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Semi-Submersible Platform Design to Meet Uncertainty in Future Operating Scenarios

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"Semi-Submersible Platform Design to Meet Uncertainty in Future Operating Scenarios"

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Background

The design of a new offshore platform needs to combine the optimisation of the vessel platform for the (likely) first contract entered into, while taking into account additional functionality and performance capabilities to meet future requirements and changes in its operating context. Such uncertainties may include increased/decreased oil prices, stricter environmental regulations, the availability of new and more cost-efficient technologies and possible new (arctic) offshore fields. To prepare for these uncertainties, design solutions related to flexibility, robustness, adaptability and real options should be assessed in best manner. To further add complexity, these additional capabilities might either be made part of the platform at design time, or they may be provided as design options to be implemented in the future dependent on information made available.

Overall aim and focus

Aker Solutions are in these days working on a semi-submersible intervention platform design, and this will be the basis for the thesis.

Thus, the overall objective is to look at functions that can deliver sustained value to stakeholders over time in a complex, uncertain and changing operating context, and how to evaluate these. A description of the proposed intervention semi design will be given, and examples related to this concept will be presented. Key concepts such as real options, flexibility, adaptability and robustness should be linked to real design characteristics and solutions. Further, discuss how the value of these characteristics can be measured to compare alternative design solutions.

Scope and main activities

The candidate should presumably cover the following main points:

1. Describe the proposed intervention semi concept provided by Aker Solutions, with corresponding design drivers and capabilities. Develop a high level functional breakdown structure for this concept, and identify modules/parts/sections realising these functions.

2. Propose/discuss which functions that are likely to meet new/changing requirements during the lifetime of the platform (e.g. operating area, regulations, technology development, etc.).

3. Discuss and propose how (some of) these changing requirements can be accommodated for at design time. Related to this, discuss aspects of flexibility, adaptability, robustness and options.

4. Suggest how these solutions (that accommodates for changing requirements) can be measured to compare alternative design solutions, and how the value of a flexible design can be presented to a potential customer – the value of flexibility.

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor.

The MSc project is within the topic area of the KMB project SHIP-4C, and is thus eligible for travelling grants from this project.

The work shall follow the guidelines given by NTNU for MSc Thesis work. The work load shall be in accordance with 30 ECTS, corresponding to 100% of one semester.

PREFACE

This master thesis is a part of the Master of Science degree in Marine Engineering, Marine Systems Design, at the Norwegian University of Science and Technology (NTNU).

Literature on the topic was given to me by Professor Stein Ove Erikstad, in addition Aker Solutions provided me with valuable information about a semi-submersible concept they are working on.

I would like to thank my responsible advisor, Professor Stein Ove Erikstad, for the necessary guidance and advices during the project work period, and for providing me with relevant literature on the topic.
I would like to thank Aker Solutions for their cooperation. As contact person in Aker Solutions, I would like to thank Anders Martin Moe for being very helpful in all matters, and giving me the opportunity to work with my thesis for some time at his department in Oslo. He was also so kind to be at assistance in the time he was away for paternity leave.
Also, I would like to thank Dr. Jørgen Glomvik Rakke, who has been very helpful in relation to the model implementation, and in addition provided general support when needed.

Due to confidentiality issues, some references are left out, and confidential material consider essential for the thesis is placed in a separate appendix, only available for responsible advisor and external examiner. As a consequence of these confidentiality issues, some parts concerning the semi-submersible in question will be somewhat inadequate.

Trondheim, June 2012

Øyvind S. Patricksson

ABSTRACT

This master thesis in marine systems design is about how to assess the future uncertainty in a design setting, or as the topic puts it; *semi-submersible platform design to meet uncertainty in the future operation scenarios*. Central terms that will be discussed are robustness, flexibility, adaptability, and real options, so-called *ilities*. Also, methods for evaluation of designs in relation to ilities and future uncertainty are presented.

The background for this thesis is the ever importance of a good assessment of investment projects in the offshore business in general, and more specific in relation to designs subjected to different forms of ilities. Now, more than ever, it is crucial to make the right decisions when designing an offshore construction, to ensure that an investment is viable. This thesis has used the concept of an intervention semi, provided by Aker Solutions, to assess problems related to these aspects.

At first, design drivers for the concept were identified. These were found to be cost, weigh and operability, where (total) cost and (total) weight are strictly correlated. Operability, meaning the ability to keep operations running in different conditions and situations, are mainly dependent on motion characteristics and layout, where vertical motions were found to be the most important.

The properties of the intervention semi was presented as a functional breakdown, divided in five main categories; well intervention, drilling, power generation, station keeping and transit, and *other functions.* The last category, the one called *other functions*, incorporated accommodation, ballast and bilge water systems, and heave compensation system. Most relevant for the intervention concept are the intervention functions and drilling functions. Of well intervention procedures, the concept should be able to do *wireline operations,* coiled *tubing operations,* and for drilling, *through tubing rotary drilling* will be the main procedure.

After presenting the properties for the intervention semi concept, aspects of changing requirements due to uncertainty in the future, were discussed. The design functions of changing requirements identified were *operation method and technology, environment and legislation, area of operation,* and *economics.* Following this, a discussion of how to accommodate for these changing requirements were presented, with focus on aspects regarding *flexibility, robustness, adaptability,* and *real options*.

After these terms and aspects had been discussed, an evaluation of the concept in relation to the ilities presented was done. Most relevant was the possibility of a development of the coiled tubing equipment, the aspect of *managed pressure drilling* as a function that might be needed in the future, and the use of rental equipment. Also, ilities were identified and discussed in a concept similar to the intervention semi presented in this thesis. From this, it was found that functions related to the environment (regarding emissions) would be a potential area of ilities, due to the continually increasing focus on such matters, and by having functions related to this designed with ilities, It would make it easier to improve these functions at a later time. Also, the aspect of extra deck space was discussed, which will give the design better flexibility, and in general, it was found that flexibility in the procedures for intervention and drilling operation was important for this concept. Some functions and aspects were also found not to be relevant for any sort of ilities. Among these were functions related to heavy drilling, increased water depth and the aspect of ice class.

To find the value of a design with functional ilities, different methods and aspects were presented. At first, economical aspects were discussed, and methods using *net present value* were found to be relevant in relation to the valuation of ilities. Another approach discussed was scenario development and assessment, where in particular one method was

found relevant. This method proposes to find an optimal design for the scenario assumed most probable, and then test this design against the other possible scenarios (using the models as simulation models) to get an impression of the resilience of the designs.

Two decision support models were proposed, *Model 1* and *Model 2*. The first model presented, *Model 1*, can be described as a “hybrid” decision model, part static, part dynamic, where an optimal design is found for a set of contracts, taking real options into consideration. The contracts should reflect the future, and from a set of base designs, with varying possibilities for functions and options, a design with an optimal combination of capabilities and options will be the result of solving the problem. *Model 2* is sort of a static variant of *Model 1,* where the possibility of real options is no longer available. The model will still find a design with an optimal combination of capabilities for a set of contracts, but all capabilities must be part of the construction initially.

Further, the two models are implemented for use in a commercial solver, and parameters and constraints are discussed. These implemented models were then used for the illustrative cases.

The case studies illustrate how the two models presented can be utilised, and in addition illustrate how the scenario assessment discussed earlier can be combined with the decision support models. There are mainly three cases presented; two where *Model 1* is used, and a third, where *Model 2* is used.

In *Case 1* there are three base designs, with different characteristics, and one only attribute (supplementary function) that should be assessed. Three scenarios are presented as a basis for the contract generation. First, an optimal design solution was found for each scenario (*Case 1a, Case 1b* and *Case 1c*). Secondly, a scenario assessment was done, where the solution from the scenario assumed most probable is tested against the other two scenarios using the model as a simulation model rather than an optimisation model. *Scenario 1* was assumed to be the most probable one, represented by *Case 1a*, and the optimal solution for this case was *Design 1*. This design was then tested against the two other scenarios, and it came out with a rather good result, illustrating the resilience of the chosen design.

Case 2 illustrated a more complex problem, where an optimal solution should be found among 16 different base designs and four possible attributes. The attributes could either be part of the design initially or made as options that can be realised at a later time. The instance tested is assumed to be somewhat more complex than a commercial problem, but illustrates in a good way the capability of *Model 1.*

Case 3 is an example of how *Model 2* can be used. In *Case 3a*, only one base design is available, and with a set of four possible attributes, an optimal design should be found. Due to the “static” character of *Model 2*, the attributes can only be part of the initial design. *Case 3b* is much the same, except here there are two base designs to choose among, in addition to the four attributes

A computational study was carried out, using *Model 1,* and only this, as it is assumed to be the most complex of the two models. The test incident assumed most relevant, with 100 contracts, four base designs, and eight attributes, can be solved one time in on the average less than two seconds, and for a full scenario analysis, consisting of about 1000 runs, the analysis will take about half an hour.

As a concluding remark for this thesis, I will say that the main scope, which I in my opinion was to discuss how different design solutions can be evaluated in relation to future uncertainty, was answered in a good way with the two decision models proposed together with how these could be used in a scenario setting.

SAMMENDRAG

Denne masteroppgaven handler om hvordan evaluere fremtidig usikkerhet i en design sammenheng, eller som emneoverskriften sier; halvt-nedsenkbar platform design for å møte usikkerhet i fremdige operasjonssenarioer.Sentrale emner som vil bli diskutert er robusthet, flekisbilitet, tilpasningsevne og realopsjoner, såkalte «illities». Metoder for evaluering av design i sammenheng med slike «ilities» og fremtidig usikkerhet er også presentert.

Bakgrunnen for denne oppgaven er den stadige viktigheten av en god evaluering av investeringsprosjekter i offshore næringen generelt, og mer spesielt i relasjon til designs gjenstand for forskjellige tilfeller av «ilities». Nå, mer enn noen gang, er det avgjørende å gjøre de riktige valgene når en offshore konstruksjon skal designes, for å sikre en levedyktig investering. Denne masteroppgaven har brukt e halvt-nedsekbar inervensjons platform konsept fra Aker Solutions for å undersøke disse aspektene.

Innledningsvis ble nøkkelfunksjoner (design drivere) for prosjektet identifisert. Disse ble funnet å være kostnad, vekt og operasjonstilgjengelighet, hvor (totale) kostnader og (total) vekt er strengt innbyrdes forbundet. Operasjonstilgjengelighet, muligheten for å opprettholde operasjon i forksjellige situasjoner og under forskjellige forhold, er antatt å primært være avhengig av bevegelseskarakteristikk og arrangement, hvor vertikale bevegelser ble funnet å være de viktigste.

Egenskapene til denne intervensjonssemien ble presentert som en funksjonell nedbrytning, delt opp i fem hovedkategorier; brønnintervensjon, boring, kraftproduksjon, posisjonsopprettholdelse og transit, samt *andre funksjoner.* Den siste kategorien, *andre funksjoner,* omhandler innkvartering/boligenhet, ballast vann og «utslags vann», samt hiv-kompensasjonssystemer. Mest relevant for dette intervensjonskonseptet er funksjonene vedrørende brønnintervensjon og boring. Av brønnintervensjonsoperasjoner skal konseptet ha mulighet til å gjøre vaierlinjeoperasjoner, kveilerørsoperasjoner, og for boring vil stigerørboring være den primære metoden.

Etter at egenskapene til intervjsonsriggen var presentert, ble aspekter vedrørende endrede funksjonskrav og omgivelser grunnet fremtidig usikkerhet diskutert. Disse var operasjonsmetode og teknologi, omgivelser/miljø og lovgivning, område for operasjon, samt økonomi. Etter dette ble det diskutert hvordan disse endrede betingelsene kunne håndteres, med fokus på områder vedrørende flexibilitet, robusthet, tilpasningsdyktighet og realopsjoner.

Etter at disse områdene og betgnelsene var diskutert, en ble det gjort en vurdering av konseptet i lys av disse «ilitiene». Mest relevant var muligheten for en utvikling i kveilerørsutstyr, muligheten for at funksjonen «managed pressure drilling» ville bli nødvendig i fremtiden, samt bruk av leieutstyr. I tillegg ble «ilities» identifisert og diskutert for et konsept tilsvarende intervensjonssemien presentert i denne oppgaven. Av dette ble det funnet at funksjoner relatert til miljø og utslipp ville være aktuelle områder for «ilities» grunnet den kontinuerlige økningen i fokus på dette området, og ved å designe funksjoner relatert til dette med forksjellige «ilities» vil det være enklere å forbedre disse funksjonene senere. Også aspektet med ekstra dekksareal ble diskutert, som vil gi designet bedre fleksibilitet, og generelt ble det funnet at fleksibilitet i operasjonprosedyrer relatert til boring og brønnintervensjon var viktig for dette konseptet. Noen funksjoner og områder ble også funnet å være lite egnet for «ilities». Dette var blant annet funksjoner relatert til tyngre boreoperasjoner, økt vanndypde, samt isklasse relaterte aspekter.

For å finne verdien av design som er gjenstand for funksjoner med «ilities», ble forskjellige metoder og aspekter relatert til dette presentert. Først ble økonomiske aspekter diskutert, og metoder som benytter «net present value», eller nåverdiberegninger, ble funnet relevante i sammenheng med verdivurdering av forskjellige «ilities. En annen vinkling diskutert var senario utvikling og evaluering, hvor spesielt èn metode ble funnet å være relevant. Denne metoden foreslår å finne et optimalt design for det senario antatt mest sannsynlig, for så å teste dette

designet mot andre senarioer (ved å bruke modellene som simuleringsmodeller) for å undersøke kvaliteten av den optimale løsningen.
To beslutningsstøtte modeller ble foreslått, *Model 1 og Model 2*, begge deterministiske MIP modeller. Den første modellen, *Model 1,* kan bli karakterisert som en «hybrid» modell (delvis statisk og delvis dynamisk), hvor optimalt design blir funnet for et sett med kontrakter, hvor muligheten for realopsjoner blir tatt med i vurderingen. Kontraktene er ment å gjenspeile fremtiden, og fra et sett med grunndesign, med varierende egenskaper og muligheter for funksjoner og opsjoner, skal et design med optimal kombinasjon av egenskaper og opsjoner vil bli resultatet av å løse problemet. *Model 2* er på mange måter en variant av *Model 1*, men hvor muligheten for realopsjoner ikke lenger er tilgjengelig. Modellen vil fremdeles finne optimal kombinasjon av egenskaper for et design for et sett med kontrakter, men alle egenskaper må være en del av konstruksjonen fra dag en.
Videre er de to modellene implementert i en kommersiell «solver», en datamodell, og parametre of restriksjoner er diskutert. Disse implementerte modellene ble så brukt for et sett med illustrative eksempler. Eksemple studiene viste hvordan de to modellene presentert kan bli brukt, og i tillegg ble det illustrert hvordan senario evaluering diskutert tidligere kan bli kombinert med modellene. Det er hovedsaklig presentert tre eksempler; to hvor *Model 1* er brukt, og et tredje hvor *Model 2* er brukt.
I eksempel 1 er det et sett med tree grunndesign, med forskjellige karakteristikker, og kun en attributt (potensiel tilleggsfunksjon) som skal bli evaluert. Tre senarioer blir presentert som en basis for kontraktgenereringen. Først ble det funnet et optimalt design for hver av de tre senarioene. Etter dette ble det gjort en senario evaluering, hvor løsningen fra senarioet antatt mest sannsynlig ble testet mot de to andre. Senario 1 var antatt mest sannsynlig, representert av eksemple 1a, og optimal løsning for dette eksempelet var design 1. Dette designet ble så testet mot de to andre senarioene, og det viste seg å gi et relativt godt resultat for også disse, som reflekterer hvor god løsningen er.
Eksemple 2 illustrerer et mer komplekst problem, hvor en optimal løsning skal finnes blant 16 grunn design, med mulighet for fire attributter (tilleggsfunksjoner). Tilleggsfunksjonene kan enten være en del av designet fra dag en, eller være real opsjoner som kan bli realisert på et senere tidspunkt. Dette tilfellet er antatt å være til en viss grad mer komplekst enn et kommersielt problem, men illustrerer på en god måte hva *Model 1* er i stand til.
Eksempel 3 er et eksemple på hvordan *Model 2* kan brukes. I eksemple 3a er kun ett grunndesign tilgjengelig, og med et sett av fire attributter skal et optimalt deisgn bli funnet. Grunnet den statiske karakteristikken til *Model 2*, kan attributtene (funksjonene) kun være en del av det initielle designet. Eksempel 3b er rimelig likt, bortsett fra at det her er to grunndesign å velge mellom, i tillegg til de fire attributtene.
En studie ble gjort av løsningstid for *Model 1*, og kun denne, da denne er antatt å være den mest komplekse av de to modellene. Testtilfellet antatt mest relevant, med 100 kontrakter, fire grunndesign, og åtte attributter, kan løses en gang på i gjennomsnitt under to sekunder, og en full senario evaluering, med rundt 1000 kjøringer, vil kunne gjøres på omtrent en halv time.

For å konkludere vil jeg si at hovedfokus, som etter min mening var å diskutere hvordan forskjellige designløsninger kan bli evaluert i relasjon til fremtidig usikkerhet, ble besvart på en god måte med de to beslutningsmodellene som ble foreslått sammen med hvordan disse kan bli brukt en scenario setting.

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Abbreviations

BOP	Blowout Preventer
BIP	Binary Integer Programming
CT	Coiled Tubing
CTD	Coiled Tubing Drilling
DCF	Discounted Dynamic Cash Flow
DP	Dynamic Positioning
E-line	Electrical line
HP	High Pressure
HVAC	Heating, Ventilation, Air Conditioning
LCC	Life Cycle Cost
LP	Low Pressure
MPD	Managed Pressure Drilling
NPV	Net Present Value
PTD	Portable Topdrive
RAO	Response Amplitude Operator
ROV	Remote Operated Vehicle
TT	Through Tubing
TTRD	Through Tubing Rotary Drilling
WL	Wireline
WLC	Whole Life Costing

Other abbreviations might occur in the text, but if so, these are explained when used. Symbols used for modelling are explicitly described in the text.

1. INTRODUCTION

This thesis, on the topic *semi-submersible platform design to meet uncertainty in the future*, serves as a part of my work towards a Master of Science degree in Marine Engineering at NTNU. It will be about how to assess the future uncertainty in a design setting, and how to find and compare designs prepared for this future uncertainty. Central terms will be robustness, flexibility, adaptability, and real options, so called *ilities*, and the models presented will be used for optimisation and simulation.

1.1 Background

In the beginning of the offshore oil industry, the well technology was mostly land-based technology transformed to function at rigid platforms at sea. This has proven to function, but in some areas this is not the ideal method, and the technology has evolved. In the last decades, there has been a great technological development, and one of the major areas is subsea well completions, to substitute the platform well completion. Today, wells with subsea completion are getting more and more common (Solheim, 2008). The drawback of the subsea well completion concept is that there is to a large degree lower recovery rates on the subsea wells than there is on a platform well. This is much because of the difficulties and expenses associated with subsea well intervention. By developing purpose built vessels and floating offshore platforms, like an intervention semi, these kinds of operations will be cheaper and more effective, and thus enhance the production from subsea wells.
An engineering company proposing an outstanding design for an offshore construction, for instance an intervention semi, with a high degree of flexibility and robustness making the design better prepared for the future, is often not chosen because of the higher investment cost. If it somehow could be proved that the more flexible design will provide significantly greater earnings during the lifetime than a cheaper less flexible design, in a scale which justifies the extra initial cost, the best design might be the chosen one after all.

The background for this thesis is thus the ever importance of a good assessment of investment projects in the offshore business, with focus on evaluation of designs with different forms of functional ilities. Now, more than ever, it is crucial to make the right decisions when designing an offshore construction to ensure that an investment is viable. In relation to this, I have in this thesis used the concept of an intervention semi, provided by Aker Solutions, to assess this problem.

1.2 Project Scope

Aker Solutions are in these days working on a semi-submersible intervention platform design. This concept will be the basis for the thesis. The overall objective will be to look at functions that can deliver sustained value to stakeholders over time in a complex, uncertain and changing operating context, and how to evaluate these. A description of the intervention semi concept design will be given, and examples related to this concept will be presented. Key concepts such as real options, flexibility, adaptability and robustness will be linked to real design characteristics and solutions. How the value of these design characteristics can be measured to compare alternative design solutions will be discussed. Also, proposals for evaluation of design solutions, taking future uncertainty into consideration, in a more general sense will be presented.

The thesis will cover the following aspects:

A description of the concept, with corresponding design drivers and capabilities, will be presented. Further, a high level functional breakdown for this concept is made, with identification of modules/parts/sections realising these functions.
It is discussed which functions that are likely to meet new/changing requirements during the lifetime of the platform (e.g. operating area, regulations, technology development, etc.), and examples related to the proposed concept are given.
It is further discussed how these changing requirements can be accommodated for at design time, related to aspects such as flexibility, adaptability, robustness and real options.
An optimisation model approach, taking future uncertainty into consideration, is suggest for how alternative design solutions with different functions and solutions accommodating for changing requirements can be compared. The result can be used for presenting the value of a more flexible design to a potential customer.

2. THE INTERVENTION SEMI CONCEPT

The concept presented in this chapter is about a purpose built light intervention semi provided by Aker Solutions. The "purpose" built term means that the functional capabilities are carefully evaluated to ensure efficient operations and beneficial day rates for a special kind of well maintenance operations. Often, drill rigs or larger intervention vessels have been used to do general well maintenance and intervention work, resulting in high costs, due to higher day rates, need for re-building, and rental of intervention equipment. The dedicated light intervention semi will be satisfying customer specifications, with the aim to reduce costs of well intervention – "Fit-for-purpose".

In this chapter, functions and specifications related to this will be presented and discussed. The information is mainly attained from Aker Solutions, but general information about equipment and functions is to a large degree from miscellaneous literature. I will first very broadly describe the concept and discuss the design divers for this type of construction in section *2.1* and *2.2*, before a more specific description of the systems and functions will be provided with the functional breakdown in section *2.3*.

2.1 Description of the Concept

The concept is about a proposal for an *intervention semi*, which basically is a semi-submersible platform with the ability to do intervention work on oil and gas wells. In relation to the intervention work, the semi should be able to do *wireline* (WL) operations, *coiled tubing* (CT) operations, and some light drilling work, called *through tubing rotary drilling* (TTRD). These functions will be discussed later in the chapter. In addition to the functions related directly to the intervention work, also a number of basic functions must be provided to keep the semi going. In Table 1 (Appendix 8 - Confidential), the main particulars for the concept are given.

Table 1 - Main particulars (only available in Appendix 8)

To do the drilling and well intervention, a lot of the deck area is dedicated to these kinds of operations. A central component is the derrick, which is a tower like construction that supports drilling equipment and various kinds of intervention systems. The drilling system, the TTRD function, should be compatible with the two intervention systems. By having these three different operation possibilities, a variety of well intervention procedures can be done, for example; pumping, well workover, production enhancement, cementing and well testing. The different well intervention operations will be further described in the section about the platform functions. As this semi to a large extent will be temporary stationed at the worksite, it must be able to move from site to site. To do this, it will be equipped with azimuth thrusters. In addition to provide transit propulsion, the thrusters will be used for the dynamically positioning (DP) system. All the functions presented until know need some sort of power supply; the thrusters and accommodation needs electrical power, a lot of the intervention

equipment are hydraulically driven, and some equipment will also need pneumatic power. To supply the platform with this power, a set of diesel generators are installed.
The semi is designed to have accommodation for 100 persons. This requires a large part of the platform to be used for living quarters and like. Below, in Figure 1, a rough sketch of an intervention semi, category B, is shown, which is comparable to the concept presented in this paper.

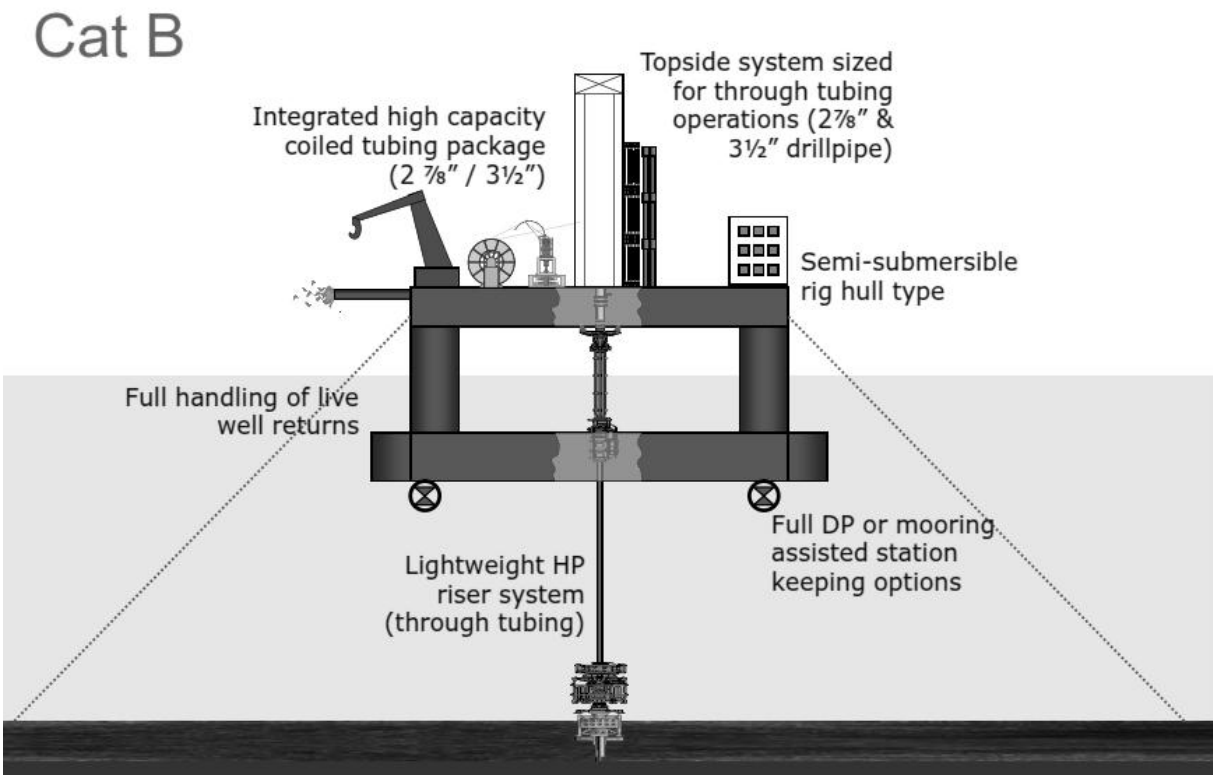

Figure 1 - Sketch of intervention semi (Source: Statoil (2010))

2.2 Design Drivers

When working on a project like this, there are a number of important factors to consider. Early in the concept phase, it is important to establish the most important design drivers, with corresponding limits and goals. In this case, the most important design drivers are said to be cost and weight, where these are strictly correlated, according to Akers Solutions. Usually, a guideline for these design drivers is given by functional requirements (what the rig should be able to do, reflects cost and weight of the rig), and often there is a customer with a list of demands and standards to satisfy, called a tender. In addition to the two mentioned above, platform motions and layout are important aspects, due to the close relation to ensuring good operability. This can again be related to the highly relevant aspect of robustness, which I will come back to later. The motions and layout will also be something that often is specified by a customer in a tender.

2.2.1 Importance of Weight – a Direct Relation to Cost

When designing a semi-submersible, it can be argued that weight equals cost. This is widely known, so an engineering company must have this in mind when making a design, a rig company (or the oil company as the end user) will look at the weights and estimate the total cost from this. When an engineering company is replying to a tender from a potential customer, the bitter truth is that very often the cheapest solution that satisfies the minimum specifications is the one chosen. This will not necessarily be the best design (in fact, it will rarely be so), not even the best in sense of "value for money", but it is chosen because of the low investment cost. In cases where a total cost not is proposed from the constructor, the buyer often looks at the weight, more precisely the displacement, and makes an assumption about the total cost. Since this is a common way of evaluating a relay to a tender, it is difficult to make the potential buyers see the benefits of a more costly, but more flexible/robust design. The result of this can often be that the flexibility and robustness of a design is reduced.

On a semi-submersible platform, everything you put on it adds weight that the buoyancy of the hull must handle. If the equipment gets bigger and heavier, or the design is uncritical over equipped, the hull will again have to be bigger, and a bigger hull might need larger propulsion, and so it goes. This does naturally lead to a direct increase in the cost of steel, but as indicated, it might also result in the need for larger and more expensive power generation units, more expensive propulsion units, and so forth. In the utmost consequence, the deck size is increased, even more equipment added, - and so it goes. This illustrates the importance of a good evaluation of equipment, necessary functions, and need for spare capacity.

In the end, a good assessment of the design drivers cost and weight is important for most likely to end up with a result within project scope and budget limits.

2.2.2 Operability – Motions and Layout

Operability, meaning how good the design is to keep operations going under different conditions, is also one of the important design drivers. The operability is dependent on many factors; examples of "internal" factors are size and motion characteristics of the construction, the layout and general arrangement, and specifications for essential functions. An example of an "external" factor could be area of operation. Regarding the operability for this intervention semi concept, motions and layout will be of greatest interest. In relation to this, Aker Solutions () states that:

> *Since the North Sea is characterized by a harsh climate, the vessel will need to behave satisfactorily in relatively rough weather conditions.*

Motions

The most important motions for a semi-submersible intervention platform, concerning operability, will be the vertical motions. These are critical for both intervention and drilling operations. In the concept study about the proposed intervention semi (Aker Solutions), it is stated that "*the response amplitude operator (RAO) for heave will be the important variable to consider*".

As a representation for the vertical motions of the platform, heave motions can be described by a *response amplitude operator* (RAO), also called a transfer function. In Aker Solutions (), it is said that the number of columns on the platform seems to have little influence on the vertical motions, while the draft have a significant influence. This connects the motions, and the RAO, directly to the other important design driver, weight. A result of this is that the consequence of adding equipment not only influences the cost directly, but also indirectly through changed motion characteristics. In worst case, it can result in reduced earning capacity due to deteriorated operability. Related to motions, design draft and payload capacity is important factors that can give the design increased flexibility when related to the GM (centre of gravity vs. metacentre height). Without going too deep into stability calculations, a high GM, meaning a large distance between centre of gravity and the metacentre, will give better initial stability, but more rapid motions and a "stiffer" construction. This should be considered when evaluation possibilities of payload on deck, since weights on deck will increase the motions significantly due to its fairly high placement. An example of robustness concerning motion characteristics is that if the rig has good characteristics for a "high" draft, it has the possibility of increasing payload on deck for some instances when this is needed, white a price of less beneficial motion characteristics, but without being critically deteriorated. A "high" draft often means bigger construction (more volume), which can result in a higher total cost, which might not be appreciated.

Motions in general are also important regarding safety of the crew, in the sense of their ability to move around the rig with reduced probability of injuries, and thus making it possible to keep on working in harsher conditions. In addition, the construction will be less exposed to fatigue problems with reduced motions.

An important function for good operability, regarding motions, is the heave compensation system for intervention and drilling systems. This will be discussed later, under sub-section *2.3.5*.

Layout

The layout, or general arrangement, is basically an assessment of what equipment to be placed where. The layout of an intervention semi is a complex puzzle, dependent on factors like safety, efficiency, stability, human factors, environmental issues and structural mechanics (Ji-xiang, Yao-guang, Wen-sheng, Lei, & Yi-pu, 2009). According to *Ji-xiang et al.* (2009), the layout influences the operation performance directly, based on stability, security and work efficiency. An important aspect of the security part is that there needs to be a clear separation between the living quarters and operations and material assumed hazardous. Examples of hazardous material is the well returns (as mud) and fuel storages, and the living quarters should be physically separated from such material, with a fire/blast wall between, and often placed on opposite sides of the platform.

A semi-submersible intervention platform is usually divided into three main areas; upper deck/working deck, lower deck/cellar deck, and columns and pontoons. On a rig with drilling capability, like the concept proposed in this paper, also the drill floor is assumed to be an own area of significance, where drill pipes, casings, and other drilling/intervention equipment is received for different operations. The upper deck is usually an area for storage of operation related material and equipment handling. Also, an area dedicated to pipe handling, called pipe deck, is used on this intervention semi concept. An example of a layout for the upper deck for an intervention semi is shown in Figure 2 (restricted information).

Figure 2 - Only available in Appendix 8

The lower deck, or cellar deck, usually contains a mud mix area, transportation routes for material, a moonpool area, and storage and handling facilities for well returns. Other systems and facilities will also require some space at this deck, like handling of BOP and x-mas tree.
In the columns and pontoons, there are storage tanks for fuel, brine, ballast and bilge water, and miscellaneous drilling stores (e.g. cement, drilling mud, etc.).
In (Ji-xiang et al., 2009), which assesses optimisation of layout for a drilling semi; it is proposed that the upper deck should be designed based on the lowest transportation cost, while the lower deck layout should be based on the best-fit scope. It is further suggested that the layout in the end should be adjusted according to optimal centre of gravity.

2.3 Functional Breakdown

The concept in question is, as mentioned introductorily, a semi-submersible well intervention rig – an *intervention semi.* The main purpose of such a construction is to do well intervention, and in relation to this, the rig is also designed to do light drilling work, primarily *side-track drilling* (discussed further under sub-section *2.3.2*). Other important functions are accommodation of crew, station keeping (DP and mooring capabilities), and since this rig is supposed to do short term maintenance, or other temporary well interventions, it has to be able to get to the site by it selves.

The functional breakdown will be on a fairly high level, but in the assessment of some of the functions, lower levels will be discussed. I will focus on the functions that are essential to the concept as an intervention semi. Below, in Figure 3*,* a rough functional breakdown is presented.

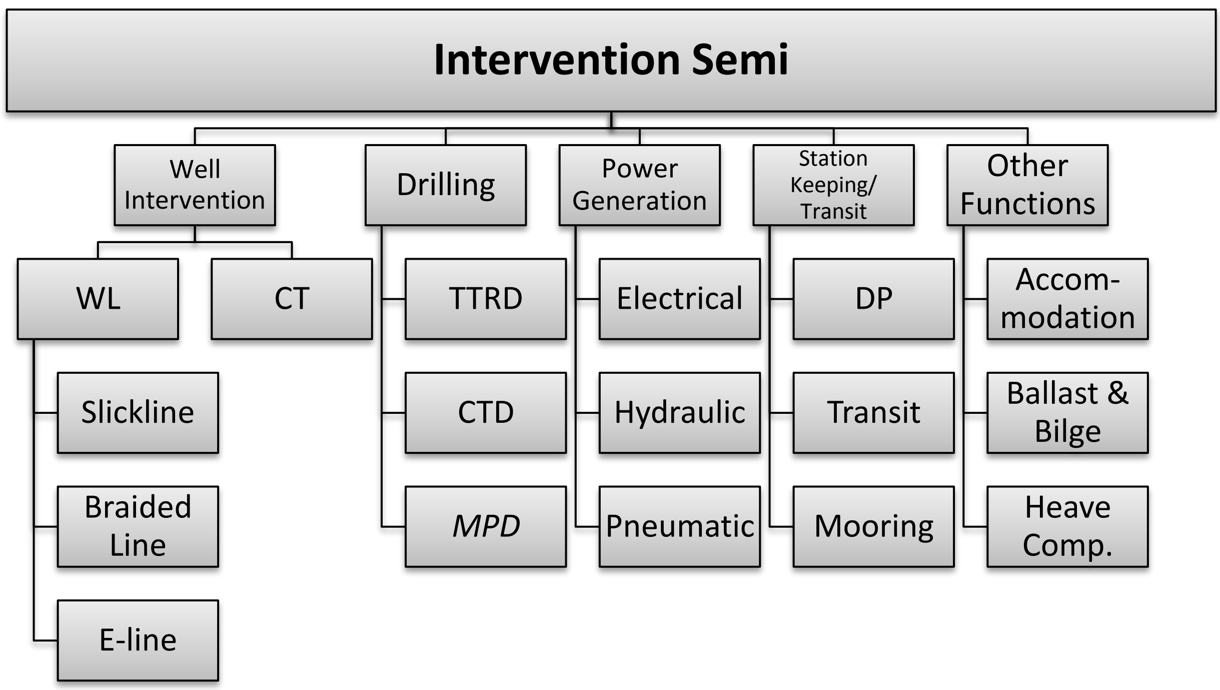

Figure 3 - Functional Breakdown (Source: Author)

In addition to the functions and capabilities mention above, that are more or less directly related to the concept distinctiveness, also HVAC (Heating, Ventilation and Air Conditioning), lifesaving/safety systems, ballast water systems and telecommunication systems are examples of high level functions that is vital for the total platform function. To limit the scope of the paper, these areas will not be further discussed.

2.3.1 Well Intervention

As the number of offshore oil and gas wells increase every year, and the du to the fact that some of the older wells will need rapidly maintenance, the need for well intervention vessels is increasing. The notion *well intervention* is a collective term for the different maintenance and modifications that can be done to an offshore oil or gas well during its lifetime, and can involve everything from cleaning to shut down of the well. More concrete, examples of operations are; wellhead and christmas tree (x-mas tree) maintenance, production enhancement (by varying means), well testing, cementing and well completion. In addition to these, a number of other operations can be done as well.

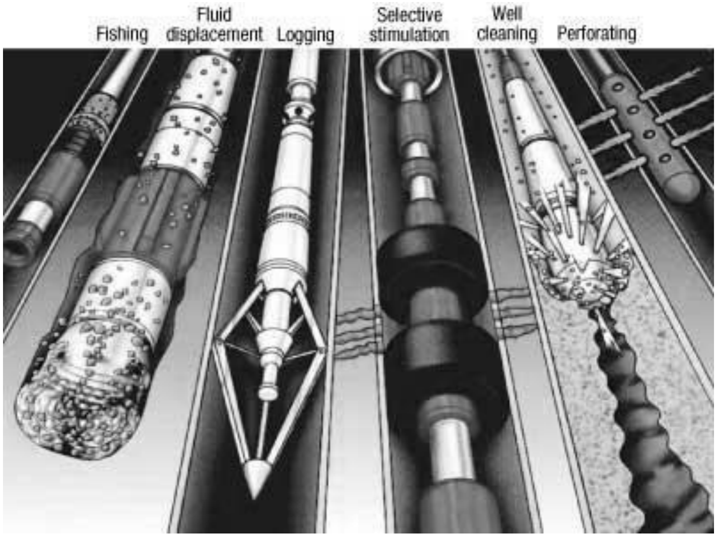

Figure 4 - Intervention Procedures (Source: (Pennet.com))

There are mainly two categories of well intervention; *Wireline (WL) operations* and *Coiled Tubing (CT) operations*. These will be further discussed in the following two sections.

Wireline

The wireline technology is used to lower equipment into the well for the purposes of well intervention or reservoir evaluation. It is a high tensile cable that can be spooled on and off an electric or hydraulic driven reel drum. A wireline tool string can have multiple separate tools installed to perform multiple operations at once, like carrying measurement devices at the same time as for instance cleaning equipment. A possibility is also to have electrical connection and/or a fibre optic communication path to the operator. The different tasks will make use of different kinds of wirelines; *slick line, braided line* or *e-line* (Trent, 2011).

Slick line is the simplest of them, according to Trent, and is mostly used for pulling and pushing, with a jarring function (upward and downward impacts). This can be used to open/close valves, pulling plugs or chokes, and running light injection/intervention equipment.

Braided line is a stronger version of the wireline, and consists of two layers of spirally coiled wire. The function is similar to slick line operations, but more heavy duty. Because the braided line has an inner core, this needs to be sealed off to withstand the pressure of the well when not in use (the “core” can be used for electrical wiring, which will be described later). The most common use of braided line is heavy fishing (retrieve broken drill pipe, etc.), but also cleaning and well stimulation different sort can be done.

The third variant is the *e-line*, or electrical line. Here, one or more electric conductors, or fibre optic cables, are inserted in the core of the braided wire. This enables operations with tools that need electric powering or interactive communication. Most common use is data gathering/logging, perforation (opening production zones) and chemical cutting (Trent, 2011).

The well intervention system for wireline will normally consists of the following main items, according to *Norwegian Technology Center* (2000):

- *wireline unit;*
- *control cabin;*
- *data acquisitions;*
- *clamps/sheaves and hay pulley;*
- *power package;*
- *pressure test pump;*
- *wellhead pump;*
- *well control system;*
- *logging container (for logging and well tractor);*
- *wireline mast (crane);*
- *transport and storage racks for wireline equipment;*
- *slick, braided and electrical line down hole tools.*

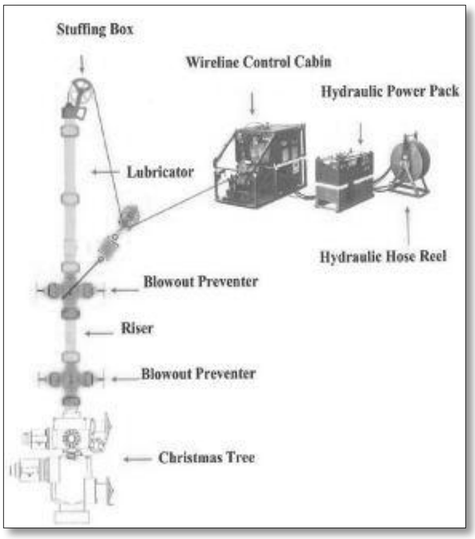

Figure 5 - Wireline Schematics (Source: (Fjelde))

Coiled Tubing

Coiled tubing is a very effective and versatile tool for well intervention. As it is a continuous string of tubing it can be rolled on and of a reel, but due to its dimensions (usually 1" to 3.5") and stiffness, it can be forced down the well and carry out a number of different operations. It is often used to pump chemicals or gasses directly into the well to relieve blockage and increase flow, but also tasks like drilling (side-tracking or small-diameter holes), logging, cleaning, cementing, " fishing" and well completion (in some cases even production can be done). Since CT is a continuous length of ductile steel tubing, it eliminates having to connect and disconnect threaded sections of pipe when going into and coming out of the well, which makes it efficient. Since the tubing is coiled on and of a rail regularly, manufacturers operate with a fatigue limit. This is typically 50 times or more (this will vary) before metal fatigue forces retirement, and it has to be replaced (NETL).

A CT operation needs a framework to support surface equipment, and to lower the sub-sea equipment down to the well head. This can be done with a dedicated tower, but usually it is done through a drilling derrick (this will be further described in sub-section *2.3.2*, about drilling). The framework should also provide heave compensation (sub-section *2.3.5*). Another important component of the necessary CT equipment is the injector head, which is the driving mechanism forcing the tubing in and out of the well. This particular device is today the limiting factor regarding the length of the tubing, and thus the maximum well depth that can be intervened (more about this in sub-section *4.1.1*). In addition, a reel (for the tubing), a gooseneck (guiding unit placed on top of the injector head), power pack (hydraulic/pneumatic/electric), mud/fluid system, and well control equipment are needed. The well control equipment usually consists of a BOP (Blowout Preventer) stack, a stripper (sealing function) between the injector head and the BOP, and a shear BOP (to cut the CT and seal of the well in case of an emergency) installed on top of the x-mas three. A well control system, with various indicators and CT management systems should be integrated in an operation control room. In the proposed concept, there should be installed two coiled tubing drums, with 8000 meters of 2 7/8" tubing on each.

2.3.2 Drilling

The ability to do drilling operations as a part of the intervention work is another important function for an intervention semi. When doing well intervention, the purpose is often to enhance the production, and this might imply *side-track drilling*, *re-perforation* or other types of drilling operations on existing wells. As the concept in question should be a dedicated intervention rig, it should not be able to drill production wells as a regular drill rig, and the primary drilling procedure should be *through tubing rotary drilling* (TTRD). Another function that will be mentioned is *managed pressure drilling (*MPD), which is more of an advanced drilling method to assist in challenging operations, and is not a part of the rig functions at design time.

Through Tubing Rotary Drilling (TTRD)

The dedicated drilling function for this concept is called *Through Tubing Rotary Drilling (TTRD). Through tubing* (*TT*), means, as the name suggests, that one goes through an existing production well and drills a new secondary well straight out of the production riser. This method is assumed to be cheaper than conventional drilling, since it involves less heavy equipment, and, according to Statoil, it is a way to prolong the lifetime of the well, and give higher production rates from mature fields (Salthe, 2009). One should note that the method has it limits, compared to conventional production well drilling.

The most used TTRD feature is *side-track drilling*, which is used to get instant access to isolated oil accumulation, and thus better drainage of the reservoir (Solheim, 2008). The function of directional drilling, which is the technic used to do side-track drilling, is also used to avoid salt dome structures, cross with right angle (if faults or hard formations layers), and multi-laterals (drilling of two or more horizontal production holes from a single surface location) (Fjelde).

Equipment needed for TTRD operations are 2 7/8" and 3 ½" drill pipes, with a fully mechanised and remote controlled pipe handling/set back system. Also, a system for handle drilling fluid/drill water, drill strings, and a system that takes care of the well returns (drilling mud, etc.) will be needed. The systems should be able to drill to a depth of 8,000 meters.

CTD

Another drilling possibility assumed to be available is *coiled tubing drilling* (*CTD*). As regular CT operations, CTD uses continuous pipe rolled on and off a reel at the surface. Combined with downhole mud motors, it can drill fast and cost-effective wellbores. Among the beneficial outcomes of CTD is protection of the reservoir (reduces formation damage), increased production and increased reservoir contact (AnTech Ltd).

Other advantages of CTD, according to *NETL* (), are that it provides the possibility of *slimhole drilling* (wellbores and related casing of less than 6 inches in diameter), and even *microhole drilling* (ultrasmall-diameter boreholes with 4½-inch-diameter casing or less). Also, it provides safer drilling, minimises pressure surges, allows for improved well control, and has a smaller environmental footprint (NETL). CTD is unique in that it is the only solution that

provides the ability to drill underbalanced 100% of the time, meaning that the pressure in the wellbore is less than that in the formation. This ensures that the reservoir is protected from damage, and oil and gas production can continue whilst drilling (NETL). CTD is a closed system, which combined with the use of energised fluids (e.g. nitrogen), ensure that downhole pressures are maintained, and it remains underbalanced (AnTech Ltd).
Examples of applications are (AnTech Ltd):

- *Re-entry Drilling – ability to re-enter the casing of an existing well and drill branches (multilaterals) that are created off the main horizontal section to help drain the reservoir and increase the well potential*
- *Quick, efficient and controlled horizontal and directional drilling in the formation*
- *Controlled directional drilling along the bottom of the formation to link the injection well to the production well*

The equipment needed is primarily the same as for ordinary CT intervention operations.

Managed Pressure Drilling (MPD)
MPD is a more advanced form of drilling, and requires both extra equipment and specialised personnel, in addition to the standard drilling requirements. For this concept to have this function it will be required additional equipment, that not will be included in the initial design, but it is not unlikely that it will be implemented at a later time. On this basis, I consider this as an option, and will discuss this feature later in the paper, under sub-*section 4.1.2*.

Other Functions Regarding Drilling Operations
Previously, the different drilling methods have been presented, with appurtenant equipment. In addition to the function specific equipment and components, there are also more general facilities and parts that are necessary for drilling operations. The primary structure to support drilling operations is the derrick.

The derrick is one of the most central structures on a semi-submersible with drilling and intervention capabilities, and is used for handling of drilling equipment, and also some of the equipment used for well intervention. In addition to the equipment installed at the derrick, also a pipe handling bride crane, a PTD/CT-frame guiderail system, a guide dolly for the CT frame, and a CT frame garage should be part of the design. To do various kinds of operations, different standpipes must be available close to the derrick; mud standpipe, cement standpipe, vent pipe and derrick air-supply standpipe.

There should also be a through tubing (TT) high pressure (HP) riser system, called TTHP riser system, which is a matter of necessity in relation to the TTRD function. From similar concepts, it is recommended that the arrangement should be capable of combining drilling-, well intervention and well testing operations through the same system. Components in the TT HP riser system used for drilling purposes also need to withstand the temperatures/pressures that they may be exposed to during well testing or intervention operations. A TT HP riser system should meet the requirements for subsea live well intervention operations, as well as requirements for drilling operations. In addition, this usually implies meeting the requirements for managed pressure drilling, which is one of the

functions I will discuss later, regarding real options. The dimension of the HP marine riser is proposed to be *7 1/16".*
In relation to the drilling functions, systems for mud/brine and different types of well returns must be provided. This will consist of, among others, a system for low and high rate mud mixing, a high pressure mud circulation system and a mud/gas separator.

2.3.3 Power Generation

To keep all systems running, a steady supply of power is needed. Under this topic, I will look at electrical power generation and the hydraulic power system. Also, the pneumatic (air) power supply will be shortly discussed.

Electric Power

The electric power is used for a variety of functions on the platform, and is the main power supply for a semi-submersible. The electrical power is used for the DP system (with the thrusters), most of the intervention equipment, and the accommodation facilities, to mention some. The DP class, whether the construction should be classified as DP1, DP2 or DP3, is said to be one of the main drivers for the power demand.
The power generation is done by the use of *diesel direct driven generators*, each capable of delivering about 5.5 MW. The storage capacity for generator fuel will be approximately 1500 m^3, making it possible to operate the engines for a fair amount of time. Two of the four diesel generator sets are designed and equipped for emergency operation. The electric power distribution system contains a set of switchboards, located in redundancies segregated electrical switchboard rooms, together with the low voltage utility distribution. This distribution system allows for 2 or 4-split operation of the electrical network. Due to extended usage of DP, the main generators should be designed as energy efficient as possible to minimise CO_2 emission.

Hydraulic Power

A great deal of the drilling and intervention equipment is hydraulically driven, and an integrated hydraulic power system shall provide supply for the various HP & LP systems. To secure the hydraulic power, a power unit with a total capacity of about 2500 l/min should be used. It is driven by a set of smaller motors. Examples of hydraulic driven equipment are the monkeyboard, access basket, gripper claw, bridge crane, and roughneck *(Aker Solutions)*. In addition, the hydraulic distribution shall be based on a redundant philosophy.

Pneumatic Power

Some equipment does require pneumatic power supplies (high pressure air). This is, among others, the facilities for storage of barite/bentonite and cement, where a pneumatic system must be in place for loading and back loading, as well as for transfer to surge tanks.

2.3.4 Station Keeping & Transit

Station keeping is essential for well intervention/drilling operations. An important aspect is that an intervention semi usually is temporary stationed at the work site, which means that permanent mooring rarely is an option. The primary station keeping utility will be DP, but also rigid mooring will be used. Also, since the rig is temporary stationed it must have the capability of moving around, and will be spending a lot of time in transit.

Transit

The movability, meaning the ability to move from one location to another, is important for an intervention semi. The semi-submersible will have a transit speed of about 8 knots, fully loaded. This is achieved by the use of the 4 azimuth thrusters.

DP

DP is a computer based system that uses global positioning systems together with information about wind and currents, and other references, to keep the semi in position. Algorithms (according to *Merriam-Webster Inc.*), this is *a step-by-step procedure for solving a problem or accomplishing some end especially by a computer*) are used to control the thrusters. The DP mode can be used alone in water depths between 200 and 500 meters, but for waters of 100-200 meters depth, anchor mooring will be used in addition. For this purpose, the rig is equipped with an 8 point anchor line system, with corresponding chain, anchors and winches. While stationary positioned by DP only, the platform will still be able to hold the position adequately in the event of a single thruster failure. Also, the rig shall have sufficient power supply and thruster force available after the foreseeable worst case single failure, to remain on station, head to sea, in a sea state that exceeds the limiting operational sea state.

Mooring

As mentioned in the last section, using DP only is not an option for water depths below 200 meters. The mooring system on a semi-submersible will normally consist of chain, fibre ropes or wire, or a combination of these, based on the water depth. For this particular design, only water depths from 100 meters to 500 meters are within the project scope. This, together with eigen period characteristics (motions), limited weight saving potential, and poor safety factor of fibre and wire compared to chain by itself, only chain is considered to be relevant for both water depths. The mooring line configuration considered will thus be of 76 mm stud link chain, with eight mooring lines spread evenly around the vessel. The anchors will be of approximately 10 tonnes.

2.3.5 Other Functions

In addition to the functions mentioned above, which are relatively distinctive for an intervention semi concept, there are also a number of other important functions and requirements. Some of them are presented below.

Accommodation

The rig will be host for a various persons, including roughnecks (technical crew etc.), engineers, executives, and other crew members (like kitchen personnel, cleaning staff, etc.). This particular intervention semi is supposed to be capable of accommodating 100 persons.

They should have access to cabins (either single or double), and other facilities, like lavatory/showers, gym, day room, and mess. Also, offices for different engineering tasks must be provided. This will occupy a great deal of deck space, and cause restrictions on the surrounding constructions, due to safety regulations.

Ballast and Bilge Water System

The ballast and bilge water system will depend on the size and weight of the total rig configuration. For the concept in question, there are planned two ballast pumps and two bilge pumps in each pontoon. The ballast water tanks are designed to hold about 25 000 tonnes, divided between the two pontoons. The ballast water control system should be redundant.

Heave Compensation

A heave compensation system should be included to compensate the drill string and corresponding components. The system, located between the hook and the rotary swivel, should carry the drillstring, and compensate for vertical motions. Further, the CT and WL will be installed and operated above the compensated riser stack, and during normal operations, the heave motion should be fully compensated. Another criterion for the heave compensation system is that it should be possible to work on the surface assembly in compensated mode. Also, a back-up system should be in place to avoid lock-up of the system. The TT HP Riser stack should be landed in active heave compensated mode.

3. DESIGNING FOR UNCERTAINTIES IN THE FUTURE

Until now, the focus has been on the characteristics of the existing intervention semi concept. Most of the functions presented are designed to optimally fulfil their task given the current environment and situation. In this chapter, I will discuss factors suggesting that some functions or facilities should be assessed in relation to the possibility of changes, due to future uncertainties related to these environments and aspects. I will also discuss measures that can prepare the design for these uncertainties in the future.

3.1 Design Functions of Changing Requirements

The offshore industry, as any, faces continually changes, and associated challenges. Examples of such challenges are the uncertainty in the marked financial situation, altered operation scenarios (technology development, etc.), changes in legislation (environment, safety, etc.), and the possibility of new operation areas (i.e. arctic areas). In the following sections, I will try to identify these potential areas of possible changes in the future, and look at which design functions that will be affected because of this.

3.1.1 Operation Methods and Technology

The operational methods will change, usually in close relation to technological development. One possibility is that it will be an increase in sub-sea operations, with development in technology making it possible to do standard intervention work from light weight ships. This would, perhaps, make other parts of the world more attractive as operational areas (more about this in sub-section *3.1.3*), or, maybe good flexibility in the design could keep the semi in business. To have potential drilling and intervention functions available as options, or adaptable features, would provide such flexibility. This will be discussed later.

The technology will as always be subject to research and evolution. This goes for all segments, and all functions in an offshore design, from the actual intervention systems, to the more general power generation and accommodation. The development of technology might also cause a change in the daily operational procedures for an intervention semi. To cope with the ever evolving technology can be difficult, but one way to prepare the structure, would be to modularise some of the equipment. Another possibility is to have spare area and capacity at design time, for the possibility of having unknown functions or equipment extensions. By having some of the equipment modularised, it would make it easier to make a switch to up-to-date technology. If extra capacity is provided in the design, new technology can be installed parallel to existing equipment, or, by having overcapacity in deck weight capability, larger equipment with better characteristics could replace old and outdated parts. An example in relation to spare weight is when equipment is replaced or changed, and the new equipment needs a larger power supply, which adds additional weight to the construction.

Another aspect of the ever evolving technology, related to well intervention, is that the operations might be all subsea in the future, and thus the need for an intervention semi would no longer be necessary in particular areas. This brings us to the next subject; different operations areas.

A concrete example of technological development that should be taken into consideration is regarding the WL equipment. Birkeland (2005) writes in his thesis that; *"in a few years, the WL may be replaced by a carbon composite line".* This would be a good reason for having the WL equipment prepared for a technological development, like for instance an adaptable solution for the drum.

3.1.2 Environment and Legislations

The environmental aspect, as any, will continue to evolve; there are continually new legislations about emissions and environmental issues introduced, and the possibility of *zero emission zones* must be taken into consideration. To cope with this, the propulsion system must be evaluated, and different measures to reduce emissions might be necessary. This goes for all auxiliary power production on the semi as well.

The design processes should be efficient at the same time as it provides support for implementation of *ilities*, like flexible power production facilities, in the design. The goal will be to design a semi-submersible intervention platform which is either insensitive or adaptable towards the continually changing environments, which implies robust, flexible and adaptable designs.

Regarding emissions due to power production, it is in these days a project going on the Norwegian continental shelf dealing with electrification of oil and gas fields. If this project should seem to incorporate intervention rigs as well, designs solutions supporting this feature should be made. As the concept in question in this paper is supposed to be moving a lot, from well to well, it is not expected that the electrification will concern this type of rig.

Legislation and regulations for the offshore sector will always change to some degree, as new technologies are developed and daily operations are changed. This may prove to be problematic for existing constructions, and may demand upgrading for several millions. To prepare for this, possible future regulation changes should be mapped, and measures evaluated. Here, everything from designing the project with real options, to "over classify" the design initially to cope with the future, would be plausible measures. This would result in either a robust design in relation to legislation, or a design that is flexible and able to adapt to future legislations. Some of the legislations and regulations applying for an offshore construction are IMO, SOLAS, and MARPOL, and also industry standards like API, ASME, and ISO will be of concern.

As the environment is an ever important issue, one of the largest players at the Norwegian continental shelf has made guidelines for their approach to CO_2 emissions in 2020. As a part of this, they will try to implement various CO_2-reduction measures in all their projects. This involves, among other things, power production form gas generators (instead of diesel generators), carbon catching and storing, and electrification of oil fields when possible (as previously discussed). Since this company will be a potential customer for an intervention-semi, these actions, to reduce the impact on the environment from the oil sector, are worth bearing in mind.

3.1.3 Area of Operation

For this intervention semi concept, the operational area will first and foremost be in the North Sea, in depths between 100 and 500 meters. In the future, this marked might not be the most beneficial, due to for instance this subject of subsea technology. In my opinion, the North Sea would be the first place for these kinds of subsea intervention operations to occur, and thus, other places in the world would be more attractive to operate in for this particular intervention semi concept. This could be, for instance, outside Australia, or West Africa, where one can find similar depths as on the Norwegian shelf. Still, conditions might be different from the North Sea, with for instance higher temperatures (and humidity), and other well characteristics.

Another aspect is that the demand for intervention semis capable of operation in deeper waters will continue to grow. However, this is assumed to be outside the scope of the intervention concept in question (discussed shortly in *section 4.3*).

The on-going discussion about oil and gas operations in the arctic could also be an issue. This will most certainly demand vessels and platforms with characteristics that are designed specifically for these conditions, with the necessary classifications, so this alternative of operational area is not assumed relevant for this intervention concept.

3.1.4 Economics

The operational costs for an intervention semi could be rather good estimated for a given time into the future, due to an abundance of contracts, and relatively stable revenues for these services. Still, the longer into the future one gets, the more uncertain everything will be. This goes for everything from the cost of CO_2 emissions (fees), labour, cost of power generation and transit costs (fuel cost). To better prepare for events like these, the design should be very robust and flexible, or have the adaptability to do the necessary changes to keep costs down. A robust design would typically be one that to a high degree keeps CO_2 emissions down from the beginning, one that is to a smaller degree dependent on a large staff to run the operations, and also have the flexibility to supply the rig with power in various ways.

Another aspect regarding the financial aspect is the investment cost for a project like this, which is rather considerable. Usually, a large amount of the investment sum is borrowed, and the rates are often high, and might be volatile. In relation to this, the subject of real options will be relevant. This will be discussed later, in sub-section *3.2.3*.

3.2 How to Accommodate for These Changing Requirements; *Ilities*

In this chapter, some technical terms associated with designing for the uncertainty in the future will be presented. First of all, the word *ilitie* is used in close relation to the subject of this paper, and also used freely in scientific literature, like for instance in the article "*Defining Changeability"* by Ross, Rhodes, and Hastings (2008). The term is used to refer to different possibilities of system properties. Examples of ilities are reliability, availability, and adaptability, all ending with "ility", but also robustness is often used in relation to ilities. An ilitie can also be described as a systematic property, since it is the system as a whole that will have the property of an ilitie, not the specific component. In this paper, however, there are three ilities that are particularly central, as they are used in the assignment text. These are robustness, flexibility and adaptability. The understandings of these ilities are often subjective, and they might also have different meanings in different contexts. To make it somewhat clearer for the rest of the paper, I will try to explain them both in a general way, and in a more specific semi-submersible design context. In addition, the subject of real options, which in many ways can be said to add robustness and flexibility to a project, will be discussed.

3.2.1 Flexibility and Robustness

One way of making the design better prepared for the future is to make it robust and flexible by sort of "over classifying" it in the design phase. When designing for robustness, the purpose is to make functions and equipment not only capable of doing their primary task satisfactorily, but also to have the possibility to do operations beyond this, that might be needed in the future. This could be in respect of altered operating area, improvements of daily operations, or the possibility to satisfy anticipated future environmental and safety legislations without larger upgrades.

Flexibility

From Oxford Dictionaries (), the most design related definition is "*the ability to be easily modified to respond to altered circumstances*". In a general design perspective, a flexible system is a system that is able to change in an attempt to meet the future in a best possible way. In Ross et al. (2008), flexibility is used in a more specific way, where they say that "*if the change agent is external to the system, then the change under consideration is a flexible-type change*".

When discussing flexibility, there are some examples in relation to the intervention semi concept. Something that should be thought of is that the rig might need more people in the future, to satisfy future legislations or for manning of new functions. This might be caused by changed operations, for example, the use of ROV, if this is not a part of the original design. In relation to this, the 100 persons that the rig is said to be design for might include a margin, and thus have room for possible future workers. Another alternative regarding flexibility in the accommodation is to have some of the rooms designed for different operations.

More general, the ballast water calculations are important, and must be seen in correlation to the spare buoyancy of the platform, which can be a part of a basic form of flexibility. When more weight is added on deck, or the deck load is getting lightened, the ballast water limitation is important, and provides flexibility.

Robustness

Robustness can be defined in many ways, often in connection to humans and their health and strength, or for an object, that can be "sturdy in construction". In the context of design, a general definition is that "*robustness is a property to withstand unfavourable situations without actively changing a system*" (Wang, 2005). An even more specific way of defining robustness, in relation to design of a system, is provided by Ross et al. (2008), who states that "*robustness is the ability to remain "constant" in parameters in spite of system internal and external changes"* . In the same article (Ross et al., 2008), it is referred to a *Dr. Marvin Sambur,* who argues that a robust project or system should be;

- *capable of adapting to changes in mission and requirements*
- *expandable/scalable, and designed to accommodate growth in capability*
- *able to reliably function given changes in threats and environment*
- *effectively/affordably sustainable over their lifecycle*
- *developed using products designed for use in various platforms/systems*
- *easily modified to leverage new technologies.*

The reason why a customer wants to design for robustness is quite obvious, since change in the future in one way or the other, is certain, and one way to cope with this is to design a robust system.

An example of robustness in a semi-submersible design, is regarding motions. A good design will have favourable motion characteristics, which results in better operability, which again will result in better earning capacity.

Another example of robustness, presented in the design concept from Aker Solutions (), is the DP3 setup, which requires at least three independent position reference systems.

The power supply will always be somewhat robust, with some over capacity, where one should have sufficient power generation and availability for the rig to simultaneously cover specified drilling and intervention activities, maintaining position in maximum operational conditions, applicable margins to comply with DP Class III operation, use of utility stations, and utilities for crew in normal operating environments. The extent of overcapacity in power production and availability will be important in relation to the possibility of changes to the design in the future. Also, the ability to further extent the power supply will be a flexible/robust feature.

3.2.2 Adaptability

In everyday life, we speak of an adapter, in terms of power generation and electricity, which basically is a box that changes the voltage. The dictionary *(Oxford Dictionaries)* suggests the definition "*ability to adjust to new conditions*", which basically is what adaptability is all about. Also, for adaptability there is an own definition in context of changeability: "*If the change agent is internal to the system, then the change under consideration is an adaptable-type change*"(Ross et al., 2008).

As the other ilities spoken of, an adaptable design will make a construction better prepared for the uncertainty in the future. By definition, one can say that flexibility, robustness and adaptability is the same, but in a specific design context, they are not. Adaptable design involves modularisation, and the ability to adapt to new challenges by making simple changes to facilities or functions.

An example of this is a crane installed as a module, originally capable of doing one type of lifting operations, but it has the possible of easily be swapped to a crane that are able to do other types of lifting operations. This can be compared to what is called a *switching options* (discussed in the following section), but the difference is in the extent of the switching operation, where a switching option usually is done once or twice, whereas an adaptable module might be switch several times within a limited time period.

Other forms of modularised adaptability could be containerisation. Here, an area of the platform will be dedicated to modules in standardised container sizes (usually 10, 20 or 40 feet containers), and infrastructure to support different types of operations form these modules are pre-installed. On a storage site, the standardised container modules with different kinds of functionality are ready to be shipped out to the semi. This could for instance be diagnostic facilities, diving support facilities, stores, or any other function that can be fitted into a container. By doing this, the semi would be prepared for a number of different, and also unknown, operations in the future.

For this particular intervention semi, there are some functions that are more relevant for containerised modules than others. This might be diving support, well diagnostics facilities, and miscellaneous stores.

Today, some basic forms of adaptability already exist in the intervention semi design. This is typically the ability to easily switch between the different intervention operations the rig is capable of doing, such as coiled tubing operations, wireline operations and various drilling (TTRD) operations.

3.2.3 Real Options – Managerial Flexibility

One way to accommodate for functions subject to changing requirements during the lifetime of the semi, to make the construction more flexible and adaptable, is to design with *real options*. This can be done in different ways, and to a variable extent for different functions. The idea is in any case that the construction in some way should be prepared for an expansion or upgrade at a later time. In relation to real options, flexibility can be described as the ability to make decisions at different stages in time. To be able to make such decisions you need options to choose among – you need real options. To give an impression of what it is all about, I quote:

> *A real option is the right, but not the obligation, to take an action (e.g. deferring, expanding, contracting, or abandoning) at a predetermined cost called the exercise price, for a predetermined period of time – the life of the option.* (Copeland, 2001)

There are basically seven main types of real options, according to *Fleten, Jørgensen, and Wallace* (1998); the *option to defer*, the *option to abandon*, *stage investment option*, *scaling option*, *switching option*, *growth option*, and *multiple interaction option*.

There are of course also other options, but these are to most common in design projects. From *Fleten et al.* (1998), a description of the different possibilities of real options are presented below.

A Presentation of Different Real Option Possibilities (Fleten et al., 1998)

The option to defer is essentially the ability to postpone the start-up of a project. It can be argued that the more uncertain the future is, the more the value of this flexibility increases. In the sense of this particular intervention semi project, this option will probably not be of interest, since the market is very good for such vessels at the time.

The option to abandon a project is in fact the admittance that a particular project, or a part of a bigger project, does not add any value to the owner, and has to be terminated. For a smaller part of a larger project, this could be a valuable option that adds flexibility to the big picture.

The stage investment option is common in research and development projects, and other projects with technical uncertainty. By applying this option, one will have the opportunity to divide the project into stages, and determine after each stage whether to continue or not. This will not be relevant for the semi concept project.

The scaling option is the first of the options that have a direct cost associated with it. The three options mentioned already comes “free of charge”, but to alter the scale of an operation, or for instance make a construction larger, will come with a cost. This option will be relevant for the project in question, and will be dealt with in the following section.

Also the next one, *the switching option*, does also come with a cost, and is in many ways quite similar to the last one. Here, instead of altering the scale, you plan for an option to switch the produced product, or maybe the operation method. In a large construction project, with a high level of technical solutions, and a lifetime of several decades, as an offshore installation project, this option is highly relevant.

The growth option is the last of the “autonomous” options that will be discussed. Growth, in this context, does not mean to make the specific project or product bigger, but rather that the project allows for growth for the owner, such as follow-up projects, and thus creates new real options. This will not be further discussed in this paper, since it will be a more company related option.

There can also be a combination of the different categories already mentioned, called multiple interacting options. This will not be subject for further discussion.

Real Options Related to the Intervention Semi Concept

Usually, real options in a construction like an offshore installation involves a stronger structural design, bigger areas than necessary from day one, and preparations for installation of facilities, equipment or systems that might be necessary in the future. For this particular intervention semi design, some options are more relevant than others. In the following, I will try to make a connection between the identified functions that are subject for changing requirements.

The option to scale, for this intervention semi the option to expand, will always be something to consider. To have this option it would be suggested that the rig at design time is constructed somewhat stronger than initially necessary. By doing this, an expansion would be cheaper at a later time than without any preparations. To only make the structure stronger is the absolute basic form for a real option to scale. To take this option a step further, various section of the semi could be prepared, for instance regarding piping, electricity or sanitary functions.

An expansion of the accommodation facility could be used as an example; at design time, an area suitable for a possible future expansion of the accommodation could be strengthened,

and dependent on the likelihood of the option to be realised/exercised, preparation for sanitary, electricity and HVAC could be made.
The switching option will in the case of the intervention semi be relevant for the intervention equipment. This equipment, as discussed in the previous chapter, is continually subject for development, and thus it might be desirable to switch to technology that is more modern sometime in the future. To facilitate for this option, it would be necessary to first identify functions that might be subject for a switching option. When the function is identified, one way of preparing for the switching option would be to make sure that it is possible to remove the old technology without having to take apart larger parts of the structure. Another possibility would be to make connections and brackets that easily could be adapted and modified. If there is a technology already available at design time, but might be too expensive for the moment, brackets could be made to fit both technologies.

4. *ILITIES* IN INTERVENTION SEMI CONCEPTS

The term ilitie, and different forms of ilities, were presented in the previous chapter. In relation to the subject of designing for future uncertainty, and how to best prepare the designs for these uncertainties, I will now try to connect the identified functions of changing requirements to possible ilities in the intervention semi design. At first, I will discuss the proposed concept in relation to existing ilities in the current design.

4.1 *Ilities* in the Proposed Concept

In the proposed intervention semi concept, there exist features subjected to different forms of flexibility, adaptability, robustness or options. These design solutions are made to either prepare the concept for the uncertainty in the future, or for having the possibility of a higher profit for known scenarios. Some of the design solutions are identified as subject to an ilitie based on a deviation between the desired functional abilities and current technical capabilities, where a change of equipment is expected. Others measures are meant to cut the investment costs, and/or save weight in the initial design.

To begin with, an example of adaptability can be seen in relation to the intervention functions. As there is intervention work that demands different types of functions, there will be practical to have solutions that let you change between the different operations in an easy way. This is particularly essential concerning changing between CT, WL and TTRD, and it is suggested that there should be an arrangement for swift change over between operation modes wireline, CT and TTRD.

Another example of flexibility is regarding the functional requirements of well completion and production enhancement, where the report states that there should be ”*reserve space for equipment, boat service, no mobilization on rig”* (Aker Solutions). This can be seen as an attempt to save investment cost by not buying equipment for functions that are assumed rarely used, but to have the flexibility to do the operations if needed.

In the three following sections, the previously identified examples regarding design option for technical development, and the use of rental equipment for flexibility are discussed more thorough.

4.1.1 Development in CT Equipment

As presented in the beginning of the study, in the section with concept main characteristics, the designed intervention depth (the maximum well depth) was said to be 8 000 meters. This is rather significant, and in relation to this, it is foreseen a development in the coiled tubing equipment. The report states:

> *When it comes to design of the coiled tubing equipment with the specified capacities, there is challenges specially related to the injector head size. Today’s standard injector head have a capacity of 100,000 lb, which can be used for a CT length of about 3-4,000 meters with the specified size. As the specified design well depth is 8,000 meters, development of the CT equipment has to be foreseen.* (Aker Solutions)

This is a clear statement of a wish to design for the uncertainty in the future. As I see it, it is foreseen a technological development in the future related to the injector head and/or the coiled tubing itself. There are several possibilities for how to accommodate for this challenge. The coiled tubing itself is winded on a modularised reel, and designed to be changed every now and then ("drop in drum"), so this will not necessarily need major design changes to begin with. Since current technology allows for tubing lengths of 3-4000 meters, it will be natural to have a this length range installed initially, but with the ability have a reel module with capacity of 8000 meters installed at a later time.
The technological development that should make it possible for deeper CT operations will most likely be related to the injector head. As described earlier, this is the component that drives the tubing into the well. This is also to some degree made as a module, which should make it rather easy to change, if that should be desired. In addition to have the option to change the injector head, other functions related to this component should also be considered; the facilities that support the injector head will have to have a robust design, if possible with some over capacity, since the new injector presumably will be somewhat heavier. In addition, a more powerful injector head might have a higher power demand, so the power pack should be assessed with this in mind – add robustness to the design.

4.1.2 Managed Pressure Drilling – Proposal for Real Option

According to *Weatherford* (), there are often challenges in relation to wellbore construction. To cope with problems like wellbore instability, lost-circulation zones, and over pressurised formations, managed pressure drilling is assumed to be a successful method for mitigation of many of these problems. This is done, as the name *managed pressure drilling* suggests, by keeping the well pressure constant through the drilling operations (for instance TTRD operations). According to *Rasmussen* (2008), MPD methods are the more attractive method for advanced drilling in combination with TTRD.

The methods of MPD uses a closed mud return system with the ability to be pressurised, which makes it possible to both drill and make jointed-pipe connections while maintaining the appropriate annular pressure profile *(McCaskill et al.). Some of the essential parts for the MPD system are (McCaskill et al.):*

- *Float valve (a non-return valve or NRV)*
- *Rotating control device (RCV)*
- *An enclosed flow line,*
- *A flow choke manifold (*Figure 6*) separate from the existing rig well control manifold*
- *Optionally, a degasser or mud/gas separator system.*

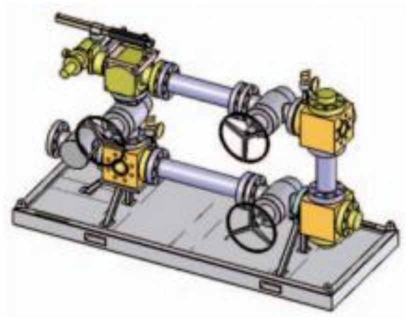

Figure 6 - Flow choke manifold (Source: (McCaskill, Kinder, & Goodwin)

A proposal is to have MPD as a functional option, a real option, for the intervention semi design discussed in relation to this intervention semi concept. The design could be prepared for a MPD system by having the back-pressure system (a system for the mud circulation) as a part of the high-pressure (mud pumping) system from day one, and make sure the system have sufficient pumping capacity for MPD operations. An interface for the MPD system could also be installed, if it is assumed likely that the option will be realised within a reasonable time. Another preparation that could be done is to have the riser system meet requirements for MPD operations, in addition to standard drilling and intervention operations.

4.1.3 Rental Equipment

In relation to the concept in question, there are some components that are listed as rental equipment. To have functions depending on rental equipment indicates flexible design solutions; the owner will not have to buy the (often) expensive equipment, but they will have the infrastructure prepared for it, so they have the opportunity to have the particular functional capability by temporary renting the necessary equipment. Not only do they save investment money, they will also have a lighter structure to begin with, which provides spare capacity that can be used for other functions than the ones initially thought of – which makes the design robust as well. Some of these functions related to the “rental equipment” flexibility are presented below:

ROV

The semi will be designed for operation of two remote operated vehicles (ROV). The ROV’s can be used for a number of different types of operations on an intervention semi. First and foremost, it is a tool for observation, with direct video support of subsea operations, but it can also to some degree aid in the direct operation, for instance on a x-mas tree, by open or closing valves.

Since such ROV’s are expensive to buy, and assumed rather rarely used for this concept semi, they will not be permanently installed, but rather rented when needed. This will be a form of ilite, making the design more flexible. The semi will have to be designed with the ability to do ROV operations, but the extent of this “ROV readiness” can vary. There must to some degree be infrastructure to support the operation, but to what degree depends on how much preparations that should be necessary to do in advance of each planned ROV operation. One alternative is to have all facilities and necessary equipment installed, in addition to full accommodation for the ROV operation crew. Another alternative is to have a given area of the platform deck available and ready to temporary install the necessary ROV modules, utilising the design in an adaptable way. These two alternatives can also be done to a varying degree, all depending on what seems logical and economically beneficial.

Other Rental Equipment

In the concept regarding the intervention semi in question, it is stated that the cement liquid additive system, mixing system with surge tank and batch mix tank with associated control system should be rental service equipment. Typically, this is a large unit that demands both large amount of space, power and raw materials. A pneumatic system incorporating storage facilities for, among others, cement will be available, allowing for loading and back loading as well as transfer to surge tanks. This suggests a partly adaptable cementing system.
Another part of the service equipment that is noted as “rental equipment” is the *burner heads,* which are the end piece of the burner booms. The burner is used if it necessary to flare, to burn gas, during well testing. Also, a helicopter fuel system, are suggested to have

rental tanks, and the test separator, used for intervention procedures involving well testing, is proposed as rental equipment.

4.2 *Ilities* in Similar Concepts

A company interested in buying a vessel will normally make a *tender*, a description of functional requirements and required specifications, on the project they are planning to initiate. These tenders will potential contractors respond to, with the best possible solutions and price they can offer. In the offshore business, these tenders are often very specific, which means that the contractor will have limited freedom to act in sense of design solutions. In relation to the work on the intervention semi concept from Aker Solutions, I had the opportunity to look at a tender for a quite similar project to the intervention semi discussed in this paper. Even though there is a high degree of specifications, there are some areas where the tender indicates a possibility of flexibility or robustness. Something worth mentioning is that in a similar project, the byer, in this case Statoil, delayed the contract award "*in response to input from bidders and is intended to give them more time to improve the robustness of the concept*" (Marshall).

In the following, some functions and systems that could be related to different forms of flexibility, design options, or other ilities are discussed.

The Environment (Emissions)

Regarding the external environment, in particular emission to air, there are some aspect worth discussing. Regarding the main generators, they should, in addition to compliance with general regulations, be designed as energy efficient as possible to minimise CO_2 emission, due to and assumed considerable usage of DP. Also, the latest catalytic cleaning technology for NO_x gases should be investigated and implemented in the design. In relation to these aspects, it could be suggested that parts of the generator set are made robust, in terms of emissions, to comply with new regulations in the future. Regarding the NO_x cleaning technology, there could be preparations for technology still not commercialised, as a real option, for having the possibility to easily implement this at a later time.

Extra Deck Space

The availability of unassigned deck space will, for a construction like the intervention semi concept, be important to allow for mobilisation of temporary equipment for special operations such as nitrogen, through tubing stimulation (e.g. fracturing) and remedial sand control. This will give flexibility in relation to operations carried out on deck.

Well Testing/Clean-up

The requirement for clean-up during CT operations will be a key function for the Cat B rig, and an integrated package with high capacity and flexibility should therefore be permanently installed. Compared to traditional testing equipment, where containerised space consuming equipment will occupy essential deck space and requiring massive rig-up/rig-down efforts, an optimised layout arrangement should be provided. This would give the design better flexibility, but reduce the adaptability.

Flexibility in Drilling and Intervention Operations

The switching between drilling and intervention operations is assumed essential. In relation to this, it is preferred that the TT HP riser system is capable of combining drilling-, well intervention and well testing operations through the same system. This will give a good flexibility, and improved operability, due to reduced switching time.

Another example of flexibility in an intervention semi design is regarding the permanent installation of intervention equipment. For a regular drilling rig, the drilling equipment is normally permanently installed, while well testing and intervention equipment normally is considered temporary, while for a dedicated intervention semi, all equipment must be designed for permanent installation.

Other Relevant Aspects

In addition to the aspects discussed above, also the statements presented below are assumed relevant in relation to potential ilities, whether it is flexibility, robustness, adaptability or the possibility of a real option:

- *The piping shall be such that foam cementing is possible through coiled tubing.*
- *The network shall have the capacity to run as minimum 1GB and 50% spare capacity.*
- *Robustness for handling by standard pipehandling equipment (in relation to HP riser system).*
- *The necessary cabling shall be based on the cabling needs for mud-, well and LWD/MWD logging systems +50% spare capacity.*
- *Sufficient power generation and availability for the rig to simultaneously cover the following requirements: All consumers required for performing the specified drilling and intervention activities; all consumers required for maintaining position in maximum operational conditions; applicable margins to comply with DP Class III operation; all utility stations in use; utilities for crew in normal operation.*

4.3 Functions Assumed Not Relevant for *Ilities*

As I will discuss in this section, there are functions not considered relevant for design ilities. There can be many reasons for this, but obvious reasons are technical infeasibility, cost issues, and that the function in question will be outside the project concept. For this particular concept, where a dedicated intervention semi is the scope, there are first and foremost the design drivers (cost and weight) that are limiting factors. This means that features with a close relation to these, like having the possibility of doing advanced drilling (which would increase the weight considerably, and thus comes with a considerable extra cost) is not an option. Also, operations in deeper waters and operations in areas with ice are not supposed feasible.

Heavy Drilling

The option to have heavy drilling capability, as an ordinary drilling rig, is not assumed to be a feasible real option. The spare weight and deck space capacity that would be needed for this function would exceed all limitations of the original design. The purpose of a dedicated intervention semi should be to do intervention work and light drilling work, and the heavy drilling work should be left for dedicated drilling rigs.

Water Depth

To have the ability to operate in deeper waters, if that would a marked segment with high earnings in the future, is a vessel characteristic that seems ideal for flexibility in the design. The problem with having this possibility is that to be able to operate in deeper waters, there is a variety of aspects to consider. To mentions some; better mooring system will be required; bigger, heavier and more rigid TTRD/CT/WL systems will be needed; and bigger and heavier support equipment will be needed on board.

Ice Class

To have ice class is not really technical feasible as a real option, since there are so many factors that needs to be satisfied before a vessel can be classified as ice class. The construction would have to be of a different strength category, the HVAC system would have to be more complex, the mooring and DP systems would have to be designed for this kind of environment, just to mention some aspects. Today, there are being developed rigs capable of operation in areas with ice, and these often have distinct designs, engineered specifically for this environment.

5. EVALUATION OF DESIGN SOLUTIONS IN RELATION TO UNCERTAINTY IN THE FUTURE

The purpose of most projects is to make money. In relation to this, an important aspect is to design for uncertainties in the feature, with the intention to make a project more robust in relation to expected profit. As mentioned earlier, the total cost of a project is often heavily weighted when a project is chosen, and since a design prepared for uncertainties in the future usually is more expensive than those that are not, an important aspect is the ability to prove the value of such a design. According to *Fleten et al.* (1998), "*the value of flexibility is the difference between the value of a design with a certain flexibility and a design without this flexibility".* This statement is not only about subtracting one value from another, but just as much about the whole picture, concerning uncertainties in the future, economic assessments, scenario development, and the ambition of an optimal design. Even though the word flexibility is explicitly used in the statement, all ilities discussed earlier in the paper could be assessed in the same manner.
In relation to this, I will in this chapter first present some aspects of cost calculations and economics, before continuing with an introduction to scenario development and application of scenarios in a decision support setting. As a last part of this chapter, I will propose two models for evaluation of different design solutions in an uncertain environment, and discuss how these can be used in a commercial setting.

5.1 Some Economical Aspects

When ordering a semi-submersible platform, or when making other comparable investments, the main objective usually is to earn money in the future, as discussed introductorily in this chapter. All decisions made in the design phase should support this objective, at the same time as the building cost should be kept as low as possible. In Fleten et al. (1998), it is stated this about the value of a project:

> *To maximize the value for shareholder, the investment projects with the highest value should be selected. All decisions, both in selecting projects and in carrying them out, should reflect this criterion.*

An important aspect when designing with flexibility, robustness, adaptability and options, beyond what is necessary to comply with rules and regulations, will be the value of such a design compared to a design without this ilities. A project group must be able to make a trustworthy cost/benefit analysis of the particular design solution. Cost estimations and estimation of earning potential will be necessary in any case, whether you do a strictly economical net present value (NPV) analysis, or a more complex optimisation procedure with scenario development.

In this section, some of the terms needed for design evaluation related to economics will be presented, and also some of the economic aspects of decision analysis will be discussed.

5.1.1 Essential Economic Terms

At first, I will present some terms that are widely used when discussing economics in projects. These terms are also used later in the text, when the decision models are presented, and an understanding of these are assumed necessary for a good result. The terms I will present are *life cycle cost* (LCC), *whole life costing* (WLC) and *net present value* (NPV).Also *dynamic discounted cash flow* (DCF) will be presented briefly.

LCC & WLC

There are many ways to do cost calculations and other economic considerations, but when such an analysis not only is intended for internal usage, it can be a good idea to use a standard for this. From British Standards Institution (2008), the definition of *Life Cycle Cost* and *Life Cycle Costing* are as following:

> *Life cycle cost (LCC) is 'cost of an asset, or its parts throughout its life cycle, while fulfilling the performance requirements'. (BS ISO 15686-5, 3.1.1.7)*
>
> *Life cycle costing is 'methodology for the systematic economic evaluation of life cycle costs over a period of analysis, as defined in the agreed scope'.*
> *(BS ISO 15686-5, 3.1.1.8)*

Also, British Standards Institution (2008) defines *Whole Life Costing* (WLC), which has a broader scope than lifecycle costing:

> *Whole life costing is 'methodology for the systematic economic consideration of all whole life costs and benefits over a period of analysis, as defined in the agreed scope'.* (BS ISO 15686-5, 3.1.1.15)

As the definitions suggests, an important difference between LCC and WLC is that WLC also considers the income (benefits) of a project, not only costs.

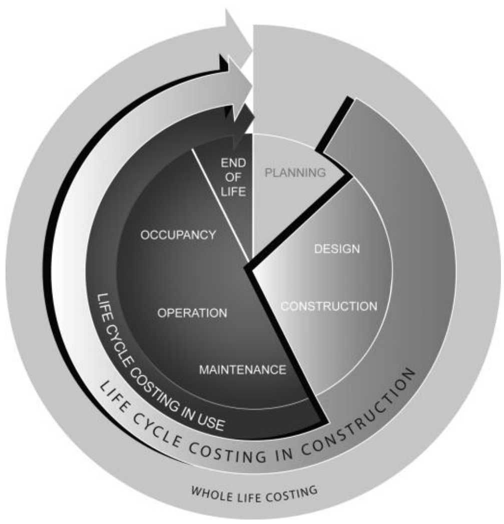

Figure 7 - Life cycle cost planning at different stages during a building or constructed asset's lifespan (adapted from BS ISO 15686-5, figure 4. Source: (British Standards Institution, 2008))

As shown in the figure above (Figure 7), the life cycle costing and whole life costing are divided in sub-categories, arranged from start of project, till what is assumed to be the end of the projects life. The *life cycle costing* consists of design costs, construction costs, maintenance costs, operation costs, occupancy costs and costs associated with project termination/closure. The *whole life costing* includes everything, including planning costs, non-construction costs and other externalities, in addition to the ones mentioned for the life cycle costing. As stated earlier, also project earnings are a part of the whole life costing.

In calculation of both LCC and WLC, it is necessary to do net present value (NPV) calculations of some or more of the amounts involved. The NPV term will be presented next.

Net Present Value (NPV)

When discussing economic aspects, the NPV term often shows up. Net present value is used to find the present value of future cash flows, where the cash flows are adjusted for risk and time value of money, with a so called *discount rate* (Moneyterms.com).
Net Present Value is the difference between the present value of cash inflows and the present value of cash outflows (Investopedia). The formula for calculation NPV can be seen below (Investopedia).

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - CF_0 \tag{1}$$

Where CF_t is the cash flow in time period *t*, *r* is the discount rate, *t* is the time variable (normally in years), and CF_0 is the initial cash flow (usually year 0). When investing in a project, a positive NPV is preferable.

As mentioned, a discount rate is needed to adjust for risk and time value of the money, represented by *r* in the formula above. This is perhaps the weakest link in the NPV calculations, since it is often difficult to estimate, and small changes in this rate can have large effect on the calculated NPV (Moneyterms.com). It represents a considerable uncertainty, and the longer a project is expected to last, the more uncertain this factor will be. An alternative will be to have a discount rate varying with time. The formulation will then be (Moneyterms.com):

$$NPV = \frac{CF_1}{(1+r_1)} + \frac{CF_2}{(1+r_1)*(1+r_2)} + \cdots + \frac{CF_n}{(1+r_1)*\ldots*(1+r_{n-1})*(1+r_n)} - C_0 \tag{2}$$

It is worth mentioning that estimating future cash flows and then applying the NPV criterion is referred to the traditional model of purely economic decision analysis (Fleten et al., 1998). Another weakness of the NPV calculation is the estimates of the future cash flows. When finding the NPV of a whole life costing analysis, both cash outflows and cash inflows needs to be estimated, which is subject to great uncertainties. To cope with this one can do the NPV calculation for a set of WLC, derived from different scenarios for the future. These models are referred to as *dynamic discounted cash flow* (DCF) models, and will be shortly discussed next.

Dynamic Discounted Cash Flow (DCF)

In Fleten et al. (1998) the *dynamic discounted cash flow* (DCF) model is presented as a tool for evaluation real options. Models using this principle assume the existence of several different scenarios, where the NPV of the different cash flows are found. These scenarios are assigned probabilities, saying something of the possibility of the given scenario to actually happen. This is a potential source of error, since the estimation of these probabilities often is difficult. Another problem with the DCF models, as for the NPV calculations (since the NPV criterion is used on the cash flows), is the estimation of the discount rate.

5.1.2 The Value of Flexibility by Economic Measures

When analysing a project with ilities, like flexibility, robustness or adaptability, the value of an ilitie will equal the NPV of the projects WLC with the ilitie subtracted the project value without this ilitie. One way this can be assessed, to get the best possible result, will be to make these calculations for a number of possible scenarios for the future. Thus, when finding the value of flexibility in each case, probabilities for the different scenarios can be used to get an expected value for the flexibility. This method does not apply to real options. The result from a cost/benefit analysis of a flexible function will depend on the level of detail, and might not reflect the actual cost/benefit, but rather act as a model for comparison of possible flexibilities, with a score system.

When considering a project, like building an offshore installation, there will be challenges related to calculating the projected earning potential. This will be highly dependent on marked development, and should thus include different scenarios (scenario development will be further discussed in section *5.2*.).

One way of assessing the future potential earnings is to look at day rates of different types of existing contracts, and derive an expected future value of contracts from this. This will be a rather easy approach if there is a clear distinction between contracts that demands a flexible function in question and those without, but this is rarely the case. And, even if it is possible to distinct between the contract types, one will need to do a simulation or estimation of the possibilities for what value these contracts can have in the future, and also the ratio between "regular" contracts and "flexible feature" contracts must be projected in some way.

Another important factor is the estimated *design life*, the service life intended by the designer. This will typically be between 25 and 30 years for a semi-submersible. This is a rather long time, in relation to a WLC calculation and the estimating expected earnings.

5.2 Scenario Development and Assessment

In *Scenario development: a typology of approaches, Van Notten (2005)* proposes a specific definition of the word *scenario* in relation to scenario development:

> *Scenarios are consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action*.

This definition is in my opinion very good, and reflects all the important aspects of using scenarios to better be prepared for the uncertainty in the future.
There are several challenges associated with the development of scenarios. First of all, to get a good model for the scenarios, you have to focus on the right factors. Secondly, the prediction of how these factors will change with time must be as good as possible. Another aspect of scenarios thinking is the assessment of the scenarios – how to use the scenarios to make decision for the uncertainties in the future. I think that an understanding of scenario development and use is an important part of assessing uncertainties in the future. As Van Notten (2005) states: "*The diversity in scenario approaches makes working with scenarios a flexible approach to exploring the future, which can be shaped to fit different tasks".*
Another aspect is that we have no facts about the future, knowledge is about the past, and all our decision are about the future (Wilson, 2000). To aid in the planning for the unknown future, scenarios based on knowledge about the past could be a tool, or as Wilson (2000) puts it; "…v*irtually, any decision or area of strategic concern in which external factors are complex, changing, and uncertain, is a suitable target for the scenario process".*

When working with scenarios, there a roughly two main phases. The first is to develop the scenarios for the specific business segment or project, like for instance for an investment in an offshore installation. Secondly, and arguably just as important, decide how to use the scenarios to make the best possible decision for the future, and do the full analyses of the problem. In short, the process consist of finding key factors, like for instance oil price and marked demand vs. supply, for then to analyse these factors given a number of plausible scenarios. I will discuss these aspects further in the following sub-sections.

5.2.1 Development of Scenarios

When dealing with scenario developing, some might jump straight to assumptions about the future and the generation of scenarios, and take it from there. This is not advisable, according to *Wilson* (2000), who argues that the first approach should be to agree upon the strategic decisions that the scenario should be designs for. In other words; first come up with the decision alternatives, and then generate scenarios on this background. This approach is suitable for the context of this paper, where designs are proposed, and the best should be selected on basis of expected profit. Further, the most relevant aspects from the previous section will be that of pre-policy research and product-oriented processes.

An important aspect regarding scenario development is already brought up in section *3.1*, regarding design functions of changing requirements, where presumptions about areas assumed to be affected of future uncertainty are made. To recall, these are the discussed factors for the intervention semi in question;

- technology;
- operation methods;
- environment;
- legislation;
- geographical area of operations;
- and economic changes

For the different factors of changing requirements, an evaluation of possible growth rates and development will be of great importance for the scenario development. In relation to this, knowledge about the past and present are vital aspects, as discussed earlier. There are different methods for generating growth rates and development for the different factors, from the most elemental ones, to highly sophisticated programming and analysis. The most primitive methods could, for instance, be to make a regular graph on the basis of what is known from the past. This can to a certain degree be done with success regarding some technological, environmental and economic aspects, but would be useless in terms of for instance legislation and methods of operation. The more sophisticated ways of assessing the future development of the different factors are stochastic programming, and analysis using *geometric browning motion* (GBM). Regarding factors like legislation and methods of operation, which was assumed not suitable for graphical assessments or sophisticated analysis, there is a need for a thorough logical and fact related investigation of their possible development.

When the decision alternatives are agreed upon, and the key factors are identified and evaluated, a set of scenarios should be proposed. Each scenario should represent a realistic development of the marked or area in question, based on the evaluation of the identified key factors. The more factors that are assumed to be important, the need for more scenarios could be a problem. An example of this, in the most extreme form, could be that there are six factors, assumed just as important, and these again are anticipated to develop in three different ways. If a scenario should be made for all combinations of these possible developments, it would be a practically impossible task. To cope with this, there should be generated a limited number of scenarios, representing the most realistic combination of development as a whole.

5.2.2 Scenarios Assessment

According to *Wilson (2000),* scenarios are not an end in themselves, but rather "*a management tool to improve the quality of executive decision making"*. This is by all means the right opinion in context of this paper. A first important aspect when discussing application of scenarios in a decision making context, is the assignment of probabilities to the different scenarios. The probability of a scenario to actually happen is a key factor in itself, and must be handled with care. Wilson (2000) argues that *"probability has more to do with forecasting than with scenarios*", and further that scenarios are not forecasting. He also argues that it can result in an excessive focus on the most possible scenario, and thus forget the others, which would *"negate the whole value of the scenario planning exercise"* (Wilson, 2000). When that is said, he recognises that probabilities often are assigned to scenarios, and in my opinion it is important in relation to what Van Notten (2005) referred to as pre-policy research and product oriented scenario application. When it is decided to assign probabilities this should be done in the best manner, making sure as many participants as possible get to say their opinion on each scenario. This will reduce the risk of a faulty subjective probability assignment. A template/step-by-step approach which legitimates the use of probabilities is what Wilson (2000) refers to as *strategy development using a "planning-focus" scenario*. This will be further discussed below, in addition to two other approaches assumed to be of relevance for this paper.

Application of Scenarios

In *From Scenario Thinking to Strategic Action* (Wilson, 2000), Wilson argues that to begin with, any one dealing with scenario development could need a template, or a step-by-step approach for scenario assessments. In the same paper, four approaches are presented; *sensitivity/risk assessment, strategy evaluation, strategy development with planning focus, and strategy development without planning focus* (Wilson, 2000). These are, according to the author, ranged from the most elemental to the more sophisticated. I find the three first ones most relevant, and will thus focus on these.

The most elemental one, the sensitivity/risk assessment approach, is relevant when the decision possibilities are known, and the question is whether or not to proceed with a project. This can easily be related to offshore investments and decisions about which design to choose. In short, this method is about identifying requirements regarding key factors, like market growth rate and technological development, and see if these requirements are met in the future, given the different scenarios. After comparing the scenario conditions with the required conditions, and assessing how resilient a "go" decision would be in each scenario, a decision of whether to initiate a project or not should be made. The second approach, the strategy evaluation, is more or less the same as the last one, where the purpose is to evaluate the viability of an existing strategy, by testing the strategy against the different scenarios.

The third approach, called *strategy development using a "planning-focus" scenario (Wilson, 2000)*, can also be related to decision making in an uncertain environment like the offshore business, and is in my opinion the most relevant one of the four. The concept of this approach is to select the scenario assumed most realistic (the one with the highest probability of happening), develop the strategy from this, and then use the other scenarios to test the resilience of the chosen strategy. According to *Wilson* (2000), this method

> …*does not commit the ultimate sin of disregarding the other scenarios entirely; and, in its step-by-step process, it does address many of the key questions that scenario-based strategy should ask*.

When relating this approach to the topic of this paper, what is referred to as *strategy* should be represented by design solutions. By doing this, an optimal design should be found from testing the most probable scenario (having assigned probabilities for the different scenarios, or at least having a "most probable scenario"), with any of the two decision support models presented in section *5.3*. The optimal solution is then tested against the other scenarios, and the resilience of the optimal design, can be evaluated.

This approach will be discussed further in section *5.5*, regarding evaluation and suggestions for use of the proposed optimisation models. Also, an example of such a scenario assessment of a problem is presented in *Case 1,* section *6.2.*

As a concluding remark to this section about scenario development and assessment, I will take the freedom to quote Van Notten, in that

> *…no matter how good a "toolbox" of methodologies and approaches might be, a scenario study is likely to fail if the interest is lacking. It is therefore inadvisable to focus on tools alone but also invest in nurturing a "culture of curiosity". (Van Notten, 2005)*

5.3 Models for Decision Support (Design Optimisation)

Many engineering companies are very good at making tailor maid projects, with the aim to satisfy the customers' needs in the best possible manner. Often, the engineering company could come up with designs that in many ways are better than the proposed "tender design", by adding flexibility to better be prepared for the uncertainty in the future. The problem, however, is that this will usually result in slightly higher investment costs, which can be seen straight away on the bottom of the cost calculations, and the value of a more flexible design can be difficult to prove. The engineering companies need a tool, or procedure, that can show the value of a flexible design, which also accounts for the uncertainty in the future.

The ideal tool in a business with significant investments and great uncertainties for the future, like the offshore business, would be an optimisation model taking uncertainty into consideration. To have a model finding the definite optimal design for the full expected lifetime of a project will not be realistic, due to this uncertainty in the future. When that is said, there should be possible to make models to aid in the decision making. In the following, I have tried to make the basis for such a model, with two different approaches. In addition, it is proposed how these models can be used as simulation models in a scenario assessment related to evaluation of design solutions.

5.3.1 Model Introduction and Background

The basis for the models I will present is the *Ship Design and Deployment Problem* (SDDP), described by *Erikstad, Fagerholt, and Solem (2011),* where contract scenarios are used to find an optimal design. The SDDP model is a binary integer programming (BIP) model, which can be used as decision support when designing non-cargo, service type of ships, facing a set of available contracts or market opportunities with different start-up periods, durations and vessel capability requirements (Erikstad et al., 2011). The SDDP problem uses different contract scenarios for the expected lifetime of a project to investigate what design that will give the highest profit. Typically, a number of vessels with a set of capabilities are put up against a number of contracts with corresponding requirement parameters. The different designs will be able to serve a set of contracts, where the capabilities satisfy the contract requirements. By solving this, the total revenue for the different designs can be found, and thus, by subtracting costs, the profit for the given design is found, and the optimal design is presented.

The models presented in this chapter (*Model 1* and *Model 2*) are primarily meant as decision support tools when designing an offshore vessel for a non-cargo, service type of vessel environment, but they can also be used as simulation models. The models are both, as the SDDP model, deterministic BIP models, and can be used for a variety of instances, depending on the input data. In any case, the design with the optimal set of specifications, on basis of the input data, will be the result of solving the problem, when used as optimisation models. After an optimal design is found for one instance, the models can be used for testing this solution for other instances, as simulation models (discussed further in sub-section *5.5.3*). The intended use of *Model 1* will be to aid in decision making regarding whether a set of potential functions for a design should be real options or included in the design from day one, to achieve maximum value through its lifetime. A variant of *Model 1*, called *Model 2*, can

be used to find which functions a design should have without taking real options and other forms of flexibility into consideration, to maximize project profit throughout its lifetime. The two variants of the model will be described in more detail later in the chapter.
For the models to function properly, the creation of future contracts (reflecting different possibilities for the future) with revenue as an important component, and also cost estimations for different designs and functions, are essential. As mentioned, the model will be dependent on input values, like contract specifications (e.g. revenue and functional requirements) and design characteristics (e.g. capabilities, capital cost, option realisation cost).

5.3.2 *Model 1* – "Hybrid Model"

The model presented in this section, *Model 1*, can be described as a "hybrid" model, meaning that it do both select an initial design (static) and investigates the possibilities of real options (a dynamic problem). I will present this hybrid model as the basic model, and in the next section (sub-section *5.3.3*), I will present an alternative formulation.

The model will use a set of pre generated design alternatives, with individual design capabilities, a capital cost, and different forms of real options (with associated costs). There will be generated a set of random contracts for the expected lifetime of the project. These contracts will have functional requirements corresponding to the possible design capabilities (attributes). The result from running the model should be a design with an optimal combination of functions and real options to achieve the highest possible profit throughout the expected lifetime of the design.

Mathematical Formulation; Model 1

In this model, the following parameter sets are used;
A set *D* of different designs *d*, set *K* of available contracts *k,* set *A* of attributes *a,* set *T* of time periods *t.* The input parameters for the model are the net revenue R_k, for servicing contract *k* in time period *t*, C_d^{cap} representing the initial capital cost of design *d*, C_{da}^{U} is the cost of doing an upgrade of attribute *a* for design *d*, and A_{at}^{T} is the time-cost adjustment factor of attribute *a* in time period *t* . Also, there are parameters representing constraints, where K_{kt}^{T} is the contract (time) availability parameter, and K_{ka}^{A} the contract functional requirement (attribute) parameter.

Let δ_{kt} be a binary variable equal to 1 if and only if contract *k* in time *t* is used in the optimal solution, and let x_d be a binary variable equal to 1 if and only if design *d* is used in the optimal solution. Also, let y_{dat} be a binary variable equal to 1 if and only if design *d,* upgrades attribute *a,* in time period *t* in the optimal solution.

The model is then

$$maximize \sum_{d\in D}\sum_{k\in K}\sum_{t\in T} R_k \delta_{dkt} - \sum_{d\in D} C_d^{cap} x_d - \sum_{d\in D}\sum_{a\in A}\sum_{t\in T} C_{da}^{attr} A_{at}^T y_{dat} \qquad (3)$$

Where:

Decision variables:	δ_{dkt}	Contract decision variable
	x_d	Design decision variable
	y_{dat}	Design attribute decision variable
Parameters:	R_k	Revenue for contract *k,* per time period
	C_d^{cap}	Capital cost of design *d*
	C_{da}^{attr}	Cost of upgrade for design *d, attribute a*
	A_{at}^T	Upgrade time factor, for attribute *a* in time period *t*
	K_{kt}^T	*Contract Availability*, for time period *t, binary*
	K_{ka}^A	*Contract functional (attribute)* requirement, *binary*

Subject to constraints:

$$\sum_{d\in D} x_d \le 1 \qquad (4)$$

$$\sum_{d\in D}\sum_{k\in K} \delta_{dkt} \le 1, \quad t \in T \qquad (5)$$

$$\delta_{dkt} \le x_d, \qquad d \in D, k \in K, t \in T \qquad (6)$$

$$\delta_{dkt} \le K_{kt}^T, \qquad d \in D, k \in K, t \in T \qquad (7)$$

$$\delta_{dkt} \ge \delta_{dk(t-1)} K_{kt}^T, \qquad d \in D, k \in K, t \in T\setminus\{1\} \qquad (8)$$

$$\delta_{dkt} K_{k(t-1)}^T \le \delta_{dk(t-1)}, \qquad d \in D, k \in K, t \in T\setminus\{1\} \qquad (9)$$

$$\delta_{dk1} K_{ka}^A \le y_{da1}, \qquad d \in D, k \in K, a \in A, t = 1 \qquad (10)$$

$$\delta_{dkt}K_{ka}^{A} \leq \sum_{t_2=1}^{t_2=t-1} y_{dat_2}, \qquad d \in D, k \in K, a \in A, t \in T \setminus \{1\} \tag{11}$$

$$y_{dat} \leq x_d, \quad d \in D, \quad a \in A, t \in T \tag{12}$$

$$\sum_{t \in T} y_{dat} \leq 1, \qquad d \in D, a \in A \tag{13}$$

$$\delta_{dkt} \in \{0,1\}, \quad x_d \in \{0,1\}, \quad y_{dt} \in \{0,1\} \tag{14}$$

In this formulation, the objective function (3) equals the maximum profit achieved from the chosen contracts (the sum of contract revenues minus capital cost for the chosen design, minus the cost of upgrading the design to required standard in the given time period). Constraint (4) ensures that only one design is chosen, and constraint (5) states that there can only be chosen one contract for a given time period *t*. Constraint (9) ensures design activation. Constraint (7) states that a contract must exist in the time period *t* before it can be chosen for this time period. Constraints (9) and (9) are contract continuity and contract running constraints. Constraint (10) and (11) ensures that attribute *a* is upgraded before it is needed, and constraint (12) states that design *d* must be activated before attribute *a* can be activated. The last constraint, constraint (13), makes sure that if a contract *k* requires attribute *a*, design *d* must be upgraded to be able to take this. Constraint (11) uses a help variable, t_2, making it possible to do an upgrade in any time period *t* before attribute *a* actually is needed.

5.3.3 Alternative Formulation; *Model 2* – "Static Model"

A variant of the model presented above (*Model 1)*, is *Model 2,* will look at the optimal combination of pre-defined design functions, in a more static way than before. This means that there are no real options available. The decision variables will decide which base design (if alternatives are available) should be used, whether to take a given contract for a given time period, and a variable deciding which functions the design should have, based on which functions the chosen contracts requires. This gives a difference from the previous model in that the decision variable deciding which functions to have now is independent of time, the attributes now have only one pre-determined cost (the time factor of the attribute upgrade cost is left out). I have chosen to keep the parameter set representing the base designs. This gives the possibility to consider only one design, but also a set of designs with varying cost and capabilities. In any case, by solving the problem the optimal combination of functions for a finale design will be attained.

Mathematical Formulation; Model 2

In this model the following parameter sets are used;

A set *D* of different designs *d*, set *K* of available contracts *k,* set *A* of attributes *a,* set *T* of time periods *t.* The input parameters for the model are the net revenue R_k, for servicing contract *k* in one time period, the cost C_d^{cap} representing the capital cost of design *d*, and C_{da}^{funct} , the cost of having attribute *a* for design *d*. Also, there are parameters representing constraints, where K_{kt}^{A} is the contract (time) availability parameter, and K_{ka}^{A} the contract functional requirement (attribute) parameter.

Let δ_{kt} be a binary variable equal to 1 iff contract *k* in time *t* is used in the optimal solution, let x_d be a binary variable equal to 1 iff design *d* is used in the optimal solution, and let z_{da} be a binary variable equal to 1 iff attribute *a* is used in design *d*.

The model is then

$$maximize \sum_{d\in D}\sum_{k\in K}\sum_{t\in T} R_k\delta_{dkt} - \sum_{d\in D} C_d^{cap}x_d - \sum_{d\in D}\sum_{a\in A} C_{da}^{attr}z_{da} \qquad (15)$$

Where:

Decision variables:	δ_{dkt}	Contract decision variable
	x_d	Design decision variable
	z_{da}	Design attribute decision variable
Other parameters:	R_k	Revenue for contract *k,* per time period
	C_d^{cap}	Capital cost of design *d*
	C_{da}^{attr}	Cost of having *attribute a* for design *d*
	K_{kt}^{T}	*Contract Availability,* for time period *t, binary*
	K_{ka}^{A}	*Contract functional (attribute)* requirement*, binary*

Subject to constraints:

$$\sum_{d \in D} x_d \leq 1 \tag{16}$$

$$\delta_{dkt} \leq x_d, \qquad d \in D, k \in K, t \in T \tag{17}$$

$$\sum_{d \in D} \sum_{k \in K} \delta_{dkt} \leq 1, \quad t \in T \tag{18}$$

$$\delta_{dkt} \leq K_{kt}^{T}, \qquad d \in D, k \in K, t \in T \tag{19}$$

$$\delta_{dkt} K_{ka}^{A} \leq z_{da}, \qquad d \in D, k \in K, a \in A, t \in T \tag{20}$$

$$z_{da} \leq x_d, \qquad d \in D, a \in A, \tag{21}$$

$$\delta_{dkt} \geq \delta_{dk(t-1)} K_{kt}^{T}, \qquad d \in D, k \in K, t \in T \backslash \{1\} \tag{22}$$

$$\delta_{dkt} K_{k(t-1)}^{T} \leq \delta_{dk(t-1)}, \qquad d \in D, k \in K, t \in T \backslash \{1\} \tag{23}$$

$$\delta_{dkt} \in \{0,1\}, \quad x_d \in \{0,1\}, \quad z_{da} \in \{0,1\} \tag{24}$$

In this formulation, the objective function (15) equals the maximum profit achieved from the chosen contracts (the sum of contract revenues minus capital cost for the chosen design and capital cost of having a function). Constraint (16) ensures that only one design is chosen, constraint (17) ensures design activation, and is needed for those cases where chosen contracts do not require any of the attributes in question. Constraint (18) ensures that there can only be chosen one contract for time period *t*, and constraint (19) states that contract *k* must exist in time period *t* to be chosen in this time period. Constraint (20) is ensuring attribute activation for design *d* if contract *k* requires attribute *a*. Constraint (21) is superfluous, but ensures consistency, saying that attribute *a* only can be activated for design *d* if and only if design *d* is activated. Constraints (22) and (23) are contract continuity constraints.

5.3.4 Contracts and Base Designs

In this section, I will discuss the necessary input data for the two models. Basically, the models need a set of contracts, and a set of base designs with belonging attributes. The contracts will be much the same for *Model 1* and *Model 2*, but the base designs and attribute constraints will be somewhat different.

Contracts –Parameters and Constraints

As seen from the mathematical models, and mentioned introductorily in this chapter, a set of contracts are needed. These contracts can either be real contracts, which of course would be ideal, or they can be simulated as part of a scenario development. Some real contracts might exist for the next couple of years, but with an expected lifetime of about 30 years, contract scenarios will necessarily have to be simulated, or produced in another way. This will naturally give rise to great uncertainties, regarding expected earnings. To minimize these uncertainties, potential contract simulation models will have to be as accurate as possible. Another important element that must be considered is that offshore constructions often are built for a first contract, which can limit the design freedom. Also, when a first contract exists, the contract scenarios for the rest of the projects expected lifetime will not be relevant before the end of this contract. Practically, this means that the model should be defined for a time period starting after this first contract ends.

There are some contract characteristics that are necessary for all contracts. These are presented in the table below.

T_k^S	Starting time of contract *k*
D_k	Duration of contract *k*
R_k	Revenue of contract *k*
K_{ka}^A	Attributes (the set of capability requirements)

Table 2 - Model contract parameters

The starting time, T_k^S, of a contract will generally be somewhere between project commissioning, or the end of an anticipated first contract, and the projected end of the constructions lifetime.

The duration, D_k, should reflect a real life contract situation, but a reasonable limiting factor would of course be that the end of a contract is not after the anticipated end of the constructions lifetime. The contract revenue, R_k, will be one of the key factors for a good result. This should be as close to a real contract as possible, and reflect the value of the capability requirements. The revenue should be per time period, meaning that if a total contract value is given this should be divided by the duration (the number of time periods this contract lasts).

This brings us to the contract functional requirements, called attributes, represented by K_{ka}^A. These should correspond to the pre-defined design capabilities (discussed further down), and they should, as mentioned, have an influence on the contract revenue. Normally, real contracts will have a whole lot of requirements and demands, from safety and equipment requirements, to operation depth and environment characteristics. When modelling contracts, most of these characteristics will be strictly pre-determined and assumed fixed for all contracts, like for instance safety requirements, while a set of additional requirements, related to uncertainties in the design, will be the variable contracts/design attributes. The reason for calling it attribute requirements, and not functional requirements or just functions,

is that I do not consider all requirements as dependent on functions, but rather capabilities in themselves. An example of this is a requirement about capability of operation in a certain water depth.
It can be mentioned that for offshore operations like well intervention and maintenance work, a contract might only demand actual operation for a given number of days per year. This opens up for the possibility of taking spot marked work simultaneously as long term contracts, which will increase the potential earnings of the vessel. This will however not be a part of the model at this stage.

As mentioned, the attributes specifying the capability requirements will have to be pre-determined. In the table below, examples of additional attributes used for intervention contracts are presented:

K_{k1}^{A}	Water depth requirement; [80 – 400 meters]
K_{k2}^{A}	Water depth requirement; [400 – 800 meters]
K_{k3}^{A}	Well bore depth requirement; [500 – 8000 meters]
K_{k4}^{A}	Wireline capability
K_{k5}^{A}	Coiled tubing capability
K_{k6}^{A}	TTRD capability
K_{k7}^{A}	MPD capability
K_{k8}^{A}	Cementing capability
K_{k9}^{A}	ROV ability

Table 3 - Examples of contract requirements (attributes)

These attributes will all be linked to vessel specifications; many vessels have depth limitations, both in water depth and well operation depth, and the available equipment will vary with the size (and thus cost) of the vessel.

Now that a framework for the contracts is made, scenarios for contract generation will have to be made. The challenges are many, including probability distributions for contact attributes and value estimation for the contracts. Other variables to consider in a contract development process will be the duration and distribution of contract availability, where the latter also will be dependent on competition from other market players. In relation to the illustrative cases in chapter 6, a simple contract generator is presented.

Designs – Parameters and Constraints
A set of base designs must be established, in addition to the contracts. These designs will represent a basis for the optimal design solution. Both models can function with only one design, but usually there will be many designs, with variations in capabilities and cost. Common for all designs is that they must have a set of pre-defined characteristics that match contract characteristics/requirements (and vice versa). These are presented in the table below.

C_{d}^{cap}	Capital cost of design *d*
ϑ_{da}	Design capabilities (to match contract requirements)
γ_{da}	Ability to upgrade attribute *a* for design *d**
C_{da}^{attr}	CosUpgrade cost of attribute *a* for design *d**

A_{at}^{T}	Option realisation time factor for attribute *a*, time period *t**
** Different for Model 1 and Model 2 – discussed blow*	

Table 4 - Parameters, model designs

The capital cost of the base design, denoted C_d^{cap}, can include everything from building cost, to a sum of building cost, financial cost, maintenance costs, and more, but despite this, I have chosen to call it *capital cost.* What the capital cost should include will be something the "user" of the models must decide, but in this paper it will only be dependent on which functions (represented by attributes) a design is able to have.
The designs should, as indicated earlier, have capabilities corresponding to the contract attributes (requirements), denoted ϑ_{da}. These can either be fully functional at commissioning, as is the only possibility for *Model 2*, or they can be planned as an option in *Model 1*.
This brings us to the next parameter, the ability to realise a real option, denoted γ_{da}, where some designs might have many possibilities, while others none. The option realisation, or upgrade, will come with a cost, denoted C_{da}^{U}, representing the base cost of the attribute. For *Model 2*, these two parameters are time independent, and represent the design/attribute capability and attribute cost. The C_{da}^{U} parameter is also used to decide which functions that are available for the different designs, by having a "big M" cost, a fictive large cost, assigned to the attributes not available.
To take the aspect of time into consideration in *Model 1*, a time factor A_{at}^{T} is added, representing the cost adjustment of attribute *a* in time period *t*. This is due to the assumption that it will get cheaper to realise the option the longer one waits. This factor can be different for all attributes, and should represent a realistic reduction, if any, in the attribute realisation cost. The cost of realising an option (and thus the time factor) is also assumed to be a key factor for a good result, and should ideally represent the true cost of having the specific function installed on the construction. It is desired that the total cost of having a function (attribute) as an option will cross the cost of having it initially somewhere during the projected lifetime. This is illustrated in Figure 8.

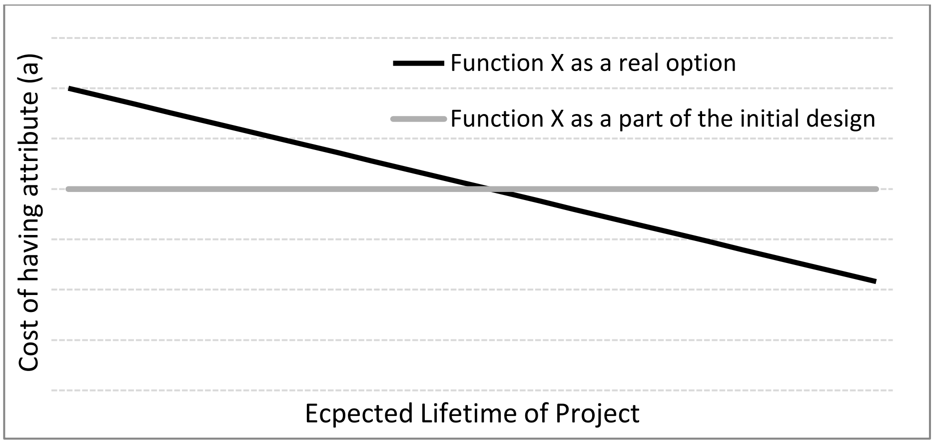

Figure 8 - Hypothetical Cost of Function X (Source: Author)

5.4 Model Implementation

In this section, I have implemented the two models in Xpress Mosel. This is done to better illustrate how these models can be used as decision support. The mosel code for the models is included in Appendix 6 and Appendix 7.
To run the models in the solver, a data file with input data is required. The content of this data file will be matrixes and values representing the parameters presented in relation to the two mathematical models. The exact content will be somewhat different for the two models, and will be presented in the sub-sections presenting the models.
In the two following sub-sections, it is shown how *Model 1* and *Model 2,* and their respective parameters and constraints, are programmed to be solved in Xpress.

5.4.1 *Implementation of Model 1* – "Hybrid Model"

In the implementation, all decision variables, parameters and constraints correspond to the ones in the mathematical model. As discussed introductorily in this section, data file with input data is needed. These input data are presented in the following.

Decision Variables

The decision variables are as following:

DesignSelected	Representing the x_d variable
DesignUpgrade	Representing the y_{dat} variable
ContractSelected	Representing the δ_{dkt} variable

Table 5 - *Model 1* decision variables

These are the same as in the mathematical formulation for *Model 1*, and can be seen in the script in Appendix 6 under '*Declaration of decision variables*'. They are all binary variables, which are explicitly stated in the code.

Parameters

The parameters used are as following:

nDesigns	Number of base designs, *d*
nContracts	Number of contracts, *k*
nAttributes	Number of functions/attributes, *a*
nTimePeriods	Number of time periods, *t*
CapitalCostD	Capital cost of design *d*
UpgradeCostDA	Option realisation cost, for design *d*, attribute *a*
UpgradeTimeFactorAT	Time factor for the real option cost; attribute *a*, time period *t*
ContractAvailableKT	Contract availability, for contract *k* in time period *t*
ContractRevenueK	Revenue of contract *k*
ContractAttributesKA	Requirement of attribute *a* for contract *k*

Table 6 - Model parameters

As one can see, the parameters do to a large degree correspond to the ones in the mathematical formulation presented under sub-section *5.3.4*. A difference is that the notations that earlier were mathematically formulated with superscripts and subscripts now are written in full. This is done for programming reasons. Also, one might notice that the

parameter deciding design capabilities, ϑ_{da}, and the upgrade ability parameter, γ_{da}, has disappeared. These are both incorporated in the *UpgradeCost* parameter and the *UpgradeTimeFactor*, discussed next.
The *UpgradeCost* will be the cost of realising an option for a given design. With this parameter, as mentioned, the design characteristic of whether a function is available or not will be given. This is done by having a fictive high upgrade cost, representing "not possible to upgrade to this function", "assigned" to an attribute not available for the particular design.
The *UpgradeTimeFactor* is a factor between zero and one, assumed decreasing throughout the project lifetime, where a higher factor in the start of the lifetime indicates that it is more expensive to realise an option soon after commissioning. Also, as mentioned, this factor is used to obtain the cost of having an attribute in the initial design, by setting a lower value in time period one.

The *ContractAvailable* parameter is made as a matrix of contracts and time periods, by converting the starting time and duration into a matrix with zeros and ones. An example of this is shown below, in Table 7. For example, *Contract 4* starts in time period two, and has duration of five periods.

	Time Period, t= 1...10									
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
Contract_1	0	0	0	0	0	0	1	0	0	0
Contract_2	0	0	0	0	0	1	1	1	1	0
Contract_3	0	0	0	0	0	1	1	1	1	0
Contract_4	0	1	1	1	1	1	0	0	0	0
Contract_5	0	0	0	0	0	0	0	1	1	0
Contract_6	0	0	0	0	0	1	1	1	0	0
Contract_7	0	0	0	0	1	0	0	0	0	0
Contract_8	0	0	1	1	1	1	1	0	0	0
Contract_9	1	1	1	1	1	0	0	0	0	0
Contract_10	0	0	0	0	0	1	1	1	1	1

Table 7 - Contract availability example

ContractAttributes parameter is represented by a binary matrix of contracts and attributes. If an attribute is required for a given contract, this will be 1, and zero otherwise.

An example of matrices for the input file is shown in *Appendix 3* and *Appendix 4,* and the mosel code for *Model 1* can be seen in Appendix 6.

5.4.2 *Implementation of Model 2* – "Static Model"

Model 2 is, as the model formulation in sub-section *5.3.3* describes, a simplification of *Model 1*, where the possibility to have real options is removed. The complete data script can be seen in Appendix 7.

As for the mathematical formulation of the model, most of the programming is the same, but there are some changes;

- the DesignUpgrade decision variable has changed to AttributeSelected
- the UpgradeCost is now AttributeCost
- the UpgradeTimeFactor is no longer necessary

Before, in *Model 1*, the *DesignsUpgrade* decision variable decided whether a function should be a part of the design initially, or designed as a real option. Now that the real option part is out, the only possibility to have a function is by making it as a function for the base design at commissioning. This variable is now called *AttributeSelected.*
The *CapitalCost*, as before, represents the cost of the base design with a pre-determined set of additional functions possible, and the *AtributeCost*, former *UpgradeCost*, will represent the extra cost of having these functions. A fictive high cost ("big M") in the *AttributeCost* matrix is also here assigned to an attribute not available for a design.
Since the model no longer evaluates design decisions in respect of time (only contract decisions), and there are assumed to be no possibilities of doing upgrades during the constructions lifetime, the parameter adjusting the time value of the upgrade cost, the *UpgradeTimeFactor,* is no longer necessary.

The set of decision variables and parameters for model two is shown in Appendix 1.

5.5 Evaluation and Discussion of the Models

In this section, with the four sub-sections, I will make an evaluation of the two models presented. At first, I will make some comments about how the two models work and some general aspects, before I discuss possibilities for extensions and improvements. Further, I will present a method for using the models together with scenario assessment. Last, a computational study is presented.

5.5.1 General Comments to the Models

The models are developed for decision support in a setting with uncertainties in the future. At first, *Model 1*, the "dynamic" model, were developed as a proposal for how an optimisation model could assist in the problem of choosing the best design when taking the possibility of real options into consideration. As an alternative to this perhaps a bit unconventional approach, a more conservative formulation was proposed. Taking away the possibility of options, this model (*Model 2*) became more of a static problem, and thus not as complex as *Model 1*.
As presented, *Model 1* should be able to find which attributes a design should have, and if they should be a part of the initial design or made as options. If one function is in question (one attribute), and maximum profit is achieved by having this function, the design with the lowest total cost of having this function at the time the function is needed will be the chosen design. This will vary when the set of contracts change for each model run. Another situation

is if a design has the function in question from day one with a lower total cost than all other designs are able to have the same function throughout the time frame of the model. Then, this design will always be the preferred one, and there is no need to use the model.
Regarding the result from running the models, the models will only find the optimal solution for each set of contracts; they are not able to find the second or third best design. In an evaluation setting, this means that one is not able to compare the optimal solution with other possible solutions for a given set of contracts, which could result in a weakened assessment of the robustness of the optimal design. In my opinion, the second and third optimal solution will not be necessary when a full assessment of a problem is done (described in the sub-section *5.5.3*, below), when a distribution of optimal designs is found and evaluated.
As a last comment, I will mention a change made to the models after they were more or less completed. The two models did originally have a parameter constraining which contracts that were available for which designs, due to capability/requirement match. After some time, I found that by having a fictive high cost on the attribute not feasible for a design (a "big M"), combined with a constraint saying that all attributes must have a design/contract match, a contract not feasible would in principle be "unavailable". This resulted in that the parameter was removed, and thus reduce the amount of input data. This choice is also acceptable in relation to model run time, where I found that the run time to a small degree was dependent on this change.

5.5.2 Possibilities for Model Extensions and Improvements

There are indeed some aspects that could be subject to improvements, or at least an extension in some way.
When proposing designs for the model, it is important that main design drivers are satisfied. In this particular case with the intervention semi, this is cost and weight, and also motions are important to have in mind. Also, it is necessary to identify which functions/capabilities are potentially profitable to have, which that are out of the question, and not least, whether they should be made part of the design initially or as options. Normally, the majority of functions and facilities for a construction should be pre-determined, and only a few will be up for evaluation, making the number of "attributes" in the model limited.
In relation to the contract generation, attention should be given to the value of the contracts. When generating contracts for a real case, the revenue of these should be adjusted for the time value of money, meaning that a contract available in ten years from now, compared to a similar contract available today, should have a higher value (because of inflation, and other factors). If it is decided to take this into consideration, also other miscellaneous costs in the future should perhaps be adjusted the same way. And related to this, the cost assessment of the designs and contracts could to a large degree be more detailed than what is presented in this paper. For example, an operational costs could be incorporated, which might change when functions are added, creating a more dynamic model.
In the current models, all decision variables are binary, meaning that all attributes represents a given capability, whether it is a function or a depth range, which the design either can have or not. If variations of a capability, like for instance crane capacities of either 40 or 80, two "attributes" must be assigned to this function to make the diversification. In general, there needs to be an attribute for every functional characteristic possible to have.
An alternative to this is to use an integer approach. If an integer model is used, there two possible ways of doing it. Firstly, the attributes can have a pre-defined integer for the given

function capability, meaning that if a contract requires an ability on a given level, the design should "be assigned" an integer representing the contract requirement. As an example of this, a contract might require an operation depth capability of 600 meters, represented by the attribute with integer "2", which represent an operation depth range of 500 to 1000 meters, whilst for instance the number 1 represents 0 to 500 meters. The other way of using an integer model is to have requirement equal the actual contractual demand (but of course only integers), like the actual operation depth for the contract. En example of this is if the depth requirement is 600 meters, a design must then have a depth capability of more than 600 meters to be able to take the contract. In general, the design will have to have an actual capability larger than or equal to the contract requirement.

5.5.3 Scenario Assessment – a Resilient Way of Using the Models for Decision Support

The models previously described in this chapter (*Model 1* and *Model 2*) are presented as design optimisation models, which will find an optimal design, and by running the model a given number of times for a specific scenario, a distribution of optimal solution will be found. This alone is not enough to make a decision, and a scenario assessment of the results should be done. In relation to this, the two models will be used as simulation models, which test a pre-determined design against a set of contracts.

Different approaches for this were presented in sub-section *5.2.2*. One of the approaches assumed more relevant than the others is the approach presented as strategy development using a "planning-focus" scenario (Wilson, 2000). Here, the concept is to select the scenario assumed most realistic, develop the strategy from this, and then use the other scenarios to test the resilience of the chosen strategy. In this setting, as mentioned before, the "strategy" will be the optimal design found by solving the model. More precise, after running the model as an optimisation model for the scenario assumed most probable, an optimal design is proposed for this instance. This solution should then be tested against other possible scenarios, with the same model working as a simulation model, to investigate the resilience of the proposed design solution. If found necessary, other design from the distribution of optimal designs (form the scenario assumed most probable) could also be tested. In my opinion, this is a sound way of using the optimisation model as decision support. This method can be used for both *Model 1* and *Model 2*, and will be illustrated in section *6.2*, where *Case 1* is presented.

5.5.4 Computational Study

When using the model for commercial problems, the input parameters will vary from time to time. An important aspect related to this is the run time for the model, which will vary with the size of the problem. Since *Model 1* in general is a larger problem than *Model 2*, I have only used *Model 1* for this computational study. In particular, the parameters regarding number of base designs, number of contracts and number of attributes are the ones having an influence. To test how an increase in number of base designs, attributes and contracts affects the solvability of the model, a number of random tests were performed, representing varying problem size. The number of possible base designs, attributes and contract types has been varied as shown in Table 8 (next page). For each combination, five different instances were generated and solved. The contracts used as test instances are generated with the same excel model as the illustrative case, discussed in the next chapter (under *Contracts,* section *6.1)*. A commercial solver was used for the tests on a computer with Intel® Core™2 Duo Processor T8300 2.40 GHz, and 4 GB RAM.

Number of contracts	Number of attributes	Number of designs	Avg. solution time [s]	Std. deviation [s]
50	4	4	0,8	0,4
		8	4,0	0,0
		16	7,0	0,6
	8	4	0,2	0,4
		8	2,8	0,4
		16	8,4	1,0
100	4	4	1,8	0,7
		8	6,8	1,2
		16	28,0	1,3
	8	4	2,4	0,5
		8	9,0	3,1
		16	33,6	4,6
150	4	4	4,0	0,9
		8	12,6	0,5
		16	66,2	12,4
	8	4	5,0	0,0
		8	22,8	1,2
		16	69,2	5,8
200	4	4	8,0	0,0
		8	23,2	4,1
		16	76,0	4,8
	8	4	9,0	1,1
		8	34,2	3,4
		16	120,4	6,0

Table 8 - Solution times and standard deviation for a set of test incidences

Table 8 shows average solution time and standard deviation for varying number of contracts, base designs, and attributes. From the table, one can see that the smaller problems in terms of number of base designs and attributes had fairly short solution time in general, and naturally that the largest problem had the longest solution time. For instance, examples with 100 contracts, 4 attribute, and 8 base designs can be solved on the average in less than 7 seconds. The largest example, with 100 contracts, 8 attribute, and 16 base designs was solved on the average in about two minutes, while the smallest one would take less than one second. It seems that the solution time is more sensitive to the number of base designs than the number of attributes and the number of contracts.

In my opinion, the most relevant case is 100 contracts, 4 base designs, and 8 attributes. This is because I believe that after a first screening, there are a limited number of potential base designs left, maybe 4-8 design attributes are still uncertain (since most of the specifications for a project is set), and during a time period of 25 to 30 years (representing expected lifetime of a project) about 100 potential contracts available should be a realistic number. Such a case can be solved one time in on the average less than two seconds, and for a full scenario analysis, consisting of about 1000 runs, the analysis will take about half an hour.

6. ILLUSTRATIVE CASES

To illustrate the use of the models presented in the previous chapter, I have done three cases. The optimisation is done in Xpress (commercial solver using Mosel version 3.2.3) (FICO), and for my input values I have created a primitive data set creator in excel, simulation contracts, and making the necessary matrices. The mosel code for the two models used can be seen in Appendix 6 and Appendix 7.

As said earlier, the assumptions about the future contracts specifications, especially revenue, represents great challenges, and should in some way be calculated with a stochastic model. The results of both optimisation models are fully dependent on the quality of the input values. Due to this, and the limited scope of this thesis, the cases are all illustrative, with only fictive numbers. In a real case, a simulation model should be made, so that contract scenarios are made automatically and the optimisation model could be run a given number of times to make a distribution of the solutions, with different scenarios. In the cases presented here, only one set of contracts are used for each example. Still, *Case 1* will illustrate how a full assessment, as described in sub-section *5.2.2* and section *5.5.3*, can be done.

The complete input data files for all cases are attached in a zip file, together with the solver models.

6.1 Assumptions Relevant for All Cases

The general setting for all case is that you are an investor in the offshore marked, interested in the intervention semi segment. You would like to know what design to choose, and from gathering information from the past and present, predictions for the future can be made:

- The design must in any case be able to do some basic operations, like wireline and coiled tubing
- Estimates of project costs (LCC), all values in NPV, for a number of possible designs are found. This includes cost estimates for potential real options (initial investment and realisation cost), where "cheapest solution" is found.
- As today, contracts for the basic operations are abundance, but there are indications that there will be a revenue drop for these during the lifetime of the project, and other functions might be desirable.
- Contract values, given different scenarios (will be used for developing contracts in the future) are estimated. A set of functional requirements will have influence on the contract values.

The time aspect is divided into years, where the full time frame should represent the entire expected life of the construction, in these cases 25 years. The information about the contracts must, as discussed earlier, contain availability, revenue and functional requirements. The availability consists of a starting time and duration. The revenue is per year, so the total revenue for a contract will be revenue [$/year] multiplied with contract duration [year]. The attributes, which are the contract requirements and design capabilities, are in these cases all design functions, and will thus typically be spoken of as functions. Scenarios are presented as basis for generation of future contracts. These scenarios will vary from case to case, and they will give a new set of contracts for each model run. In addition to the contract specification discussed below, also general input values and design characteristics for the solver are generated/decided in an excel sheet, ready for the solver data file. An example of this is shown in Appendix 4.

Contracts

For all cases, all contracts will have a starting time, duration and revenue, but they will all be different for each set of contracts. Other contract characteristics, primarily the ones specifying contract requirements, will vary for the different cases. For each model run, a set of 52 contracts are generated, where 50 of them are random contracts, and the two last represents the *sport market*. The spot marked contracts are always available, and do only require basic functions, but they are assumed to have a lower revenue than the other contracts on average.

The contracts are generated in a simple excel model, as shown in Appendix 2, where contracts for case 1 is used as an example. The contract generator will, by updating the excel sheet manually, produce a set of random numbers for the contracts. These parameters are described below (Table 9). The contract generator is intended for illustrative cases only (with its simplicity and assumptions), and does not feed the solver automatically with input data.

Revenue/year [mUSD]	Contract value divided by duration
Contract value [mUSD]	*Base amount *duration*rand*(1+MPD*omega)*
Start time [year]	Random, between 0 and end of time scale, here [0, 25]
Duration [year]	Random between 1 and 11, or time left of time scale
Base amount [mUSD/d]	Chosen base value for all contracts (fictive)
Rand [-]	A random number to create diversity, here [0.8, 1.2]
MPD [-]	Gives whether a contract requires MPD or not [0,1]
Omega [-]	A random number for diversity in MPD value, here [0.26, 0.35]

Table 9 - Parameters for contract generation

The duration, here set to be between 1 and 11 years (or what time is remaining from start of contract till the end of the time scale) is decided on the basis of what I believe is a realistic duration for a contract. This will be the same for all cases.

The MPD parameter, which is the only attribute in question for this example taken from case 1, is assigned a probability, given by a prediction for the future. If it has a probability of 80%, it means that on average, 8 of 10 contracts will require this function (or attribute, in a general setting) For instance, in one particular scenario, it is assumed that a function will be abundant, and thus will this be assigned a reasonable larger possibility of occurring being required for a contract. For cases where there are more than one attribute the principle will be the same.

Further, these values must be transformed into matrices for the solver input data file. An example of this is shown in Appendix 3. These matrices (contract value, contract availability, and contract attributes) can be extended with additional contracts, longer time scale, and more attributes.

6.2 *Case 1* – Only One Function in Question

For this case, only one function is studied, which makes this first case fairly simple. Due to the simplicity in the problem, I will use *Case 1a* as an example of the scenario assessment discussed earlier in the paper. The function in question is the former discussed MPD (Managed Pressure Drilling). In addition to the assumptions common for all cases (see section *6.1*), it is also assumed that there are cost estimates both for having the MPD function as a part of the initial design and as a real option (a first investment cost, and an option realisation cost). This is used for the design characteristics.

When this is known, a set of alternative designs are made. In this case, three base designs are available;

Design alternative 1:
- No possibility of having the MPD function
- Only a one time capital cost of the base design. Relatively inexpensive.
- Can only take contracts not requiring MPD

Design alternative 2:
- Real option to have the MPD function in the future
- Will have an additional building cost (added to the capital cost of the base design), and an option realisation cost (decreasing with time, as discussed in sub-section *5.3.4*)
- Can take all contracts, given that the option is realised

Design alternative 3:
- The design is built with full MPD functionality
- The design will have a significantly increased building cost (added to the capital cost of the base design)
- Can take all contracts

To evaluate the different design alternatives, three scenarios are generated. (The scenarios are made extremely simple, and are only suited for illustrating how scenarios can be assessed in relation to the model.) The scenario characteristics are as following:

Scenario 1:
- The value (revenue) and distribution of contracts requiring MPD is assumed to be the same as today, on average throughout the project lifetime.
- The distribution of the contracts is 80/20 (80% do not require MPD, 20% requires MPD)
- The revenue for contracts requiring MPD is slightly higher than for those that do not require this.

Scenario 2:
- Contracts requiring MPD is assumed to have a larger marked share than today
- The distribution of contracts will on average be 50/50
- The revenue for contracts requiring MPD is slightly higher than for those that do not require this.

Scenario 3:

- Contracts requiring MPD will have a larger marked share than those that do not require this function.
- The distribution of contracts will on average be 60/40, in favour of MPD requirement.
- The revenues for contracts requiring MPD is slightly higher than those without.

It is assumed that *Scenario 1* is the most probable one, while the others are only fairly probable. I will not assign probabilities to the scenarios in this case, but in a real setting, this should be done as a part of the assessment to find which is the most probable.

Assumptions for Solver

In addition to the assumptions given above, there are also made some assumptions related to the solver model;

- For each scenario, a set of contracts are generated according to the given distribution of MPD.
- One set of contracts are generated for each run of a scenario, with revenues influenced by whether the contract requires MPD or not – a factor giving higher revenues for contracts demanding MPD is used. This factor is also calculated from a distribution, giving each contract a unique value.
- Instead of solving with three base designs, as stated introductorily in this case, only two are used for the solver to make the problem smaller, where the second base design also represents the third. This is done by having a fictive cost of having the MPD function in year one assigned to the base design alternative two, representing the cost of having a design with the function from day one.

6.2.1 Data Set – Case 1

To make the data set for this case, it is first and foremost the contracts that must be generated (discussed in the section about contracts above). In addition to the contracts, these are the input data used in the solver:

Number of designs	2* [-]	
Number of contracts	52**[-]	
Number of attributes	1 [-]	
Number of time periods	25 [years]	
*"Design 2" also represents "Design 3" **Two contracts are fixed "spot contracts"		
CapitalCost:	Design 1	Design 2
	750	900
UpgradeCost:	Attribute 1	
Design 1	10000	
Design 2	250	

Table 10 - Input data, Case 1

These design characteristics will comply with the three designs presented earlier. As one can see, *Design 1* is the cheapest one, and has a fictive high cost for the cost of upgrading *attribute 1*. This reflects that the design is not able to have any other functions than the initial design. *Design 2* has a somewhat higher initial cost, due to the fact that both *Design 2* and *Design 3* will be able to have *attribute 1*. There is also a time adjustment factor for the cost of realising the option (the *UpgradeTimeFactor)*, which can be seen in the bottom of Appendix 4. This factor, as one can see, is lower in year one than the in year two, representing the cost of having the function initially.

6.2.2 Results – *Case 1*

As discussed earlier, in this case there are three scenarios, where the only difference in the three cases is the probability of a contract to require the MPD function. As first, all three scenarios are tested separately, respectively in *Case 1a Case 1b* and *Case 1c,* while in the next section, the scenario assessment described earlier will be presented. The results are to some degree "produced" to illustrate the different possibilities of designs solutions, but it is only contract values that are manipulated in advance of the model run. The results can be seen in the next three pages.

Results Case 1a

Below, in Table 11, the result from solving case 1a with one set of contracts is presented. In this case, there should be a distribution of contracts that do/do not require the MPD function of 20/80.

```
Optimal objective value : 4748

Design 1 is the chosen design

It will choose contract 21 in time period 2
It will choose contract 21 in time period 3
It will choose contract 21 in time period 4
It will choose contract 21 in time period 5
It will choose contract 26 in time period 7
It will choose contract 26 in time period 8
It will choose contract 26 in time period 9
It will choose contract 26 in time period 10
It will choose contract 26 in time period 11
It will choose contract 26 in time period 12
It will choose contract 26 in time period 13
It will choose contract 26 in time period 14
It will choose contract 26 in time period 15
It will choose contract 26 in time period 16
It will choose contract 20 in time period 18
It will choose contract 20 in time period 19
It will choose contract 20 in time period 20
It will choose contract 9 in time period 21
It will choose contract 9 in time period 22
It will choose contract 9 in time period 23
It will choose contract 9 in time period 24
It will choose contract 9 in time period 25

It will choose to be in the spot market in time periode
1, 6, 17,

No option realisations
```

Table 11 - Results case 1a

From the result, one can see that design 1, the design without the possibility of MPD, is the chosen design. Due to the low rate of contracts requiring the MDP function, this result was as expected. Also, since the design chosen has only the most basic capabilities, it is reasonable that it chooses the spot marked for some time periods.

Results Case 1b

Below, in Table 12, the result from solving case 1b is presented. In this case, the distribution of contracts that do/do not require the MPD function should be 50/50.

```
Optimal objective value : 5570.25

Design 2 is the chosen design

It will choose contract 8 in time period 1
It will choose contract 8 in time period 2
It will choose contract 40 in time period 3
It will choose contract 40 in time period 4
It will choose contract 40 in time period 5
It will choose contract 40 in time period 6
It will choose contract 40 in time period 7
It will choose contract 40 in time period 8
It will choose contract 40 in time period 9
It will choose contract 40 in time period 10
It will choose contract 40 in time period 11
It will choose contract 36 in time period 12
It will choose contract 36 in time period 13
It will choose contract 36 in time period 14
It will choose contract 49 in time period 15
It will choose contract 49 in time period 16
It will choose contract 49 in time period 17
It will choose contract 49 in time period 18
It will choose contract 49 in time period 19
It will choose contract 49 in time period 20
It will choose contract 47 in time period 21
It will choose contract 47 in time period 22
It will choose contract 46 in time period 23
It will choose contract 5 in time period 24
It will choose contract 5 in time period 25

 It will realise option 1 in time periode 11
```

Table 12 - Results case 1b

From the result, one can see that design 2, the design with the possibility of having MPD as an option, is the chosen design. It is also suggested that the MPD function (here, represented by option 1) should be built as an option. It should be noted that this is the result of one model run (since this only are illustrative cases), so the information about which time period the option should be realised should in a real situation only be a source to further discuss the result. The expected profit, the *optimal objective value,* is somewhat higher than for *Case 1a*, which is as expected, since it now is a better chance of having a contract with higher value.

Results Case 1c

Below, in Table 13, the result from solving *Case 1c* is presented. In this case, there should be a 60/40 distribution of contracts that do/ do not require the MPD function.

```
Optimal objective value : 6127.5

Design 2 is the chosen design

It will choose contract 28 in time period 1
It will choose contract 28 in time period 2
It will choose contract 28 in time period 3
It will choose contract 28 in time period 4
It will choose contract 28 in time period 5
It will choose contract 28 in time period 6
It will choose contract 28 in time period 7
It will choose contract 28 in time period 8
It will choose contract 28 in time period 9
It will choose contract 28 in time period 10
It will choose contract 39 in time period 11
It will choose contract 39 in time period 12
It will choose contract 39 in time period 13
It will choose contract 39 in time period 14
It will choose contract 49 in time period 15
It will choose contract 49 in time period 16
It will choose contract 31 in time period 17
It will choose contract 31 in time period 18
It will choose contract 31 in time period 19
It will choose contract 31 in time period 20
It will choose contract 31 in time period 21
It will choose contract 31 in time period 22
It will choose contract 46 in time period 23
It will choose contract 46 in time period 24
It will choose contract 46 in time period 25

Function 1 will be a part of the initial design
```

Table 13 - Results case 1c

From the result, one can see that design 2 is the chosen design for this case, but due to the fact that the function should be a part of the initial designs, this solution represents designs 3. This is an expected result, due to the fact that there should be more contracts demanding the MPD function than those that do not, and the ones that do are in general better paid. The expected profit, the *optimal objective value,* has increased, which also is as expected.

6.2.3 Scenario Assessment *Case 1*

In this section, I will illustrate how the scenario assessment described in sub-section *5.2.2* and *5.5.3* can be used for this case. As earlier stated, *Scenario 1* is assumed to be the one most probable. To do the assessment, I have used the result from *Case 1a* as the base solution, and tested this solution for the two other cases. This, I have done by only keeping the design that was the optimal one in *Case 1a*, namely *Design 1*, and then used *Model 1* as a simulation model. The input data file I will use for *Scenario 2 and Scenario 3* will now look like this:

Number of designs	1 [-]
Number of contracts	52**[-]
Number of attributes	1 [-]
Number of time periods	25 [years]
**Two contracts are fixed "spot contracts"	
CapitalCost:	Design 1
	750
UpgradeCost:	Attribute 1
Design 1	10000

Table 14 - Input data for scenario assessment of *Case 1*

If I wanted, I could also have removed the attribute, since the chosen design will not take use of this, but I recon it is more work removing it than it will slow down the solving process.

The optimal design from *Scenario 1, Design 1,* can now be tested for *Scenario 2* and *Scenario 3*

Test Results, Scenario Assessment

After running the model with the input data as presented and contracts representing *Scenario 2* and *Scenario 3,* these are the results:

Scenario	Optimal Objective Value (Profit)
Scenario 2	4801
Scenario 3	4686

Table 15 - Result scenario assessment of *Case 1*

The objective value for *Scenario 1* was 4748. From Table 15, one can see that for *Scenario 2* the profit did even increase (to 4801), while for *Scenario 3*, with a profit of 4686, the profit is still not bad. From this, one can draw the conclusion that *Design 1* will be a resilient design for the three scenarios presented. In an even more thorough assessment, also other designs from the solution distribution from running *Scenario 1* could be tested, to see if any of the other solution would have a higher expected profit on average. For this, probabilities should be assigned to the scenarios.

6.3 *Case 2* – Multiple Functions and Real Options

For this case, there are a set of design functions together with a set of base designs that will be evaluated against a set of contracts, to find the optimal design. The functions can either be made part of the initial design, or they can be made part of the design as real options and realised during the project lifetime for an additional cost. In addition to the assumptions common for all cases, also this is assumed:

- There are four optional functions (TTRD, MPD, cementing, ROV), which will affect contract revenues.
- There are cost estimates for having the different additional functions. There will be a cost for having the function in the initial design, an initial cost of having the option, and an option realisation cost (which decreases with time, as discussed earlier).
- The vessel subject to investigation will be fully "tailor made", meaning that all combinations of functions and options are possible.

Design alternatives

This case is rather complex, since a large number of base designs will be needed to have all possibilities available. Each attribute will have the same cost for all designs, but a base design only capable of having one of the functions (one real option) will have a smaller capital cost then one that can have all functions (in this case, four real options). If all solutions are just as interesting, there should be made a design for all possibilities. In this case, with 4 alternative options, the designs will be as following

Design 1: No additional functions possible
Design 2: Only function 1 possible
Design 3: Only function 2 possible
…
Design X: Function x and x possible
…
Design 16: All functions possible (as option or part of the base design)

0	0	0	0
1	1	1	1
1	1	1	0
1	1	0	0
1	0	0	0
0	1	1	1
0	0	1	1
0	0	0	1
1	0	1	0
0	1	0	1
1	0	0	1
0	1	1	0
0	1	0	0
0	0	1	0
1	1	0	1
1	0	1	1

Table 16 - Design/ capability matrix

Table 16, the designs versus capability matrix, illustrates the full set of designs, where column one represents attribute (function) one, row one represents design one, and so forth.

From this, one can derive that it will be needed 2^n base designs, if absolutely all combinations of base designs and capabilities should be available, where *n* equal the number of functions available. It is further assumed for this case that all design alternatives are potential optimal designs.

As for the first case, different scenarios can be applied for contract generation, but only one setting will be applied in this example:

- The revenue will be dependent on TTRD, MPD, cementing and ROV requirements, and will typically be higher if one or more of these are required, than for those contracts that do not.
- The distribution of the functions (for the contracts) will be uniform.

A natural extension of this illustrative case is to have a number of different scenarios, where the different required functions will be more and less promising in the future. This will, however, not be done in this paper.

Decision Model Implementation:
In addition to what is assumed above, also for this case there are made some assumptions for the sake of modelling. First, randomised contract values are generated for each run of a scenario. Secondly, the cost of having an option as a part of the base design will be represented by a fictive “upgrade cost” in year one, equivalent to the additional building cost for this function (As done in case 1).

6.3.1 Data Set – Case 2

The data set for case 2 is larger than for the previous case. This is because of the large number of designs, as illustrated in Table 16. There are also three more functions to consider. The contracts are also somewhat more complex, due to the additional attributes, but the principle of creating them are still the same (discussed in section *6.1*). The some of the input data for the solver, in addition to the contracts that are generated, are as following:

Number of designs	16 [-]
Number of contracts	52*[-]
Number of attributes	4 [-]
Number of time periods	25 [years]
*2 contracts are fixed “spot contracts”	

Table 17 - Input data, Case 2

The capital cost for the different base designs, the attribute upgrade costs, and also the time factor for realising the attributes, can be seen in Appendix 5. As the appendix shows, the different base designs come with different capital cost, dependent on which functions the design is capable of having. The cheapest designs, design 1, cannot have any of the functions, while the most expensive, design 2, can have all functions. This is also reflected in the design/attribute upgrade cost, where a fictive high cost (“big M”) is assigned to the functions that a design cannot have. The factor adjusting the time value of the upgrade cost is the same for all attributes in this case, but it can be seen in year one that the factor is lower than in year two, representing the cost of having the function initially.

6.3.2 Results – Case 2

Below, in Table 18, the result from running case 2 in the solver is presented. Here to, the result is "produced" to illustrate an interesting solution. This is done by manipulating contract specifications.

```
Optimal objective value : 524

Design 6 is the chosen design

It will choose contract 33 in time period 1
It will choose contract 33 in time period 2
It will choose contract 33 in time period 3
It will choose contract 33 in time period 4
It will choose contract 33 in time period 5
It will choose contract 33 in time period 6
It will choose contract 33 in time period 7
It will choose contract 33 in time period 8
It will choose contract 33 in time period 9
It will choose contract 33 in time period 10
It will choose contract 16 in time period 11
It will choose contract 16 in time period 12
It will choose contract 16 in time period 13
It will choose contract 16 in time period 14
It will choose contract 17 in time period 15
It will choose contract 17 in time period 16
It will choose contract 17 in time period 17
It will choose contract 17 in time period 18
It will choose contract 17 in time period 19
It will choose contract 29 in time period 20
It will choose contract 13 in time period 21
It will choose contract 13 in time period 22
It will choose contract 13 in time period 23
It will choose contract 13 in time period 24
It will choose contract 14 in time period 25

The contracts chosen requires function 2, 3, 4,

Function 4 will be a part of the initial design
It will realise option 2 in time periode 10
It will realise option 3 in time periode 10
```

Table 18 - Results Case 2

From the results shown in the table above, one can see that the contracts chosen require function 2, 3 and 4. Design 6, which is capable of having the functions needed, is the optimal design. Also, it is shown that the design should be built with function 4 initially, while function 2 and 3 should be options. Function 1 is assumed not necessary. As one can see from Table 16, the sixth row, representing design six, matches the functional requirements of the chosen contracts. From the result in Table 18, one can also see that there are no spot contracts chosen, which is as expected, since there are so many contracts to choose among, and also the large amount of design alternatives makes it sensible that a "path" of contracts is found without using the spot marked.

6.4 *Case 3 – Model 2*; Multiple Functions, Without Real Options

In this third case, *Model 2* is used. There will be presented a case 3a and 3b, to illustrate how the model can be used first with one base design, and then with a set of possible base designs. Further description of *Model 2* can be seen in sub-section *5.3.3* and *0.* As discussed earlier, this model can be called static, due to the fact that a complete design, without options, will be the result from running the model. This implies that for both case 3a and 3b, a given number of possible functions are evaluated, but they can only be a part of the design from the time of commissioning (otherwise they are assumed not available at all). In addition to the assumptions common for all cases (see section *6.1*), this is also assumed:

- There are four optional functions, TTRD, MPD, cementing and ROV, that can be required, and they will give higher revenue if required for a given contract.
- There are cost estimates for having the different additional functions in a design.
- In case 3a, only one base design with a set of possible functions will be available, and in case 3b a number of base designs with different capabilities are available.

Different scenarios can be applied for contract generation, but in this case, only one setting will be applied:

- The revenue will be dependent on TTRD, MPD, cementing and ROV requirements, and will typically be higher for contracts requiring these than for those contracts only requiring WL and CT.
- The distribution of the functions in question (for the contracts) will be uniform.

6.4.1 Data Set – Case 3

The data set, with model input data, will be somewhat different from the ones in *Case 1* and *Case 2*, in relation to the designs characteristics. The general differences from the previous cases (and thus *Model 1*), can also be seen in sub-section *5.4.2*. The contracts are much the same as for the previous cases, and are equal for *Case 3a* and *Case 3b*. The input data file contains matrices for contract characteristics; *ContractValue*, *ContractAttributes* and *ContractAvailability*. An example of this can be seen in Appendix 3 (for these cases, it will be four attributes, instead of one).

Case 3a

Case 3a will have only one base design, where four functions should be chosen among and combined to get an optimal design. There will be 52 contracts to choose among, where two of them represents the spot market. The 50 “ordinary” contracts will have a uniform distribution of requirements, as stated earlier. The general input data for the solver is summarised in Table 19 below.

Number of designs	1 [-]
Number of contracts	52*[-]
Number of attributes	4 [-]
Number of time periods	25 [years]
*2 contracts are fixed “spot contracts”	

Table 19 - Data set input values; Case 3a

In addition to the contract information and the general information presented above, also *CapitalCost* and *AttributeCost* matrices are needed;

CapitalCost:	d1			
	1500			
AttributeCost:	a1	a2	a3	a4
Design 1	200	500	400	300

Table 20 - CapitalCost and AttributeCost, Case 3a

Case 3b

For *Case 3b*, there are two base designs to choose among (with values as presented in Table 22). This gives a larger flexibility in finding an optimal design. The general input data for the solver is summarised in Table 21, below.

Number of designs	2 [-]
Number of contracts	52*[-]
Number of attributes	4 [-]
Number of time periods	25 [years]
*2 contracts are fixed “spot contracts”	

Table 21 - Data set input values; Case3b

As for *Case 3a*, there are also matrices representing the *CapitalCost* and *AttributeCost* for the designs*,* and as one can see from Table 22*,* it is slightly more complex than for *Case 3a.*

CapitalCost:	d1	d2		
	1500	1600		
AttributeCost:	a1	a2	a3	a4
Design 1	10000	400	400	300
Design 2	500	400	400	300

Table 22 - CapitalCost and AttributeCost, Case 3b

From the table above, one can see that designs 1 (d1) is slightly cheaper than design 2 (d2). This is because design 1 not is able to have function 1 (a1), while design 2 can have all functions. The fictive high cost for function 1 in designs 1 represents the “big M” cost making this function unavailable.

6.4.2 Results – Case 3

After running the numbers in the solver, results were acquired for *Case 3a* and *Case 3b*. The results are attained by the use of the case characteristics presented above, and a random set of contracts.

Results Case 3a

Below, in Table 23, the result from solving *Case 3a* in the solver for a set of contracts is presented.

```
Optimal objective value : 1008

It will choose contract 36 in time period 1
It will choose contract 36 in time period 2
It will choose contract 36 in time period 3
It will choose contract 36 in time period 4
It will choose contract 36 in time period 5
It will choose contract 36 in time period 6
It will choose contract 36 in time period 7
It will choose contract 36 in time period 8
It will choose contract 36 in time period 9
It will choose contract 36 in time period 10
It will choose contract 24 in time period 11
It will choose contract 24 in time period 12
It will choose contract 24 in time period 13
It will choose contract 24 in time period 14
It will choose contract 24 in time period 15
It will choose contract 24 in time period 16
It will choose contract 24 in time period 17
It will choose contract 40 in time period 18
It will choose contract 40 in time period 19
It will choose contract 40 in time period 20
It will choose contract 40 in time period 21
It will choose contract 32 in time period 22
It will choose contract 32 in time period 23
It will choose contract 32 in time period 24
It will choose contract 35 in time period 25

The contracts chosen requires function 1, 3, 4,
```

Table 23 - Results case 3a

From the result, one can see that the optimal solution requires functions 1, 3 and 4, meaning that the construction should have these three functions from day one. Since there are no base designs for this particular case, there is not selected any design. No spot marked contracts are chosen, reflecting the large amount of contracts available, with a great variety of functional requirements.

Results Case 3b

Below, in Table 24, the result from solving *Case 3b* is presented.

```
Design 2 is the chosen design

Optimal objective value : 554

It will choose contract 22 in time period 1
It will choose contract 22 in time period 2
It will choose contract 22 in time period 3
It will choose contract 22 in time period 4
It will choose contract 22 in time period 5
It will choose contract 22 in time period 6
It will choose contract 4 in time period 8
It will choose contract 4 in time period 9
It will choose contract 4 in time period 10
It will choose contract 4 in time period 11
It will choose contract 4 in time period 12
It will choose contract 7 in time period 13
It will choose contract 7 in time period 14
It will choose contract 7 in time period 15
It will choose contract 7 in time period 16
It will choose contract 8 in time period 17
It will choose contract 33 in time period 18
It will choose contract 33 in time period 19
It will choose contract 33 in time period 20
It will choose contract 33 in time period 21
It will choose contract 33 in time period 22
It will choose contract 33 in time period 23
It will choose contract 33 in time period 24

The contracts chosen requires function 1, 2,
```

Table 24 - Results case 3b

From the result, one can see that the optimal solution requires functions 1 and 2. For this case, there are two base designs to choose among, where design 2 is the preferred one. The design should be able to do operations regarding function 1 and 2 from day one, while function 3 and 4, which design 2 also could have had, will not be necessary. No spot marked contracts are chosen for this instance either, which was as expected.

6.5 Discussion of Cases

In my opinion, all cases presented could possibly be real problems, where the models could aid as decision support tools. The main differences between real cases and these illustrative ones are the cost of designs and functions, the value of the contracts, and the distribution of functional requirements for the contracts. I believe that in a commercial setting, all these factors could be estimated with an acceptable tolerance.
Further, these cases are all either tested with one random set of contracts, or with a manipulated set of contracts, to get the preferred results. For a real case, something like 1000 random sets of contracts should rather be tested for each case, instead of that one set of contracts. From this, one would get a distribution of optimal solutions, where, hopefully, there is a trend giving which design with which characteristics that will be optimal on the average.

Case 1

Case 1 is primarily an example of how the models (in this case *Model 1*) can be used with a set of scenarios, and how a scenario assessment can be done. Even though it is the most primitive example, with only one attribute in question and three possible designs, the scenario assessment presented I believe is a good reflection of how it is intended to work. As mentioned, a full assessment would in addition to only testing one solution from the most probable scenario against the other scenarios also include testing of other designs from the distribution of optimal designs.
Another observation worth noticing for this example is that in comparison to *Case 1b* and *Case 1c*, which test *Scenario 2* and *Scenario 3* with all design possibilities (though with some numbers to some degree manipulated), the profit has in general drop a bit when only *Design 1* is available, which would be as expected. In my opinion, this illustrates that the model produces sound results.

Case 2

As discussed earlier, *Case 2* is assumed to be more complex than a commercial problem normally would be, by having all 16 possibilities regarding base designs. Because of this, it can be regarded a represents of what the model is able to do. In relation to this, it was also shown in the computational study, in sub-section *5.5.3,* that the incidents with many base designs available where the ones with the highest computational time (with less dependent on the number of contracts). Still, the problem could be solved in 7 seconds, ref. Table 8 page 52, making it possible to do more than 500 test incidences within an hour.
Also for this case, an assessment like the one done for *Case 1* could have been done, but in my opinion this is not necessary, since the procedure would be just the same, only far more work intensive.

Case 3

Case 3, as an example of how *Model 2* can be used, is not as complex as the cases based on *Model 1*, but is in my opinion still an example of how an optimisation model can be used as decision support. Even though the aspect of real options is removed, the model will still take the future uncertainty into consideration by the use of scenario development and assessment. For the case presented (both *a* and *b*), only on scenario was used (and there was only one set of contracts used), so the result will only reflect the best solution for that particular scenario, and thus a full assessment of the future has not been made. Also for this case, a scenario assessment like the one presented for *Case 1* can be used for a full analysis of the problem.

7. CONCLUDING REMARKS

After writing this thesis on the topic *Semi-Submersible Platform Designs to Meet Uncertainty in the Future*, I find the last part, about evaluation of design solutions in relation to future uncertainty, most relevant in relation to the main objective of this thesis.
The two models proposed as decision support in relation to evaluation of design solutions for an uncertain future, proved to function as intended. The models were meant as optimisation models, for finding an optimal design for a given set of contracts created from an assumed scenario. In addition, they proved to be useful in a broader perspective when used as simulation models in relation to scenario assessment. The illustrative cases did in my opinion in a good way show how the proposed models can be used in a decision support setting, both as optimisation models and simulation models. Even though it was only *Model 1* that was used as a simulation model in *Case 1* (where a simple scenario assessment was done), the method would be much the same for *Model 2*, and the application should be no different.

To conclude, I will say that the main scope, which I in my opinion was to discuss how different design solutions could be evaluated in relation to future uncertainty, was answered in a good way with the two decision models proposed, together with how these could be sued in a scenario setting.

7.1 Proposal for Further Work

As a last section in this thesis, I will propose some areas for potential further work. In my opinion, there are mainly two approaches that are particularly relevant; to develop the decision models further, and to make a better environment for these models with a more detailed scenario development.

The first proposal for a model expansion is to introduce a new variable for real option initiation in the deterministic model. Now, the model (speaking of *Model 1*, assumed to be the main model) will only implicitly evaluate which possibilities of real options a design will have, meaning that it is pre-determined a set of base designs with a set of possibilities for real options. A step further would be to not having any base designs at all, only a project initiation price, representing all costs associated with the minimum requirements of the project (basic functions, engineering, etc.). By doing this, the model will be more “complete”, in the sense of making more choices explicitly in the model, and thus reducing pre-processing work (and also reducing the size of the input data file)
Another proposal is a stochastic model approach, where decisions made in the model will influence a “next stage” of decisions in a changed environment, and so on for a given number of decision stages. This involves an almost full re-programming of the model. To use such a model will require a more thorough examination and assessment of information required for the data file, for instance, regarding probabilities of different scenarios to happen and links between the different stages of decision making (what the consequence of making a decision will be in the “next stage”).

The second main approach for further work is to take a better look at the problems associated with scenario development, and in more detail take future uncertainty into consideration. The area of scenario assessment is wide, and advanced methods for investigating trends and development are often used, like Geometric Brownian Motion, and in general mathematical programming. This area will not be an approach for decision support alone, but rather a side approach to combine with the development of a decision model and simulation model.

As a final step, these approaches for further work should be combined to provide a best possible decision support tool for design decision taking future uncertainty into consideration.

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APPENDICES

Appendix 1 - *Model 2*; Variables, Parameters and Constraints for Solver

Decision Variables

DesignSelected	Representing the x_d variable
ContractSelected	Representing the δ_{dkt} variable
AttributeSelected	Representing the z_{da} variable

Parameters

nDesigns	Number if base designs
nContracts	Number of contracts
nAttributes	Number of functions
nTimePeriods	Number of time periods
CapitalCostD;	Capital cost of design *d*
AttributeCostDA;	Attribute cost, for design *d*, attribute *a*
ContractAvailableKT;	The contract availability, for contract *k* in time period *t*
ContractRevenueK;	Revenue of contract *k*
ContractAttributesKA;	Attributes *a* requirement for contract *k*

Appendix 2 - Contract Generator Excel (Example from *Case 1*)

Scenario	X					**Probability of postive MPD marked**				**0,5**
						Probability of negative MPD marked				**0,5**
	Rev./yr	Contr. value								
Name	[mUSD]	[mUSD]	Start	Dur. [yr]	[Days/yr]	[mUSD/d]	rand	**MPD**		*omega*
Contract 1	234	2 578	9	11	365	0,60	1,07	**0**	0,59	0,35
Contract 2	208	1 040	17	5	365	0,60	0,95	**0**	1,00	0,29
Contract 3	266	798	20	3	365	0,60	0,92	**1**	0,29	0,32
Contract 4	230	460	6	2	365	0,60	1,05	**0**	0,82	0,31
Contract 5	227	2 271	3	10	365	0,60	0,81	**1**	0,33	0,28
Contract 6	350	6 641	6	19	365	0,60	1,20	**1**	0,05	0,33
Contract 7	255	1 532	9	6	365	0,60	0,87	**1**	0,13	0,34
Contract 8	195	2 144	3	11	365	0,60	0,89	**0**	0,93	0,29
Contract 9	191	572	23	3	365	0,60	0,87	**0**	0,83	0,29
Contract 10	281	1 406	16	5	365	0,60	0,98	**1**	0,23	0,31
Contract 11	212	637	9	3	365	0,60	0,97	**0**	0,77	0,26
Contract 12	199	2 192	15	11	365	0,60	0,91	**0**	0,98	0,26
Contract 13	239	3 103	5	13	365	0,60	1,09	**0**	0,74	0,29
Contract 14	315	3 466	13	11	365	0,60	1,09	**1**	0,47	0,32
Contract 15	270	2 975	14	11	365	0,60	0,98	**1**	0,43	0,26
Contract 16	237	3 311	4	14	365	0,60	1,08	**0**	0,65	0,26
Contract 17	310	310	4	1	365	0,60	1,05	**1**	0,27	0,35
Contract 18	279	557	13	2	365	0,60	1,01	**1**	0,20	0,26
Contract 19	258	2 067	11	8	365	0,60	1,18	**0**	0,60	0,25
Contract 20	313	1 567	14	5	365	0,60	1,06	**1**	0,05	0,35
Contract 21	269	2 422	6	9	365	0,60	0,96	**1**	0,30	0,28
Contract 22	245	2 208	2	9	365	0,60	1,12	**0**	0,66	0,28
Contract 23	239	478	14	2	365	0,60	0,82	**1**	0,32	0,33
Contract 24	234	937	5	4	365	0,60	1,07	**0**	0,71	0,33
Contract 25	254	254	24	1	365	0,60	1,16	**0**	0,65	0,33
Contract 26	210	1 261	6	6	365	0,60	0,96	**0**	0,87	0,27
Contract 27	199	3 587	5	18	365	0,60	0,91	**0**	0,82	0,32
Contract 28	337	1 348	21	4	365	0,60	1,14	**1**	0,14	0,35
Contract 29	279	1 953	9	7	365	0,60	0,98	**1**	0,11	0,3
Contract 30	182	727	22	4	365	0,60	0,83	**0**	0,74	0,29
Contract 31	241	241	23	1	365	0,60	0,82	**1**	0,01	0,34
Contract 32	313	1 564	21	5	365	0,60	1,09	**1**	0,31	0,31
Contract 33	263	526	15	2	365	0,60	1,20	**0**	0,91	0,33
Contract 34	204	815	19	4	365	0,60	0,93	**0**	0,80	0,29
Contract 35	248	248	25	1	365	0,60	0,85	**1**	0,28	0,33
Contract 36	278	1 110	22	4	365	0,60	0,96	**1**	0,16	0,32
Contract 37	254	4 319	3	17	365	0,60	1,16	**0**	0,68	0,3
Contract 38	346	346	22	1	365	0,60	1,17	**1**	0,13	0,35
Contract 39	188	2 637	1	14	365	0,60	0,86	**0**	0,72	0,35
Contract 40	297	297	25	1	365	0,60	1,06	**1**	0,48	0,28
Contract 41	237	473	12	2	365	0,60	0,80	**1**	0,41	0,35
Contract 42	228	2 505	4	11	365	0,60	1,04	**0**	0,54	0,33
Contract 43	327	6 541	3	20	365	0,60	1,14	**1**	0,36	0,31
Contract 44	258	775	19	3	365	0,60	1,18	**0**	0,86	0,31
Contract 45	239	1 671	11	7	365	0,60	1,09	**0**	0,54	0,26
Contract 46	199	2 591	3	13	365	0,60	0,91	**0**	0,65	0,27
Contract 47	292	2 336	6	8	365	0,60	1,05	**1**	0,01	0,27
Contract 48	310	6 209	6	20	365	0,60	1,05	**1**	0,21	0,35
Contract 49	223	223	24	1	365	0,60	0,80	**1**	0,16	0,27
Contract 50	254	763	12	3	365	0,60	0,86	**1**	0,36	0,35

Appendix 3 - Example of Contract Matrices for Solver Input Data

ContractValueK	**Contract, k= 1...50**												
	250	316	283	228	339	256	191	319	238,71	175,2	...	292,694
	Time periode, t= 1...25											
ContractAvailabilityKT	**1**	**2**	**3**	**4**	**5**	**6**	**...**	**25**		**ContractAttributesKA**		**MPD**
Contract_1	0	0	0	0	0	0	...	0			Contract_1	0
Contract_2	0	0	0	0	0	0	...	0			Contract_2	1
Contract_3	0	0	0	0	0	0	...	0			Contract_3	1
Contract_4	0	0	0	0	0	1	...	1			Contract_4	0
Contract_5	0	0	0	0	0	0	...	0			Contract_5	1
Contract_6	0	0	0	0	0	0	...	0			Contract_6	1
Contract_7	0	0	0	0	0	0	...	0			Contract_7	1
Contract_8	0	0	0	0	0	0	...	0			Contract_8	1
Contract_9	0	0	0	0	0	0	...	0			Contract_9	0
Contract_10	0	0	1	1	0	0	...	0			Contract_10	1
Contract_11	0	0	0	0	0	0	...	0			Contract_11	0
Contract_12	0	0	0	0	0	0	...	0			Contract_12	0
Contract_13	0	0	0	0	0	0	...	0			Contract_13	0
Contract_14	0	0	0	0	0	0	...	0			Contract_14	1
Contract_15	0	0	0	0	0	0	...	1			Contract_15	1
Contract_16	0	0	1	1	1	1	...	0			Contract_16	1
Contract_17	0	0	0	0	0	0	...	0			Contract_17	1
Contract_18	0	0	0	0	0	0	...	0			Contract_18	0
Contract_19	0	0	0	0	1	1	...	0			Contract_19	0
Contract_20	0	0	0	0	0	0	...	0			Contract_20	0
Contract_21	0	0	0	0	0	0	...	0			Contract_21	1
Contract_22	0	0	0	0	0	0	...	0			Contract_22	1
Contract_23	0	0	0	0	0	0	...	0			Contract_23	1
Contract_24	0	0	0	0	0	0	...	1			Contract_24	0
Contract_25	0	1	1	1	1	1	...	0			Contract_25	1
Contract_26	0	0	0	0	0	0	...	0			Contract_26	0
Contract_27	0	0	0	0	0	0	...	1			Contract_27	0
Contract_28	0	0	0	0	0	0	...	0			Contract_28	0
Contract_29	0	0	0	0	0	0	...	1			Contract_29	0
Contract_30	0	0	0	0	0	0	...	0			Contract_30	1
Contract_31	0	0	0	0	0	0	...	0			Contract_31	1
Contract_32	0	0	0	0	0	0	...	0			Contract_32	1
Contract_33	0	0	1	1	1	1	...	0			Contract_33	0
Contract_34	0	0	0	0	0	0	...	0			Contract_34	1
Contract_35	0	0	0	0	0	0	...	0			Contract_35	0
Contract_36	0	0	0	0	0	0	...	0			Contract_36	0
Contract_37	0	0	0	0	0	0	...	0			Contract_37	1
Contract_38	0	1	1	1	1	1	...	0			Contract_38	0
Contract_39	0	0	0	0	0	0	...	0			Contract_39	0
Contract_40	0	0	0	0	0	1	...	0			Contract_40	0
Contract_41	0	0	0	0	0	0	...	0			Contract_41	0
Contract_42	0	0	1	1	1	1	...	0			Contract_42	0
Contract_43	1	1	1	1	1	1	...	0			Contract_43	1
Contract_44	0	0	0	0	0	0	...	0			Contract_44	1
Contract_45	0	0	0	0	0	0	...	0			Contract_45	1
Contract_46	0	0	0	0	0	0	...	0			Contract_46	1
Contract_47	0	0	0	0	0	0	...	0			Contract_47	0
Contract_48	0	0	0	0	0	0	...	0			Contract_48	0
Contract_49	0	0	0	0	0	0	...	0			Contract_49	0
Contract_50	0	0	0	0	1	1	...	0			Contract_50	0

Appendix 4 - Example of Matrices for Solver Input Data and UpgradeTimeFactor

Number of designs	*D*										
Number of contracts	*K*										
Number of Attributes	*A*										
Number of time periods	*T*										
CapitalCostD	**Design, d= 1...D**										
	2500	2950	2850	2750	2600	2850	2700	2600	2700	...	2700
UpgradeCostAD	**a1**	**a2**	**a3**	**a4**							
Design 1	10150	10150	10250	10100							
Design 2	150	150	250	100							
Design 3	150	150	250	10100							
...	...	...	...	...							
Design D	150	10150	250	100							
UpgradeCostFactorAT	**TimePeriode, t= 1...T**										
Attribute 1	**0,70**	0,79	0,78	0,77	0,76	0,75	...	0,59	0,58	0,57	0,56
Attribute 2	**0,70**	0,85	0,83	0,81	0,79	0,77	...	0,45	0,43	0,41	0,39
Attribute 3	**0,70**	0,79	0,78	0,77	0,76	0,75	...	0,59	0,58	0,57	0,56
Attribute 4	**0,70**	0,79	0,78	0,77	0,76	0,75	...	0,59	0,58	0,57	0,56
Attribute A	**0,70**	0,79	0,78	0,77	0,76	0,75	...	0,59	0,58	0,57	0,56

UpgradeTimeFactor – *Case 1a*, *1b* and *1c*:

UpgradeCostFactor	**TimePeriode, t= 1...25**																								
Attribute 1	**0,750**	0,960	0,935	0,910	0,885	0,860	0,835	0,810	0,785	0,760	0,735	0,710	0,685	0,660	0,635	0,610	0,585	0,560	0,535	0,510	0,485	0,460	0,435	0,410	0,385

Appendix 5 - Input data, *Case 2*

Number of designs	16	#
Number of contracts	52	# *2 "fixed" spot market contracts
Number of Attributes	4	#
Number of time periods	25	[yr]

CapitalCost	Design, d= 1...16															
	2500	3000	2850	2750	2600	2900	2750	2650	2700	2800	2750	2750	2650	2600	2900	2850

UpgradeCost	**a1**	**a2**	**a3**	**a4**
Design 1	10150	10150	10250	10100
Design 2	150	150	250	100
Design 3	150	150	250	10100
Design 4	150	150	10250	10100
Design 5	150	10150	10250	10100
Design 6	10150	150	250	100
Design 7	10150	10150	250	100
Design 8	10150	10150	10250	100
Design 9	150	10150	250	10100
Design 10	10150	150	10250	100
Design 11	150	10150	10250	100
Design 12	10150	150	250	10100
Design 13	10150	150	10250	10100
Design 14	10150	10150	250	10100
Design 15	150	150	10250	100
Design 16	150	10150	250	100

UpgradeCostFactor	TimePeriode, t= 1...25																								
Attribute 1	**0,75**	0,79	0,78	0,77	0,76	0,75	0,74	0,73	0,72	0,71	0,70	0,69	0,68	0,67	0,66	0,65	0,64	0,63	0,62	0,61	0,60	0,59	0,58	0,57	0,56
Attribute 2	**0,75**	0,79	0,78	0,77	0,76	0,75	0,74	0,73	0,72	0,71	0,70	0,69	0,68	0,67	0,66	0,65	0,64	0,63	0,62	0,61	0,60	0,59	0,58	0,57	0,56
Attribute 3	**0,75**	0,79	0,78	0,77	0,76	0,75	0,74	0,73	0,72	0,71	0,70	0,69	0,68	0,67	0,66	0,65	0,64	0,63	0,62	0,61	0,60	0,59	0,58	0,57	0,56
Attribute 4	**0,75**	0,79	0,78	0,77	0,76	0,75	0,74	0,73	0,72	0,71	0,70	0,69	0,68	0,67	0,66	0,65	0,64	0,63	0,62	0,61	0,60	0,59	0,58	0,57	0,56

Appendix 6 - Mosel Script *Model 1*

```
! Mathematical model of the Design-Option Optimisation Problem
! by Øyvind Patricksson, NTNU, Trondheim, spring 2012

model OptionOptimisation

options explterm
options noimplicit
uses "mmxprs";

!A data file for each problem approach
parameters
		DataFile = "datafile.txt";
end-parameters

declarations
		nDesigns:		integer;
		nContracts:		integer;
		nAttributes:		integer;
		nTimePeriods:	integer;
end-declarations

initializations from DataFile
		nDesigns;
		nContracts;
		nAttributes;
		nTimePeriods;
end-initializations

declarations
		Designs:		set of integer;
		Contracts:		set of integer;
		Attributes:		set of integer;
		TimePeriods:		set of integer;
end-declarations

Designs		:= 1 .. nDesigns;
Contracts		:= 1 .. nContracts;
Attributes		:= 1 .. nAttributes;
TimePeriods		:= 1 .. nTimePeriods;

finalize(Designs);
finalize(Contracts);
finalize(Attributes);
finalize(TimePeriods);

declarations
		CapitalCostD:			array(Designs)
	of integer;
		UpgradeCostDA:		array(Designs, Attributes) of
integer;
		UpgradeTimeFactorAT:	array(Attributes, TimePeriods)
	of real;
		ContractAvailableKT:
	array(Contracts,TimePeriods)	of integer;
```

```
                ContractRevenueK:          array(Contracts)
     of integer;
                ContractAttributesKA: array(Contracts,Attributes)
     of integer;
end-declarations

initializations from DataFile
                CapitalCostD;
                UpgradeCostDA;
                UpgradeTimeFactorAT;
                ContractAvailableKT;
                ContractRevenueK;
                ContractAttributesKA;
end-initializations

! Declaration of decision variables, with binary constraints
declarations
                DesignSelected:          array(Designs)
                of mpvar;
                DesignUpgrade:         array(Designs, Attributes,
TimePeriods)    of mpvar;
                ContractSelected:        array(Designs, Contracts,
TimePeriods)        of mpvar;
end-declarations

forall (dd in Designs)
do
                DesignSelected(dd) is_binary;
end-do

forall (dd in Designs, aa in Attributes, tt in TimePeriods)
do
                DesignUpgrade(dd, aa, tt) is_binary;
end-do

forall (dd in Designs, kk in Contracts, tt in TimePeriods)
do
                ContractSelected(dd, kk, tt) is_binary;
end-do

! Declaration of constraints
declarations
                TotalRevenue:                  linctr;
                DesignselectedMax:               linctr;
                ContractsCon:
     array(TimePeriods)                                        of
linctr;
                DesignSelectedCon:               array(Designs,
Contracts, TimePeriods)               of linctr;
                DesignUpgradeCon1:             array(Designs,
Attributes, TimePeriods)              of linctr;
                DesignUpgradeCon2:             array(Designs,
Contracts, Attributes, TimePeriods)   of linctr;
        ContractContinuityCon:          array(Designs, Contracts,
     TimePeriods)                     of linctr;
```

```
                ContractRunningCon:             array(Designs,
Contracts, TimePeriods)                     of linctr;
                ContractAvailableCon:      array(Designs, Contracts,
TimePeriods)                           of linctr;
end-declarations

!Objective function:
TotalRevenue :=
                sum (dd in Designs, kk in Contracts, tt in
TimePeriods)
        ContractRevenueK(kk)*ContractSelected(dd,kk,tt)
                -
                sum(dd in Designs)
CapitalCostD(dd)*DesignSelected(dd)
                -
                sum(dd in Designs, aa in Attributes, tt in
TimePeriods)

UpgradeCostDA(dd,aa)*UpgradeTimeFactorAT(aa,tt)*DesignUpgrade(dd,
aa, tt);


! Constraints:

! Only one design selected
                DesignselectedMax :=
                     sum(dd in Designs) DesignSelected(dd) <= 1;

! Ensure "design activation"
forall (tt in TimePeriods, dd in Designs, kk in Contracts)
do
                     DesignSelcetionCon(dd,kk,tt) :=
                          ContractSelected(dd,kk,tt) <=
DesignSelected(dd);
end-do

! Only one contract for each time period
forall (tt in TimePeriods)
do
                     ContractsCon(tt) :=
                          sum(dd in Designs, kk in Contracts)
ContractSelected(dd,kk,tt) <= 1;
end-do

! To choose a contract with a given requirement, the attribute must
be upgraded in advance
forall (dd in Designs, kk in Contracts, aa in Attributes, tt in
TimePeriods)
do
     if (tt = 1)
            then
               DesignUpgradeCon2(dd, kk, aa, tt) :=

     ContractSelected(dd,kk,tt)*ContractAttributesKA(kk,aa) <=
                DesignUpgrade(dd, aa, tt);
     else
```

```
                DesignUpgradeCon2(dd, kk, aa, tt) :=
                ContractSelected(dd,kk,tt)*ContractAttributesKA(kk,a
                a) <=
                sum(t2 in 1..tt-1) DesignUpgrade(dd, aa, t2);
     end-if
end-do

! Design can only be upgraded if it is used
forall (dd in Designs, aa in Attributes, tt in TimePeriods)
do
                DesignUpgradeCon1(dd, aa, tt) :=
                DesignUpgrade(dd, aa, tt) <= DesignSelected(dd);
end-do

! Upgrade in only one TimePeriode for design d
forall (dd in Designs, aa in Attributes)
do
                     sum(tt in TimePeriods) DesignUpgrade(dd, aa,
tt) <= 1;
end-do

! If a contract was assigned the previous period, it must be
assigned this period if it is still available.
! The tt=1 case is a dummy case for programming purposes
forall (dd in Designs, kk in Contracts, tt in TimePeriods)
do
     if (tt = 1)
     then
     ContractContinuityCon(dd, kk, tt) :=
     ContractSelected(dd,kk,tt) * ContractAvailableKT(kk,tt) >= 0;
     ContractRunningCon(dd, kk, tt):=
     ContractSelected(dd,kk,tt)*ContractAvailableKT(kk,tt)<=1;
          else
     ContractContinuityCon(dd, kk, tt) :=
     ContractSelected(dd,kk,tt) >= ContractSelected(dd, kk, tt-1)
*ContractAvailableKT(kk,tt);
     ContractRunningCon(dd, kk, tt) :=
     ContractSelected(dd,kk,tt) * ContractAvailableKT(kk,tt-1) <=
ContractSelected(dd, kk, tt-1);
            end-if
end-do

! A contract can be assigned only if it is available
forall (dd in Designs, kk in Contracts, tt in TimePeriods)
do
                ContractAvailableCon(dd, kk, tt) :=
                          ContractSelected(dd,kk,tt) <=
ContractAvailableKT(kk,tt);
end-do

! Writes out optimization characteristics - only used if necessary
!!setparam('xprs_verbose',true);

! Maximizes objective value
maximize(TotalRevenue);
```

! Output text

```
writeln('Optimal objective value : ', getobjval);
writeln;

if nDesigns <> 1
then
forall (dd in Designs)
do
      if getsol(DesignSelected(dd)) >= 1
      then
                  writeln('Design ', dd, ' is the chosen design');
      end-if
end-do
end-if
writeln;

forall (dd in Designs, tt in TimePeriods, kk in Contracts |
getsol(ContractSelected(dd,kk,tt)) > 0)
do
      if (kk <> 21 AND kk <> 22)
      then
                  writeln('It will choose contract ', kk, ' in time
            period ', tt);
      end-if
end-do
writeln;

if (sum(dd in Designs, kk in Contracts, tt in TimePeriods)
     (getsol(ContractSelected(dd,51,tt)) +
getsol(ContractSelected(dd,52,tt)))) >  0
then
                  write('It will choose to be in the spot market in
time periode ');
end-if

forall (dd in Designs, tt in TimePeriods, kk in Contracts |
getsol(ContractSelected(dd,kk,tt)) > 0)
do
      if (kk = 21 OR kk = 22)
      then
                  write(tt, ', ');
      end-if
end-do
writeln;

if nAttributes <> 1
then
      write('The contracts chosen requires function ');

      forall (dd in Designs, aa in Attributes )
      do
              if sum(tt in TimePeriods, kk in Contracts)
      getsol(ContractSelected(dd, kk,
      tt))*ContractAttributesKA(kk,aa) >= 1
```

```
            then
                         write(aa, ', ');
     end-if
     end-do
end-if
writeln;

if nDesigns <> 1
then
     forall (dd in Designs, tt in TimePeriods, aa in Attributes)
     do
          if getsol(DesignUpgrade(dd, aa, tt)) >= 1 AND tt = 1
          then
                    writeln('Function ', aa, ' will be a part of
the initial design');
               elif getsol(DesignUpgrade(dd, aa, tt)) >= 1
               then
                    writeln('It will realise option ', aa, ' in
time period ', tt);
               end-if
     end-do
end-if

if sum(dd in Designs, tt in TimePeriods, aa in Attributes)
getsol(DesignUpgrade(dd, aa, tt)) < 1
then
                    write('No option realisations');
end-if

end-model
```

Appendix 7 - Mosel Script *Model 2*

```
! Mathematical model of the Design Optimisation Problem
! by Øyvind Patricksson, NTNU, Trondheim, spring 2012

model FunctionOptimisation

options explterm
options noimplicit
uses "mmxprs";

!A data file for each problem approach
parameters
                DataFile = "datafile.txt";
end-parameters

declarations
                nDesigns:             integer;
                nContracts:           integer;
                nAttributes:          integer;
                nTimePeriods:   integer;
end-declarations

initializations from DataFile
                nDesigns;
                nContracts;
                nAttributes;
                nTimePeriods;
end-initializations

declarations
                Designs:              set of integer;
                Contracts:            set of integer;
                Attributes:           set of integer;
                TimePeriods:          set of integer;
end-declarations

Designs              := 1 .. nDesigns;
Contracts       := 1 .. nContracts;
Attributes      := 1 .. nAttributes;
TimePeriods     := 1 .. nTimePeriods;

finalize(Designs);
finalize(Contracts);
finalize(Attributes);
finalize(TimePeriods);

! Declaration of parameters
declarations
                CapitalCostD:              array(Designs)
           of integer;
                AttributeCostDA:      array(Designs, Attributes)
     of integer;
                ContractAvailableKT:
     array(Contracts,TimePeriods)          of integer;
```

```
                ContractRevenueK:          array(Contracts)
           of integer;
                ContractAttributesKA: array(Contracts,Attributes)
           of integer;
end-declarations

initializations from DataFile
                CapitalCostD;
                AttributeCostDA;
                ContractAvailableKT;
                ContractRevenueK;
                ContractAttributesKA;
end-initializations



! Declaration of decision variables, with binary constraints
declarations
                DesignSelected:          array(Designs)
                of mpvar;
                AttributeSelected:         array(Designs,
Attributes)                of mpvar;
                ContractSelected:          array(Designs, Contracts,
TimePeriods)    of mpvar;
end-declarations

forall (dd in Designs)
do
                DesignSelected(dd) is_binary;
end-do

forall (dd in Designs, aa in Attributes)
do
                AttributeSelected(dd,aa) is_binary;
end-do

forall (dd in Designs, kk in Contracts, tt in TimePeriods)
do
                ContractSelected(dd,kk,tt) is_binary;
end-do

! Declaration of constraints
declarations
                TotalRevenue:                        linctr;
                DesignselectedMax:              linctr;
                ContractsCon:
     array(TimePeriods)                                        of
linctr;
                DesignselectedCon:         array(Designs, Contracts,
TimePeriods)                  of linctr;
                AttributeSelectedCon1:     array(Designs,
Attributes)                              of linctr;
                AttributeSelectedCon2:          array(Designs,
Contracts, Attributes, TimePeriods) of linctr;
                ContractContinuityCon:          array(Designs,
Contracts, TimePeriods)                   of linctr;
```

```
                ContractRunningCon:             array(Designs,
Contracts, TimePeriods)                    of linctr;
                ContractAvailableCon:      array(Designs, Contracts,
TimePeriods)                      of linctr;
end-declarations

! Objective function
TotalRevenue :=
       sum (dd in Designs, kk in Contracts, tt in TimePeriods)
       ContractRevenueK(kk)*ContractSelected(dd,kk,tt)
                -
                sum(dd in Designs)
CapitalCostD(dd)*DesignSelected(dd)
                -
                sum(dd in Designs, aa in Attributes)
AttributeCostDA(dd,aa)*AttributeSelected(dd,aa);



! Constraints:

! Only one vessel/design is selected:
                DesignselectedMax :=
                     sum(dd in Designs) DesignSelected(dd) <= 1;

! Ensures "design activation":
forall (tt in TimePeriods, dd in Designs, kk in Contracts)
do
                     DesignselectedCon(dd,kk,tt) :=
                          ContractSelected(dd,kk,tt) <=
DesignSelected(dd);
end-do
! Only one contract for each time period:
forall (tt in TimePeriods)
do
                     ContractsCon(tt) :=
                          sum(dd in Designs, kk in Contracts)
ContractSelected(dd,kk,tt) <= 1;
end-do
! Attribute constraint:
forall (dd in Designs, kk in Contracts, aa in Attributes, tt in
TimePeriods)
do
     AttributeSelectedCon2(dd, kk, aa, tt) :=
     ContractSelected(dd,kk,tt)*ContractAttributesKA(kk,aa) <=
AttributeSelected(dd, aa);
end-do
! Vessel can only have an attribute if it is used:
forall (dd in Designs, aa in Attributes)
do
          AttributeSelectedCon1(dd, aa) :=
          AttributeSelected(dd, aa) <= DesignSelected(dd);
end-do
! If a contract was assigned the previous period, it must be
assigned this period if it is still available.:
! The tt=1 case is a dummy case for programming only
```

```
forall (dd in Designs, kk in Contracts, tt in TimePeriods)
do
      if (tt = 1)
      then
      ContractContinuityCon(dd, kk, tt) :=
      ContractSelected(dd,kk,tt) * ContractAvailableKT(kk,tt) >= 0;
      ContractRunningCon(dd, kk, tt):=
      ContractSelected(dd,kk,tt)*ContractAvailableKT(kk,tt)<=1;
           else
      ContractContinuityCon(dd, kk, tt) :=
      ContractSelected(dd,kk,tt) >= ContractSelected(dd, kk, tt-1)
*ContractAvailableKT(kk,tt);
      ContractRunningCon(dd, kk, tt) :=
      ContractSelected(dd,kk,tt) * ContractAvailableKT(kk,tt-1) <=
ContractSelected(dd, kk, tt-1);
             end-if
end-do
! A contract can be assigned only if it is available:
forall (dd in Designs, kk in Contracts, tt in TimePeriods)
do
                   ContractAvailableCon(dd, kk, tt) :=
                   ContractSelected(dd,kk,tt) <=
ContractAvailableKT(kk,tt);
end-do

! Displays optimisation characteristics - only used if necessary:
!!setparam('xprs_verbose',true);
maximize(TotalRevenue);
```

! Output text:

```
if nDesigns <> 1
then
forall (dd in Designs)
do
                if getsol(DesignSelected(dd)) >= 1
        then
                writeln('Design ', dd, ' is the chosen design');
                end-if
end-do
end-if

writeln;
writeln('Optimal objective value : ', getobjval);

writeln;
forall (dd in Designs, tt in TimePeriods, kk in Contracts |
getsol(ContractSelected(dd,kk,tt)) > 0)
do
                if (kk <> 21 AND kk <> 22)
                then
                            writeln('It will choose contract ', kk,
' in time period ', tt);
                end-if
```

```
end-do
writeln;

if (sum(dd in Designs, kk in Contracts, tt in TimePeriods)
    (getsol(ContractSelected(dd,51,tt)) +
getsol(ContractSelected(dd,52,tt)))) > 0
then
                write('It will choose to be in the spot market in
time periode ');
end-if

forall (dd in Designs, tt in TimePeriods, kk in Contracts |
getsol(ContractSelected(dd,kk,tt)) > 0)
do
                if (kk = 21 OR kk = 22)
                then
                            write(tt, ', ');
                end-if
end-do

writeln;
write('The contracts chosen requires function ');

forall (dd in Designs, aa in Attributes )
do
      if sum(tt in TimePeriods, kk in
         Contracts)getsol(ContractSelected(dd, kk,tt))
           *ContractAttributesKA(kk,aa) >= 1
                 then
                      write(aa, ', ');
       end-if
end-do

end-model
```

Appendix 8 - Confidential Information

Can be seen in separate appendix (“Appendix 8 – Confidential Information”)