Assessing Flexible Offshore Construction Vessel Designs combining Real Options and Epoch-Era Analysis

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Abstract:

Recent events in offshore oil and gas markets show the need for elaborate treatments of uncertainty throughout the design process and lifecycle management of maritime engineering systems. Offshore construction vessels are subject to uncertainty stemming from both economic factors modelled as stochastic processes, and from discrete factors like regulations and contract requirements. In this paper, we present a simulation framework for valuation of flexible offshore construction vessels incorporating simultaneously real options analysis and epoch-era analysis. Based on compliance with a set of contracts and the potential revenue to be earned from these contracts, the model seeks to maximize expected net present value for each contract period. Benchmarking a flexible design of an offshore construction vessel against an inflexible design, we estimate the value of flexibility and find strategies for managing the design through the lifecycle. The results show that significant gains in the value of the vessel result when design changes are taken into account.

Keywords:

Ship design; Offshore construction vessels; Uncertainty; Flexibility; Epoch-era analysis; Real options analysis

1. Introduction

The recent fall in oil prices has caused a downturn in offshore activity around the world. Contracts for new offshore field developments are scarce and activity in existing fields is being reduced to cut costs. Not so long ago, the offshore industry was booming, and many innovative and expensive new offshore construction vessels (OCVs) were ordered. Many of these vessels are now being laid up, as the supply of vessels far exceeds demand. The few contracts available no longer offer the time charter rates these expensive vessels require to operate profitably. At the same time, oil companies and large offshore contractors can pick and choose between the best of the available vessels, with capabilities exceeding the requirements of the contract, for chartering rates that do not defend the initial investment in the vessel.

While uncertainty in shipping markets is nothing new, it seems to surprise repeatedly. Stopford (2009) provides accounts of shipping market cycles back hundreds of years, and claims they have an almost Darwinian effect of forcing out the least fit market players. Besides market fluctuations, marine systems also face technical and regulatory uncertainties. These act like trend-breakers that alter the operating conditions drastically. Innovation may render a system non-competitive, due to the emergence of alternative technology, and is notoriously hard to predict. Compliance to changing policies is also a challenge, as signified by environmental regulations. Hence, ship owners should not make ship design and investment decisions based merely on the current operating context. The successful ship owner of the future will be the one who invested his capital of today in vessels that deliver value in a vast range of possible scenarios throughout their lifecycles.

OCVs are not solely transportation ships, but can be regarded as tools that can provide a number of different services throughout the lifecycle of an oil field, most involving some constructionrelated work. For example, Inspection, Maintenance and Repair operations typically require module handling towers, and chemical tanks, while for subsea installation tasks, a large crane and even cable-laying equipment may be needed. Light well intervention has recently emerged as a viable operation for OCVs, requiring that designers include a large intervention tower in the design. Diving support operations are yet another type of operation the vessels can engage in, provided saturated diving systems are installed on board.

Considering the differences in offshore mission scopes, one should seek to design a ship that matches mission requirements as well as possible (Gaspar, Hagen, & Erikstad, 2016). One can choose to build inflexible, specialized vessels with relatively low operating costs, due to their highly optimized nature. Alternatively, inflexible multi-purpose vessels with many different capabilities can be built. The specialized vessel will fare well even when rates are very low, while multi-purpose vessels may be unprofitable under these conditions. However, multi-purpose vessels will more likely win contracts, and match the requirements of several alternative contracts. Erikstad, Fagerholt, & Solem (2011) present an optimization model aiming at designing offshore vessels for specific contractual requirements, without taking future uncertainty regarding rates and requirements into account. A third possibility is to design a flexible vessel on a modular platform, which can be adapted to match several possible future markets. This vessel may achieve low operating costs, while potentially matching a large number of alternative contracts, thus drawing the best aspects from both the specialized design and the multi-purpose design. Hence, the flexible vessel can take advantage of emerging opportunities while mitigating risks (De Neufville & Scholtes, 2011).

For this paper, we define flexibility as the “ability of the system to be modified to do jobs not originally included in the requirements definition” (McManus & Hastings, 2006). From a systems perspective, design principles for changeability, an umbrella term including flexibility, are discussed by Fricke & Schulz (2005). They argue that changeable designs should be designed with simple interfaces between system elements to minimize the impact of design changes. Changeability is further defined using a network formulation by Ross, Rhodes, & Hastings (2008). For valuation of flexibility in systems from an economic perspective, real options is increasingly applied, following the distinction between real options “on” projects, and real options “in” systems (Wang & De Neufville, 2005). Several applications of real options exist for reconfigurable, complex ships. Page (2012) applies real options theory to the design of a specific naval ship concept for valuation of flexibility. Another application of real options in naval ships is to use prospect theory to account for stakeholder loss averseness (Knight & Singer, 2015).

To account for uncertainties in context and perception, epoch-era analysis represents a novel approach to evaluate value sustainment over time (Ross & Rhodes, 2008), which allows consideration of technical and operational perspectives. Maritime systems studied with epoch-era analysis include anchor handling, tug, and supply (AHTS) vessels taking future uncertain contracts into account (Gaspar, Erikstad, & Ross, 2012), AHTS design with more elaborate treatment of stakeholder preferences (Gaspar, Rhodes, Ross, & Erikstad, 2012), lifecycle assessment of machinery systems (Gaspar, Balland, Aspen, Ross, & Erikstad, 2015), and an industrial case of the design process for an OCV (Pettersen et al., 2017). Another notable strategy for designing marine systems under uncertainty are Markov decision processes and dynamic programming to identify optimal strategies for management of ship design reconfiguration through the lifecycle (Kana & Harrison, 2017; Niese & Singer, 2014).

The current work presents a novel takes the operational and technical aspects of contractual requirements into account through epoch-era analysis, and combines this with a real options model using stochastic processes to model commercial uncertainties. Section 2 shows how relevant methodologies such as real options and epoch-era analysis can be adapted and reconciled to suit the flexible OCV design problem, and other similarly complex marine systems. Section 3 synthesizes the methods, presenting an approach to calculate net present value (NPV), depending on which cash flow the ship gets. Section 4 outlines a design case for the OCV, and serves as an illustrative example for the methodology presented in Section 3. Section 5 discusses the benefits and drawbacks of the current approach and concludes.

2. Methodology

2.1. Real options and flexibility

Real options in a system “refer to elements of a system that provide ‘rights, not obligations’ to achieve some goal or activity” (De Neufville, 2003). By speaking of elements in a system, we distinguish between real options “on” projects and real options “in” systems, which are more complex and require a thorough understanding of the technology involved (Wang & De Neufville, 2005). The systems installed on board of a ship may constitute potential real options “in” the system. A real option will generally be exercised if it is perceived to increase the value of the system. Real options are therefore a viable response to changes in market situations or the operating context of the system. Real options analysis can be used as a decision support tool for determining when to apply changes to an existing system.

A complementary view to real options is that of viewing the design as existing in multiple system states (Niese & Singer, 2014; Ross et al., 2008). A ship being retrofitted could hence be seen as a system moving between two states. A subsequent possible measure of flexibility is the number of other system states that are reachable from the current system state at an acceptable cost, defined as the filtered outdegree (Ross et al., 2008). Further, we can formulate rules based on technical and economic feasibility for moving between different designs in the design space. The decision to transition between two system states is equivalent to exercising a set of real options “in” the system.

2.2. Modelling uncertainty

2.2.1. Stochastic processes

The real options literature commonly uses various stochastic processes to model the fluctuation of economic parameters through time. The most common assumption in the early financial options theory is that prices follow a geometric Brownian motion (Black & Scholes, 1973), where the next price in the next time step will be completely independent of the path. For shipping markets, it is reasonable to expect some cyclical behavior that capture the effects of supply and demand. A mean-reverting process embed these business cycles by generating random motions that tend to revert back to a mean value over time (De Neufville & Scholtes, 2011). Mean-reverting stochastic processes have previously been used to study market switching flexibility in combination carriers that can operate either as an oil tanker, or as a dry bulk carrier (Sødal, Koekebakker, & Ådland, 2008).

Stochastic processes used to simulate fluctuations in future revenue rely on the assumption that there exists historical data that will reflect what is likely to happen in the future. This makes the approach limited to processes that are in a steady state (De Neufville & Scholtes, 2011). A consequence is that this approach alone faces severe limitation when it comes to producing scenarios involving emerging markets, or other situations that face a large amount of technical and operational uncertainty that do not relate directly to economic parameters.

2.2.2. Epoch-era analysis

Epoch-era analysis is a quantitative scenario building technique that relies on eliciting sources of future uncertainty by specifying epoch variables. The epoch variables capture contextual factors that may influence system value over time. An epoch represents a possible static system context, in which all epoch variables remain fixed. An era is a sequence of epochs along a timeline, hence capturing the dynamics of system value in an evolving context. Eras can represent the system lifecycle, or shorter dynamic long-term system contexts (Ross & Rhodes, 2008).

Compared to the stochastic processes that underlie real options models, epoch-era analysis aims to capture contextual uncertainties facing the system more generally. These include regulations, operating environment, and contractual requirements, to name a few. Epoch-era analysis also opens the door for a more subjective treatment of uncertainty, considering that several strategies can be used to devise long-term scenarios, including storytelling and use of simulation models. Stakeholders can produce eras according to their best guesses regarding future uncertainties, and analyze the subsequent effect on value sustainment.

3. Evaluating flexible ship performance

3.1. Model overview

We here present a framework for valuing flexibility based on the insights of epoch-era analysis and real options models that use stochastic processes. On an overall level, epoch-era analysis is used to control the contract model, while stochastic processes simulate the revenue for all possible contracts. Figure 1 presents the elements of the model in a flowchart. The process illustrated is repeated a large number of times to provide decision-makers with the distribution of possible outcomes.

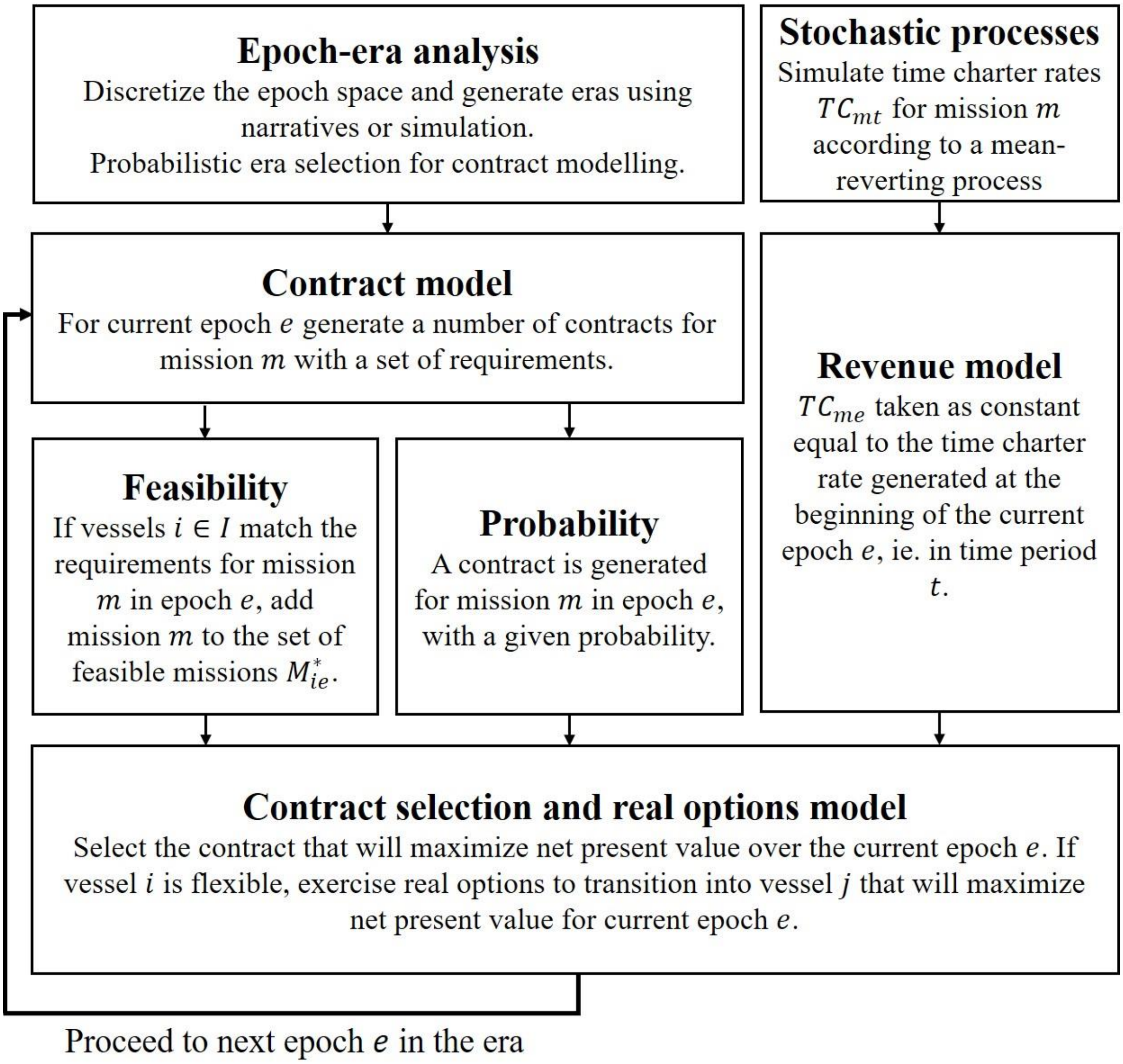

Figure 1: Flowchart for the model integrating stochastic processes and epoch-era analysis for real options evaluation.

The contract model uses epoch-era analysis to steer the access to new contracts and the technical requirements associated with mission m. The probability of there being an available contract for a specific mission type is determined based on the current instantiation of epoch variables in epoch e. Further, the match between contract requirements for a possible mission and a design is controlled by the current epoch. The feasibility check assesses whether each of the possible vessel designs i in the set of all possible designs I will match with the current contract requirements. If a vessel i matches the contract requirements for mission m in epoch e, then the mission is added to the set of feasible missions M_{ie}^{*}.

A mean-reverting stochastic process generates sample paths of the revenue stream for each mission over the entire era. To connect the time charter rates TC_{mt} generated at each time increment t with current mission contracts, the rate the vessel actually earns throughout the epoch, will be equal to the time charter rate TC_{me} for the mission at the beginning of the epoch. The time charter rate for a contract will hence be the rate at the initial time increment of an epoch $t = e_{start}$, as shown in Equation (1).

$$TC_{me} = TC_{me_{start}} \tag{1}$$

The final element of the simulation model consists of contract selection and real options evaluation. We assume that the decision criteria will be to find the contract that maximizes the net present value over the next epoch. Profit maximization could imply that design changes be implemented in order to comply with the requirements of a more lucrative contract, hence signifying an exercise of a set of real options.

3.2. Economic performance of inflexible systems

To determine the value of flexibility we benchmark the flexible system design against an inflexible design. For all inflexible designs i, the net present value NPV_{ie} achieved during an epoch e consisting of several time periods (years) t, can be presented in the following way:

$$NPV_{ie} = \sum_{t=e_{start}}^{e_{end}} \frac{D_O \cdot \max\limits_{m \in M_{ie}^{*}} (TC_{me}) - 365 \cdot (C_{it}^{O} + C_{it}^{C})}{(1+r)^{t-1}} \tag{2}$$

Here, we calculate the NPV for a system i in epoch e, lasting from the year given as the epoch starting year, e_{start}, to the year given as the epoch end year, e_{end}. D_O is the number of days operative each year. The contract in market m that maximizes time charter rate TC_{me}, is chosen from the set of markets M^*_{ie} that are feasible for design i in the current epoch e. Costs are paid each day of the year, C^O_{it} being the operating expenditures, and C^C_{it} being the capital expenditures for a design i in epoch e. r is the discount rate. As the system to be built is inflexible, one should choose design i in a set of design alternatives I, maximizing NPV over the system lifecycle consisting of an era E, so that:

$$NPV^{INFLEX} = \max_{i \in I} \sum_{e \in E} NPV_{ie} \tag{3}$$

3.3. *Economic performance of flexible systems*

When building a flexible system that is able to transition between several different points on a design space, we need to assess the transition costs. By defining a cost for the later installation of any system element and removal of obsolete system elements, we obtain the costs of transitioning between any two designs in the design space. Transition costs C^T_{ij} are formulated by:

$$C^T_{ij} = h \cdot \sum_{k=1}^{K} C^E_{ik} + g \cdot \sum_{l=1}^{L} C^E_{jl} \tag{4}$$

Here, C^E_{ik} is the cost of the system element k being removed from the design transitioning away from design i. C^E_{jl} is the cost of buying system element l that is added to the design when transitioning into design j. The retrofit installation factor g and the retrofit removal factor h account for additional costs of installing and removing subsystems during a retrofit.

We now find the NPV achieved during epoch e for a design i being changed possibly into any design j, in order to find the contract maximizing the NPV for the next epoch. The expression for net present value NPV_{ije}^{FLEX} now becomes:

$$NPV_{ije}^{FLEX} = \sum_{t=e_{start}}^{e_{end}} \frac{(D_O)_{ij}^{FLEX} \cdot \max_{m \in M_{je}^{*}} (TC_{me}) - 365 \cdot \left(C_{it}^{O} + C_{it}^{C}\right) - C_{ij}^{T}}{(1+r)^{t-1}} \tag{5}$$

Here, $(D_O)_{ij}^{FLEX}$ is the number of days operational per year, if the system is to transition between designs i and j. We choose the contract for market m available to design j, in the set of feasible markets M_{je}^{*}, which will yield the maximum time charter rate TC_{me} for epoch e. As before, C_{it}^{O} are operational expenditures, C_{it}^{C} are capital expenditures and r is the discount rate.

Finally, we choose to transition into the design j which maximizes the NPV for the current epoch e. This means that we select a design transition between designs i and j, that maximizes the following expression:

$$NPV^{FLEX} = \max(\max_{j \in J_i^{*}}(NPV_{ije}^{FLEX}, NPV_{ie})) \tag{6}$$

Here, the notation is the same as before. In addition, J_i^{*} is the set of designs j which design i can be transitioned into. Note that the transition is only performed for this epoch if the NPV achieved through making the transition is higher than the NPV that can be achieved by not doing the transition. For each lifecycle simulation run, a flexible strategy can be obtained, providing the decision makers with potential trajectories for how retrofits will be utilized throughout the lifecycle of the system. Over the lifecycle of the system, the net present value NPV^{FLEX} for the flexible ship then becomes:

$$NPV^{FLEX} = \sum_{e \in E} NPV_e \tag{7}$$

Once the stochastic elements are included in the mathematical model presented in Equation (1) – Equation (8), thousands of model runs are simulated. Hence, the expected value of flexibility $E[V^{FLEX}]$ is calculated as follows (De Neufville & Scholtes, 2011):

$$E[V^{FLEX}] = E[NPV^{FLEX}] - E[NPV^{INFLEX}] \tag{8}$$

4. Case study: Designing a flexible offshore construction vessel

4.1. Case description

An OCV is to be built for 25 years life, potentially being operated in several alternative markets during its lifecycle. The markets are inspection, maintenance and repair (IMR), subsea installation, umbilicals, flowlines and risers (SURF), light well intervention (LWI) and diving support (DSV). Contracts in these markets are assumed to last five years each, and be represented by a set of system requirements, which may be subject to change at the end of the contractual period. There are also differences in the day rates that can be earned in the markets. Starting with a five-year IMR contract, the ship owner will later attempt to select the contract that will maximize NPV.

Due to differences in contractual requirements, and conflicting needs for system placements on board the vessel, a flexible approach to vessel design is needed. This also has the advantage of letting a vessel remain relevant should its context change during its lifecycle. For example, the crane may need to be upgraded if there is a need for larger lifting capabilities or operations move to deeper waters. However, there are many possible options to consider when adapting the vessel to future operating conditions. Decisions need to be made, regarding both what initial design should be selected, and regarding what future retrofits that can be done to maximize the performance of the vessel.

The case serves mainly as an illustration and implementation of the proposed mathematical model and the underlying methodology. Hence, it provides strategies for profit maximization through active management of a design through lifecycle context shifts. The economic data has been based on regression analyses of large numbers of ships, and historical time charter rate data (Clarkson Research Services, 2017; Ulstein International, 2017).

4.2. Design representation

The design space is the set of all possible vessel configurations. We specify some design variables that constitute the design space, in Table 1. There are some constraints with respect to physical feasibility. For example, mission specific equipment such as the module handling tower, the well intervention tower, and the J-lay tower all work through the moonpool of the vessel, and these systems cannot co-exist in the same vessel configuration.

[Table 1 near here]

The vessel configuration and installment of equipment drives costs. A marine platform vessel design is assumed to include the state-of-the-art equipment for all the ship-related systems, while the mission-related equipment summarized in in Table 1 is accounted for in addition. The size of the platform vessel is captured through the total deck area, and is the only design variable that is considered constant through the lifecycle. The cost of the smallest marine platform is 62.5 million USD, and further scaled linearly according to the size of deck area. For other design variables, real option exercise is possible and equivalent to changing the design variables. Consequently, free deck area is derived from the total deck area minus the footprint of installed equipment. The remaining equipment costs are given in Table 2, based on industry provided data (Ulstein International, 2017). For the equipment types for which multiple capability levels exists, the costs are assumed to scale linearly for simplicity.

[Table 2 near here]

Retrofits are done to ensure compliance with the requirements for contracts for each of the four mission types considered; IMR, SURF, LWI and DS. While changes in contract requirements will be considered through specification of epoch variables in the next subsection, Table 3 summarizes the initial contract requirements for each of the missions.

[Table 3 near here]

4.3. Uncertainty representation

4.3.1. Contract model

The contract model uses input from a discretization of contextual uncertain factors that affect the probability of winning contracts and their requirements for all mission types. The epoch variables are given in Table 4.

[Table 4 near here]

A vessel can bid for a contract if the capabilities of its equipment fulfill or exceed the contractual requirements. The weight of modules to be lifted, the operational water depth, the need for tie-ins, and the emergence of new fibre rope technology will affect the contract requirements across all possible missions. For example, when calculating required crane capacity for compliance with contract requirements, we account for the weight of steel wire in water. An increase in required crane capacity due to increasing water depths may hence be offset by the introduction of fibre rope technology replacing steel wires.

In addition to ensuring compliance with contract requirements, the epoch variables direct the probability of winning contracts for each mission. The oil price has a positive effect on the probability of winning contracts for all types of missions, as a positive oil price development can be expected to drive offshore oil and gas activities generally. Further, development of offshore projects as tie-ins to existing offshore projects, affect the number of SURF and DS contracts positively. The influence of epoch variables on the match between contract requirements, and the probability of winning a contract is shown in Figure 2. For the probability of winning contracts, we show the direction of the influence from the epoch variables. Based on the realization of epoch variables, the model provides a probability estimate for each mission type.

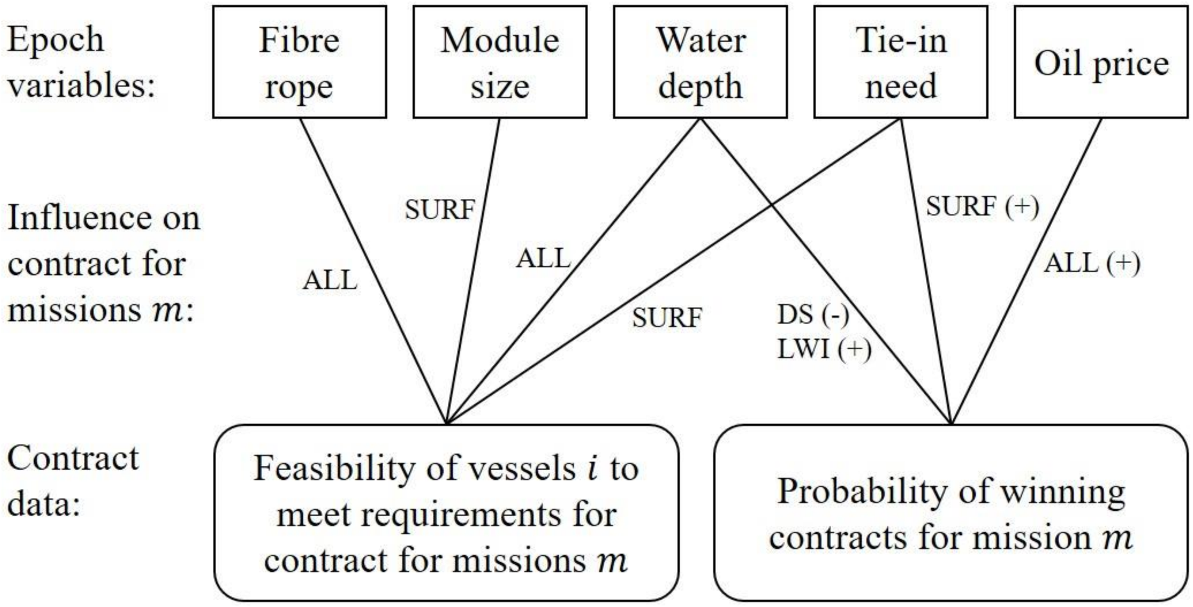

Figure 2: Mapping the influence of epoch variables on the contract requirements and the probability of winning contracts.

The epoch variables thus contribute to defining what changes will occur in the requirements that the alternative vessel designs will have to fulfill in order to compete in a market, and affect the probability of successful bids on a contract. Throughout the vessel lifecycle, the epoch variables will change. To capture believable causal relationships between epochs that represent the stakeholder expectations of the future system context, the stakeholders formulate eras based on a narrative approach. Keep in mind that all eras will start with an IMR contract given by the initial requirements in Table 3. We construct five eras based on stakeholder expectations of the future, and consider all eras equally likely to occur. A short, qualitative description of each era is given below:

- **Era 1 - Early dip with swift recovery:** Early offshore market dip with a swift recovery to medium-to-high oil price levels. New field developments at deep waters, focusing on tie-ins to existing subsea infrastructure.
- **Era 2 – Early dip with slow recovery:** Early offshore market dip with slow recovery through the remaining vessel lifecycle. As more oil and gas production is done subsea, module sizes to be lifted will increase over time.
- **Era 3 - Stable market with innovation:** Stable offshore market conditions, with medium oil prices. Increasingly heavy requirements over time, due to difficult operating conditions. This is coupled with a strong technology development, signified by fibre rope technology becoming available.
- **Era 4 - Strong market with innovation:** Strong offshore market spurring development of marginal fields built as tie-ins at deep waters, with increasing module sizes and subsequent development of fibre rope technology.
- **Era 5 - Strong market collapsing:** Strong initial market, with heavy technical development including development of deep water marginal fields as tie-ins. A market collapse for offshore activities lead to a reversion of requirements and new technologies are not introduced.

4.3.2. Revenue model

We use a mean-reverting stochastic process to simulate the time charter rates that can be obtained by complying with the contractual requirements. The input distributions for these stochastic processes are supported by historical data collected from market reports (Ulstein International, 2017) and commercial databases (Clarkson Research Services, 2017). We assume that the time charter rates follow normal distributions, with differences in the mean time charter rates and volatility. We see that LWI contracts generally earn a high day rate, but are more volatile. IMR contracts have little volatility, earning low but stable day rates, as these services are needed throughout the lifecycle of an offshore oil and gas field. The input data for the simulation of rates in the four possible markets the vessel can engage in are given in Table 5. Further, future cash flows are discounted with a 20% discount rate.

[Table 5 near here]

4.3.3. Contract selection and real options model

The strategy of the ship owner is to maximize net present value for the duration of the current epoch. If necessary, this is done by altering the design to comply with the requirements of the contract that will maximize profits over next epoch. Hence, a set of real options are exercised to facilitate the change of design into a configuration that match with the current requirements of the IMR, SURF, LWI or DS missions.

The exercise cost of a real option is the cost of doing a retrofit by adding or removing equipment from the vessel. The cost of removing equipment is set to 10% of its initial purchasing cost, so that the retrofit removal factor h is 0.1. The retrofit installation factor g is set to 1.25, indicating a 25% added cost for equipment installed as a retrofit. These factors accounts for the costs of a shipyard doing the rebuild, assuming that there is free capacity in yards to do the retrofit, and that the equipment to be installed actually is available.

4.4. Results

What are “optimal”, flexible strategies for the implementation of design options throughout the vessel lifecycle, and what are the economic benefits associated with these strategies? For illustrative purposes, we run the simulation model for three alternative designs extracted from the proposed design space in Table 1, and compare their inflexible economic performance against the flexible economic performance. The vessels we assess are represented by the design vectors provided in Table 6.

[Table 6 near here]

The main objective of the analysis is to understand what benefits a flexible vessel design provides. The simulation model will select contracts that maximize the next epoch NPV, taking into account potential retrofit costs, as well as the charter rates for the contract alternatives. Based on this simple decision rule, the model can select to retrofit the vessel to comply with a new contract. The retrofit indicates a transition between two point designs specified in the design space. This is illustrated in Figure 3, showing the resulting retrofit of OCV Design 1 to Design 36 based on a single simulation run.

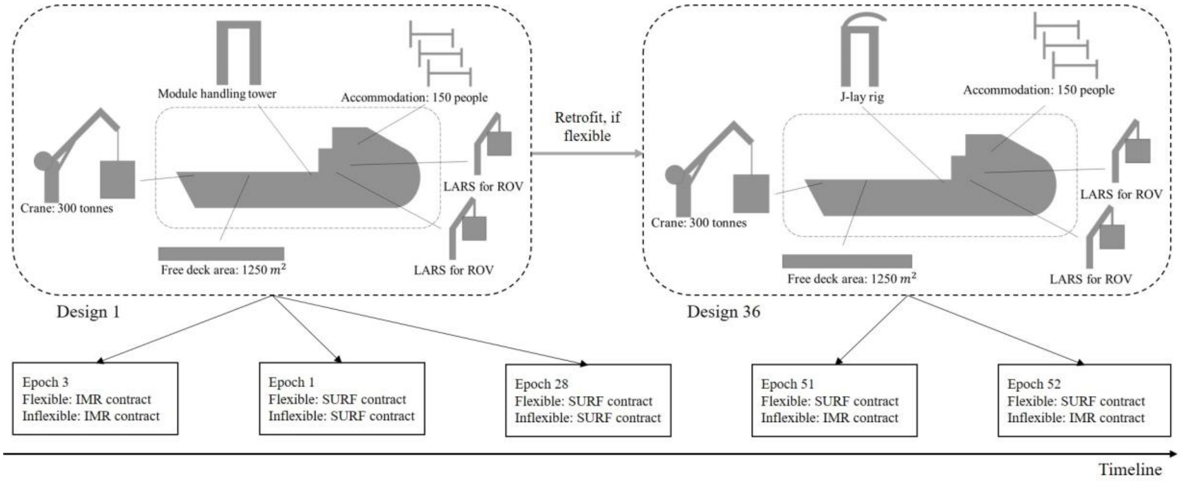

Figure 3: Retrofit of Design 1 to Design 36 to comply with most attractive future contracts through one era.

From the realization of context parameters in Figure 3, we see that the inflexible vessel reverts from a valuable SURF contract to a less valuable IMR contract at Epoch 51, as it does not comply with new requirements for this mission type. On the other hand, the flexible vessel is reconfigured to Design 36, allowing it to continue to comply with the changed requirements of a SURF contract.

When running the model 10 000 times, we acquire distributions of the NPV. This allows comparison between the value of the inflexible variant and the flexible variant of the vessel. The cumulative distribution of NPV from the simulation for Design 1 is shown in Figure 4. We observe that the probability of losing money throughout the lifecycle is reduced from almost 70% to 30% for the flexible design, and the expected NPV (ENPV) becomes positive for the flexible design.

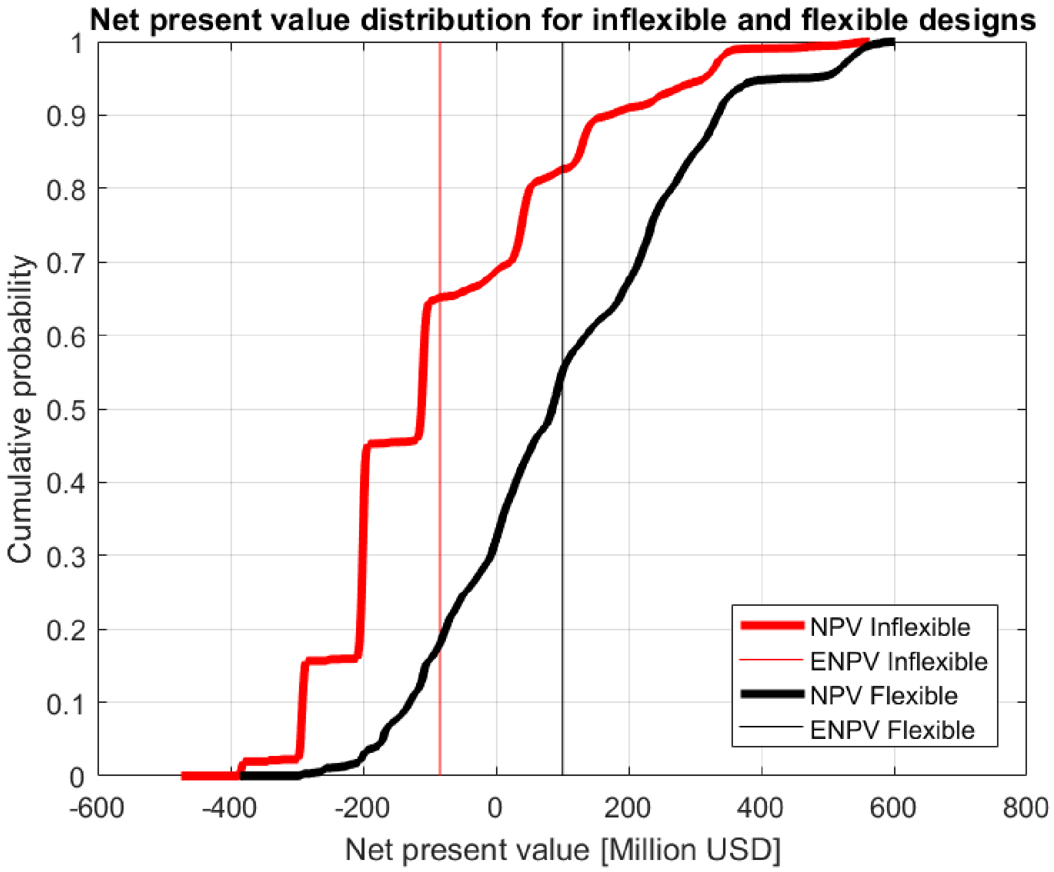

Figure 4: Cumulative NPV distribution for inflexible and flexible versions of Design 1.

The cumulative NPV distribution for Design 11 is shown in Figure 5. The difference between inflexible and flexible versions of Design 11 is even greater. We see that the difference between Design 1 and Design 11 is the size of the marine platform, as manifest in the free deck area variable. This design variable is not changed by the model, but is a function of the footprint of all equipment installed on the vessel. These results indicates that investing in the smaller vessel

(Design 11) is better than the larger vessel (Design 1). As long as a smaller vessel can accommodate the same requirements as a larger vessel, it will be more profitable.

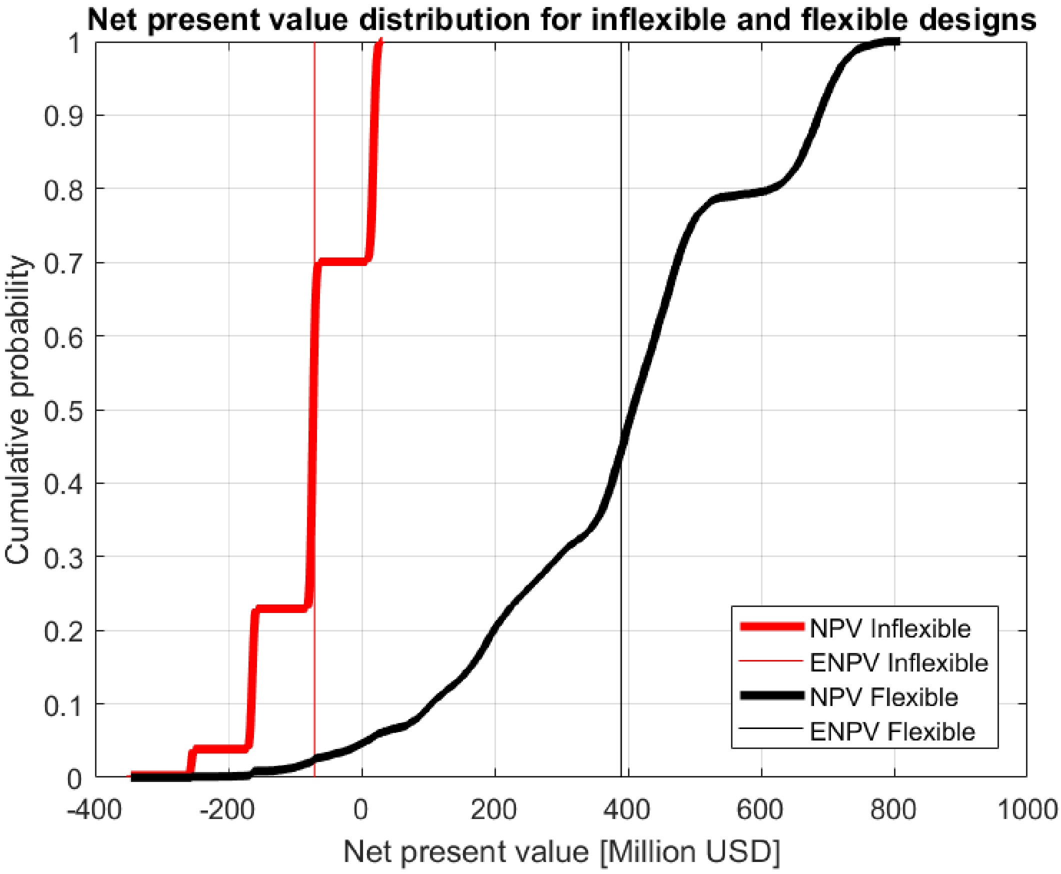

Figure 5: Cumulative NPV distribution for inflexible and flexible versions of Design 11.

The cumulative NPV distribution for Design 51 is shown in Figure 6. Design 51 is the only design studied that provide a positive NPV in the inflexible case. This configuration has a relatively low added value for flexibility, due to initially being configured with advanced equipment that may be required by future contracts, but not required by the original contract. Relatively seldom will it be necessary to reconfigure this configuration, meaning that flexibility is valued lower than in the other cases.

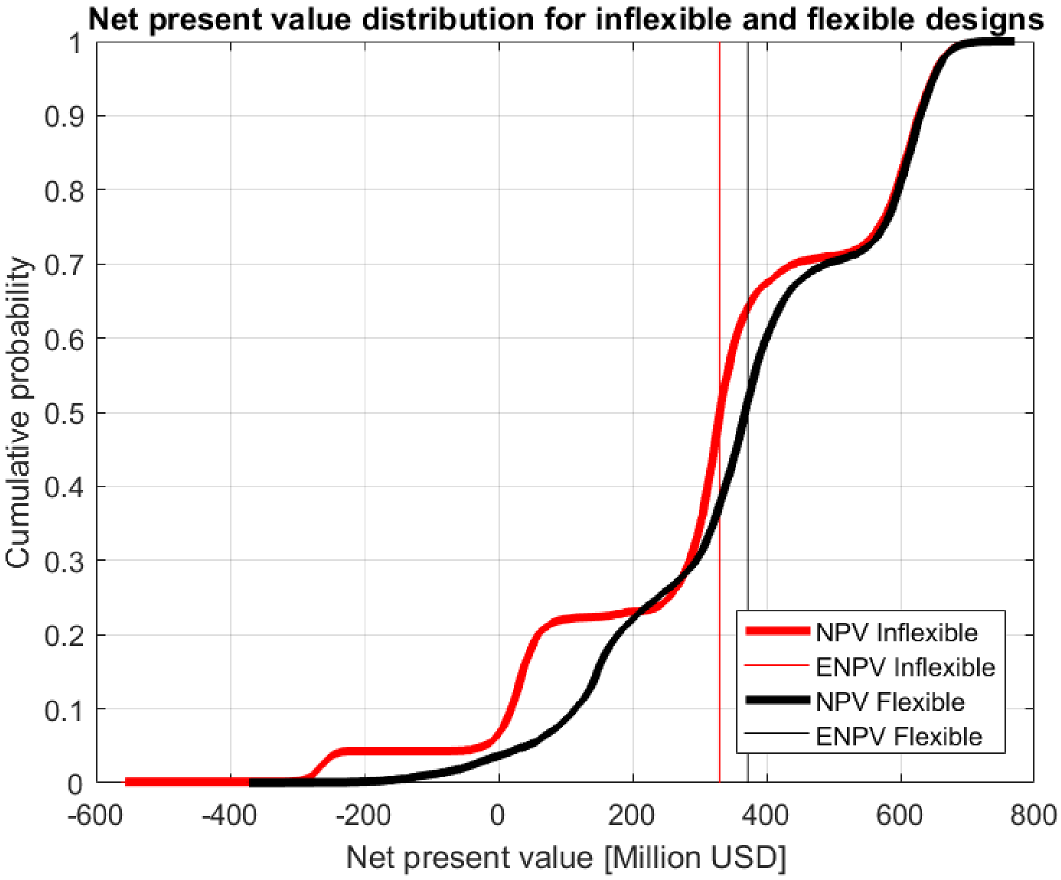

Figure 6: Cumulative NPV distribution for inflexible and flexible versions of Design 51.

The results for all three designs assessed using the model are summarized in Table 7. Two of the ship design projects become attractive in a lifecycle perspective only when flexibility is accounted for. Consequently, there are significant gains from considering flexibility in ship design. In summary, the results show that ship owners in general can derive a benefit from designing for flexibility. The increasing number of contract options that may be available for a ship owner once reconfiguration is an opportunity explains this.

[Table 7 near here]

4.5. Sensitivity analyses

While the analyses show that flexibility normally is useful, we should carefully assess how correct the exact results are. Even though parts of the input data used in this study are based on information obtained from existing databases (Clarkson Research Services, 2017; Ulstein

International, 2017), the model relies on certain parameters that are particularly difficult to estimate. This concerns mainly the costs assumed for retrofit, which are given as a percentage of the purchasing price for the equipment being removed or installed. These parameters are highly dependent on the actual retrofit project. The retrofit project itself is influenced by shipbuilding risks and possible actions that suppliers of equipment may take.

Hence, sensitivity testing is done for the retrofit installation factor g, a leading indicator of the real option exercise price, to understand how dependent the value of flexibility is on the cost of retrofits. The retrofit installation factor g is altered in a range from 1 to 4 for the three designs that were analyzed earlier. Figure 7, Figure 8, and Figure 9 illustrates how sensitive the value of flexibility is to changes in the retrofit installation factor g, for Design 1, 11, and 51 respectively.

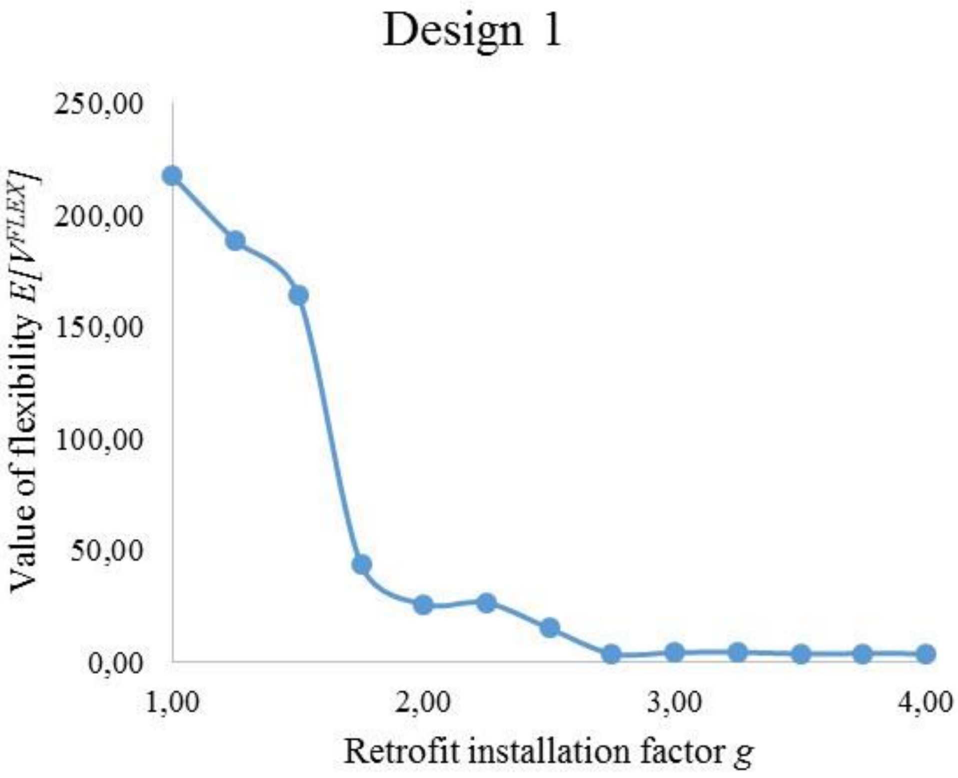

Figure 7: Sensitivity of value of flexibility against changes in retrofit installation factor g for Design 1.

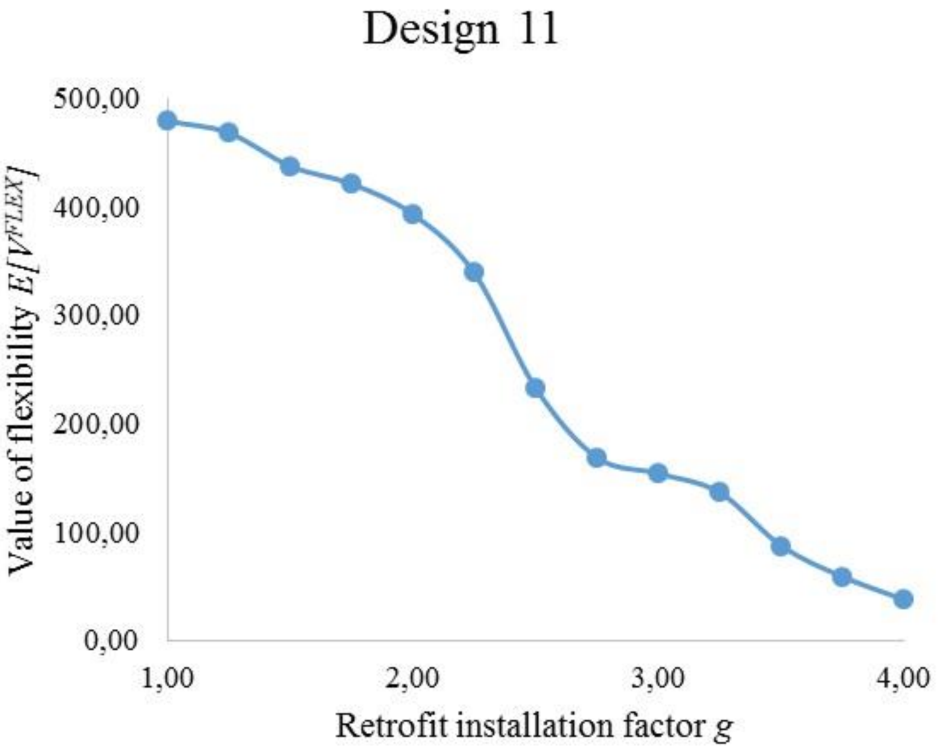

Figure 8: Sensitivity of value of flexibility against changes in retrofit installation factor g for Design 11.

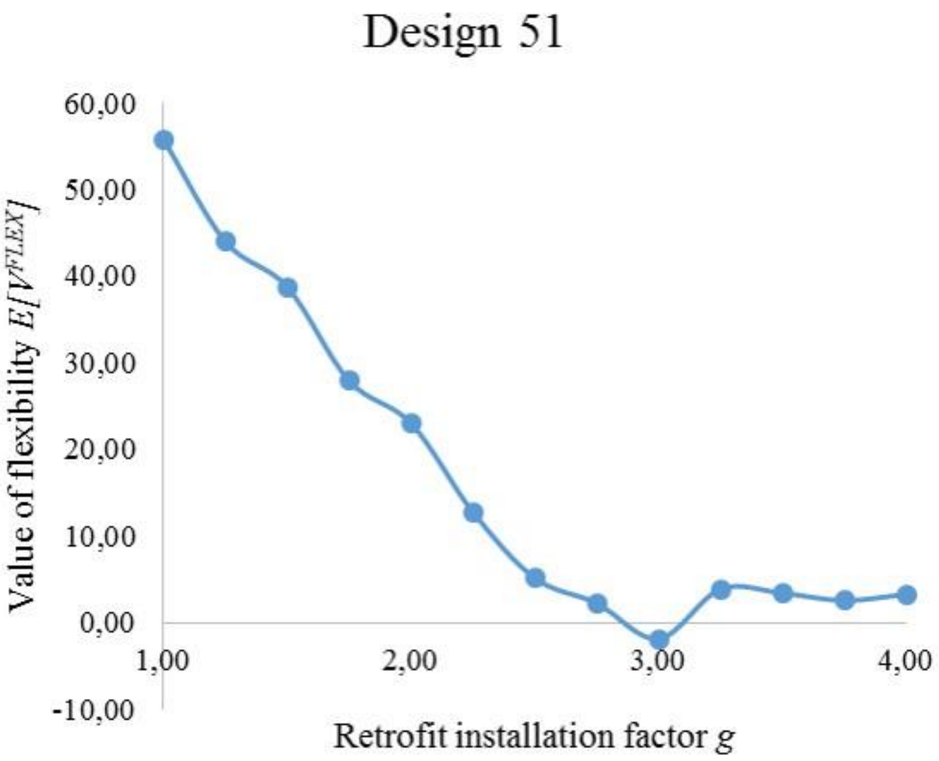

Figure 9: Sensitivity of value of flexibility against changes in retrofit installation factor g for Design 51.

As expected, the sensitivity analyses show that the value of flexibility decreases with the costs associated with implementation of design changes. The more expensive an option gets, the less flexibility will be worth. There is variation in the sensitivity of the value of flexibility towards change in g for all three designs. $E[V^{FLEX}]$ is very sensitive to changes in g for Design 1, with a relative low value of flexibility when increasing the cost of design changes beyond a doubling of the investment cost in new equipment. For Design 11, g has relatively little influence on $E[V^{FLEX}]$ around its initially chosen value. Design 51 exhibits almost a linear relationship between $E[V^{FLEX}]$ and g, nearly until a point where flexibility in the design becomes so expensive relative to the increase in the net present value that the value of flexibility seems to converge to zero.

5. Concluding remarks

This work presents a simulation framework combining real options analysis and epoch-era analysis to evaluate flexible system designs under multiple sources of uncertainty. Combining stochastic processes that are used to simulate the revenue streams with an epoch-era framework to model contractual uncertainties, we enable real options to be applied to more complex, technical systems. The lack of reliable historical data on offshore construction vessel markets that are needed for a traditional real options analysis implies that strategies for retrofit should not be based on this alone. Instead, the stochastic processes underlying a typical real options model are balanced against an epoch-era approach that builds on stakeholder-defined scenarios regarding future mission requirements and the probability of winning contracts for each mission. Even though there are multiple uncertainties in input data, the analysis finds good strategies for future retrofits, and shows that there is value in considering design flexibility. These results should be particularly interesting for ship owners with expensive assets that can be repurposed to perform a variety of missions.

The probability of winning a contract for a specific mission is here considered strongly dependent on the oil price. A higher oil price implies more offshore oil and gas activity. The probability of winning a contract is also influenced by some uncertainties that relate to future field development, including the water depth. While there is likely that there is a relation between these uncertainties and the probability of winning a contract, the exact strength of these relationships are very difficult to quantify. In reality, the availability of new contracts for a vessel could potentially be a function of ship owner-customer relations, ship owner reputation, crew experience, and vessel capabilities. The lack of understanding of exactly what determines the probability of winning a contract is a weakness of any economic analysis that seeks to quantify the expected value of an engineering system where there are risks regarding market entry. There is a need for further investigation of factors that may influence the probability of winning contracts in offshore markets. Empirical studies can cast light on why oil companies decide to charter certain vessels, and tools like game theory and system dynamics could support the modeling of the competitive aspects that where simplified in this analysis.

While the combination of epoch-era and real options analysis offers remedy to the complex decision environment of offshore vessels, multiple uncertainties remain. For example, shipbuilding risks are not considered in the analysis. Naturally, like the maritime industry overall, the shipbuilding industry is also highly cyclical (Stopford, 2009). In good times shipyards may have many projects going on, and may have trouble to find time for retrofits in their schedule. In bad times retrofits may become cheap as shipyard availability increases. However, in bad times options such as lay-up also become more attractive. Beyond yard availability, cost slips and delays are common problems for complex projects in general (Ross et al., 2008), and should be accounted for before considering a retrofit. When installing new equipment on a vessel, we also implicitly assume that this equipment is available when needed. In reality, there are a limited number of producers for many types of offshore equipment. This adds to supply risk, especially for more advanced systems. The sensitivity analyses remedy these project risks to an extent, as we gain understanding of how expensive retrofits can get before flexibility provides no additional value. Option valuation procedures applicable for complex engineering systems should in general expand their scope and take these risks properly into account.

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[To be placed here]

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Figures (supplied in separate files, as according to Taylor and Francis guidelines)

Figure 1: Flowchart for the model integrating stochastic processes and epoch-era analysis for real options evaluation.

Figure 2: Mapping the influence of epoch variables on the contract requirements and the probability of winning contracts.

Figure 3: Retrofit of Design 1 to Design 36 to comply with most attractive future contracts through one era.

Figure 4: Cumulative NPV distribution for inflexible and flexible versions of Design 1.

Figure 5: Cumulative NPV distribution for inflexible and flexible versions of Design 11.

Figure 6: Cumulative NPV distribution for inflexible and flexible versions of Design 51.

Figure 7: Sensitivity of value of flexibility against changes in retrofit installation factor g for Design 1.

Figure 8: Sensitivity of value of flexibility against changes in retrofit installation factor g for Design 11.

Figure 9: Sensitivity of value of flexibility against changes in retrofit installation factor g for Design 51.

Tables (supplied here, as according to Taylor and Francis guidelines)

Table 1: Design variables for the OCV.

Design variable	**Unit**	**Range (Min-Max)**	**Step length**	**No. of levels**
Crane	[tonnes]	100 – 300	50	5
LARS for ROV	Integer	1 – 2	1	2
Accommodation	[people]	50 – 150	100	2
Module handling tower	Binary	0 – 1	1	2
Well intervention tower	Binary	0 – 1	1	2
J-lay tower	Binary	0 – 1	1	2
Saturated diving system	Binary	0 – 1	1	2
Total deck area (Ship size)	[m^2]	1000 – 2000	250	4
Free deck area	[m^2]	0 – 1500	250	6

Table 2: Equipment cost data.

Design variable	**Cost (min) [USD]**	**Cost (max) [USD]**
Crane	3 750 000	6 250 000
LARS for ROV	1 250 000	2 500 000
Accommodation	1 250 000	3 750 000
Module handling tower	0	18 750 000

Well intervention tower	0	25 000 000
J-lay tower	0	25 000 000
Saturated diving system	0	25 000 000
Total deck area	62 500 000	82 500 000
Free deck area	0	0

Table 3: Initial contract requirements.

Design variable	**Unit**	**IMR**	**SURF**	**LWI**	**DS**
Crane [tonnes]	[tonnes]	100	200	100	100
LARS for ROV	Integer	1	1	1	2
Accommodation [people]	[people]	50	150	150	150
Module handling tower	Binary	0	0	0	0
Well intervention tower	Binary	0	0	1	0
J-lay tower	Binary	0	0	0	0
Saturated diving system	Binary	0	0	0	1
Free deck area	[m^2]	500	1000	500	0

Table 4: Epoch variables for the context of the OCV.

Epoch variable	**Unit**	**Range (Min-Max)**	**Step length**	**No. of levels**
Oil price	[USD]	10 – 100	30	4
Module size	[tonnes]	200 – 300	50	3
Water depth	[m]	1000 – 3000	1000	3
Tie-in need	Binary	0 – 1	1	2
Fibre rope technology	Binary	0 – 1	1	2

Table 5: Time charter rate data for simulation model.

Markets	**Mean day rate [USD]**	**Mean-reversion rate**	**Standard deviation [USD]**
IMR	62 500	0.8	12 500
SURF	200 000	0.5	25 000
LWI	200 000	0.5	37 500
DS	125 000	0.8	15 000

Table 6: OCV designs analyzed.

Design variable	**Design 1**	**Design 11**	**Design 51**
Crane	300	300	300
LARS for ROV	2	2	2
Accommodation	150	150	150
Module handling tower	1	1	0
Well intervention tower	0	0	1
J-lay tower	0	0	0
Saturated diving system	0	0	0
Total deck area	2000	1250	1750
Free deck area	1250	500	1500

Table 7: Economic performance based on 10 000 simulation runs, measured in USD, rounded to closest million.

Cases	Measures	Design 1	Design 11	Design 51
Flexible case	$E[NPV^{FLEX}]$	100 000 000	390 000 000	372 000 000
	Lower 95% conf.	97 000 000	386 000 000	368 000 000
	Upper 95% conf.	104 000 000	394 000 000	376 000 000
Inflexible case	$E[NPV^{INFLEX}]$	-83 000 000	-70 000 000	330 000 000

	Lower 95% conf.	-87 000 000	-72 000 000	325 000 000
	Upper 95% conf.	-80 000 000	-69 000 000	335 000 000
Value of flexibility	$E[V^{FLEX}]$	183 000 000	460 000 000	42 000 000