Versatility vs. retrofittability tradeoff in design of non-transport vessels

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Abstract:
In this paper, we study the relationship between economic performance and flexibility for non-transport vessels. More specifically, we investigate the difference between two means of achieving flexibility: retrofittability and versatility, i.e., the ability of a vessel to satisfy diverse needs *with* or *without* change of physical form, respectively. A model is presented to study this relationship, where we first generate design alternatives with relevant, flexible properties before we subsequently evaluate the design alternatives based on their expected discounted economic lifecycle performance. The evaluation model is based on a two-level decomposition of the planning horizon to handle temporal complexity, using scenario planning and Epoch-Era analysis (EEA) for long-term strategic considerations, and Monte Carlo simulation and optimization for medium-term tactical ship deployment. The proposed model is applied to an offshore construction ship design case. Findings indicate that retrofittability significantly can increase economic performance for non-transport vessels operating in an uncertain heterogeneous context.

Keywords: Ship design, Retrofittability, Versatility, Flexibility, Uncertainty

1. Introduction

Determination of the design-specifications of a new ship is a complex strategic problem every shipowner needs to solve as part of a fleet renewal or expansion program. Due to long time horizons and a high degree of contextual uncertainty in the maritime markets (Alizadeh and Nomikos, 2009; Erikstad and Rehn, 2015), this problem is complex and strategic in nature (Christiansen et al., 2007). The ship design problem is different for transport and non-transport vessels. Non-transport vessels serve various service-related needs in the maritime industry, such as offshore construction and anchor handling. This contrasts with traditional ships designed for transportation purposes, such as oil tankers and bulk ships. The revenues for non-transport ships come from contracts with various technical requirements and durations. The ship designer thus needs to determine whether the ship should be designed only for the short-term contract specifications or to be *versatile* and have additional capabilities to handle a broader set of missions after the first contract has ended. However, adding extra equipment increases the initial investment costs. Alternatively, the ship can be optimized for the initial contract, but be *retrofittable* and prepared to be easily retrofitted later. The retrofit decisions can then be made after future uncertainty has been resolved. Following, the degree to which a ship is designed to be flexible is thus a decision to be made at the conceptual design stage, as it will significantly influence the choice of design-concept. This motivates the following research question: What is the relationship between economic performance and flexibility for non-transport vessels? By economic performance, we mean aspects of investment cost, retrofit costs, and revenue potential.

In ship design, one needs to understand the operational phase of the lifecycle to evaluate and compare the performance of different design alternatives. In traditional design literature, this is often reduced to the process of requirements elicitation, or elucidation (Andrews, 2011). However, to study the link between contextual uncertainty and the ability of a system to change form, function, and operation, we need to explicitly consider temporal and contextual complexities of the operational part of the lifecycle (Rhodes and Ross, 2010). Operations research, therefore, becomes an integrated part of this extended design problem. Operations research is a well-established field, with extensive contributions for maritime transportation applications. An excellent review of transportation ship routing and scheduling is presented by Christiansen et al. (2013). However, operations research for non-transport shipping cases is less covered in the literature. A case for operational planning of offshore ships is presented by Fagerholt and Lindstad (2000), where optimal policies for supply in the Norwegian Sea are determined with the objective to reduce operational costs. Gundegjerde et al. (2015) present a case study of a *fleet size and mix problem* for maintenance operations at offshore wind farms using a stochastic optimization model. Christiansen et al. (2007) discuss strategic, tactical, and operational planning in the context of maritime transportation. Even though their perspective is from maritime operations research, they clearly relate strategic decisions to ship design, such as *fleet renewal* and *fleet size and mix*. They thus classify ship design as a long-term strategic decision problem.

Erikstad, Fagerholt, and Solem (2011) present the ship design and deployment problem (SDDP), which is applied to the design of non-transport vessels. This problem involves the determination of the best specification for a non-transport vessel facing a set of available contracts with different start-up periods, durations, and capability requirements. The authors propose a binary integer programming model to select the optimal design and its deployment specifications. Therefore, the SDDP explicitly considers the deployment of the vessel in the operational phase of the lifecycle, with the purpose of improving the initial design specifications. Building on SDDP, Gaspar, Erikstad, and Ross (2012) discuss aspects of handling temporal complexity in design using Epoch-Era Analysis (EEA). However, SDDP, as presented by these collective authors, does not consider the possibility of changing a ship's capabilities after it is built, which we explicitly address in this paper.

The ability of a system to change form, function, or operation, generally called *changeability* (de Weck et al., 2012), is extensively covered in the systems engineering literature. Changeability is a collective term for change-related system properties such as flexibility, adaptability, versatility, and agility. Fricke and Schulz (2005) introduce the term Design for Changeability (DFC) and discuss principles enabling changeability in design. Ross, Rhodes, and Hastings (2008) present a design-neutral framework for defining changeability and explicitly connecting it to change-related ilities, including adaptability and flexibility. Traditional methods for evaluation of changeable design alternatives have roots in the financial derivatives literature, with real options applied to physical systems (Trigeorgis, 1996). However, traditional option pricing methods rely on various assumptions that do not necessarily hold for applications of systems design (Wang and de Neufville, 2005). To separate between traditional, well-defined real options on assets and more ill-structured real options in systems design, Wang and de Neufville (2005) introduce real options "on" and "in" projects respectively. Real options "in" projects do not treat technology as a "black box," in contrast to traditional real options "on" projects. A good reference for flexibility in engineering design, including practical applications and examples, is de Neufville and Scholtes (2011).

The literature on design of non-transport vessels under uncertainty has increasingly focused on aspects of changeability to handle operational uncertainty. Choi, Rehn, and Erikstad (2017) present a module configuration model for adaptable ship design. They use a rolling horizon optimization approach for tactical decision-making in the operational phase of the lifecycle and use that to evaluate and compare two initial main body design alternatives. They conclude that flexibility enabled by modularity can mitigate risks and increase performance. Changeability in ship design is also covered by Niese and Singer (2014), using Markov decision processes for changeability evaluation studying a case from ballast water treatment.

While most contributions on changeability in ship design provide insights into the *evaluation* of one changeable design alternative, they typically do not explicitly study *different changeable design alternatives*. That is, little or no focus is on the characterization and exploration of alternative design solutions with different types and levels of changeability built in. This especially accounts for design characteristics that enable retrofits. Versatility, or multi-functionality by design, is to some degree addressed in the literature, e.g., by Stopford (2009), who introduces *lateral cargo mobility* (LCM) measuring the number of different types of cargo a vessel can carry. Rehn et al. (2018) differentiate between two main aspects of changeability in systems engineering practices: quantification of changeability level for a design alternative, and valuation of a given level of changeability for a design alternative. They further present a case from offshore shipping to illustrate how different levels of changeability in design can be quantified. A more practical perspective on ship design and retrofit is presented by Ullereng (2016), who studies how offshore shipping companies can reutilize platform supply vessels (PSVs) in poor offshore markets. Ullereng focuses both on classical operational real options such as sell, layup, or scrapping, in addition to exploring retrofit options. He mentions that offshore shipping companies have discarded potential ship conversions due to too high conversion costs. This supports the research topic explored in this paper, as we investigate how retrofittability, enabling reduced conversion costs and times, can be of importance for the next generation offshore ships.

2. Flexibility in non-transport shipping

2.1. Concepts and definitions

Changeability represents the ability of a system to change form, function, or operation (de Weck et al., 2012), and is a collective term for change-related ilities such as flexibility, adaptability, versatility, and agility. In this paper, we generally use the term flexibility, as it assumed best suitable for the targeted ship design audience. Changeability and flexibility are thus used interchangeably. We are interested in studying two nuances of flexibility, which relate to the ability to satisfy a diverse set of needs *with or without* change of form. Change of form represents physical change of an engineering system, which can be collectively called retrofits. Change of form can result in a change of function, but change of function do not necessarily require change of form. For example, a multi-functional offshore ship can handle different types of missions, without the need for any retrofits. This built-in multi-functionality is characterized as *versatility* (Chalupnik et al., 2013). This example illustrates the two different aspects of flexibility in design:

- **Versatility:** the ability of a system to satisfy diverse needs, *without* change of form.
- **Retrofittability:** the ability of a system to satisfy diverse needs, *by* change of form.

We define *retrofittability* as a general change-related ility involving change of form, for lack of a better word. Other, more specific ilities in the literature relating to change of form are reconfigurability, modifiability, scalability, and extensibility. de Weck et al. (2012) define these as: reconfigurability – ability to change component arrangement and links reversibly; modifiability – ability to change the current set of specified system parameters; scalability - ability to change the current level of a specified system parameter;

and extensibility – ability to accommodate new features after design. Retrofittability thus represents a superset encapsulating these four change-related ilities, explicitly contrasting versatility. One relevant application of the phrase *retrofittable* in the literature is by Baker et al. (2016), who study requirements engineering for retrofittable subsea equipment.

2.2. Examples from the industry

Market changes are the driving factors for flexibility in commercial maritime systems. The needs-specifications from the industry are operationalized through tenders. For offshore shipping, the market is heterogeneous, with tenders of various length, technical requirements and at different operational areas. The shipping industry is capital intensive, coupled with an uncertain heterogeneous market, therefore is it natural to see retrofit and redesign of vessels. Table 1 provides some recent examples from retrofits in the maritime industry.

Table 1: Vessel retrofit examples with approximate cost estimates (Rehn and Garcia, 2018), PSV= platform supply vessel, OCV = offshore construction vessel.

Vessel name	**Type**	**Year of**		**Cost $ millions**		**Retrofit description**
		Build	**Retrofit**	**Built**	**Retrofit**	
Belle Carnell	PSV	2004	2013	25	40	Accommodation, equipment
Aker Wayfarer	OCV	2010	2016	220	90	Equipment
Vestland Cygnus	PSV	2015	2015	38	18	Beam, equipment
Enchantment of Seas	Cruise	1997	2005	300	60	22 m. elongation
MSC Lirica (+3 sis.)	Cruise	2003	2014	250	65	24 m. elongation

It has been demonstrated in the marine industry that several ships are prepared for retrofits at the design stage. For non-transport vessels, examples typically involve being prepared for equipment retrofits. In the classification societies, there exist class notations for flexibility such as *Gas Ready* (DNV GL, 2015). This class notation represents a set of predefined characteristics that enable a ship to easily change from diesel to dual-fuel, i.e., to diesel and natural gas, for propulsion. Table 2 presents examples from the industry with vessels prepared for retrofits.

Table 2: Examples of retrofittable ships in the industry (Rehn and Garcia, 2018), PSV = platform supply vessel, AHTS = anchor handling tug supply, MSV = multiservice vessel.

Vessel name	**Type**	**Built**	**Retrofittability, prepared for:**
Olympic Intervention IV	MSV	2008	Light well intervention tower
Olympic Zeus	AHTS	2009	250 tonnes crane
Go Matilda / Mundara	PSV	2016	Crane, remotely operated vehicle
Dina Polaris	MSV	2017	150 tonnes crane, helideck

Contrasting retrofittability, several ships are also built versatile of which there are multiple examples, as presented in Table 3. The cases presented in Table 1, 2 and 3 demonstrate the need for explicitly considering flexibility in design of non-transport vessels.

Table 3: Examples of versatile ships (Rehn and Garcia, 2018).

Vessel name	Type	Built	Versatility description
Front Striver	Oil bulk ore	1992	Can carry either dry or wet bulk
AKOFS Seafarer	Well Intervention Unit	2010	Multi-purpose offshore ship
Wes Amelie	Container ship	2011	Dual fuel engine: diesel/natural gas

3. Methodology

3.1. Overall stepwise methodology

A stepwise methodology illustrated in Figure 1 is used to investigate the relationship between flexibility and economic performance. Two main aspects of the design process are outlined: 1) generating flexible design alternatives and 2) evaluating flexible design alternatives. This is in line with the short two-stage definition of systems design by Hazelrigg (1998). The procedure in terms of searching for solutions and identifying candidate flexibilities can be described as patterned search using a simple bottom-up screening model (de Neufville and Scholtes, 2011). That means that a low-fidelity model of the system is utilized and explored with guidance from conceptual models familiar for the design team.

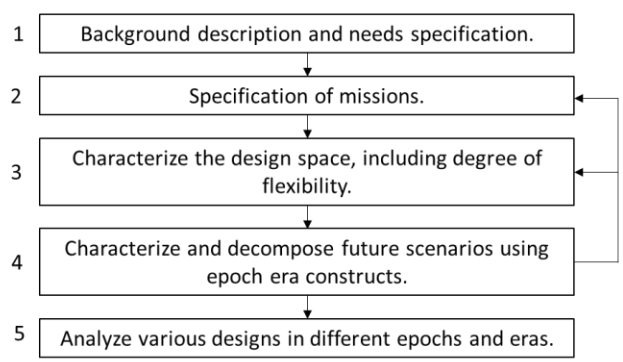

Figure 1: Proposed stepwise methodology.

3.2. Generation of flexible design alternatives

The procedure used to generate design alternatives is based on the technical requirements from the possible missions in the market. As motivated in the introduction of the paper, we are interested in investigating the design of non-transport vessels that can provide capabilities beyond the specifications of the first contract. Three cases are considered:

- **(i)** *Base case:* the vessel is optimized for the first contract.
- **(ii)** *Retrofittable:* the ship is primarily optimized for the first contract but is prepared to be retrofitted later.
- **(iii)** *Versatile:* additional multi-functionality is included in the design from the beginning.

Moreover, there are multiple nuanced design alternatives that can be retrofittable, versatile, or combinations of both. We, therefore, need a smart way to structure flexible design alternatives and measure the degree to which one alternative design is flexible compared to another.

Characterizing flexible design alternatives

A system-change can be represented by a transition between two functional states, e.g., the ship before and after a retrofit. Let us, for example, consider the case of an offshore construction vessel (OCV) with a crane, which is to be retrofitted with a large well intervention tower (LWI), as illustrated in Figure 2. Here, alternatives (i) and (ii) are retrofitted into alternative (iii). The retrofittable alternative (ii) has a moonpool (path-enabler), which makes the transition cheaper. Alternative (ii) is thus more retrofittable. A moonpool is an opening through the hull of a ship to access the water, which is required capability of the ship platform for the retrofit of well installation tower equipment. Additional path-enablers can be included, such as a pre-reinforced deck. Further, sufficient margins on the stability and deadweight of the vessel are also crucial for reducing change costs, analogous to having a *flexible base platform* (Rehn et al., 2018a). Combinations of path-enablers built into a design alternative can be explored to investigate various aspects of flexibility for an otherwise similar design solution.

Quantifying the level of flexibility for a design alternative

Quantifying the level of flexibility for a design alternative involves measuring the impact on change cost, and or change time, from the inclusion of a set of path-enablers in a design. An example of a path-enabler that reduces the cost of the retrofit installation of a light well intervention (LWI) tower on an offshore construction vessel is a moonpool. A moonpool is expensive to retrofit on an existing vessel, and a preinstalled moonpool can save about $9 million in retrofit costs, on a total cost of about $90 million (Rehn et al., 2018b). The cost of this potential retrofit can therefore be reduced by about 10%, this is however at the up-front moonpool pre-installation expense of about $1 million. This example is illustrated in Figure 2.

Different aspects of quantification of flexibility level is discussed by Ross et al. (2008b) and Rehn et al. (2018b).

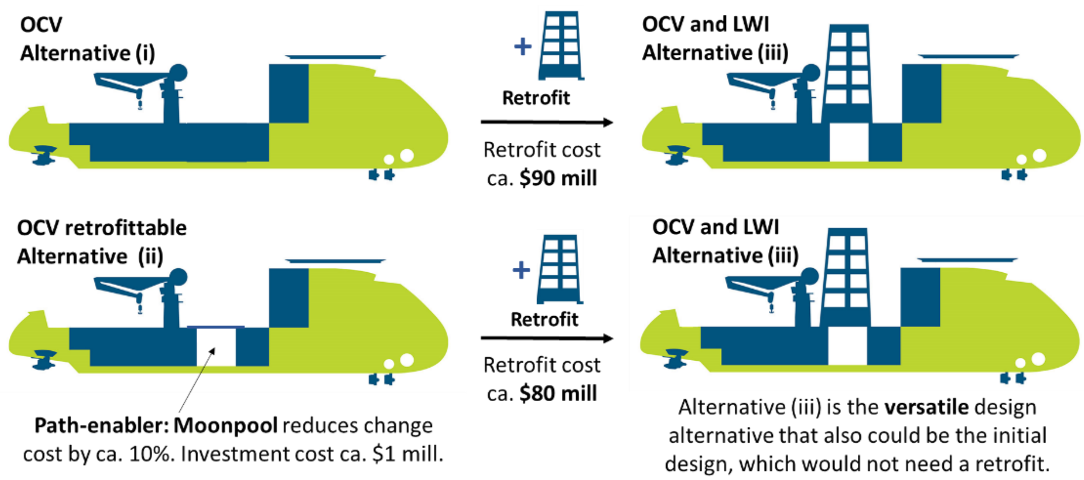

Figure 2: Flexible design alternatives, change cost illustration, OCV = offshore construction vessel, LWI = light well intervention, 500 tonnes tower installation (models provided by Ulstein International AS).

3.3. Evaluation of flexible design alternatives

3.3.1. Evaluation approach

Evaluation of flexibility is generally done using real options theory. However, traditional option pricing methods rely on several assumptions that do not necessarily hold for systems design applications. These include constructing a replicating portfolio that can be traded in an arbitrage-free market (Wang and de Neufville, 2005). When these conditions do not hold, instead of using risk-neutral "probabilities" and risk-neutral discounting, we perform "actual valuation" using *actual probabilities* and *risk-adjusted discount rates*.

3.3.2. Temporal decomposition of the planning problem

The design alternative evaluation method is decomposed mainly into two segments based on the length of the planning horizon: tactical and strategic. Strategic, tactical, and operational planning are three terms used to characterize managerial planning horizons. Strategic planning refers to decisions with long-term implications, typically from five years to multiple decades. Tactical planning refers to decisions with medium-term implications, typically from months to five years. Operational planning refers to decisions with short-term implications, typically day-to-day to months, such as a specific lifting operation. In this paper, we use scenario planning and Epoch-Era Analysis (EEA) at the long-term strategic level, and Monte Carlo simulation and optimization at the tactical level. Operational aspects are not explicitly considered in this paper. The two-level decomposition is illustrated in Figure 3. This approach is inspired by Gaspar, Erikstad, and Ross (2012). A similar decomposition is presented by Kaut et al. (2014) who call it a multi-horizon approach. Schoemaker (1991) also presents a decoupled method, using scenario planning for strategic issues, and Monte Carlo simulation at the operational level.

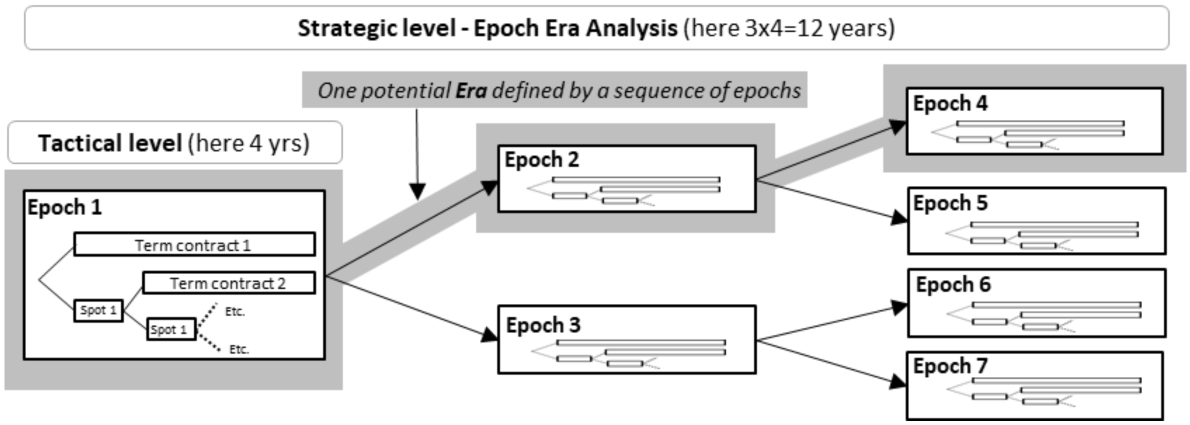

Figure 3: Planning horizon decomposition for the operational part of the lifecycle of a non-transport vessel. The long-term strategic analysis is conducted using Epoch-Era Analysis (EEA). Within an epoch, tactical planning of which contract to assign a ship to is determined, where the ship either can take "term" contracts (4 years duration) or "spot" contracts (3 months duration).

Strategic level: Epoch-Era Analysis

Epoch-Era Analysis (EEA) is used to handle the long-term contextual and temporal complexities of the operational part of the lifecycle (Ross et al., 2008a). This includes both the structuring and generating long-term futures through use of short-term epochs as building blocks for long-term eras and subsequently performing strategic analyses based on these constructs. A short-term *epoch* is a period with fixed *context and needs*, for a given level of abstraction, described by well-defined epoch variables. Long-term eras emerge when sequences of short-term epochs are assembled in time, representing the lifecycle-scenario of a system, as illustrated in Figure 3. Two main steps are thus needed to generate short-term epochs and long-term eras:

1) *Short-term epoch characterization*

   The goal of this step is to identify and parameterize uncertainties in the context and stakeholder needs. We are mainly interested in the uncertain contextual factors that can potentially affect the system success. Essential uncertainties usually originate in domains such as market, technology, and regulations. Identification of epoch variables may involve methods like brainstorming and consultation with subject matter experts. This step results in a well-defined epoch vector comprising the epoch variables, and a combination of the epoch variables will thus define an epoch.

2) *Long-term era construction*

Long-term eras represent the operationalization of futures through the sequencing of short-term epochs, as illustrated in Figure 3 (one Era is highlighted in grey, comprising the sequence of epochs 1, 2 and 4). Eras can be developed using multiple approaches, for example using expert judgment which accounts for possible narratives, or one can use more quantitative methods. For cases with a high degree of uncertainty and complexity, narrative scenario generation in line with *scenario planning* is a recommended approach (Schoemaker, 1991). Scenario planning is a process for exploring alternative futures, where we seek to answer *"What can conceivably happen?*", and "*What would happen if…?"* (Lingren and Bandhold, 2003).

Tactical level within short-term epochs: Monte Carlo simulation and optimization

At the tactical level, within a well-defined, short-term epoch with constant contextual parameters, we quantify the economic performance of different design alternatives. To do this, we find the optimal deployment and retrofit decisions for each design alternative. That is, given the set of available contracts sampled, with specified technical requirements, we identify the most valuable decision path for a given design alternative. Since the economic performance of a design alternative may vary significantly based on the specific contract scenario sampled within an epoch, we sample multiple contract-scenarios and take the average. The tactical model is based on two main parts:

1) *Mission generation within a short-term epoch*

Within an epoch of four years, mission scenarios are generated with a resolution of one quarter of a year. In each time step, there is a set of available contracts in the market. The contracts, each with technical requirements, market rates and durations, are sampled for each time step. This sampling is dependent on the epoch variable instance. A Monte Carlo simulation of the multiple tactical scenarios within an epoch is performed.

2) *Optimal deployment for a given contract scenario within a short-term epoch:*

For a given contract scenario within an epoch, an optimal deployment model is solved. Deciding which contract to take, and potentially which retrofit to make is determined by a complete enumeration of the decision alternatives, of which the one with the highest net present value is chosen. Alternative strategies of operation are tested, regarding whether the ship is to be operated on spot or term contracts.

4. Case study

4.1. Step 1: Background description

The business case emerges from an expected strong demand for energy in the future, materialized through continued demand for offshore oil and gas over the next couple of decades despite recent oil price volatility. This business opportunity is targeted by a shipowner, contracting a ship first for a given four-year contract and thereafter on speculation. After the first contract ends, several missions are identified as described in Table 4. The goal of the shipowner is profitability.

First contract (M1): The first contract is an inspection, maintenance, and repair (IMR) mission, with a low technical requirement level and a duration of 4 years. The technical requirements of this contract are given in Table 4 (M1), including accommodation capacity for 50 people, remotely operated vehicles (ROV) and a deck area of 700 m^2. The first contract rate is $85 000 per day.

4.2. Step 2: Mission specification

Five mission types, each with two technical requirement levels, are identified to generate ten possible missions, as described in Table 4.

Table 4: Mission details, including technical requirements. Acc. = accommodation (ppl.), ROV = remotely operated underwater vehicles.

Mission description			Technical mission requirements					
Type	Number	Req. level	Tower [tonnes]	Crane [tonnes]	Acc. [ppl.]	ROV [y/n]	Deck area [m2]	Gangway [y/n]
Inspection maintenance	M1	Low	0	0	50	1	700	0
and repair (IMR)	M2	High	0	150	100	1	1000	0
Subsea installation and	M3	Low	0	200	50	1	1000	0
construction (OSC)	M4	High	0	400	100	1	1500	0
Light well intervention	M5	Low	200	100	130	1	1000	0
(LWI)	M6	High	600	300	180	1	1000	0
Field decommissioning	M7	Low	0	300	100	1	600	0
support (ODS)	M8	High	600	600	200	1	1400	0
Offshore wind support	M9	Low	0	0	100	0	250	1
(SOV)	M10	High	0	50	150	1	500	1

4.3. Step 3: Characterization of design alternatives

Three main types of design alternatives are investigated: (i) baseline, (ii) retrofittable, and (iii) versatile. The general vessel details are given in Figure 4. An overview of technical details of the nine design alternatives is given in Table 5. To ensure technical feasibility of the design alternatives, stability and structural integrity of the hull were tested. For more technical details see (Rehn et al., 2018a).

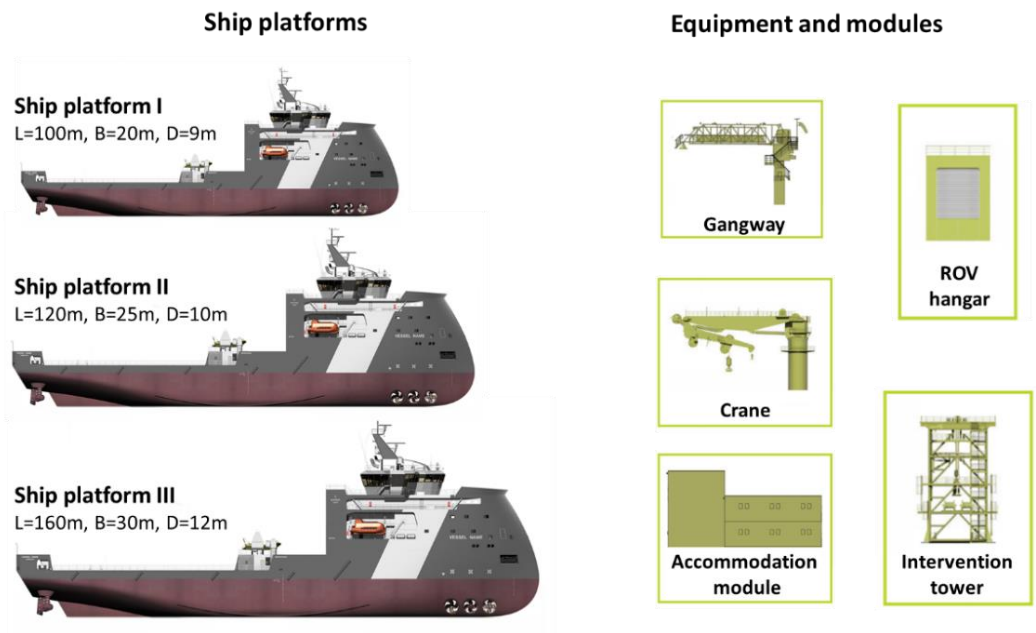

Figure 4: General ship details, decomposed into the ship platform and value-enabling equipment and modules to be placed on the ship platform which together constitute a design alternative (models provided by Ulstein International AS).

Table 5: Overview of the nine design alternatives analyzed, LOA = length overall, B = beam, D = depth, Dwt = deadweight, POB = persons on board (accommodation), LWI = light well intervention tower.

#	Name	Plat-form	LOA [m]	B [m]	D [m]	Moon pool [y/n]	Deck reinf. [y/n]	SPS code [y/n]	Dwt [ton]	Deck area [m2]	Crane [ton]	POB [ppl]	LWI [ton]	ROV [no.]	Gang-way [y/n]	Cost [m$]
A	Baseline	I	100	20	9	0	0	0	3000	1400	0	50	0	2	0	50.40
B	Retrofittable 1	I	100	20	9	0	1	0	2950	1400	0	50	0	2	0	50.42
C	Retrofittable 2	I	100	20	9	0	1	1	2950	1400	0	50	0	2	0	50.52
D	Retrofittable 3	II	120	25	10	0	1	1	4650	2450	0	50	0	2	0	64.92
E	Retrofittable 4	II	120	25	10	1	1	1	4200	2350	0	50	0	2	0	65.92
F	Retrofittable 5	III	160	30	12	1	1	1	10100	4100	0	50	0	2	0	110.6
G	Versatile 1	II	120	25	10	0	0	1	3500	2000	400	100	0	2	0	99.80
H	Versatile 2	II	120	25	10	1	1	1	3150	1650	400	200	200	2	0	137.00
I	Versatile 3	III	160	30	12	1	1	1	7050	3050	600	200	600	2	1	254.00

Alternative (i) – Baseline design

The design alternative that is optimized for the first contract (Mission M1 in Table 4) is characterized as the *baseline*. This design alternative has remotely operated underwater vehicles (ROV) and accommodation for 50 persons, but no gangway, crane, or light well intervention tower. Furthermore, it has the smallest of the three platforms outlined in Figure 4. This is because platform I can carry the equipment needed for mission M1 at the lowest investment cost. However, the small platform provides lower margins on stability and deadweight to support for retrofits for other missions later in the lifecycle.

Alternative (ii) – Retrofittable design

The retrofittable design alternatives considered are based on the baseline design in terms of immediate technical capability level (can only take contract M1) but are prepared for retrofits to satisfy a broader span of missions. The space of potential missions is defined in Table 4. What is of interest, is thus to investigate which system-characteristics (path-enablers) that can be included in the baseline design to make the future retrofits cheaper. The common denominator is that the system-characteristics collectively reduce the change cost in the event of a retrofit, at an up-front investment cost. An overview of the four identified system-characteristics enhancing retrofittability for this case study is given below.

- *Deck reinforcement:* Additional strength in the main deck reduces the need for additional steelwork when retrofitting equipment and, therefore, also reduces the overall retrofitting cost. The largest cost saving comes from the reduced need of labor and engineering work for the retrofit operation, as the reinforcement can be done with little additional effort during the initial design process.
- *Special Purpose Ships (SPS) Code:* The SPS code is required for vessels carrying more than 12 special-personnel onboard. The special-personnel can for example be crane operators, offshore technicians, and ROV drivers. In order to fulfill the SPS code, the vessel is required to comply with stricter stability and subdivision requirements. To satisfy these requirements after the initial construction of the vessel, in most cases it is necessary to add additional bulkheads and watertight doors, which can significantly increase the cost and complexity of a retrofit.
- *Moonpool:* A moonpool is an opening through the hull to access the water and is required (in most cases) for the installation of a light well intervention tower. A pre-installed moonpool significantly reduces the tower retrofit costs, as the retrofit of a moonpool has a high impact on the integrity of the main ship platform.
- *Ship platform:* The ship platform carries the value-enabling equipment and is in this case defined by the main dimensions: length overall (LOA), breadth (B) and depth (D). For a ship to be feasible, there are multiple criteria that must be satisfied, such as regarding stability and sufficient deck area and deadweight, where the platform plays a vital role.

The four characteristics described above can be included in baseline design in multiple combinations. The Design for Changeability (DFC) variable is used to structure sets of characteristics included in the design. Five alternative retrofittable designs are considered, as described in Table 6.

Table 6: Design for changeability (DFC) descriptions for the offshore case, with associated investment costs.

DFC	**DFC description**		**Total cost**	**Extra cost**
	Platform	Extra characteristics		
0	I	Baseline (none)	\$50.40m	-
1	I	Deck reinforcement	\$50.42m	\$0.02m
2	I	Deck reinforcement and SPS code	\$50.52m	\$0.12m
3	II	Deck reinforcement and SPS code	\$64.92m	\$14.52m
4	II	Deck reinforcement, SPS code, and moonpool	\$65.92m	\$15.52m
5	III	Deck reinforcement, SPS code, and moonpool	\$110.62m	\$60.22m

To understand how much more retrofittable the combinations of characteristics make the ship, we investigate their impact on the retrofit costs. The costs for each potential equipment retrofit is given in Table

7, as a function of DFC. That is the costs of adding a piece of equipment to the baseline design (which already has accommodation for 50 people and ROV hangar). For simplicity, we assume that the main platform remains the same during the lifecycle of the ship. In Table 7, we can see that the larger platforms are needed to be able to take on the larger equipment. These numbers are estimated based on historical ship design and retrofit data.

Table 7: The retrofit cost *for the design alternatives with different design for changeability (DFC) levels, retrofit costs are based on retrofit from the baseline design, numbers in million USD.*

DFC	**Crane (from 0)**		**Tower (from 0)**		**Acc. (from 50)**		**Gangway (from 0)**
	200t	400t	200t	600t	100ppl	200ppl	Yes
0	7.50	-	-	-	2.70	5.70	4.40
1	7.30	-	-	-	2.50	5.40	4.20
2	7.30	-	-	-	1.50	4.40	4.20
3	7.30	10.40	24.60	-	1.50	4.40	4.20
4	7.30	10.40	21.60	-	1.50	4.40	4.20
5	7.30	10.40	21.60	72.20	1.50	4.40	4.20

Alternative (iii) – Versatile design

The versatility of a vessel is relatively easy to conceptualize, compared to retrofittability, as it is a static measure of the set of needs a ship can satisfy without performing any retrofits. The degree to which one design alternative is versatile can, for example, be measured by the span of possible missions that can be served. The maximum number of possible missions to serve is ten – covering all potential missions in Table 4. The baseline design alternative (i) can only serve one mission (M1). Three alternative versatile designs are considered, as described in Table 5. The span of missions that can be served for design alternative "versatile 1, 2, and 3" is five, six and ten (max) respectively.

4.4. Step 4: Characterization and breakdown of future scenarios

4.4.1. Short-term epoch construction and ship-contract allocation

Short-term epochs variables are elicited in Table 8. The complete epoch space spanned by these variables comprise 24 epochs. We assume that one epoch is of length 4 years. The first epoch, where the first term contract (M1) is manifested, is called Epoch 1 and is described in Table 8.

Table 8: Short-term epoch characterization at the strategic level.

Epoch variable	**Unit**	**Values**	**Epoch 1**
Oil price	USD/barrel	30, 80, 130	80
Competition	[-]	Low, high	High
Renewable focus	[-]	Low, high	Low
Decommission focus	[-]	Low, high	Low

Within a short-term epoch, we perform a Monte Carlo simulation to estimate the expected performance of each ship design alternative. The organization of the simulation comprises two main parts: 1) sampling multiple contract scenarios based on the overall orientation of the epoch, and 2) simulation of the managerial operation (contract-allocation) to estimate the expected economic performances of each design alternative in each epoch. The parametric details of the simulation model are calibrated based on discussions with subject matter experts. Having a realistic and well-calibrated model is obviously essential for the correct estimation of performance. However, the estimated absolute values from the model are in fact not that important for us, as we are most interested in studying the *differences between* the performances of design alternatives.

1) Contract sampling within a short-term epoch

Multiple potential contracts may exist in the market in a given time step, of which one is to be selected. A contract is a mission with an associated market rate and duration. Ten different missions are considered in this analysis, as described in Table 4. The market rate for a given contract is sampled on a scale between 10 000 USD/day and 250 000 USD/day, which is dependent on the epoch details and technical difficulty of the mission. The contract duration is either *spot* or *term*, with durations of 3 months or 4 years respectively. That means, given an epoch state described by the epoch variables, e.g., Epoch 1 in Table 8, a set of contracts for a given time-period is generated.

2) Ship-contract allocation model

A model is developed that determines the allocated contract for each time-step the ship is idle. A short-term epoch is assumed to be four years, and we use a time step of three months to be able to capture the temporal dynamics of the spot market within an epoch. We assume that the functionality requested for a mission in the spot market must be provided immediately, such that retrofits are only considered for term contracts. Unless a ship already is assigned to a term contract, the shipowner must decide in each time step whether to allocate the ship to a term contract, or a spot contract – for a given contract availability. If a spot contract is assigned, a similar decision must be made next quarter – after the spot contract is finished. Two operational strategies that dictate the market preferences of the shipowner are explored. This is done to untangle managerial complexity.

- **S1 – Term market priority:** The most profitable spot market contract is chosen.
- **S2 – Spot market priority:** The most profitable term market contract is chosen, but if there are no profitable term contracts available, the ship is offered in the spot market until a possible term contract emerges.

If there is a contract yielding a positive contribution margin, the ship will be in operation. If not, the ship will be temporarily put into layup. The contribution margin is estimated as the dayrate of the contract, minus the cost of the crew which is assumed to be $650 per day per person. We assume a discount rate of 15% in this case study, which is in line with similar industries (Kaiser, 2014). However, we note that for real applications, the choice of discount rate is highly case- and stakeholder-specific, and should be carefully estimated as the results can be highly dependent on this assumption.

4.4.2. Long-term era construction

The length of an era is assumed to be 12 years, as illustrated in Figure 3, of which the first four years are determined by Epoch 1. Thus, the different eras are described only by two subsequent epochs. Two market segments are considered for era construction: the traditional oil and gas (O&G) market, and emerging markets. Five narrative scenarios are developed, as described in Table 9. O&G is the targeted marked, of which we assume three main scenarios: (1) Petroleum upswing, (2) Business as usual and (3) Oil crisis. Two additional scenarios, describing the emerging markets are (4) Renewable revolution and (5) Decommission boom.

Table 9: Overall description of the five long-term eras considered in the analysis, and details of the two short-term epochs characterizing the era after the Epoch 1, from time period 4-8 years and time period 8-12 years.

#	**Era name**	**Description**	**Short-term Epochs (after Epoch 1)** *[oil price, competition., renew., decom.]* **4-8 years**	**8-12 years**
1	Petroleum upswing	Strong O&G market: Oil price increasing and staying high, good market conditions.	[130, low, low, no]	[130, high, low, no]
2	Business as usual	Medium O&G market: Oil price relatively stable at medium levels, medium market conditions.	[80, high, low, no]	[30, low, low, no]
3	Oil crisis	Pool O&G market: Oil price decreasing and stays low, poor market conditions.	[30, high, low, no]	[30, high, low, no]
4	Renewable revolution	Wind market emerges after five years, O&G market medium.	[80, low, high, no]	[80, low, high, no]
5	Decom. boom	Decommission market emerges after five years, O&G market poor.	[30, low, high, yes]	[30, low, high, yes]

4.5. Step 5: Design alternative evaluation analysis

The net present values (NPVs) from the first contract alone for the nine design alternatives are presented in Table 10. In the model, we assume for simplicity that the cost of the vessel occurs instantaneously at t=0. That is, the owner does not have to pay for the ship until the it is delivered and the first 4-year contract starts. The market rate for the first contract is $85 000 per day, and the crew costs for the 50 people crew is ca. $29 000 per day. The aggregated contract contribution margin from the first contract is $72.1 million, which is discounted to $51.5 million. We can see from Table 10 that design alternative A has the highest NPV from the first contract. This is as expected, as this is the ship which can satisfy the technical requirements of the first contract at the lowest investment costs. What we are more interested in, however, is what happens after the first contract has ended.

Table 10: Economic performances of the design alternatives, NPV= net present value, numbers in million USD, for the first contract with length of four years.

	Design alternative	Invest. cost	Present value of contribution margin	NPV first contract
A	Baseline	50.4	51.5	1.1
B	Retrofittable 1	50.4	51.5	1.0
C	Retrofittable 2	50.5	51.5	0.9
D	Retrofittable 3	64.9	51.5	-13.5
E	Retrofittable 4	65.9	51.5	-14.5
F	Retrofittable 5	110.6	51.5	-59.2
G	Versatile 1	99.8	51.5	-48.3
H	Versatile 2	137.0	51.5	-85.5
I	Versatile 3	254.0	51.5	-202.5

An overall representation of the economic performance of the nine design alternatives is presented in Table 11 for the term contract priority, and in Table 12 for the spot contract priority. In these tables, the present value of the contribution margins (PVCM) over the lifecycle for each era is presented, in addition to the expected present value of the contribution margin (EPVCM) over all eras, assuming equal probability for each era for simplicity. Subtracting the investment costs gives us the expected net present values (ENPVs). We also estimate the lower ten-percentile of the ENPV, which is called Value at Risk (VaR).

Table 11: Term strategy: Economic performances of the design alternatives, numbers in million USD, including the first contract., PVCM = present value of contribution margin (net revenue), EPVCM = expected net present value of contribution margin, ENPV = expected net present value, VaR = Value at Risk.

	Design alt.	**Invest.**	**Era 1**	**Era 2**	**Era 3**	**Era 4**	**Era 5**		**Total performance**	
		cost	$PVCM_1$	$PVCM_2$	$PVCM_3$	$PVCM_4$	$PVCM_5$	EPVCM	**ENPV**	10% VaR
A	Baseline	50.4	207.2	82.5	55.9	88.5	87.0	104.2	**53.8**	16.1
B	Retrofittable 1	50.4	207.2	82.6	55.9	88.6	87.1	104.3	**53.9**	16.2
C	Retrofittable 2	50.5	207.3	82.8	56.0	89.1	87.4	104.5	**54.0**	16.2
D	Retrofittable 3	64.9	410.1	122.8	61.2	113.7	113.6	164.3	**99.4**	17.3
E	Retrofittable 4	65.9	402.7	116.4	61.4	111.4	110.8	160.5	**94.6**	15.2
F	Retrofittable 5	110.6	409.8	112.1	61.5	109.3	110.7	160.6	**50.0**	-30.0
G	Versatile 1	99.8	426.7	130.4	62.4	117.7	116.1	170.7	**70.9**	-16.0
H	Versatile 2	137.0	420.0	126.9	62.9	116.0	115.3	168.2	**31.2**	-53.1
I	Versatile 3	254.0	435.4	138.0	63.3	122.2	120.8	175.9	**-78.1**	-167.7

From Table 11, presenting the results with term contract strategy, we can see is that the retrofittable design alternatives have superior expected performance, and lower downside, compared to the versatile design alternatives. The versatile design alternatives do however have higher expected income potential (measured by EPVCM), but the high up-front cost of versatility reduces their overall performance. We can also see the significant difference in income potential for the design alternatives with different platform sizes.

Table 12: Spot strategy: Economic performances of the design alternatives, numbers in million USD, including the first contract., PVCM = present value of contribution margin (net revenue), EPVCM = expected net present value of contribution margin, ENPV = expected net present value, VaR = Value at Risk.

	Design alt.	**Invest.**	**Era 1**	**Era 2**	**Era 3**	**Era 4**	**Era 5**		**Total performance**	
		cost	$PVCM_1$	$PVCM_2$	$PVCM_3$	$PVCM_4$	$PVCM_5$	EPVCM	**ENPV**	10% VaR
A	Baseline	50.4	96.0	56.4	51.7	56.2	54.5	62.9	**12.5**	2.4
B	Retrofittable 1	50.4	96.0	56.4	51.7	56.2	54.5	62.9	**12.5**	2.4
C	Retrofittable 2	50.5	96.0	56.4	51.7	56.2	54.5	62.9	**12.4**	2.3
D	Retrofittable 3	64.9	96.0	56.4	51.7	56.2	54.5	62.9	**-2.0**	-12.1
E	Retrofittable 4	65.9	96.0	56.4	51.7	56.2	54.5	62.9	**-3.0**	-13.1
F	Retrofittable 5	110.6	96.0	56.4	51.7	56.2	54.5	62.9	**-47.7**	-57.8
G	Versatile 1	99.8	333.3	98.5	53.3	87.7	70.1	128.6	**28.8**	-39.8
H	Versatile 2	137.0	357.5	106.3	53.5	93.6	73.5	136.9	**-0.1**	-75.5
I	Versatile 3	254.0	401.4	142.1	53.8	143.6	127.9	173.8	**-80.2**	-170.6

From Table 12, presenting the results with spot contract strategy, we can see that the retrofittable design alternatives do not have the same economic superiority as with the term strategy. One of the reasons for this is the agility that versatility provides, i.e., the swiftness to which a ship can change contracts. In the spot market, which is characterized by being short-term, retrofits may take too long and are thus not allowed in this mode. This explains why the income potentials (PVCM) are identical for ships with the same capabilities.

5. Discussion

The results presented in Table 11 and Table 12 indicate that retrofittability can be of significant value in design of non-transport vessels. The reason for this is the increased upside it enables as a relatively low up-front investment cost. These insights account explicitly for the multi-year (term) contracts. In the spot market, it is less obvious which type of flexibility that is better. This illustrates the operational complexity of the non-transport ship design problem, and that specific preferences of the stakeholders dictating contract preferences, e.g. risk attitude, can have significant impact on the overall economic performance. When operating in the spot market, the ship is more exposed to both downside risks and upside opportunities, and the overall performance of the design alternative is dependent on whether the ship hits a “jackpot contract,” or the market surges when the ship is idle.

In contrast to traditional transportation shipping, non-transport shipping is characterized by a heterogeneous market. That is, the contracts span a wide range of technical requirements, which make the design problem more ill-structured. As essentially no contract is similar, we encounter issues with market modeling. This is one of the reasons why we chose to decompose the scenario model and utilize narrative scenario planning on the overall strategic level. This approach increases transparency and makes it easier to understand under which conditions one design alternative performs better compared to another. Furthermore, as there exist little long-term market data, especially for the emerging markets, pure quantitative scenario modeling relying on historical data naturally becomes difficult. The proposed scenario planning model provides especially useful as it allows for exploration of extreme scenarios, and in a straightforward manner can facilitate communication between analysts and decision makers. In the expected value calculations, we assumed for simplicity that each era has the same probability of occurring. This assumption is made to help drawing clear and straightforward conclusions. For real-life considerations, a more rigorous analysis of scenario probabilities is central for making proper design decisions. Furthermore, the expected net present value (ENPV) criteria may not even be appropriate, and other measures of merit, such as payback-time, can be considered.

Regarding the method utilized to structure flexible design alternatives, we need to estimate the costs of future retrofits. However, for multiple reasons, the actual retrofit costs are uncertain. For example, the costs of occupying a shipyard to perform a retrofit can fluctuate with the general market, which is not considered in this model. Furthermore, we assume that the change cost is linearly additive for combined equipment retrofits, which is a significant simplification as there would be synergy effects of changing multiple pieces of equipment at the same time. The estimation of retrofit cost and duration may also in itself be difficult, as system-changes can propagate and have unforeseen consequences (Eckert et al., 2004). To make the change costs as accurate as possible in this case study, they are estimated based on historical ship retrofit data from Ulstein ship design company.

6. Conclusion

This paper studies the relationship between economic performance and flexibility for non-transport vessels. We focus on two aspects of flexibility: retrofittability and versatility, i.e., the ability of a vessel to satisfy diverse needs *with* or *without* change of physical form, respectively. A model is presented to study this relationship, which first generates design alternatives, before subsequently evaluating them based on their discounted economic lifecycle performance. Albeit being case specific, we conclude that retrofittability can be of significant value in design of non-transport vessels. Versatility provides income potential, but at a higher up-front cost. Retrofittability is of particular value due to the increased upside potential enabled at a relatively low up-front cost. An interesting area of research for future work could be the identification of retrofittable ship design alternatives.

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