on resilience in other task-driven environments.

We outline the remainder of this paper as follows: First, we go through the theoretical background of the concepts we apply, such as resilience, failure modes and the role of redundancy and flexibility as design strategies. Second, we present the relevant systems engineering methodology we adapt and apply to our design problem. Third, we present a case in which we apply the methodology to the problem of designing a resilient fleet for maritime emergency response, with the ultimate objective of protecting the maritime environment. Finally, we argue that the approach we take can serve as the basis for a new conceptual design methodology for resilience.

Designing for resilience

In this section, we present the theoretical background, and introduce the main concepts, definitions, and strategies that are important to understand when designing resilient systems. We herein introduce resilience, and discuss it in relation to failure modes, and resilience-increasing design strategies based on flexibility and redundancy.

Relating performance to resilience and vulnerability

We can define resilience as the ability of a system to recover, and return to a new stable situation, after an event disrupts the normal operation of the system. In a supply chain context, many authors refer to resilience as the "ability to bounce back" from a disruption (Rice Jr. and Caniato, 2003). By this definition, we allow the performance of the system to drop, before restoring it (Asbjørnslett, 2009). We thus focus on handling the consequences of an unwanted event, rather than trying to foresee every eventuality that may disrupt the system (Berle et al., 2011b). Note that resilience is different from robustness as robustness keeps the performance of the system constant throughout the undesired event. This often comes at a significant cost. While robust systems have the ability to resist the event, resilient systems adapt to the event. Designing resilient systems, we build the ability to be adapted into the design, thus easing the recovery process. Figure 1 illustrates the performance of a resilient system experiencing a disruptive event.

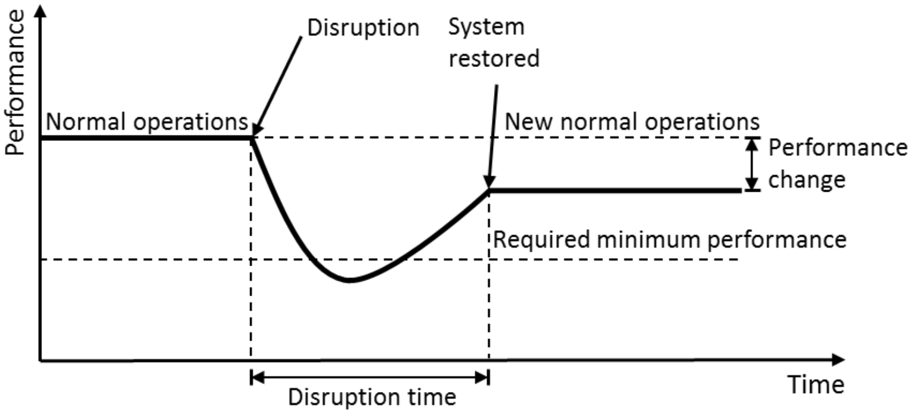


Figure 1 - Performance during normal operations and disruption (Pettersen et al., 2016).

In Figure 1, we show the performance of a system operating at a constant, stable level. After some time, a disruption of the operation occurs. This disruption can be due to a failure mode in the system that performs the operation. The disruption causes the performance level to drop below a threshold set for a required minimum performance. The operation therefore has to stop until the capabilities of the system performing the operation has been restored to a level above the required minimum performance. Finally, when the performance level stabilizes at a new level of normal operations, we can consider the system as restored. The question of restoring the functionality of a disrupted system often becomes a trade-off between restoring performance, and reducing the disruption time. The new operational performance level must be achieved within a timeframe acceptable for the mission, and reduction of delays may be more important than the quality of the new normal performance level.

It is likely that the system will perform at a lower level than before, due to the trade-off mentioned above. When delays are very costly, the drive towards letting the operation continue at a stable level will be stronger than the drive to get the performance back to the earlier level. However, in some cases, we can argue that performance after disruption actually gets better. One example is safety management system as applied in the aviation industry, where the safety level of the whole industry increases after accidental events. Taleb (2012) argues that the latter phenomenon may actually deserve the new notion of “antifragility”.

Vulnerability is often treated as an opposite to resilience, and can be defined as the properties of the system “that may weaken or limit the ability of the system to endure threats and survive accidental events originating both within and outside the system boundaries” (Asbjørnslett and Rausand, 1999; Asbjørnslett, 2009). Vulnerability is seen as different from risk, which is defined as the triplet of scenario, frequency and consequence (Kaplan and Garrick, 1981), as vulnerability connects more strongly to system properties. Reduction of vulnerability require adequate allocation of resources to restore the capabilities of the system, ensuring that the system performance reaches a new stable level. As we want to respond to emergencies, it is more important to ensure right allocation of resources, than correctly assess the risks. Therefore, the approach we take in this paper, takes inspiration from existing vulnerability assessment frameworks like Asbjørnslett and Rausand (1999) and Berle, et al. (2011a).

Failure modes in systems

The failure mode concept is studied heavily in safety and reliability theory (Rausand, 2011), as exemplified by Failure Modes, Effects, and Criticality Analysis (FMECA). A failure is defined as “the termination of a required function” (Rausand, 2011). Failure modes are deviations from the performance expectations of a system. Further, a function is defined as the “action for which a thing is fitted or used” (de Weck et al., 2011). For many technical systems, we find handbooks with data estimating failure rates based on experiments. The risk associated with a failure mode can then be estimated as the product of probability and consequence (Rausand, 2011).

Depending on the definition of system boundaries, failure modes can also be due to some external effect. They are not necessarily technical failures with consequences solely for the operability of the system, but also disruptions in the surrounding environment. Berle, et al. (2011b) discuss failure modes in the context of maritime supply chains. They define failure modes as “loss of the key functions and capabilities of the supply chain”, and further claim that loss of any such function or capability would reduce the performance of the maritime transportation system. The reason for using failure modes rather than other risk assessment tools is that this approach more easily lets us assess and respond to low-frequency, high-impact events. Through interviews and surveys, Berle, et al. (2011b) identify failure modes for many subsystems of the maritime transportation system, such as ports, terminals, navigable waterways, intermodal connections, and vessels. In this paper, we will apply the failure mode concept to indicate any emergency for which we may have to use the fleet we design, in other words an accidental event external to the emergency response fleet.

The role of redundancy and flexibility in building resilience

When designing for resilience we primarily use redundancy and flexibility as strategies for restoring the system after the occurrence of a failure mode (Rice Jr. and Caniato, 2003). We discuss the role of these strategies in relation to the system design.

Redundancy exists when several components, or equipment units, can perform the same function. Thus, in the initial system design phase, redundancy can be perceived as a form of overcapacity, or “slack” (Berle et al., 2011a). If we choose to neglect the existence of vulnerabilities, the redundancy will not have a value. However, functional redundancy may have value when we decide the course of action in a disruption scenario, as we can simply switch from using one piece of equipment to another, if the two both can perform the same function. It is not always beneficial to increase the amount of redundancy, as it may come at an exuberant cost (Berle et al., 2011b). In the context of maritime emergencies, an example of redundancy can be two vessels both able to clean up after an oil spill.

Flexibility represents possibilities to redesign the system to mitigate the consequences of failure modes. Modularity in design on the equipment configuration level is an important facilitator of flexibility, as equipment becomes easier to exchange, add or remove from the system. In a maritime context, the possibility to add or remove vessels from a fleet also represents a form of flexibility. Use of flexibility to increase resilience is often more time-consuming than redundancy-based reassignment of equipment to specific functions. For example, a retrofit of the equipment configuration on a vessel may require it to go into port. This is not necessarily feasible given the mission time horizon. For example, we can consider an oil spill situation. If a vessel needs to go to port to pick up equipment to clean up the spill, the severity of the incident may have increased in the meantime. Rerouting a vessel with the needed capabilities could be a flexible solution for dealing with the oil spill more rapidly.

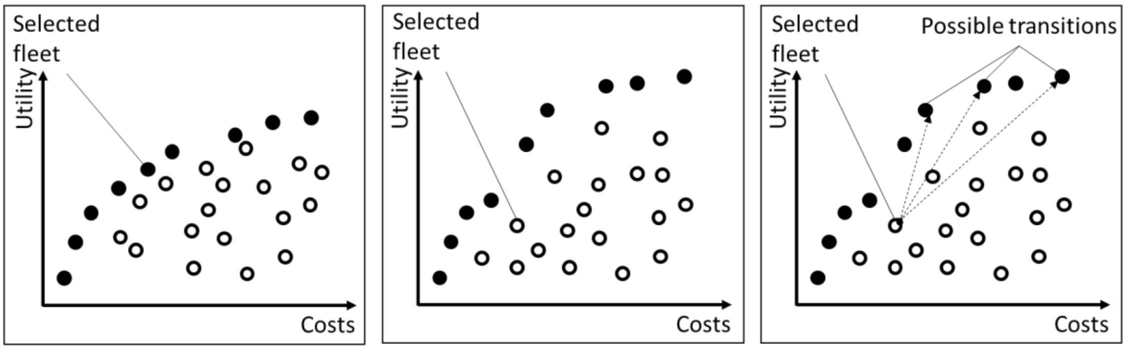
Using systems design methods for building resilience

The approach we take towards designing the fleet for maritime emergency response utilizes system design methods such as design structure matrices and tradespace exploration. We combine these methods with the failure mode approach.

Design structure matrices (DSM) are a useful tool for creating a common understanding of system architectures, with respect to the components of the system, and the functionalities that must be present in the system to perform the mission (Eppinger and Browning, 2012). The DSM framework also allows for easy mapping between different engineering system domains, such as the relations between component and function structures (Bartolomei et al., 2011). We use DSM to illustrate the link between components in the vessels and the required functionalities so the fleet can complete the maritime emergency response operation. This approach makes it easy to assign vessels, and equipment within each vessel, to specific parts of the maritime emergency response operation. When there is uncertainty in the functional requirements, as is the case for emergency response, a sensitivity DSM may also be a useful tool to identify flexible platform architectures (Kalligeros et al., 2006). The structure of DSM allows us easily to identify where functional redundancy exists. Thus, it becomes easy to decide how to redeploy equipment to complete the operation.

Tradespace exploration is based on multi-attribute utility functions expressing the performance level of system architectures (Ross et al., 2004). In addition, we need to approximate costs. The purpose is to capture several aspects of performance that are important to the stakeholders, in the utility function. As we wish to respond to a wide range of potential threats to the maritime environment, many groups will be interested in maximizing their own return from investments in emergency response capabilities. Using multi-attribute utility functions, we find compromises between these interests. As a result, we can evaluate the entire design space of alternative fleets for the maritime emergency response operation quickly, in terms of utility and costs. We now narrow the search for a good fleet, considering only Pareto optimal configurations, which for each possible budgetary constraint maximizes the utility. Thus, designers can focus the more detailed design or selection effort on these configurations.

Tradespaces refer to static system contexts. A failure mode will cause a shift in the operating context of the system. In the epoch-era framework of Ross and Rhodes (2008), “epoch” refers to a static contextual period, while “era” refers to the longer term timeline, thus sequences of “epochs”. As the epoch changes due to a failure mode, a fleet configuration specifically designed to handle this failure mode and the corresponding emergency scenario, will be seen as relatively better than before. We should regard a design performing well throughout many “epochs”, relating to failure modes and emergency scenarios, as a more resilient design. The influence of a failure mode in the maritime environment on the performance of different fleet configurations is shown in Figure 2, similar to tradespace representations of disaster scenarios in Chattopadhyay et al. (2009).



Before failure mode the fleet is on the Pareto front.

After failure mode the fleet moves from the Pareto front.

The fleet can be reconfigured into a set of other fleets.

Figure 2 – Tradespace shift due to failure mode in fleet, and subsequent reconfiguration of fleet.

To re-establish Pareto optimality for the fleet selected in the figure above, there is a need to make the fleet perform the current mission well. The capabilities of the fleet may not completely match the emergency caused by the failure mode. There is not sufficient functional redundancy to remain Pareto optimal and respond to the emergency, so a flexible strategy may be required. It may be possible to reconfigure the fleet size and mix by adding equipment to vessels, or adding new vessels to the fleet. Such a strategy would represent a flexible approach. In a tradespace context, we can imagine a tradespace network indicating which fleets we can reconfigure into sets of other fleets. Such a tradespace network will consist of a series of transition paths, described by arcs between the nodes representing fleets in the tradespace (Ross et al., 2008). The number of cost-beneficial transition paths for a given fleet represents the filtered outdegree for the fleet. When attempting to remain close to Pareto optimality, we make a cost-benefit analysis for the set of proposed transition paths, thus finding a strategy for implementing design changes.

Case: Designing a fleet for resilient maritime emergency response

The maritime environment comprises maritime transportation, as well as industrial, ocean-related sectors such as offshore energy production and the fisheries. We also include the coastal communities and ports in the scope of sectors the fleet for maritime emergency response operations must protect. We provide a taxonomy of the sectors comprising the maritime environment in Table 1. The emergency response fleet needs to comply with functional requirements related to failure modes both in open seas, and in the coastal land-sea interface.

Table 1 - Sectors in the maritime environment.

	Offshore	*Coastal*
Operations	Fisheries; sea transport	Fisheries; sea transport
Infrastructure	Oil and gas; windmills; fish farms	Ports; fish farms; coastal communities

Failure modes occur in each of the sectors defined as part of the maritime environment. In Table 2, we present some examples of failure modes in various sectors that can relate to specific emergency response missions, and thus require a given set of functionalities. This list is by no means complete, and serves only as an illustrative example. An extended list could include elements like the effects of bad weather on coastal infrastructure.

Table 2 – Failure modes with corresponding emergencies and functional requirements.

Sector	*Failure mode*	*Emergency mission*	*Functions*
Offshore oil and gas; sea transport	Oil spill	Clean up oil spill	Containment of oil Dispersion of oil Vacuuming of oil Skimming of oil
Offshore oil and gas; sea transport	Fire offshore or on vessel	Stop, or contain fire	Deliver water Spray water Direct water
Offshore oil and gas; windmills	Accident offshore (blowout, gas leak, explosion)	Evacuate offshore installation	Search for lifeboats Provide medical care Provide hotel facilities
Coastal communities; fisheries; sea transport	Ship/boat accident (capsize, sinking)	Search and rescue	Search for people in water Pick up people in water Provide medical care Provide hotel facilities
Fisheries; sea transport	Loss of navigational control	Prevent grounding	Tow vessel

We need to assign vessels to the functional requirements given by the operational profile of every possible emergency mission. We apply a DSM for the mapping of functional requirements to equipment we can include in vessel or fleet designs. Figure 3 shows this in a DSM. Figure 4 shows possible fleet configurations based on a heterogeneous set of vessels defined from the equipment included in the vessel design.

		Equipment														
		Oil boom	Skimmer	Oil tanks	Chemical tanks	Water tanks	Water pumps	Water canon	RHIB slipway	LARS for RHIB	Heli-deck	Helicopter hangar	Hospital	Hotel facilities	Deck area	AHTS winch
Functions	Containment of oil	x														
	Dispersion of oil				1											
	Vacuuming of oil	1		x												
	Skimming of oil	1	2	x												
	Deliver water					x										
	Spray water						x									
	Direct water							x								
	Search for lifeboats								2	1	2	3				
	Provide medical care												2			
	Provide hotel facilities												1	2	1	
	Search for people in water								2	1	2	3				
	Pick up people from water								2	1	2	3				
	Provide medical care												2			
	Provide hotel facilities												1	2	1	
	Tow vessels															x

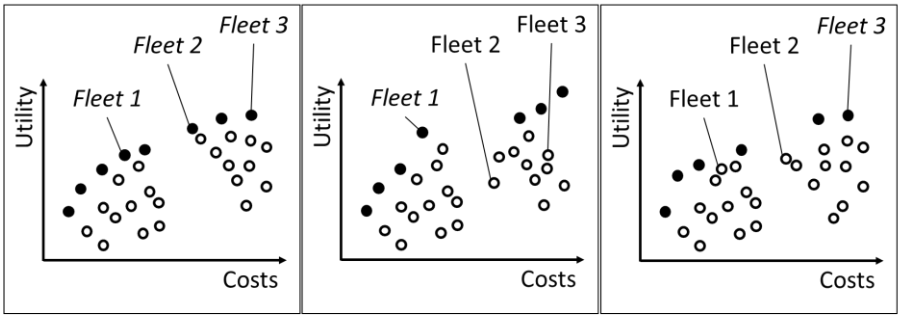
Figure 3 - Design structure matrix mapping emergency response functions against equipment. "x" means absolute requirement for performing function. "1", "2", and "3" refers to capability level of equipment to perform function, where "3" is the best.

		Equipment														
		Oil boom	Skimmer	Oil tanks	Chemical tanks	Water tanks	Water pumps	Water canon	RHIB slipway	LARS for RHIB	Heli-deck	Helicopter hangar	Hospital	Hotel facilities	Deck area	AHTS winch
Fleet 1	Vessel 1	x			x	x	x	x							x	x
	Vessel 2	x	x	x						x				x	x	
Fleet 2	Vessel 1	x			x	x	x	x							x	x
	Vessel 3								x			x	x	x		
	Vessel 4	x														
Fleet 3	Vessel 1	x			x	x	x	x							x	x
	Vessel 3								x			x	x	x		
	Vessel 5					x	x	x	x	x	x			x	x	x

Figure 4 - Design structure matrix defining fleets in terms of equipment configuration.

We select a fleet by evaluating many alternative fleet configurations against a set of objectives in a tradespace exploration. Referring to the capabilities given in Figure 3, one possible objective is maximization of overall capability. Equipment redundancy is also desirable, as a means to respond to several concurrent emergencies. Another possible target could be minimization of the number of vessels, common in fleet size and mix problems (Pantuso et al., 2014), as additional vessels contribute significantly to both capital, operating and voyage costs.

Based on the failure modes we described in Table 2, we use tradespace exploration to investigate the performance of the alternative fleet configurations in operating contexts where failure modes have occurred. As failure modes occur, we must consider alterations in functional requirements, due to specific emergency operation needs. Figure 5 illustrates the fleet configurations given in Figure 4 in tradespaces representing three different scenarios, one before failure, and two after failure modes trigger emergency response.



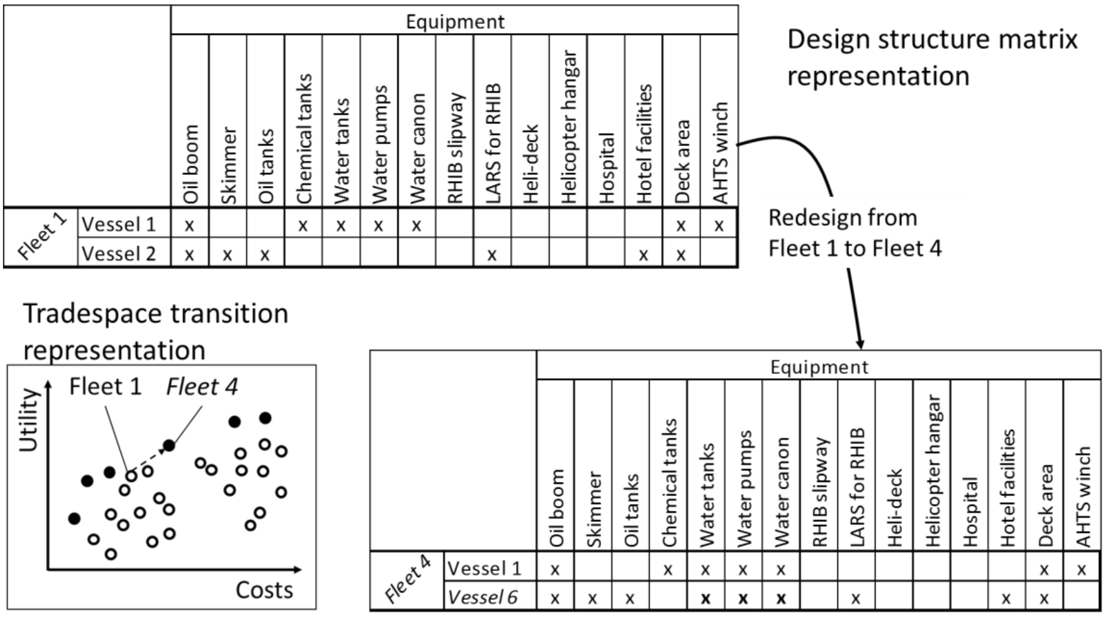
Failure mode: None *Failure mode:* Oil spill *Failure mode:* Fire offshore

Figure 5 - Fleet performance in tradespace exploration in three failure mode related contexts.

Figure 5 shows that the fleet performance varies according to the current context given by the failure mode. This is the case both for the highlighted fleets, which initially were Pareto optimal, and for other fleet configurations. The question now becomes how to make the fleet resilient, by making it match a larger number of operating contexts given by emergencies. We achieve this by utilizing the functional overlap in equipment or adding new capabilities to the fleet. An example of this functional overlap is the AHTS (anchor handling, tug, and supply) winch included in some of the vessels. This is a unit of equipment normally associated with anchor handling missions, and not with towing of drifting ships.

The selected fleets are all in need of some redesign to become resilient in the sense of meeting emergency scenarios. Fleet 1 would best serve oil spill response, due to emphasis on equipment for handling these situations. Responding to the offshore fire situation, Fleet 1 is in need for additional firefighting equipment. While all fleets have some firefighting capabilities, firefighting becomes significantly more efficient using several vessels. Thus, to achieve Pareto optimality with a fleet initially represented by Fleet 1, we must either add a vessel to the fleet, or add firefighting equipment to Vessel 2.

Figure 6 shows a proposed solution for the redesign of Fleet 1 to match the "fire" failure mode. We add firefighting equipment to Vessel 2, thus redesigning Vessel 2 to Vessel 6, as pointed to in the DSM representation below. On the fleet level, we make a transition in the tradespace, from Fleet 1 to Fleet 4. Ideally, we should evaluate many transition paths, and choose a redesign strategy based on cost-benefit analyses.



		Equipment														
		Oil boom	Skimmer	Oil tanks	Chemical tanks	Water tanks	Water pumps	Water canon	RHIB slipway	LARS for RHIB	Heli-deck	Helicopter hangar	Hospital	Hotel facilities	Deck area	AHTS winch
Fleet 1	Vessel 1	x			x	x	x	x							x	x
	Vessel 2	x	x	x						x				x	x	

		Equipment														
		Oil boom	Skimmer	Oil tanks	Chemical tanks	Water tanks	Water pumps	Water canon	RHIB slipway	LARS for RHIB	Heli-deck	Helicopter hangar	Hospital	Hotel facilities	Deck area	AHTS winch
Fleet 4	Vessel 1	x			x	x	x	x							x	x
	Vessel 6	x	x	x		**x**	**x**	**x**		x				x	x	

Figure 6 - Tradespace and DSM for transition from Fleet 1 to Fleet 4.

Concluding remarks

Designing for more resilient fleets in maritime emergency response, to protect the maritime environment, seems a promising field for further research. A synthesis of reliability theory and novel systems engineering methodologies can generate new insights into the design and deployment of assets for maritime emergency response. We show this using an illustrative, qualitative case in which we evaluate the performance of a set of fleets against a set of potential emergency missions associated with failure modes that can occur in the maritime environment.

The approach taken could well serve as a starting point for a more generic design methodology for resilience, which we seek to outline in a forthcoming book chapter (Pettersen et al., 2016). In a more generic form, one could apply this methodology to many settings where a set of assets cooperate to fulfil a mission with ambiguous or uncertain functional requirements. The methodology would enable utilization of unintended functional overlaps for responding to emergencies, as well as redesigning assets or adding new assets to the portfolio of assets.

Extensions of the current case could include the use of quantitative, empirical data, and an extended set of failure modes. Surveys and interviews with stakeholders related to the ocean space could greatly enhance the comprehensiveness of this approach, and could give valuable decision support for handling maritime emergencies.

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