Performance, cost and flexibility of reconfigurable offshore ships

Carl Fredrik Rehn[1)], Sigurd Solheim Pettersen[1)], Stein Ove Erikstad[1)] and Bjørn Egil Asbjørnslett[1)]

[1)] Norwegian University of Science and Technology (NTNU), Department of Marine Technology,
Otto Nielsens veg 10, 7052 Trondheim, Norway,

Abstract

This paper investigates technical performance, acquisition cost and flexibility level for reconfigurable offshore ships. An offshore ship can be configured with various types of equipment; thus, its base structure constitutes a platform from which several end ship design configurations can be derived. A ship with equipment retrofit flexibility will typically have excess stability, deadweight and deck area to ensure physical compatibility. However, there are complex system interactions that need consideration, such as the effects of flexibility on cost and performance. The level of flexibility is quantified using filtered outdegree based on a tradespace network representation of the system. Technical performance is measured in terms of capability, capacity and operability, where a multi-attribute utility function is used to aggregate the total performance for comparison. Findings indicate that increased platform flexibility does increase capacity, but comes at a complex compromise with operability as resistance is increased, and roll periods become unfavorable due to high accelerations.

Keywords

Ship Design; Platform; Flexibility; Uncertainty; Systems Engineering; Tradespace

1. Introduction

1.1. Motivation

In contrast to traditional deep-sea cargo transportation ships, offshore ships comprise a set of ships that are designed to provide different operational services, such as platform supply, offshore construction and light well intervention. These ships are usually build either for a particular long-term contract, which impose specialization, or on speculation, which impose multi-functionality. At early design stages, the future needs of an offshore ship are typically uncertain, due to volatile and heterogenous market conditions (Erikstad and Rehn, 2015). For this reason, there is a need to understand how offshore ships can embed flexibility to be reconfigured in response to emerging needs, and how flexibility affects technical performance and acquisition costs.

From a design perspective, it may be useful to think of offshore ships as comprised of two main groups of subsystems: ship systems and mission-related systems (Erikstad and Levander, 2012). Ship systems are similar across a wide range of final designs, and may include the main hull, accommodation unit and bridge. Mission-related systems can include cranes, remotely operated vehicle units and light well intervention towers. In this way, we adopt the notion of *platforms*, representing the subsystems that provide a common basis from which a stream of end-design configurations can be derived. An interesting aspect of reconfigurable offshore ships is that compatibility between the platform and the mission-related modules moves beyond the consideration of the platform-module interface alone. By adding mission-related modules to the ship, the behavior and performance of the whole system is changed. Such a reconfiguration may change the hydrodynamic properties of the ship, and impact compliance with stability requirements, rendering some useful reconfigurations infeasible.

1.2. Platforms and flexibility

There exists a wide body of research on platforms in system design. The segment of product family design and platform-based product development has received particular attention (Jiao et al., 2007; Jose and Tollenaere, 2005; Meyer and Lehnerd, 1997; Simpson et al., 2006). Research on product platforms are rooted in the development of product families, representing a set of similar products derived from a common platform, while still having specific functionality to meet different customer requirements. Meyer and Lehnerd (1997) define a product platform as *"a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced"*. Product platforms have traditionally been discussed in the context of manufacturing, related to mass customization of product families. This mode of platform thinking is especially useful for ship yards. Erikstad (2009) discusses modularization, product platforming and modular production in shipbuilding. Semini et al. (2014) take the perspective of customer order decoupling points to define customized and standardized designs, and discuss strategies for customized ship design and construction linked to different market characteristics. An alternative view of the platform notion is on design of large, complex systems subject to temporal uncertainty of future use and demand, such as offshore ships. This represents the ship owners' point-of-view, as ship owners need to handle uncertainty throughout a vessel's lifecycle. In this paper, we take the latter approach, and use *platform* instead *product platform* notation to be specific. However, in the literature, there seems to be overlapping definitions.

A challenge in platform and product platform design is the tradeoff between the degree of modularity, and the performance of products based on the same platform. A generic platform may work for multiple purposes, but will perhaps not be a successful design in competition with optimized alternatives. D'Souza and Simpson (2003) present a method for balancing these design properties, studying a general aviation aircraft case. Hölltä et al. (2005) use several metrics to quantify the degree of modularity for products that face both technical and business-related constraints, finding that technical constraints limit the degree to which a design should be modularized. In a more thorough study, Hölttä-Otto and de Weck (2007) find that designs driven by technical constraints in fact often exhibit integral architectures, compared to less constrained designs. These results are in partial opposition to the independence axiom of Suh (1990), and the notion that modularization is always a positive.

Several methods for design of product platforms under uncertainty exist. These include the Product Platform Concept Exploration Method (PPCEM) (Simpson et al., 2001), Design for Variety (DFV) (Martin and Ishii, 2002), and a design process for a product line design under uncertainty and competition (Li and Azarm, 2002). Gonzalez-Zugasti et al. (2000) present a method for architecting product platforms, which are evaluated using a real options approach in Gonzalez-Zugasti et al. (2001). Flexible product platform designs are addressed by Suh et al. (2007), coupling real options valuation with a structural model for the platform. A real option is in this context normally defined as the right, but not the obligation, to change system configuration at a future time (De Neufville, 2003). As there are technical limitations to using real options analysis in engineering compared to financial applications, it has been necessary to device new methods for evaluation of options "in" physical engineering systems (Wang and De Neufville, 2005). As opposed to real options "on" projects, real options "in" projects require understanding of underlying technical constraints. Identification of these options becomes equivalent to finding the design elements that should be flexible. Kalligeros et al. (2006) present a method for identifying the system elements that should constitute the platform design.

Beyond options theory, flexibility is discussed from a broad perspective by Saleh et al. (2009), reviewing the literature on flexibility from a multi-disciplinary perspective including management, manufacturing, engineering and design. Flexibility is seen as the ability of a system to be modified to meet new requirements (Chalupnik et al., 2013). Ross et al. (2008) suggest that flexibility require an external change agent to actively intervene, considering it beneath the umbrella term changeability, along with adaptability; the ability of the system to change itself through an internal change agent. Fricke and Schulz (2005) outline design principles for changeability aimed at reducing complexity, and present a framework for identification and implementation of characteristics that enable future system configuration changes. In their paper, they further discuss the difference between changeability and product platforms, and point out that changeability can be incorporated into the platform itself, which is appropriate when there is temporal uncertainty to the demand of the overall product family.

There is an important difference between valuation of changeability and quantification of the level of changeability. In this paper, we focus on the latter by use of the graph theoretical filtered outdegree metrics (Ross et al., 2008). We do not focus on monetary valuation of flexibility, but rather address the technical performance of the whole offshore ship, to be able to understand impacts of increased levels of flexibility.

The approach applied for assessment of ship design performance in this paper is based on multi-criteria decision making methods, in which a set of conflicting objectives are traded (Keeney and Raiffa, 1993). Multi-objective decision making methods have become popular within ship design, investigating multiple technical (Caprace et al., 2010; Klanac et al., 2009; Martins and Burgos, 2009) and commercial compromises (Gaspar et al., 2012; Temple and Collette, 2016). In multi-attribute tradespace exploration, the point is not merely to identify a set of Pareto optimal design, but also to understand how the set of Pareto optimal designs change with changing context and needs (Ross and Rhodes, 2008).

From this discussion, we address an interesting problem from the naval architects' point of view: How to identify good design alternatives that satisfy performance expectations, while still being flexible to change in the future? We will demonstrate a novel method for measuring the level of flexibility of an offshore product platform, and use this for understanding technical limitations and tradeoffs in technical performance that flexibility leads to.

2. Multi-attribute decision-making

2.1. Multi-attribute tradespace exploration for evaluating designs

Multi-attribute tradespace exploration is a technique for evaluation of many alternative designs against a set of value attributes reflecting the preferences of the stakeholders. Founded in multi-attribute utility theory, the utility function is a function of a set of single-attribute utility functions adhering to several requirements. The attribute set should be *complete*, representing all important properties; *operational*, possible to represent in the analysis; *decomposable*, meaning that the utility function can be broken down to parts that can be analyzed more easily; *non-redundant*, suggesting that the aspects of importance should not be double-counted; and *minimal*, meaning that the set of attributes should be kept as small as possible (Keeney and Raiffa, 1993).

The multi-attribute utility function is often represented as a linear weighted sum of all the single-attribute utility functions, as shown in Equation (1). In this function, U_j represents the multi-attribute utility estimate for a design alternative j in the design set J, while the single-attribute utility functions u_{ij} scores design alternative j with respect to value attribute i in the set of attributes I. k_i denotes the weight for attribute i.

$$U_j = \sum_{i \in I} k_i u_{ij,} \; \forall \, j \in J \tag{1}$$

In the tradespace, the multi-attribute utility for each design alternative is plotted against a measure of costs. The costs can be readily estimated for each design alternative. In Figure 1, we see an example of a tradespace. The Pareto front of non-dominated designs is highlighted.

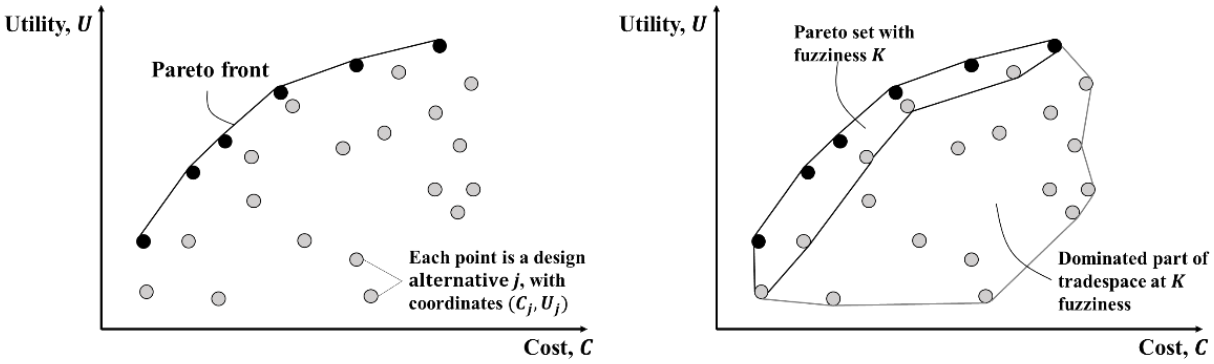

Figure 1: Illustration of a tradespace left (a), with fuzzy Pareto set included right (b).

A significant different between multi-attribute tradespace exploration and similar forms for multi-criteria decision making methods, is the focus on further concept exploration rather than directly finding an "optimal" solution. There are two primary reasons for this. First, we do not have much knowledge about the design alternatives at this stage beyond the low fidelity analysis done. Therefore, we should seek out more information before reducing the number of system concepts to explore. Second, future uncertainty may manifest itself in changes in the context and stakeholder needs, effectively changing the utility function. Solutions that once looked bad, may now look a lot better. This line of thinking is captured in epoch-era analysis (Ross et al., 2008; Ross and Rhodes, 2008).

2.2. Extending the Pareto set with fuzziness

A compromise between keeping all solutions for exploration of the tradespace, and identifying some optimal solution on the Pareto efficient frontier, is to retain some of the dominated designs for further analysis. Smaling and de Weck (2004) developed a framework for extending the set of Pareto efficient design to a fuzzy Pareto set, by introducing a relaxation factor for dominance. The relaxation factor K is a number between 0 and 1, where 0 will mean that we only consider the set of designs at the Pareto front, and 1 meaning that the whole feasible solution space is kept for consideration. A design alternative falling within the fuzzy Pareto set when $K = 0.1$, can be considered to be within 10% of the range of costs and utility relative the Pareto front (Fitzgerald and Ross, 2012). The fuzzy Pareto number $FPN(j)$ for a design alternative j was defined by Fitzgerald and Ross (2012), as the minimal K for which the design alternative j is still contained within the fuzzy Pareto set P_K, as shown in Equation (2).

$$FPN(j) = \min\{K \mid j \subset P_K\} \tag{2}$$

The concept of fuzzy Pareto sets is illustrated in Figure 1 (b). The tradespace is divided into a region that is within the fuzzy Pareto set, and the solutions that are still considered dominated under the relaxed condition for Pareto optimality. Keeping an extended amount of design alternatives for further investigation reduces the probability that potentially value robust solutions are discarded before a proper evaluation has been done, considering that the performance may change under future operating conditions.

2.3. Tradespace networks for quantification of changeability level

Physical reconfiguration changeability between point designs in the tradespace are considered next, where changeability simply represents an umbrella term from flexibility, as discussed by Ross et al. (2008). If a design from the tradespace has been selected as the preferred concept to build and deploy, the stakeholders could still reconfigure the design at a later stage in the lifetime, by adding or removing features. The addition or removal of a feature will be equivalent to moving from one system state to another. In theory, all designs can change into each other, but not all such changes between two designs are rational, when accounting for the cost and time of implementing the change.

In graph theoretical terms, each design alternative is a node, while a set of arcs represents feasible reconfigurations from the considered start node to nodes representing the new systems after reconfigurations. Multiple paths may exist between two nodes comprising an arc, as different physical ways (mechanisms) of making the state transition exist resulting in the same change effect. Details of this concepts are described in the agent-mechanism-effect framework presented by Ross et al. (2008). Associated with each transition path, there is a cost and time. Ross et al. (2008) introduce filtered outdegree (FOD) a measure quantifying the level of changeability by counting the outgoing paths or arcs from a design, counting either change mechanisms or end-states respectively reachable at a given cost and time. In this paper, we only consider counting the number of end-states for simplicity. Figure 2 illustrates a tradespace network in which a cost and time filter is applied, resulting in a reduced set of feasible arcs. An arc is thus defined to exist if there is a path between the nodes within the acceptable cost and time threshold. The node representing an initially selected design (j) that may have previously been located on the Pareto front is shown in Figure 2 (a). In Figure 2 (b), arcs which symbolize feasible transition arcs from this design are illustrated.

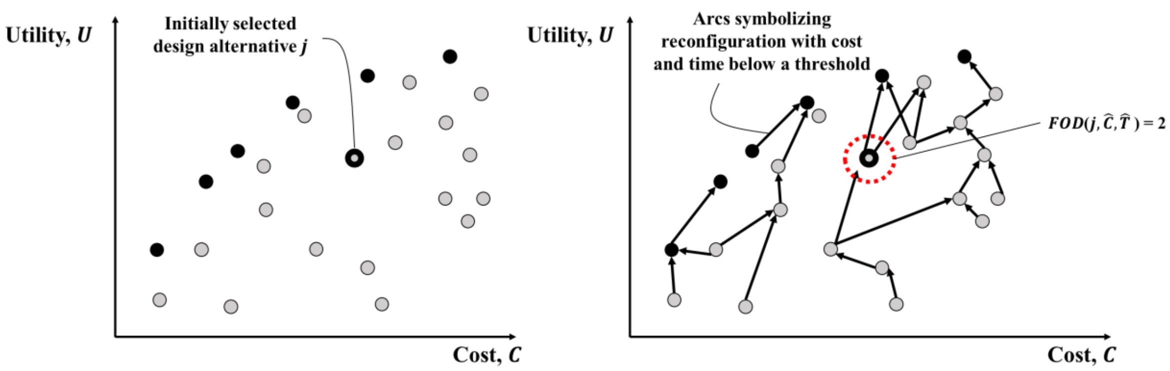

Figure 2: Tradespace network representation left (a), and filtering for cost right (b).

Using the graph theoretical constructs outlined above in combination with the notion of a tradespace network, Ross et al. (2008) present a framework for quantification of changeability. The central metric for changeability in this framework is based on the Outdegree of the system. The Outdegree is the number of outgoing arcs from a node. By applying a threshold cost and time for a state change between two nodes, the Filtered Outdegree (FOD) is defined. The $FOD(j,\hat{C},\hat{T})$ metric quantifies the number of feasible outgoing arcs from node j to all nodes in the set J, under given cost $\hat{C}$ and time $\hat{T}$ thresholds, as given by Equation (3).

$$FOD(j, \hat{C}, \hat{T}) = \sum_{d \in J} H(C_{j,d}, T_{j,d}), \;\; \forall\, C_{j,d} < \hat{C}, \;\; \forall\, T_{j,d} < \hat{T} \tag{3}$$

$C_{j,d}$ and $T_{j,d}$ are cost and time for transitioning from node j to d, and H is the Heaviside function defined as 1 if there exist a path where both change cost and time for the node transition are below the thresholds, and 0 else. Thus, we only count end-state changeability in this case. The metric can easily be changed to be defined as counting the number of change paths between two states also, if that is relevant for the analysis. The filtered outdegree allows an understanding of which real options "in" the design that should be evaluated. The measure can also be adapted by fixing certain design variables that can constitute integral to a platform design.

3. Case study

This case study uses the multi-attribute tradespace network theories to generate insights into the design of reconfigurable offshore ships. The design of offshore construction vessels has been chosen due to the spatial complexity of the design space, the heterogeneity of the markets in which they operate, and the ambiguities in perceived ability to generate value. This case study presented builds on material in Rehn et al. (2016).

3.1. Offshore ship generalized performance attributes

When assessing the performance of an offshore ship, the question *"what is a better ship?"* must be explored (Benford, 1970; Ulstein and Brett, 2015). First, when considering commercial systems, it is reasonable to argue that a good ship is a profitable ship. The ability to generate profits depend on the market situation and is not easy to untangle in terms of describing individual system substructures contributing to profitability.

From a technical point of view, we can still identify a few generalized performance attributes defining valuable systems. For example, in the consumer car industry, disregarding the price, generalized attributes that define a good car include comfort, driving capabilities such as traction and acceleration, transportation capacity in terms of people and luggage, aesthetics and safety. If all these are met, we have a good car. However, as one may find, these attributes eventually meet a physical tradeoff. Either you get a sports car, or you get an SUV. Further, not to mention that increasing attributes together quickly increases the price of the car.

For offshore ships, we can follow the same analogy. A ship designer is interested in developing designs that can be sold to their potential customers; the ship owners. What is desired of an offshore ship is the ability to meet the customer requirements, to drive profitability. We propose three generalized technical performance attributes that are assumed to serve as proxies for profitability, and thus define a better ship, as presented in Table 1.

Table 1: Offshore ship generalized performance attributes.

Attribute	**Description**
Capability	Capability to perform various tasks with equipment: crane, tower, ROV.
Capacity	Transport and storage capacity: deck area, deadweight, tank type/sizes.
Operability	Ability to operate: stability, hydrodynamic behavior, speed.

However, even when disregarding costs, bigger is not always better. For example, issues with external physical constraints may occur, such as maximum lengths at ports and canals. In addition to these three performance attributes several others may be defined, such as safety and reliability (Papanikolaou, 2009). These are more difficult to quantify at the conceptual design level, and were hence not included in this analysis. In general, it is important not to span too many attributes, as short term memory limits the number of attributes to seven, plus minus two (Miller, 1956). Further, the proposed performance characteristics are physical descriptive measures, that are important for most ship concepts. These attributes must not be confused with the “-ilities”, such as flexibility and adaptability, which are system characteristics on the lifecycle level. These enter the discussion when we consider the filtered outdegree in later parts of the analysis.

3.2. Multi-attribute utility (MAU) function

The multi-attribute utility (MAU) function for offshore construction vessels is decomposed into a set of three single-attribute utility functions, connected to the three aspects of performance: capability, capacity and operability. The structure of the utility function is shown in Figure 3. The utility function is the linear weighted sum presented in Equation (1), and the weights are assumed equal. The hierarchy in Figure 3 represents a generalized set of performance attributes for offshore construction and well intervention vessels, and does not necessarily represent the multi-attribute utility function of a particular industry actor.

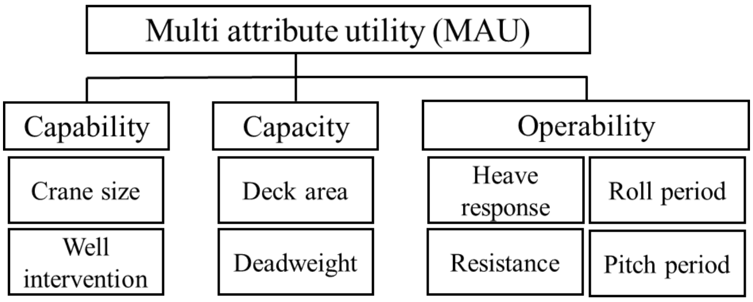

Figure 3: Three performance attributes contributing to the multi-attribute utility function.

The single-attribute utility functions for capability and capacity are easily estimated, as these are decomposable to descriptive elements of the ship topside equipment types and size measures. The single attribute utility for operability is decomposed into further performance attributes based on hydrodynamic characteristics, which map onto ship concepts through the knowledge base of naval architects.

3.3. Design space description

3.3.1. Generating feasible designs

A set of designs is enumerated on basis of design variables that are related both to the main dimensions of the ship, and to the systems installed on board. The six design variables that provide description of the design alternatives, are provided in Table 2.

Table 2: Design variables with ranges describing the set of designs assessed.

Design variable	Description	Unit	Values
L	Length	*m*	70, 80, 90, 100, 110, 120, 130, 140, 150, 160
B	Beam	*m*	15, 18, 21, 24, 27, 30, 33
D	Depth	*m*	7, 9, 11, 13, 15
M	Moonpool	m^2	0, 49
C	Main crane	*Metric ton (MT)*	0, 100, 200, 300, 400, 500
T	LWI tower	*Metric ton (MT)*	0, 250, 500, 750

Only design alternatives that adhere to some basic constraints on physical feasibility in naval architecture are enumerated. Ship concepts need to comply with stability, freeboard and structural integrity criteria. Stability is incorporated based in the requirement of that initial metacentric height (GM) must exceed a minimum required $GM_{MIN} = 0.15\ m$. The freeboard (F) must exceed a minimum required $\mathrm{F}_{MIN} = 1.5\ m$. A model that ensures structural integrity in the hull is included to prevent unreasonably slender ships. A simplified structural model is assumed, and the maximal material stress allowed is $\sigma_{MAX} = 220\ MPa$ for an assumed maximum bending moment condition, including a safety factor. In addition, we require that if well intervention tower is installed, a moonpool is required. Initial design space enumerates to 16800 designs, which reduces to 5803 after the physical compatibility screening.

3.3.2. Parametric assessment for ship properties

The analysis relies on various physical parameters, which are given in Table 3. Assumed parameters for the properties of the equipment that can be installed on the vessel are given in Table 4. The ship platform represents the ship without equipment.

Table 3: Physical parameters for the analysis.

Parameter	Description	Unit	Value
k_{LS}	Lightweight per LBD	[kg/m^3]	0.23*
k_{cost}	Cost per lightweight platform	[k$/MT]	8
k_{DA}	Deck area per LB	[m^2/m^2]	0.55*
C_B	Block coefficient	[-]	0.65*
T_P	Wave peak period	[s]	10
Hs	Significant wave height	[m]	4

** Obtained from comparison with real offshore vessels. MT= Metric tons.*

Table 4: Assumed weight, center of gravity (CoG), deck area and cost of equipment.

Equipment	Weight [MT/MT]	CoG [m]	Deck area	Costs [m$/MT]
Crane	2.5*	10	$capacity_{crane}^{0.45}$ [m^2]	0.022
Well int.	4	30	0.45 [m^2/MT]	0.13

**Including heave compensation equipment. MT= Metric tons.*

The acquisition cost C_{SHIP} for the ship is calculated using Equation (5). The scaling constant k_{cost} is given in Table 3. C_{equip}^{e} is the cost of including equipment e in the set E of possible equipment types that can be installed topside on the ship.

$$C_{SHIP} = k_{cost}\, W_{LS} + \sum_{e \in E} C_{equip}^{e} \tag{5}$$

The lightweight of the platform ship, W_{LS}, is given in Equation (6). k_{LS} is a scaling constant given in Table 3.

$$W_{LS} = k_{LS}\, LBD \tag{6}$$

3.4. Calculation of performance attributes

Performance attributes representing the single attribute utility functions are defined on a 0 to 1 scale, where 1 is the best, and 0 is the worst. For every performance attribute, the individual subcomponents are included using a linear weighted sum, as shown in Equation (1). The defined ranges for the individual performance subcomponents are given in Table 5.

Table 5: Single attributes utility ranges.

Performance attributes		Unit	Utility = 0%	Utility = 100%
Capability	Crane size	MT	0	500
	Well intervention size	MT	0	750
Capacity	Deck area	m^2	500	2 500
	Deadweight	MT	1 000	15 000
Operability	Heave response variance	m^2	0.5	0
	Roll period	s	10	20
	Pitch period	s	4	10
	Resistance	kN	500	0

3.4.1. Capability

Capability is based on the equipment installed on the vessel, and is therefore a linear combination of crane lifting capacity and well intervention tower lifting capacity. No additional calculations are needed, since the capability can be estimated directly from the design description, and connects to the utility function as shown in Table 5.

3.4.2. Capacity

The deck area, A_{DECK}, for a design is estimated by Equation (7). The scaling constant k_{DA} is given in Table 3. A_{equip}^{e} is the area that equipment e, in the set E of possible equipment types, takes up on deck. In other words, we care about the free deck area. In accordance with Table 5, the deck area should be maximized.

$$A_{DECK} = k_{DA}\, LB - \sum_{e \in E} A_{equip}^{e} \tag{7}$$

The deadweight, dwt, of a design is estimated by Equation (8). Δ_{max} is the maximum weight displacement of the ship, defined by the main dimensions, maximum freeboard, block coefficient and water density. W_{equip}^{e} is the weight of equipment e on deck, in the set E, given in Table 4, and W_{LS} is the lightweight of the platform ship given by Equation (6).

$$dwt = \Delta_{max} - \sum_{e \in E} W_{equip}^{e} - W_{LS} \tag{8}$$

3.4.3. *Operability*

Offshore ships should be operable in rough seas. Hence, the hydrodynamic ship response in waves is simplified and estimated. The heave response is determined from the main ship characteristics, in sea states described by a Bretschneider wave spectrum. To simplify, only the translational vertical response is considered. The ship is modelled as a damped mass-spring system including added mass from water (Faltinsen, 1990). The excitation force in the vertical direction is the sum of the Froude-Krylov force, and the diffraction forces. Added mass is represented by 2D strip theory. Assuming the ship as a simplified box shape, we obtain Equation (9) describing the transfer function for heave response $H_3(\omega)$.

$$|H_3(\omega)| = \left|\frac{x}{\zeta_a}\right| = \frac{\frac{2}{k}\sin\left(\frac{kL}{2}\right)\left[\rho B g e^{kz_{bottom}} - \omega^2 A_{33}^{2D} e^{kz_{middle}}\right]}{\sqrt{(C_{33} - (M + A_{33})\omega^2)^2 + (B_{33}\omega)^2}} \tag{9}$$

Here, M is the ship mass, A_{33} is the added mass, B_{33} is the damping coefficient, and C_{33} is the spring constant. ρ is the sea water density and g is the gravitational acceleration. ζ_a is the wave amplitude, ω is the wave frequency, and k is the wave number. L and B refer to the length and beam of the ship. $S(\omega)$ is the Bretschneider wave spectrum. Maximization of operability implies minimization of the heave variance (σ^2), obtained by integrating the heave response spectrum, as shown in Equation (10).

$$\sigma^2 = \int_0^\infty |H_3(\omega)|^2 S(\omega) d\omega \tag{10}$$

When it comes to roll and pitch movement, it is reasonable to desire a high period, as slow vessel accelerations are assumed beneficial for operations. The estimates for the pitch and roll period are given in Equation (11).

$$T_i = \frac{2\pi k_g^i}{\sqrt{g \cdot GM_i}} \tag{11}$$

Here, i represents the degree of freedom, either 4 for roll or 5 for pitch. k_g^i is the radius of gyration, and GM_i is the initial metacentric height. Under the objective of maximizing operability, we further seek to minimize the total ship resistance shown in Equation (12).

$$R_{tot} = \frac{1}{2}\,\rho\,V^2 A\,C_{tot} \tag{12}$$

Where, V is the speed of the ship and C_{tot} is the total resistance number. The wet surface area A is estimated using Equation (13).

$$A = a\sqrt{\nabla\,L} \tag{13}$$

Where, a is a constant assumed to be 2.6. ∇ is the volume displacement of the vessel, estimated as $\nabla = C_B \cdot LBT$, where C_B is the block coefficient, and L, B and T refer to the length, beam and draft of the ship. The non-dimensional total resistance number is assumed to follow the relation in Equation (14), in which F_N is the Froude number, given by $F_N = V/\sqrt{g \cdot L}$, assuming a constant design speed of 15 knots.

$$C_{tot} = \;3.99\,{F_N}^{5.59} + \;0.00206 \tag{14}$$

To account for the vessel being equipped with a moonpool, the resistance is assumed to increase by 10%. Keep in mind, the potential inaccuracy of the above-mentioned estimations may not be that of an issue, as they are included for enabling comparisons between the alternative vessel concepts, and not for absolute estimations.

4. Results

4.1. Initial tradespace exploration

A design space of 5803 alternative designs is generated and analyzed. These designs include ship platforms both with and without equipment installed. The corresponding tradespace is shown in Figure 4, where each point represents a design alternative. The designs that are on the Pareto frontier are highlighted, as are the designs that are within the 3% fuzziness Pareto set.

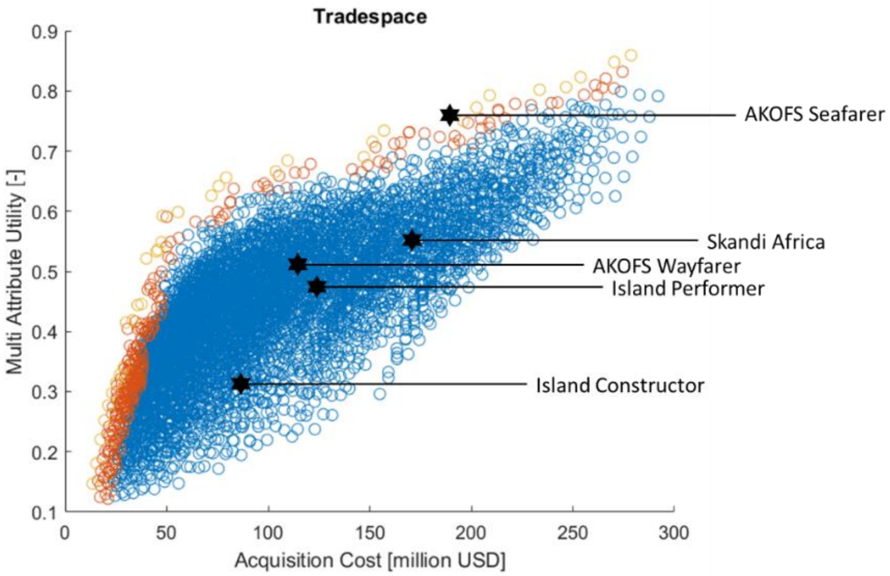

Figure 4: Tradespace of offshore ship designs alternatives.

In Table 6, cost, value, and the design variables for five offshore construction vessels are included. Acquisition cost, MAU and performance attributes for these ships are estimated by the model. These are also indicated in the tradespace in Figure 4. Two of these vessels are previous winners of the award for the Norwegian Ship of the Year.

Table 6: Evaluating recent offshore construction and light well intervention vessels in the tradespace model.

			Performance Attributes			Design variables					
Name	Cost [m$]	MAU [-]	Capability	Capacity	Operability	L	B	D	M	C	T
Skandi Africa	165	0.53	0.50	1.00	0.41	161	32	13	1	900	0
AKOFS Seafarer	187	0.73	0.86	0.76	0.72	157	27	12	1	400	450
Island Performer	123	0.47	0.49	0.48	0.43	130	25	10	1	250	300
Island Constructor	81	0.31	0.11	0.48	0.25	120	25	10	1	140	100
AKOFS Wayfarer	114	0.50	0.36	0.85	0.39	157	27	12	1	400	0

In Table 7, the details of four Pareto efficient designs identified from Figure 4 are shown, including the design variables, performance attributes, MAU and acquisition cost.

Table 7: Four Pareto optimal ship designs, from least to most expensive.

			Performance Attributes			Design variables					
Design ID	Cost [m$]	MAU [-]	Capability	Capacity	Operability	L	B	D	M	C	T
4118	17	0.22	0.00	0.12	0.33	90	15	7	0	0	0
2636	48	0.59	0.50	0.23	0.72	140	15	7	0	500	0
1322	151	0.72	0.67	0.68	0.72	150	24	13	1	500	250
7	279	0.86	1.00	0.93	0.71	160	30	15	1	500	750

4.2. Flexible ship platform analysis

The most significant retrofit cost drivers are changes in the main dimensions of the ship, that is, changing the size of the ship platform. We therefore fix platform parameters (length, beam, depth and moonpool) and only investigate change of equipment on deck (crane and tower). This enables a more meaningful comparison between platforms, since they are similar in the functional space. This reduces the platform design space to 640 alternatives.

The 5% fuzzy Pareto optimal designs in the tradeoff between filtered outdegree and acquisition cost reduces the size of the set of platform designs from 640 to 158. These are the most cost effective flexible platforms available at a given cost. These 158 platform designs are plotted in a tradespace in Figure 5, where we can see the tradeoffs between platform flexibility as measured by filtered outdegree (FOD), acquisition cost and multi-attribute utility. The threshold cost and time for the calculation of FOD are in this case manipulated so that it only enables retrofit of equipment and not of the platform, which enables us to analyze physical aspects of retrofit feasibility.

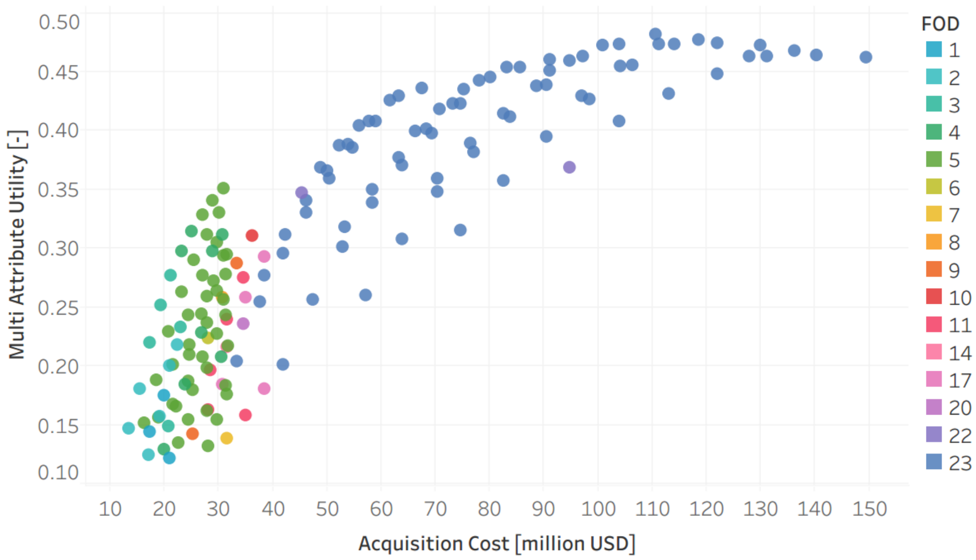

Figure 5: MAU, cost and FOD for cost-effective flexible maritime platforms.

Table 8 presents more detailed information of interesting Pareto optimal platforms in Figure 5. The platforms analyzed do not have any equipment, hence their capability levels are zero, indicated with a "-". These can obviously be changed in the events of adding equipment, which is what we analyze here. The maximum filtered outdegree for a platform in this analysis is 23, which represents being able to take all potential equipment configuration states, as predefined in the tradespace network model.

Table 8: Cost effective ship platforms.

				Performance Attributes			Design variables					
Design ID	Cost [m$]	FOD	MAU [-]	Capability	Capacity	Operability	L	B	D	M	C	T
4120	14	2	0.15	0	0.06	0.23	70	15	7	0	-	-
4111	31	5	0.35	0	0.32	0.45	160	15	7	0	-	-
5747	33	23	0.20	0	0.28	0.23	70	33	7	1	-	-
5739	67	23	0.44	0	0.74	0.40	150	33	7	1	-	-

4.3. Performance attributes trade-offs for platforms

Being on the fuzzy Pareto front in the tradeoff between filtered outdegree and acquisition cost is preferable, to enable maximum potential retrofit upside at the minimal initial cost. Figure 6 untangles the multi-attribute utility measure of the designs plotted in Figure 5, to enable further investigation of the implications of platform flexibility on capacity and operability.

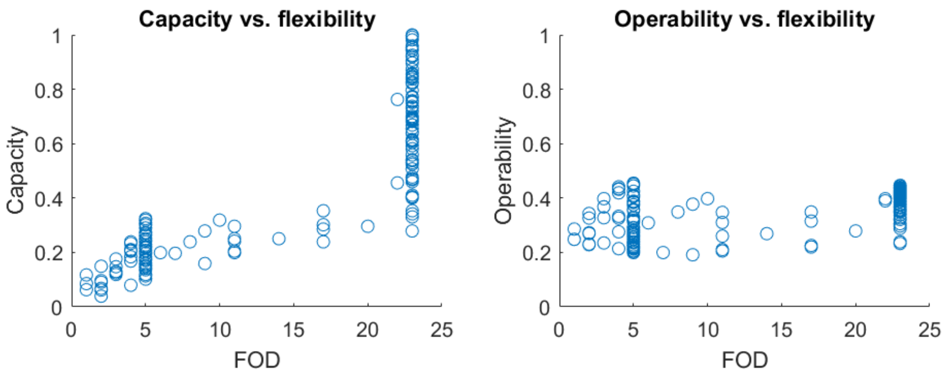

Figure 6: Capacity and operability utilities plotted against flexibility measured in filtered outdegree (FOD).

Figure 6 illustrates single utility attribute values for the platforms as a function of the level of flexibility quantified by the FOD metric. There is a relatively clear correlation between capacity and flexibility, however, operability seems to have a more complex relationship with flexibility, and hence it is of interest to investigate operability vs. flexibility further to its individual sub-attributes. Figure 7 plots FOD against roll, heave response, resistance, and pitch.

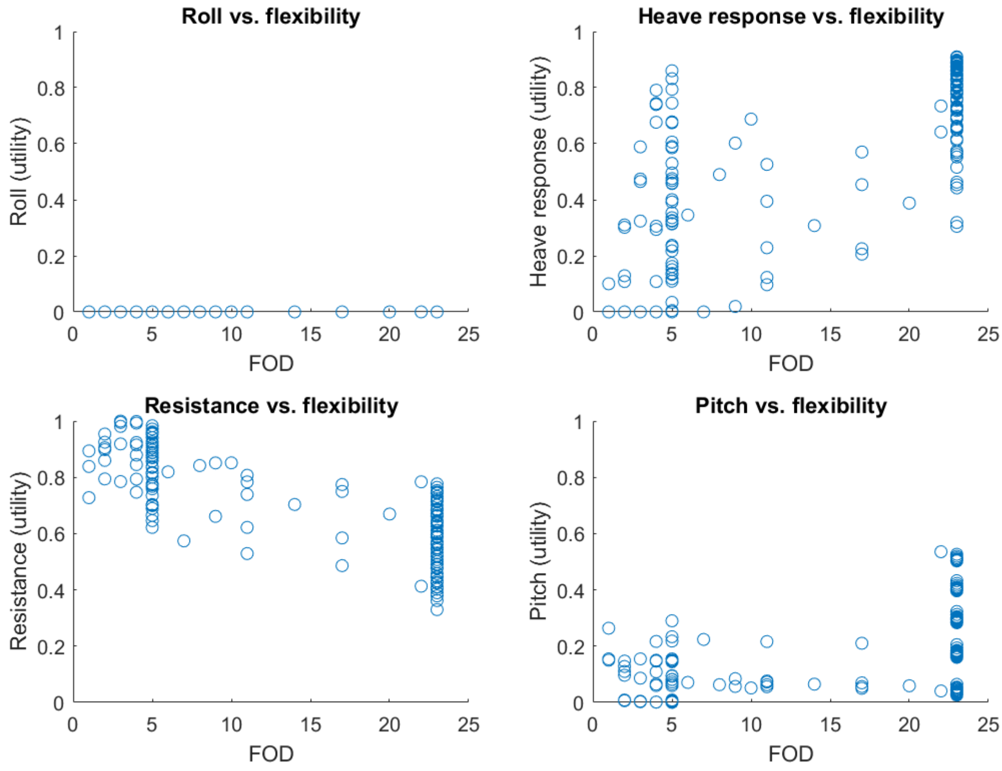

Figure 7: Subcomponent utilities of operability plotted against flexibility measured in filtered outdegree (FOD).

Flexible platforms with high operational performance at low cost are of interest to identify and understand. Four selected platforms at this complex Pareto front are given in Table 9, with best individual single sub-component operability levels.

Table 9: Flexible maritime platforms at low cost with high operational performance.

Best attr.	Design ID	Cost [m$]	FOD	MAU [-]	Performance Attributes Capabil-ity	 Capac-ity	 Operabil-ity	Design variables L	 B	 D	 M	 C	 T
Res	4115	23	4	0.30	0	0.20	0.42	120	15	7	0	0	0
Res	5759	49	23	0.37	0	0.51	0.40	130	27	7	1	0	0
Heave	5669	91	23	0.46	0	0.87	0.41	160	33	9	1	0	0
Pitch	5494	104	23	0.41	0	0.85	0.42	110	33	15	1	0	0

5. Discussion

Pareto optimal results in Table 7 represent the offshore ships that give the highest performance for the lowest cost in the tradespace plotted in Figure 4. Design 2636 in Table 4 is closest to utopia. This design is long and slender, has a large crane installed and a low acquisition cost. Compared to ships in the industry today, this ship has a high length-to-beam ration, of 9.3. It could be interesting to investigate further why this is not found in the market today. It is just a modelling oversimplification, or a so far unexplored opportunity? This points to the need for an iterative analysis process, where we for example can revisit the assumption of equal single-attribute weights. Further, the physical compatibility models in this analysis for structural integrity and stability are very simple, and high fidelity analyses should be used to further investigate the potential use for such a design.

For deeper insights in the model and results, Figure 4 also includes five real offshore ships, of which two are previous winners of the award for Norwegian Ship of the Year. Information about cost, technical performance and design variables for these are estimated by the model and given in Table 6. AKOFS Seafarer is the only of the four designs that is Pareto optimal based on our model. Island Constructor represent a first generation LWI vessel, and has substantially lower technical performance compared to the other ships in Table 6. We do not aim to criticize any of the designs, and recognize that our model may be flawed to give wrong estimates. Our estimation approach is though transparent, as presented in the paper, and the results follow directly from this. Our goal with the comparisons is to provide insight to improve decision making in offshore ship design.

In Figure 5, we can see the tradeoff between platform flexibility, measured in filtered outdegree, and platform multi-attribute utility and acquisition cost. If a platform is supposed to handle crane and tower retrofits, extra stability and deck area is needed, which comes at a cost. We are therefore interested in identifying the most flexible designs at the lowest cost. A key characteristic of the most cost-effective flexible maritime platforms presented in Table 8, is the non-slenderness of these designs. They are wide and short, indicating that cheap flexibility compromises operability.

Figure 6 illustrates the relationships between the individual performance attributes and flexibility. We can see that in terms of capacity, we have a positive correlation with flexibility. This is quite intuitive, as a larger platform can take on more equipment retrofits, and has a larger deck area and deadweight which increases the capacity. However, the relationship between operability and flexibility is more ambiguous, as shown in Figure 7. We observe that all 158 prescreened cost effective flexible platform designs perform poor in terms of rolling. These designs have low roll periods (<10s), contributing to unfavorably high accelerations. Further, Figure 7 shows that a compromise must be made between resistance and flexibility, as excess stability, deadweight and deck area are needed for a high FOD. The heave response and pitch still have an ambiguous relationship with flexibility, as they seem relatively independent from FOD. For the 158 prescreened cost-effective flexible designs, however, all have relatively undesirable roll periods. For heave motion, however, good dynamic behavior should be able to be achieved independently of the degree of flexibility. These results leave us with some insight about the properties of flexible offshore ship platforms. Multiple compromises must be made in the design, between enabling reconfigurations through excessive platform size and stability, roll period, and resistance. Ship slenderness is a critical factor that must be traded against flexibility when designing offshore ship platforms with reconfigurable topsides.

We have shown how tradespace exploration lets us study the trade-offs between utility and costs. However, the single attribute utility weights in the model are assumed constant. By considering explicitly what happens when the system context or stakeholder needs change in an epoch-era analysis (Ross and Rhodes, 2008), strategies could be elaborated for exercising specific reconfiguration opportunities. The tradespace network using filtered outdegree to quantify the level of flexibility can thus lead us to designs providing promising redesign alternatives in the dynamic setting. However, outdegree is only one measure of centrality in network theory. Further insight can be obtained by exploring other measures of centrality, such as betweenness and closeness. Curry et al. (2017) briefly include some other metrics of centrality in their tradespace analysis. Nevertheless, we demonstrate that filtered outdegree represents a good measure for quantifying the level of flexibility for offshore ship platforms.

In terms of flexible platform analysis, it could be interesting to further investigate sensitivities in terms of the design variables of the platform. For the ship in this analysis, this involves the length, beam, depth and moonpool. However, it is important to realize that it is also possible to change the platform, with for example elongation (Knight and Singer, 2012) and moonpool readiness.

6. Conclusion

This paper investigates performance, cost and flexibility of offshore ship platforms. For measuring performance, a generalized maritime model is defined based on capability, capacity and operability. A tradespace representation is used to explore the design space, and to define the tradespace network that enable the quantification of flexibility level for the ship platforms, using filtered outdegree as a quantitative measure of flexibility. Flexible platforms are characterized by having excess stability, deadweight and deck area to take on equipment retrofits. Increased platform flexibility does increase capacity, but comes at a complex compromise with operability as resistance is increased, and roll periods become unfavorable due to high accelerations.

References

Benford, H., 1970. Measures of Merit for Ship Design. Mar. Technol. 465–476.
Caprace, J.-D., Bair, F., Rigo, P., 2010. Scantling multi-objective optimisation of a LNG carrier. Mar. Struct. 23, 288–302.
Chalupnik, M.J., Wynn, D.C., Clarkson, P.J., 2013. Comparison of Ilities for Protection Against Uncertainty in System Design. J. Eng. Des. 24, 814–829.
Curry, M.D., Rehn, C.F., Ross, A.M., Rhodes, D.H., 2017. Designing for System Value Sustainment using Interactive Epoch-Era Analysis: A Case Study from Commercial Offshore Ships, in: 15th Annual Conference on Systems Engineering Research. Redondo Beach, CA.
D'Souza, B., Simpson, T.W., 2003. A genetic algorithm based method for product family design optimization. Eng. Optim. 35, 1–18.
De Neufville, R., 2003. Real Options: Dealing with Uncertainty in Systems Planning and Design. Integr. Assess. 4, 36–34.
Erikstad, S.O., 2009. Modularisation in Shipbuilding and Modular Production. Trondheim, Norway.
Erikstad, S.O., Levander, K., 2012. System Based Design of Offshore Support Vessels, in: IMDC 2012.
Erikstad, S.O., Rehn, C.F., 2015. Handling Uncertainty in Marine Systems Design – State-of- the-Art and Need for Research, in: Proceedings of the 12th International Marine Design Conference.
Faltinsen, O.M., 1990. Sea loads on ships and offshore structures. Cambridge University Press, Cambridge, UK.
Fitzgerald, M.E., Ross, A.M., 2012. Mitigating contextual uncertainties with valuable changeability analysis in the multi-epoch domain, in: 6th Annual IEEE Systems Conference. Vancouver, Canada, pp. 281–

288.
Fricke, E., Schulz, A.P., 2005. Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle. Syst. Eng. 8, 342–359.
Gaspar, H.M., Rhodes, D.H., Ross, A.M., Erikstad, S.O., 2012. Addressing complexity aspects in conceptual ship design: A systems engineering approach. J. Sh. Prod. Des. 28, 145–159.
Gonzalez-Zugasti, J.P., Otto, K.N., Baker, J.D., 2001. Assessing value in platformed product family design. Res. Eng. Des. 13, 30–41.
Gonzalez-Zugasti, J.P., Otto, K.N., Baker, J.D., 2000. A Method for Architecting Product Platforms. Res. Eng. Des. 12, 61–72.
Hölttä-Otto, K., de Weck, O., 2007. Degree of Modularity in Engineering Systems and Products with Technical and Business Constraints. Concurr. Eng. 15, 113–126.
Hölttä, K., Suh, E.S., de Weck, O.L., 2005. Tradeoff between modularity and performance for engineered systems and products, in: International Conference on Engineering Design. pp. 1–14.
Jiao, J., Simpson, T.W., Siddique, Z., 2007. Product family design and platform-based product development: A state-of-the-art review. J. Intell. Manuf. 18, 5–29.
Jose, A., Tollenaere, M., 2005. Modular and platform methods for product family design: Literature analysis. J. Intell. Manuf. 16, 371–390.
Kalligeros, K., de Weck, O.L., De Neufville, R., Luckins, A., 2006. Platform identification using Design Structure Matrices, in: INCOSE International Symposium. Orlando, FL, pp. 1–16.
Keeney, R.L., Raiffa, H., 1993. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge University Press, Cambridge, UK.
Klanac, A., Ehlers, S., Jelovica, J., 2009. Optimization of crashworthy marine structures. Mar. Struct. 22, 670–690.
Knight, J.T., Singer, D.J., 2012. A Real Options Approach to Evaluating Flexible Architectures in Ship Design, In Proceedings of 11th International Marine Design Conference.
Li, H., Azarm, S., 2002. An Approach for Product Line Design Selection Under Uncertainty and Competition. J. Mech. Des. 124, 385–392.
Martin, M. V, Ishii, K., 2002. Design for variety: Developing standardized and modularized product platform architectures. Res. Eng. Des. 13, 213–235.
Martins, M.R., Burgos, D.F.S., 2009. Multi-Objective Optimization Design of Tanker Ships via a Genetic Algorithm. J. Offshore Mech. Arct. Eng. 133, 1–12.
Meyer, M.H., Lehnerd, A.P., 1997. The Power of Product Platforms. Free Press.
Miller, G., 1956. The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psychol. Rev. 101, 343–352.
Papanikolaou, A.D., 2009. Risk-Based Ship Design. Springer, Berlin, Germany.
Rehn, C.F., Pettersen, S.S., Erikstad, S.O., Asbjørnslett, B.E., 2016. Investigating feasibility of flexible ship concepts using tradespace network formulations, in: PRADS 2016. Copenhagen, Denmark.
Ross, A.M., Rhodes, D.H., 2008. Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis, in: INCOSE International Symposium. Utrecht, the Netherlands, pp. 1186–1201.
Ross, A.M., Rhodes, D.H., Hastings, D.E., 2008. Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. Syst. Eng. 11, 246–262.
Saleh, J.H., Mark, G., Jordan, N.C., 2009. Flexibility: A multi-disciplinary literature review and a research agenda for designing flexible engineering systems. J. Eng. Des. 20, 307–323.
Semini, M., Haartveit, D.E.G., Alfnes, E., Arica, E., Brett, P.O., Strandhagen, J.O., 2014. Strategies for customized shipbuilding with different customer order decoupling points. Proc IMechE Part M J Eng. Marit. Environ.
Simpson, T.W., Maier, J.R.A., Mistree, F., 2001. Product Platform Design: Method and Application. Res. Eng. Des. 13, 2–22.
Simpson, T.W., Siddique, Z., Jiao, J., 2006. Product Platform and Product Family Design. Springer Science+Business Media, New York, NY.
Smaling, R.M., de Weck, O.L., 2004. Fuzzy Pareto Frontiers in Multidisciplinary System Architecture Analysis, in: 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. Albany, NY, pp. 1–18.
Suh, E.S., de Weck, O.L., Chang, D., 2007. Flexible product platforms: framework and case study. Res. Eng. Des. 18, 67–89.

Suh, N.P., 1990. The Principles of Design. Oxford University Press, New York, NY.
Temple, D.W., Collette, M.D., 2016. Understanding lifecycle cost trade-offs for naval vessels: Minimising production, maintenance, and resistance maintenance, and resistance. Ships Offshore Struct.
Ulstein, T., Brett, P.O., 2015. What is a better ship ? – It all depends..., in: IMDC 2015. pp. 49–69.
Wang, T., De Neufville, R., 2005. Real Options "in" Projects, in: 9th Annual International Conference on Real Options. Paris, France.