Proceedings of PRADS2016
4th – 8th September, 2016
Copenhagen, Denmark

Investigating feasibility of flexible ship concepts using tradespace network formulations

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Abstract

In this paper, we investigate the technical feasibility of flexible offshore ship design concepts with respect to retrofits. Flexibility is intended to improve performance, but there are often complex system interactions that are difficult to assess at the early design stage related to stability, resistance, hydrodynamic behavior and payload capacity. These aspects need to be understood and assessed at the conceptual stages. In this paper, we develop a tradespace network model and define transition rules to describe feasible retrofits. A multi-criteria utility function is used to assess the tradeoff between performance and cost. We demonstrate our approach using a case from offshore vessel design, where we investigate the feasibility and impact of retrofits. The low-fidelity quantitative analysis indicates that the beam is the least flexible design parameter. This knowledge can be important when defining a flexible marine platform "prepared" for future retrofits.

Keywords

Ship design; uncertainty; flexibility; systems engineering; tradespace exploration; design method.

Introduction

Ships must be designed for the right operational context. Due to long vessel lifecycles, the context will change and largely be uncertain at the design stage. Flexibility lets us reconfigure the design to meet changes in market needs, stakeholder expectations and the operating context of the ship. Operational flexibility in shipping has been assessed with real options analysis in the literature. Examples include analyses of entry, lay-up and scrapping (Dixit, 1988, 1989) and for valuation of combination carriers (Sødal, Koekebakker, and Aadland, 2008). However, these analyses are more related to the operational aspects of a ship than the design characteristics from an early stage design perspective.

In contrast to such operational real "on" options, "in" options do not treat technology as a black box (Wang and de Neufville, 2005). Traditional "on" options analysis focuses more on valuation of a given type of managerial flexibility. "In" options in design are highly dependent on the system itself. For complex systems there are numerous options that can be integrated in the design, hence identification of options also plays an important role. It can sometimes be difficult to separate between "in" and "on" options, as some options are on the borderline. This can be seen in the case of the decision on what ship to invest in, when selecting between alternatives, flexible or non-flexible. Such problems can be determined by looking at technical aspects of the vessel, such as the properties of a normal tanker versus a combination carrier (Sødal et al., 2008).

In this paper we focus on "in" options, assessing flexibility from a systems engineering perspective. There exist several approaches for representing engineering systems in order to assess how flexibility can improve performance. The design structure matrix (DSM) can be used, and related research on flexible vessel platforms is conducted with applications to floating storage, production and offloading units (Kalligeros, de Weck, and de Neufville, 2006).

Tradespace exploration and tradespace network concepts represent an alternative approach, which will be in focus in this paper. Tradespace exploration is useful for evaluating the design space in terms of cost and utility tradeoffs (Ross and Hastings, 2005). It represents an example of set-based design (Singer, Doerry, and Buckley, 2009), and thus a diversion from the design spiral (Evans, 1959). Further, tradespace exploration indicates an expansion of the role of the ship designer (Gaspar, Balland, Aspen, Ross, and Erikstad, 2014; Gaspar, Brett, Erikstad, and Ross, 2015; Keane, Brett, and Gaspar, 2015). Tradespace analysis represents a good platform for analysis of changeability and flexibility (Ross, Rhodes, and Hastings, 2008), particularly regarding the use of graph theory to investigate flexibility. This paper applies these concepts to a maritime design problem.

The oil price is one factor that is essential for the profitability of most offshore projects. In the wake of the recent (2016) oil price collapse, it is obvious that assuming a deterministic oil price in the design modelling of the performance of for example a platform supply vessel (PSV) will give misleading results. This case illustrates the importance of the research presented in this paper. In the event of an oil price collapse, and subsequent a PSV market rate collapse, one may assess the possibilities of retrofitting the ship for new markets, for example to a wind farm support vessel[1]. Such a retrofit will involve installing numerous units of equipment, including a crane, possibly more accommodation, and a heave compensated gangway. Retrofitting and installing a crane will change the stability of the ship, and there is only a certain crane size that can be installed before the critical stability requirement is breached. The stability of the ship depends several parameters that mostly are decided at the early stages of the design process. Taking into consideration the possibility of a crane retrofit at the early stages of the design process may affect the initial design. Stability can obviously also be changed after the ship is built, but at a higher cost.

In this paper, we demonstrate a method that can be used to assess initial designs, taking into consideration the possibility of future changes and retrofits that may be relevant, such as installing a crane. Further, we aim to reduce the gap between the current approaches in the industry and the state-of-the art methodologies in development, by demonstrating the use of tradespace network methods for early stage flexibility assessment.

Methods

Tradespace exploration for evaluating designs

Tradespace exploration is a technique for evaluating the whole design space in terms of costs and multi-attribute utility functions (Ross and Hastings, 2005). This facilitates a wider discussion about the design between key project stakeholders, allowing their value systems to be properly reflected in the design. The question of what constitutes a "better" ship design, has been discussed in several recent papers (Agis, Pettersen, Rehn, and Ebrahimi, 2016; Ebrahimi, Brett, Garcia, Gaspar, and Kamsvåg, 2015; Ulstein and Brett, 2015), and these perspectives are currently being implemented in industrial ship design processes.

Figure 1 shows an example of a tradespace, with the Pareto front of non-dominated designs highlighted. The Pareto optimal designs refer to designs that, for each budgetary constraint, maximizes the utility.

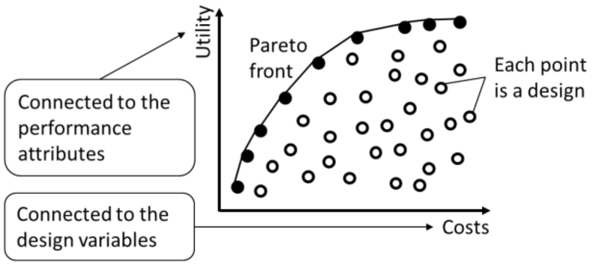

Figure 1: Tradespace example.

When we consider future uncertainty in the operating context of a vessel, throughout its lifecycle, we have to account for changes in this tradespace. Epoch-Era Analysis (EEA) can be applied as a framework for this (Ross and Rhodes, 2008). An epoch represents a static context in a tradespace, with a given duration, while an era represents the long term context or a complete lifecycle. A set of processes, including multi-attribute tradespace exploration and EEA comprise the Responsive System Comparison Method (RSC), which is used for gaining insight into developing value robust systems (Ross et al., 2009). The concept of value robustness is used to study how well each design performs through a set of different epochs. Passive value robustness refers to a design that performs well throughout the era without being changed. In this paper, we are interested in investigating the feasibility of retrofit options, which relates to active value robustness. For the vessel to remain valuable throughout the lifecycle, always remaining at or close to the Pareto front, we can choose to retrofit the vessel.

Tradespace networks for assessment of changeability

Generating a set of physically viable designs, and creating awareness of the flexibility embedded in a design space, still requires a wealth of technical knowledge about the limitations set by factors like stability, compatibility and structural integrity. If one considers each point in a design space as a potential start and end state for change, then this framework can be used to assess changeability between physically viable designs (Ross et al., 2008). A tradespace network arises when one links the different design states (nodes) with transition paths (arcs). The nodes refer to point designs, so that the transition paths indicate how a given point design may be transformed into a set of other point designs. The transition path concept thus shows us how flexible a design is, and lets us identify all possible real "in" options in the design space.

The number of other alternative designs a design can transition into, is given by the *outdegree*. The outdegree is the number of outgoing arcs from a particular design, and by applying a threshold cost for the transitions, the filtered outdegree can be defined. The filtered outdegree therefore becomes a quantified measure of changeability (Ross, 2006). Further work in quantifying and valuing changeability is done by Fitzgerald (2012). The tradespace network provides a structured way of handling the complexity of the wide range of different design options in the early stages of the design process. Figure 2 illustrates a tradespace network when accounting for the filtered outdegree.

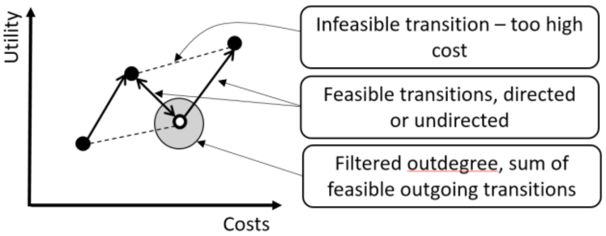

Figure 2: Transition rules and filtered outdegree.

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[1] Retrofit from a PSV to a wind farm service vessel was seen in the industry in 2015, with Vestland Cygnus.

Case study: Offshore vessel design

We illustrate the described tradespace network approach with a case from offshore ship design. The performance of a design is represented by a multi-objective utility function. Tradespace networks are used to identify feasible flexibilities in the form of retrofit opportunities.

Performance attributes for the utility function

The utility function in this case study is based on three performance indicators. First, capability is important, being enabled by mission specific equipment such as offshore cranes and well intervention systems. Second, the capacities of the vessel contribute to utility, both relating to the deck area available for storage and the deadweight indicating the overall payload, including tank capacity. For both capability- and capacity-related performance indicators, we seek maximization as they contribute positively to utility. The third performance indicator is operability, which in our case relates to heave response, roll period, and resistance of the vessel.

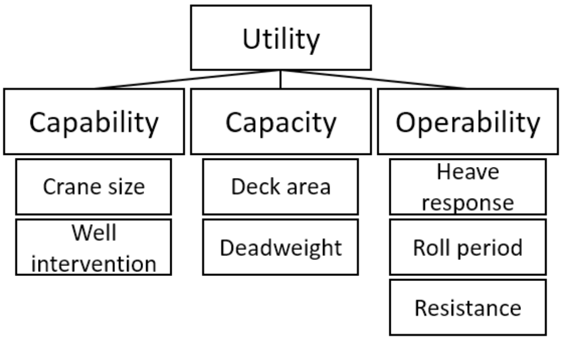

Figure 3: The performance attributes which constitute the utility function.

Figure 3 illustrates the hierarchy of attributes that comprise the utility function for this design process. Note that these aspects of value are based on the value system of a hypothetical ship owner, and does not necessarily represent the utility function of any realistic industry actor. However, the utility function is to some extent inspired by the performance index presented by Ulstein and Brett (2015).

We naturally want to maximize the ships capability and capacity. However, the performance attributes relating to operability is more ambiguous and need further specification. Offshore ships often need to be able to operate in rough seas; hence, the hydrodynamic ship response in waves is of interest. The metric we use is the heave response variance, which is determined from the shape of the ship in a given sea state described by a wave spectrum. For simplicity, we only model the translational vertical response. Inspired by Faltinsen (1990), we model the ship as a damped mass-spring system, including the added mass effects from the water. Excitation forces arise from waves described by an assumed wave spectrum. We seek to minimize the heave variance. For roll movement, we want to maximize the roll period, as we assume low vessel accelerations are more beneficial for the operations. A more stable ship will have a smaller roll period. This constitutes a potentially interesting trade-off between operability, and the possibility of adding weight-intensive systems at high locations in the vessel. Total ship resistance is also included in the utility function under operability, which it is of interest to minimize.

Design description

For the design space we evaluate in this paper, we divide the design variables into those that relate to the main dimensions of the ship and those related to the systems installed on the vessel. The design variables are described in Table 1.

Table 1: Design variables.

Class	Type	Bounds [min, max, res.]
Main dim.	L [m] - Length	[70,120,10]
	B [m] - Breadth	[15,30,5]
	D [m] - Depth	[5,10,5]
Systems installed	Crane [MT]	[0, 500,100]
	Well int. tow.	Yes/no
	Moonpool	Yes/no

We enumerate the entire design space, and delimit the design space by applying restrictions based on the knowledge about the physics of the ship design problem. We implement stability criteria by requiring that the metacentric height (GM) be above a minimum (GM_{MIN}). A freeboard criteria is also considered to constrain the design space, requiring that the freeboard (F) is above a minimum (F_{MIN}). These constraints are given in Table 2. Additionally, a well intervention tower requires a moonpool to be functional, i.e. lower equipment to the subsea wells on the seabed.

Table 2: Constraints.

Physical relation	Value
Stability	$GM > GM_{MIN} = 0.15\ m$
Freeboard	$F > F_{MIN} = 1.5$ m

Basic properties of the design, such as deck area and lightweight, are found from regression analyses of similar offshore ships. Retrofit costs for unit change in the various design dimensions depend on the direction of change. E.g. the cost of increasing the length by one meter is not the same as the cost of decreasing the length by one meter. A threshold cost C_t is used to define the feasible transitions between physically viable designs. C_t is initially assumed the value of 150 million NOK. Choosing a different value for the threshold cost can give additional insight in the price sensitivity of changeability. In this threshold analysis we focus on the monetary value, while a more rigorous analysis could involve other aspects of perceived value from the perspective of key stakeholders.

Identification of feasible transition paths

We formulate transition rules representing the knowledge about physical constraints to delimit the space of viable retrofits for the later lifecycle stages. This way, we quantify how flexible a design is. A tradespace network, as shown in Figure 2, will represent all the physically viable transition paths, thus identifying the real options "in" the vessel design. The transition rules are based on the physical aspects of each design specification. We can consider for example, that a retrofit is unviable if it increases the weight of the topside equipment, without increasing the buoyancy so that it becomes sufficient to carry this weight. Similarly, adding a well intervention tower without having sufficient stability, would constitute another unviable transition. With this approach we can for example explore the tradeoff between adding more equipment in order to increase the capability, and the reduced stability, deck area and deadweight that follows. Further, we can investigate how possible future changes in the main dimensions can affect these complex trade-off relationships in the design space.

Results

The case study model outlined above is implemented in Matlab. A sample static tradespace is provided in Figure 4, evaluating 3962 designs. The tradespace shows that the well intervention tower has significant costs, essentially separating the tradespace into two distinct groups.

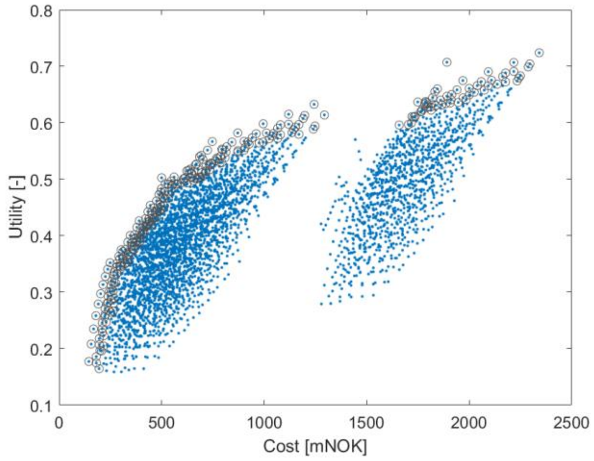

Figure 4: Tradespace of possible offshore vessel designs as function of cost and utility – two major groups due to costly decision on installing well intervention tower.

In Table 3 we present four Pareto optimal design alternatives. In the table, the design variables will have the units presented earlier. fOD refers to filtered outdegree, C refers to the crane, M refers to moonpool and W refers to well intervention tower.

Table 3: Selected Pareto front designs

ID	Cost	Utility	fOD	[L,B,D,C,M,W]
2885	1890	0.71	13	[120,30,9,500,1,1]
165	723	0.55	28	[114,30,5,500,0,0]
424	444	0.45	48	[120,15,5,400,0,0]
1406	214	0.31	32	[103,15,5,000,0,0]

In the pursuit of a final design, we narrow the search space by focusing on designs close to the Pareto front. The designs close to the Pareto front are highlighted in Figure 4. After the analysis limits the search to designs close to the Pareto front, we evaluate further the filtered outdegree (fOD) to quantify the flexibility of these design alternatives. We find the filtered outdegree by applying the threshold cost (C_t = 150 million NOK), and use the open-source graphics software Gephi to visualize the transition paths in the tradespace. Gephi can be used to cluster groups of designs that have a high degree of interconnectivity, which can help us understand which design characteristics that are more stable than others.

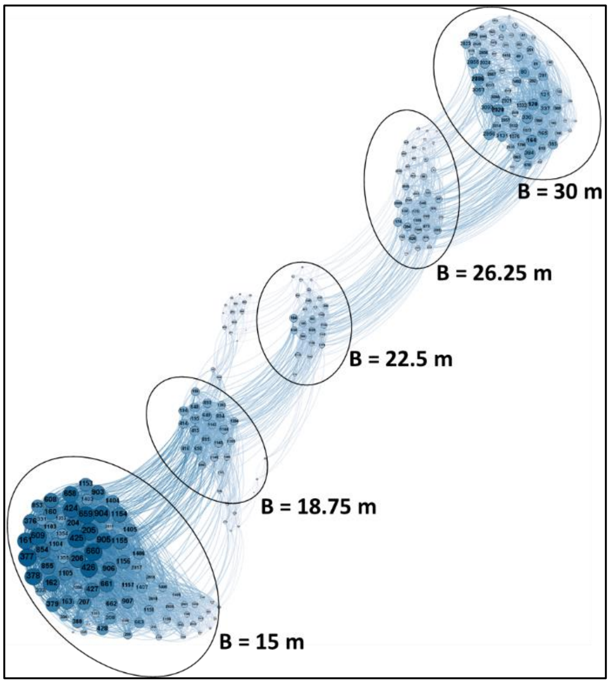

Figure 5: Filtered outdegree cluster plot, size of node depends on the outdegree, number on nodes is design "ID".

The nodes in Figure 5 each illustrate a possible design alternative, and their sizes are adjusted according to the filtered outdegree. Clusters in the figure indicate that designs have similar dimensions and configurations, and there exists a high number of transition paths between the designs within a cluster. For example, we see that there is a large group of designs mostly signified by having a beam of 15 meter. The clusters visualized in Figure 5 provide a guide to what *vessels platforms* one can consider when designing for flexibility. Four of the designs close to the Pareto front (highlighted in Figure 4) that maximize filtered outdegree are given in Table 4.

Table 4: Designs with the highest filtered outdegree (fOD).

ID	Cost	Utility	fOD	[L,B,D,C,M,W]
660	367	0.40	51	[109,15,5,300,0,0]
425	433	0.44	51	[114,15,5,400,0,0]
377	492	0.46	51	[114,15,6,400,0,0]
659	379	0.42	50	[114,15,5,300,0,0]

From Table 4 we can see that the designs with the highest filtered outdegree all have a relatively low beam of 15 meter. These results are consistent with the properties of the largest cluster in Figure 5.

Discussion

We have shown how tradespace exploration lets us study the trade-offs between costs and utility and acts as a tool for identification of flexibility. The tradespace network emerging when using the filtered outdegree illustrates how a vessel can be retrofitted into another. In other words, we can identify which retrofits are feasible, and thus describe *vessel platforms* on which we can build many alternative equipment configurations. As the entire feasible design space already has been generated, this approach lets us identify all possible design options. Thus we facilitate retrofits later in the lifecycle.

The results indicate that beam is the most important parameter to fix at the early stage when designing a flexible vessel platform. But why would it be more important than the other design parameters, such as the draft? There may be multiple reasons for this. Even though we present a simplified model of the physics and performance of an offshore ship, it is rather difficult to understand the complex interactions. In our model we have two constraints deciding if a design is physically viable or not, namely the initial metacentric height and the minimum freeboard criteria. We believe that the beam is more important to set than the draft because the beam to a higher degree affect the operability of the ship and leaves less room for buffer. For example, in the event of retrofitting a larger crane, one would need extra stability for the increased center of gravity, which would compromise on the operability properties yielding high impact on the utility function. On the other hand, the draft has a larger buffer on the payload capacity leaving more slack on the minimum freeboard constraint in our model. Hence the draft is less important. An example of this can be seen on the Vestland Cygnus, which was retrofitted from a PSV to a wind farm service vessel in 2015. This retrofit involved the installation of a large crane, and the addition of sponsors on the side to ensure stability.

Another interesting output from the model is that the ships with the highest fOD also have the smallest beam. One may assume that a wider ship would provide a platform with higher fOD since the potential retrofits have a smaller relative effect on the properties of the design. However, a wider ship also has a higher resistance and is more expensive, potentially reducing the utility yielding a performance that is further from the Pareto front. In Figure 5 we only consider the designs highlighted in Figure 4, representing designs close to the Pareto front. These results may be significantly different depending on how the utility function is designed.

The threshold cost we use to specify transition feasibility is a parameter which is strongly dependent on stakeholder preferences. A very high threshold cost could indicate that the stakeholders chase more recently identified project needs, which may spur other risks such as cost slips and delays. On the other hand, low threshold costs could make it difficult to take advantage of emerging opportunities, making the vessel less valuable in a lifecycle perspective. Perhaps real options analysis could be used to set the “correct” threshold cost for specific retrofits?

We have mainly explored the technical side of flexibility, and quantified it according to the filtered outdegree. However, there are additional perspectives to account for. Agis et al. (2016) provide perspectives about commercial and operational sides of uncertainty as well. From such perspectives, it may be reasonable to quantify the flexibility of a design concerning market switching opportunities, or the ability to successfully bid for a specific contract (Erikstad, Fagerholt, and Solem, 2011).

The technical consequences regarding machinery and structural aspects were not assessed in this paper and may be included in a more thorough analysis in the future. Further, another aspect that is not included when assessing retrofits is time. Whether the vessel can change in a day or a month should be included for better assessment, which may be associated with the value of agility. Neither have we considered explicitly what happens when the context changes and thus Pareto front changes drastically. The case should be taken further into an Epoch-Era Analysis, which gives a more detailed consideration of the future lifecycle, taking into account for example future contractual requirements and different market characteristics.

Conclusion

In this paper we have investigated feasible flexible designs from a technical perspective with tradespace network methods. We have confirmed that filtered outdegree represents an alternative approach for quantifying flexibility and identifying potential design options in a technically advanced system like an offshore vessel. Our analysis indicates that the tradespace network approach using filtered outdegree can be used to specify flexible vessel platforms. Further results indicate that beam is the most important parameter to fix for a vessel platform.

Acknowledgement

Thanks to contributions and help from Henrik Schmidt-Didlaukies, Dr. Eirik Bøckmann, Prof. Bjørnar Pettersen and Prof. Dag Myrhaug at the Norwegian University of Science and Technology.

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