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A design methodology for resilience in fleets for service operations

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Abstract

In this paper, we present a new conceptual design methodology for increasing the resilience in complex operations involving a fleet of ships. The objective of the methodology is to support design decisions to reduce vulnerabilities facing complex operations. The steps of the methodology are; 1) Defining operational context and initial fleet system design; 2) Investigating failure modes, identification and criticality assessment; 3) Proposing redesign and redeployment actions at the vessel level to increase resilience, through flexibility or redundancy; 4) Evaluating proposed actions, through assessment of the alternatives. We illustrate this methodology using a small case from a maritime service operation. The results indicate the advantage of integrating design thinking into a methodology for more resilient maritime operations.

Keywords

Fleet design; resilience; design methodology; failure modes; design structure matrix; tradespace exploration; marine operations.

Introduction

Maritime operations are often complex, and require the functionalities of multiple marine assets. Several vessels may be involved, fulfilling different tasks in order to complete the operation as a whole. When a vessel set to perform a specific task loses its functionality, it constitutes a disruption from normal operation, a failure mode (Berle, Rice Jr., and Asbjørnslett, 2011; Rausand and Høyland, 2004). Disruptions from normal operation may cause large delays and significant economic losses to the stakeholders in the project, which may possibly propagate further throughout the value chain.

While ideally all unwanted events should be avoided, this is not practically possible. No risk analysis can capture all possible scenarios, and so we need to make plans for what to do when an unwanted event disrupts the marine operation. Resilience refers to the ability of a system to bounce back after an event disrupting the normal operation of the system (Foster, 1993). There is a need for designing fleet systems that can handle disruption. By designing a fleet of vessels for resilience, we install in our fleet and vessel systems the capabilities for restoring performance in the event of a disruption.

In the context of designing a fleet of vessels for more resilient marine operations, several design-related questions must be answered. First, what functionalities does the operation require? Designers need to understand the context in which the fleet of vessels will operate, and understand the operational profile in which the vessels will engage. Second, how many vessels will be needed to cover all functionalities? This is a problem that is often addressed in the fleet size and mix literature (Pantuso, Fagerholt, and Hvattum, 2014). However, on its own, it may lead to optimized fleet configurations that are not as resilient as desired. Third, we therefore ask whether there exists any functional overlap in the fleet assigned to perform the operation. Functional overlap will imply that redundancies are present, making it easier to reassign vessels to cover other activities in an agile and timely manner. Fourth, we consider if there are any opportunities to use vessels for tasks other than the activities originally assigned to them. Thus, we consider if there is flexibility, and if actively changing the composition of the fleet system would help us complete the operation.

Designing for Resilience

Resilience is a so-called "-ility" (de Weck, Roos, and Magee, 2011), a property which stakeholders in a system would desire from their system. When the disruption happens, the performance of a resilient system is allowed to diminish. However, the system should be designed in such a way that the system quickly can absorb the shock of the disruption, and regain at least some of its previous performance, stabilizing on a new performance level. A key difference from a robust system is that the robust system will strive to keep the performance level stable through a disruptive event (Asbjørnslett and Rausand, 1999). This is often only possible at a considerable cost.

Figure 1 shows the performance level of a resilient system, which is capable of returning to a new stable situation after the disruption from initial normal operations. The new stable situation needs to be better than a given minimum required level of performance. Figure 1 also provides two potential dimensions on which the resilience can be evaluated; the disruption time, and the change in performance. Reducing the disruption time will be important to reduce the overall delay of the project of which the operation is part. Minimizing the change in performance is desirable, as it relates to meeting the objectives set by stakeholders in the project. However desirable, stakeholders should accept that it might be impossible to restore the system back to the performance level originally observed, due to the lack of time and resources available.

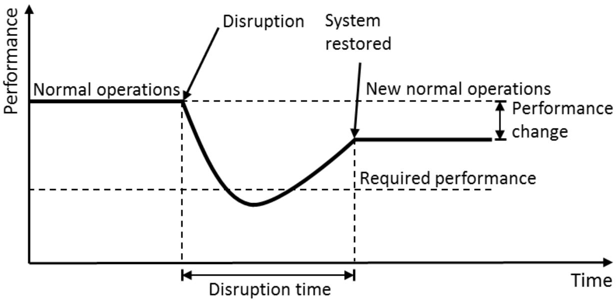


Fig. 1: Performance before, during and after a disruption of operation (Pettersen, Asbjørnslett, and Erikstad, 2016; Pettersen and Asbjørnslett, 2016)

In this paper, we will focus on the systems design aspects of resilience. We therefore consider mostly how equipment onboard vessels in a fleet can fail, thus causing a disruption of the operation of the fleet. Failure modes are defined as loss of key functionalities (Berle, Rice Jr., et al., 2011), and can therefore be thought of as the enablers of deviation from normal operating conditions. In Figure 2, we illustrate the failure mode as the loss of the function making it possible for a module to perform an activity.

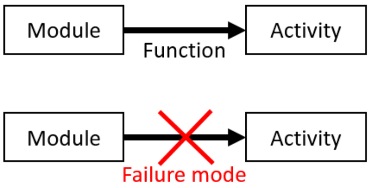


Fig. 2: Failure modes defined as loss of function in a system component.

Designing for resilience relates strongly to existing frameworks for vulnerability assessments (Asbjørnslett and Rausand, 1999; Asbjørnslett, 2009; Berle, Asbjørnslett, and Rice Jr., 2011). Unlike in a risk assessment, where the focus is on identifying and assessing risks, vulnerability assessments also focus on what designers need to do when something goes wrong, and what capabilities are needed in such situations.

The two main ways we can design resilience into systems such as maritime fleets, is by making them more flexible, or increase the amount of redundancy (Rice Jr. and Caniato, 2003; Sheffi and Rice Jr., 2005). Modular design solutions on the level of equipment added to the vessel becomes relevant to consider as a way to enhance flexibility. We can also talk about flexibility in terms of adding or removing vessels from a fleet.

On the other hand, for the fleet to have redundancy, it is enough to consider whether more than one system component has the functionalities required for performing each activity. When this is considered, bouncing back from a disruption becomes a question of reassignment of systems to specific activities, rather than a question of redesigning the system.

Design methodology for resilient operations

Synthesis of existing methods

The design methodology presented in this paper is a synthesis of systems design methods, reliability theory and supply chain risk management.

The systems design methods we integrate into our overall methodology are design structure matrices (Eppinger and Browning, 2012) and tradespace exploration (Ross, Hastings, Warmkessel, and Diller, 2004; Wasson, 2005). These are techniques that correspond well to a set-based ship design framework (Singer, Doerry, and Buckley, 2009). Tradespace exploration and the related epoch-era analysis has also been applied in the maritime domain by Gaspar, Erikstad, and Ross (2012).

Design structure matrices are modelling tools used widely in the industry for generating knowledge about system architectures (Eppinger and Browning, 2012). Design structure matrices are also useful for understanding the mapping processes between the different engineering system domains, such as processes, physical system structures, functions, social phenomena, and the system environment (Bartolomei, Hastings, De Neufville, and Rhodes, 2011). In this paper, we use design structure matrices to delimit the design space, thus eliminating infeasible vessel designs. We also use design structure matrices for assignment of specific system components to the tasks in the marine operation. This makes it easy to make an early assessment of functional redundancies in the system, which may be useful in the event of a disruption.

A tradespace is a representation of a solution space, in which alternative designs are evaluated according to the trade-offs and compromises that must be made to find feasible design solutions (Spero, Bloebaum, German, Pyster, and Ross, 2014). Multi-attribute tradespace exploration (Ross et al., 2004) captures important performance attributes in a common utility function, in a given, static system context (Fitzgerald and Ross, 2012). By plotting each possible design alternative in terms of the utility and costs associated, we can identify the Pareto front of designs to take further in the analysis. In relation to the purpose of this paper, each design in a tradespace will represent a possible fleet configuration, rather than an individual ship design.

We connect the tradespace thinking with the failure mode approach of reliability theory (Rausand and Høyland, 2004), used in failure modes, effects, and criticality analysis (FMECA). We apply this concept for understanding how functional failures influences the performance of the fleet system. Functional failures will decrease the performance of the fleet. In relation to the tradespace exploration, a functional failure thus represents a context change, a shift in the tradespace. Fleet configurations that initially performed well now perform less well due to the failure. Such a shift in the tradespace can also be studied as part of an epoch-era analysis (Ross and Rhodes, 2008), where "epoch" refers to the static context at one stage in time, while "era" refers to the longer term context.

To study how flexibility and redundancy can play a part in increasing the resilience of the fleet, we can formulate transition paths between the point fleet designs in the tradespace (Ross, Rhodes, and Hastings, 2008). A transition path could go from one initially selected design, which no longer meets the needs and expectations of its stakeholders, to a design meeting needs and expectations in a new system context, thus representing a reconfiguration of the system, or a redeployment of the equipment in the system.

We assess risks from a supply chain perspective of the marine operation, seeing that disruptions of operation have similar repercussions as supply chain disruptions. Delays propagate and their consequences become far larger than what assumed by looking at the cause of the disruption itself. The literature on supply chain risk management holds that the disruption risk is strongly connected to the design characteristics of the system, and that disruptions will happen (Craighead, Blackhurst, Rungtusanatham, and Handfield, 2007). Thus, research has focused on building resilience into systems (Christopher and Peck, 2004).

Therefore, we are inspired by the view that disruption consequences due to failure modes in a supply chain system can be dealt with using flexibility or redundancy (Rice Jr. and Caniato, 2003). We implicitly assume that some failure mode will occur eventually, and therefore it is important to design for capabilities that enable system to be restored after disruption (Berle, Asbjørnslett, et al., 2011; Berle, Rice Jr., et al., 2011). The disruption risks are to be handled through design actions, and thus we can consider the proposed methodology an example of risk-based design (Asbjørnslett, Norstad, and Berle, 2012; Papanikolaou, 2009).

Overview of the methodology

In this paper, our aim is to present a novel conceptual methodology for designing resilience into marine operations. The methodology can be viewed as an iterative process, where we go through four modules. These modules are presented in the flowchart in Figure 3.

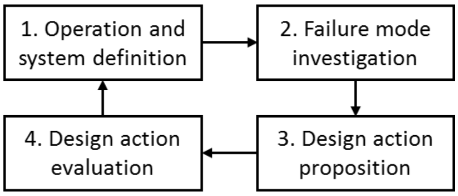


Fig. 3: Flowchart for design methodology

The first step defines the operation and the system through decomposition, letting designers fully enumerate the design space. Design structure matrices and tradespace exploration is used at this stage to evaluate alternative fleet designs.

The second step identifies failure modes, relating to the loss of key functionalities in the fleet. The criticality is assessed by reviewing the assignment of system components in the vessels to corresponding activities. Criticality is defined as the negative impact on the utility, thus impacting the tradespace.

The third step proposes design actions to get the fleet functional once again after the failure. Vessel redeployment to new tasks is one opportunity based on redundancy among system capabilities. On the other hand, reconfigurating the fleet is also a solution, which may imply adding vessels to the fleet, or actively changing vessel designs. In a tradespace context, we introduce a concept called transition paths (Ross et al., 2008), to gain an overview of all possible changes from the current, failed fleet composition to a future, more resilient fleet composition.

Fourth, tradespace exploration with transition paths is used to evaluate the possible design transitions. Based on this evaluation, we can determine how the fleet design best can be changed to account for the failure, and stabilize at a new level of performance.

Alternatively, the result of these four steps can be used to provide input to the next iteration on an initial fleet design. Thereby, it is possible to use the methodology to improve the resilience of a fleet, which may already be optimized according to a fleet size and mix problem (Pantuso et al., 2014). The optimal fleet size and mix can perhaps also be treated as an alternative to Step 1.

Case from offshore operations

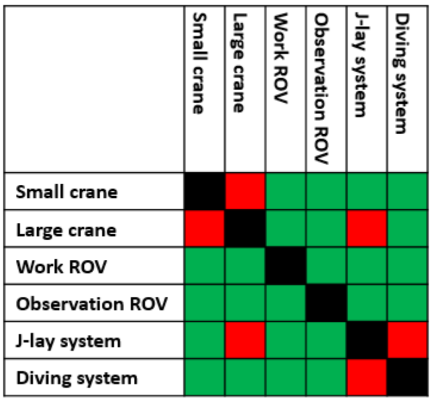
Offshore operations are often complex and may require a wide range of vessel capabilities. Diverse tasks such as pipelaying, diving and lifting of subsea equipment, cannot be performed by one single vessel. To complete an operation several vessels are needed, each covering a subset of the functionalities required to complete the operation. Addressing the needs for resilience in the offshore operation, we here develop a small case designing a fleet of vessels for a resilient offshore construction mission. We thus go through the steps outlined in the previous section.

Step 1: Operation context and system definition

The offshore operation consists of numerous tasks that must be done in the correct order. There is a need for decomposition of the offshore operation into smaller parts. Project management methods such as the program review and evaluation techniques and critical path analysis can be used at this stage to understand the operation, and how the activities relate. Each individual task must be assigned to system components with the functionalities necessary for the activity to be done.

To make this assignment one needs to make a system decomposition, getting an overview of how the fleet can be put together. A fleet consists of a set of different offshore service vessels, outfitted with equipment corresponding to the operation. Here, we will only consider the equipment that actually has a role to play in doing the operation. By treating the different equipment as design variables, we can quickly enumerate the whole design space.

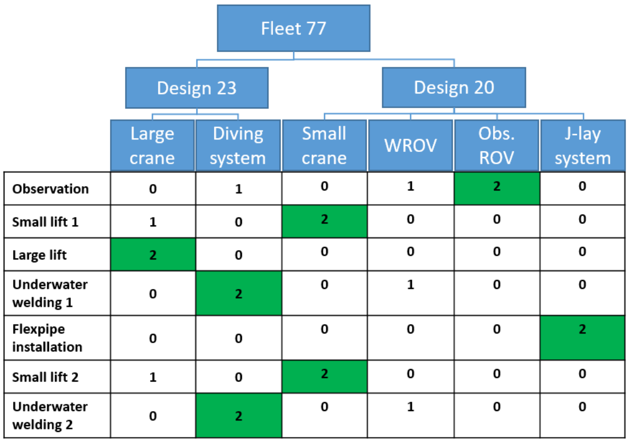
There may be some dependencies between pieces of equipment. We choose to map these dependencies using a design structure matrix, as shown in Figure 4.



	Small crane	Large crane	Work ROV	Observation ROV	J-lay system	Diving system
Small crane	⬛	🟥	🟩	🟩	🟩	🟩
Large crane	🟥	⬛	🟩	🟩	🟥	🟩
Work ROV	🟩	🟩	⬛	🟩	🟩	🟩
Observation ROV	🟩	🟩	🟩	⬛	🟩	🟩
J-lay system	🟩	🟥	🟩	🟩	⬛	🟥
Diving system	🟩	🟩	🟩	🟩	🟥	⬛

Fig. 4: Design structure matrix mapping dependencies between system components for restricting the design space of offshore vessels. Red means mutually exclusive. Green means no relationship.

Based on the restrictions of Figure 4 we generate the whole design space. Further, all fleet configurations that can fulfill the overall operation are generated. This means that every activity needs to be covered by some equipment existing in an offshore vessel within the fleet. We see an example of mapping of system equipment to activities in the offshore operation, in Figure 5 below.



	Large crane	Diving system	Small crane	WROV	Obs. ROV	J-lay system
Observation	0	1	0	1	2	0
Small lift 1	1	0	2	0	0	0
Large lift	2	0	0	0	0	0
Underwater welding 1	0	2	0	1	0	0
Flexpipe installation	0	0	0	0	0	2
Small lift 2	1	0	2	0	0	0
Underwater welding 2	0	2	0	1	0	0

Fig. 5: Design structure matrix mapping components to activities. "1" means low capability, "2" means high capability.

Next we need to perform a tradespace exploration based on the design space of the feasible fleet configurations. A multi-attribute utility function is applied. Objectives such as minimization of the number of vessels in the fleet, maximization of the redundancies on the equipment level, and maximization of capabilities, are accounted for in the utility function. Costs are directly tied to the investments required for every piece of equipment, as well as the investments in the vessel platform. The tradespace of all feasible fleet configurations with two or three vessels in the fleet are shown in Figure 6. There are two separate clusters of fleets. This is due to the difference in costs between the fleet configurations with two and three vessels.

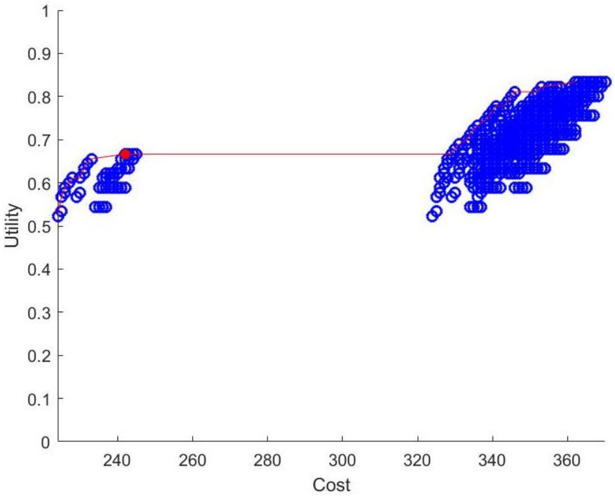


Fig. 6: Tradespace exploration for initial design. Each point represents a possible design. The initially selected Fleet 77 is shown in red.

Step 2: Failure mode investigation

The point of the failure mode investigation is to account for the possibility that something goes wrong during operation. Here we assess the criticality of functional failure in systems and equipment installed on the vessel. We define risk as the product of probability and consequence.

Probability of failure is estimated using expert judgment, historical failure data using or simulation of realistic operating conditions. For equipment used in the offshore industry, a lot of failure data for reliability analyses has been collected in handbooks (Rausand and Høyland, 2004). The consequence of a failure is in this analysis connected to the negative impact on the utility of designs in the tradespace. Therefore, the consequence will generate a shift in the tradespace. The fleet configurations utilizing the equipment that failed, will experience a negative shift in utility, indicating a fall in the level of performance.

In some cases, a system in the offshore fleet can fail in such a way that the operation still can be continued, albeit at a lower level of performance. This is the case when redundancy exists. However, if no redundancy exists to cover for the lost functionality, the fleet may become unable to fulfill the operation.

We consider the situation where the large crane installed on Vessel 23 fails. The failure impacts the performance of all fleets that include this vessel. The tradespace of all fleet configurations after this failure mode occurs, is shown in Figure 7.

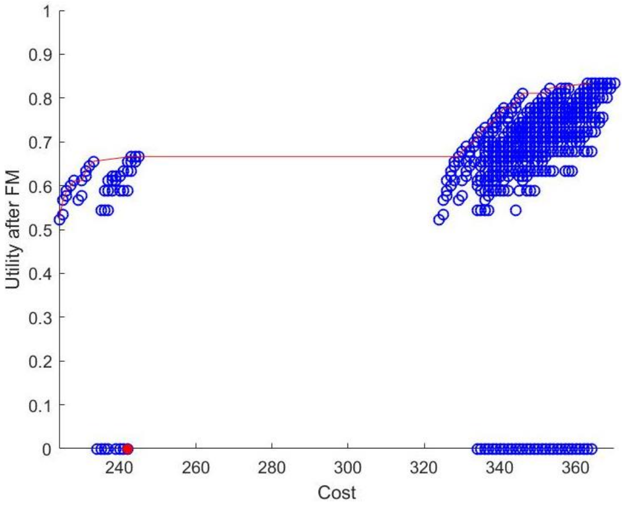


Fig. 7: Tradespace exploration after failure in the large crane on Vessel 23. Fleet 77 shown in red.

We see from Figure 7 that the fleet configuration we chose in Step 1 of the methodology actually becomes unable to perform the operation. Therefore, the utility drops to zero. The cascading effects throughout the operation and the larger value chain, due to the delay and complete disruption of the operation, fall outside the scope of this analysis. Nevertheless, it becomes important to find a solution in an agile manner in an operational time-horizon, to minimize the consequences of the disruption.

Step 3: Design action proposition

Having generated knowledge about the numerous ways that a fleet may be rendered unable to perform the operation at the required performance level, we turn to design as the solution. In the third step, we propose design action based on utilizing the redundancy and flexibility (Rice Jr. and Caniato, 2003) embedded in the fleet configuration, as a way to achieve resilience.

Redundancy based design actions are based on redeployment of equipment that already is present in the fleet system. It relates to the functional overlap inside the fleet. Redundancy is thus related to making changes to the final mapping process described in Figure 5. The equipment configuration of the vessels themselves is not changed.

Flexibility based design actions imply active reconfiguration of the fleet size and mix. Vessels can be added to the fleet to cover the lost functionalities, for example using the spot market if such a market exists. Alternatively, equipment can be added to the vessels. Modularization has been instrumental in making the latter aspect of flexibility a more readily available alternative. In the context of a marine operation, where the flexibility must be exercised quickly, there are however limits to how much can be done using modularity. One does not simply have time for a larger retrofit of the vessel. This indicates that there exists a cost threshold setting a boundary on how flexibility can be exercised in the design (Ross et al., 2008). However, some smaller, important equipment such as remotely operated vehicles can be added to the inventory of the vessel in such a time horizon.

Both redeployment using existing redundancies and redesign of the fleet configuration can be modelled as transitions from one fleet configuration to another in the tradespace. Transition paths (Ross et al., 2008) exist between the initial fleet experiencing the crane failure, and each fleet configuration it can possibly be transformed into. This will lead to a more resilient fleet configuration. Figure 8 shows the tradespace with the set of proposed new fleet configurations that we can transition to, when the initial fleet experiences the failure.

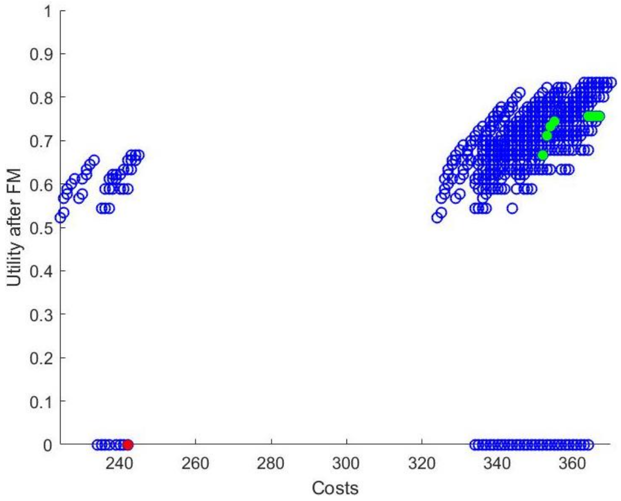


Fig. 8: Tradespace exploration after failure in the large crane on Vessel 23. Fleet 77 shown in red. New fleet configurations to transition into are shown in green.

In the case of the offshore vessel fleet we look at here, no other systems are able to fulfill the role of the crane that failed. Therefore, all the proposed transition paths to new fleet configurations include exercise of flexibility. As a crane retrofit is a quite complicated process requiring that the operation end, the model suggests adding a vessel to the fleet. Therefore, all suggested transition paths go from the initial fleet configurations, to fleets consisting of three vessels. In other words, the tradespace transition paths all recommend adding a vessel to the fleet, as the way to recover from the failure, and complete the mission.

Interestingly, we observe that none of the proposed design actions for transitioning, brings the fleet back to Pareto optimality. One reason for this result is that the resources already embedded in the existing fleet put some bounds on what changes are possible. For example, the vessel experiencing the failure, may still be able to fulfill some other functionalities. Therefore, it is still considered part of the fleet. Still, all the proposed solutions will improve the situation after the failure, restoring the fleet to an acceptable level of performance. This is in correspondence with the description of resilience through performance levels, given by Figure 1.

Step 4: Design action evaluation

The final step of the process is to evaluate the recommended design actions for restoring the fleet system after the failure. As we now have knowledge about the costs and utility increases connected with each design action, at this point we can select specific design actions for implementation in our fleet. We can now only consider the legal transition paths in the tradespace, as highlighted in Figure 8. The decision-making at this stage again becomes a question of considering the Pareto front given by the transition paths.

Discussion

In the offshore industry today, designing fleets for more resilient marine operations should be a highly relevant topic. Some years ago, the Deepwater Horizon accident highlighted the importance of better contingency planning in the offshore oil and gas sector overall. The current situation with low oil prices tells us that expensive multipurpose vessels is an inappropriate response to the need for contingency planning. Spending the resources necessary to arrive at a robust fleet design will not be a good solution, economically speaking. However, as offshore activity continues with simpler, more cost-efficient designs, we still need to have resilience on a fleet level.

Tradespace analyses are a tool we believe can put a greater emphasis on trade-offs in fleet design. Cost-effectiveness, safety and resilience can be opposite targets, and still we want to meet them all. They should all enter into our design processes as objectives, and thus influence our decision-making.

One possibility that should be further studied, is the instance where two smaller systems can cooperate to fulfill a task originally fulfilled by a single larger system. For example, could the large crane that failed by replaced by two smaller cranes working together to perform the large lifting task? Such a solution could also have been feasible for the case studied in the previous section. However, we would have to penalize that solution for increasing the complexity of the overall offshore operation in the tradespace analysis.

Conclusion

In this paper, we describe a new methodology for increasing the resilience of marine operations, through fleet design actions. The methodology synthesizes systems design, reliability theory, and supply chain risk management, and brings new insights about how we can design resilience into marine operations. The combination of tradespace analysis and failure modes allows efficient assessment of performance throughout disruption scenarios. Further, tradespace exploration also allow us to identify and assess design actions that helps bring back the operation to an acceptable performance level, by facilitating investigation of possible transition paths. This lets us make robust decisions during the early stages of fleet design.

Further work can include testing the conceptual design methodology presented here, on more detailed, data-driven case studies of marine operations. While the current application of the methodology is on a case from offshore construction operations, it may also be applicable in other industries.

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