Thomas Stolpnes

Optimization Based Design of Subsea Processing Considering Reliability and Maintenance

Master's thesis in Subsea Technology
Supervisor: Audun Faanes
Co-supervisor: Milan Stanko, Leonardo Sales
June 2022

Master's thesis

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Abstract

Subsea technology often enables cost-effective development of small marginal fields, with short production lifetime and small profit margins. However, ensuring high level of reliability and low maintenance requirements of the subsea system is critical for success and often challenging to fulfill, especially for complex systems with multiple processes. Optimization-based design tools are a good way of assuring efficient and cost-effective processes, therefore the objective of this work is to incorporate reliability and maintenance aspects in a subsea production and processing optimization model.

The optimization was formulated to find optimal subsea equipment selection and production strategy that maximize net present value (NPV) considering constraints in production, system downtime, lost revenue from production losses, operational expenditures, and reliability. The optimization model uses superstructure optimization that contains all possible alterative equipment, which allows the optimizer to choose the optimal layout. This work has the advantage that the reliability model is part of the optimization model, therefore ensuring global optimality and avoiding multi-level optimization. The reliability model uses steady-state availability to estimate the system uptime. Maintenance costs were divided into inspection, maintenance, and repair (IMR) operational costs which are dependent on the availability, and maintenance costs which are not dependent on the availability of the system.

The method was tested on a study case of a synthetic field in the Norwegian Continental Shelf. Including reliability and maintenance affects significantly the optimal subsea layout obtained with the optimization. It was found that including maintenance in the model gave a different optimal solution that the one obtained when ignoring it. The difference in NPV between the two layouts was of 11 million USD (higher for the one considering maintenance). It was found that the difference in uptime was around 50 h/year more when considering maintenance. This relates to approximately 0.60 % in increased availability. The potential savings on maintenance cost per year were 0.44 million USD/year. The methodology presented provides an advancement towards modelling and automated decision-making in subsea processing system design.

Sammendrag

Undervannsteknologi gir mulighet for å utvikle små marginale felt som ofte har liten profittmargin og kort feltlevetid ved hjelp av kosteffektive løsninger. Det er derimot viktig at disse løsningene oppfyller kravene til pålitelighet og vedlikehold for å kunne oppnå disse målene. Disse kravene kan være vanskelig å tilfredsstille, da disse undervannsinstallasjonene som sørger for produksjon og prosessering er meget komplekse når det er snakk om store systemer. Optimaliseringsbaserte designverktøy er en god måte å sikre effektive og kostnadseffektive prosesser. Derfor er målet med dette prosjektet å implementere pålitelighet og vedlikeholds aspekter i en undervannsproduksjon og prosesserings optimaliseringsmodell.

Optimaliseringen var formulert slik at det optimale designet for undervanns produksjon- og prosesseringssystemet var det som ga den høyeste nåverdien ved å se på begrensningene i produksjon, tapt inntekt fra produksjonstap, operative kostnader, og systempålitelighet. Optimaliseringsmodellen bruker superstrukturoptimalisering der superstrukturen inneholder alle mulige alternativt utstyr. Dette lar optimaliseringsalgoritmen velge den mest optimale konfigurasjon.

Arbeidet har et fortinn i at pålitelighetsmodellen er en del av optimaliseringsmodellen. Dette sørger for en global optimal løsning og forhindrer multi-nivå optimalisering. Pålitelighetsmodellen bruker stasjonær ("steady-state") tilgjengelighet for å estimere systemets oppetid. Vedlikeholdskostnadene ble delt inn i kostander knyttet til inspeksjon, vedlikehold og reparasjon (IMR) som er avhengig av systemtilgjengelighet, og vedlikeholdskostnader som er uavhengig av systemtilgjengeligheten.

Metoden ble testet på en modell av et syntetisk felt på den norske kontinentalsokkelen. Inkludering av vedlikehold og pålitelighet påvirket i betydelig grad den optimale løsningen av undervannssystemet. Det ble funnet at ved å inkludere vedlikehold og pålitelighet i modellen, ble det funnet en annen konfigurasjon enn den som ble funnet når det ble ignorert. Forskjellen i nåverdi ved de to forskjellige konfigurasjonene var 11 millioner USD, der konfigurasjonen med inkludering av vedlikehold ga den høyeste verdien. Det ble også observert en økning i oppetid på 50 timer/år ved å inkludere vedlikehold. Dette er en økning på ca. 0.6 % i total systemtilgjengelighet. Vedlikeholdskostnadene ble også redusert med 0.44 millioner USD/år med denne systemkonfigurasjonen. Metoden som er presentert bidrar til et framskritt i modellering og automatisert beslutningstaking ved undervannsproduksjon og -prosessering system design.

Preface

This Master Thesis was written in the spring of 2022 as a closing part of my 2-year master's programme in Subsea Technology, with specialization in maintenance and operation at the Norwegian University of Science and Technology (NTNU). The project was conducted at the Department of Geoscience and Petroleum (IGP), as part of a SUBPRO project in field layout optimization.

The project was supervised by adjunct professor Audun Faanes. The project was originally drafted by the co-supervisor associate professor Milan Stanko, in conjunction with Ph.D. candidate Leonardo Sales. I would like to express my gratitude and appreciation to all of them for their guidance, advice, and feedback throughout the semester.

I would also like to thank Caroline Roxane B. Harvengt, Equinor, for good advice and input during the project.

Lastly, a special thanks to UTC for giving me the opportunity to present my work to the industry as one of the student presenters at their conference in Bergen this year.

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List of Abbreviations

AHC = Active heave compensation

CAPEX = Capital expenditures

GAMS = General algebraic modeling software (a software tool)

IMR = Inspection, maintenance, and repair

ISBL = Inside battery limit

ISO = International organization for Standardization

LCC = Life cycle costing

LR = Lost Revenue

FPSO = Floating production, storage, and offloading unit

MC = Maintenance cost

MDT = Mean downtime

MINLP = Mixed integer non-linear programming

MTBF = Mean time between failure

MTTF = Mean time to failure

MTTR = Mean time to repair

NLP = Non-linear programming

NPV = Net present value

OPEX = Operational expenditures

RAMS = Reliability, availability, maintenance, and safety

ROV = Remote operated vehicle

SEN = State equipment network

SQP = Sequential quadratic programming

STN = State task network

List of Symbols

Symbol	Unit	Description
A	[-]	System availability
A_j	[-]	Availability of equipment j
C_0	[million USD]	Investment cost
C_c	[million USD]	Cost of cooler
C_{fg}	[million USD]	Cost of gas flowline
C_{fm}	[million USD]	Cost of multiphase flowline
C_{fo}	[million USD]	Cost of oil flowline
C_j	[million USD]	Cost of subsea equipment j
C_k	[million USD]	Cost of compressor
C_{mp}	[million USD]	Cost of multiphase pump
C_p	[million USD]	Cost of oil pump
C_{rg}	[million USD]	Cost of gas riser
C_{rm}	[million USD]	Cost of multiphase riser
C_{ro}	[million USD]	Cost of oil riser
C_{ss}	[million USD]	Cost of subsea separator
C_{ts}	[million USD]	Cost of topside separator
C_t^F	[million USD]	Cashflow in timestep t
$CAPEX$	[million USD]	Capital expenditure
DR_{avg}	[NOK/d]	Average daily vessel cost
DR_{LV}	[NOK/d]	Daily cost of a small IMR vessel
DR_{SV}	[NOK/d]	Daily cost of a large IMR vessel
f_{ISBL}	[-]	ISBL investment maintenance factor
f_{si}	[-]	Fraction of small IMR intervention
f_{sp}	[-]	Cost factor when including spare units
G_t	[ton/h]	Gas flow rate in timestep t
j	[-]	Equipment index
LR	[million USD]	Total discounted lost revenue
LR_t	[million USD]	Discounted lost revenue in timestep t
MC_j	[million USD]	Yearly IMR maintenance cost of equipment j
MC_t^{IV}	[million USD]	Yearly IMR maintenance cost of system
MC_t^{ISBL}	[million USD]	Yearly maintenance cost from ISBL investment
MDT_j	[h]	Mean downtime for equipment j
$MTTF_j$	[h]	Mean time to failure for equipment j
N_j	[-]	Number of equipment in the subsea system
N_t	[-]	Number of timesteps
NPV	[Million USD]	Net present value
O_t	[ton/h]	Oil flowrate in timestep t
p_{gas}	[USD/MMBtu]	Gas price
p_{oil}	[USD/bbl]	Oil price
P_t^k	[kW]	Compressor power consumption
P_t^{MP}	[kW]	Multiphase pump power consumption

P_t^p	[kW]	Oil pump power consumption
r	[-]	Interest rate
r_{EX}	[NOK/USD]	Exchange rate
r_{inf}	[-]	Inflation rate
t	[-]	Index for timestep
x	[-]	Flow vector
y_j	[-]	Binary variable for equipment j
α	[h/year]	Operating time per year
α_0	[h/year]	Base operating time per year
λ_j	[1/h]	Failure rate for equipment j
μ_j	[1/h]	Repair rate for equipment j

1 Introduction

1.1 BACKGROUND

The export of oil and gas is one of the largest sources of income for the Norwegian economy [1]. Norway is recovering and processing oil and gas from the coast of Norway from reservoirs that are located below the sea. The oil and gas are contained in the reservoirs before brought to the surface by wells drilled from the surface down to the reservoir. Historically the fields have produced to an offshore oil-platform and transported to land using pipelines or ships. Subsea technology seeks to eliminate the need for such platforms by placing a significant part of the production and processing equipment on the seabed [2]. Examples of equipment that has been placed subsea are oil-gas separators, water-oil separators, sand separators, multiphase meters, multiphase pumps, coolers, and gas compressors to name a few.

The processing equipment used is designed specifically with the parameters and characteristics of the producing reservoir, their distance to receiving facilities, the temperature of the environment, and the pressure in the reservoir and the composition of the well-stream. Since no two reservoirs are identical, the design and sizing of the subsea processing facilities are unique for each field development project.

To find the best design for a facility with subsea processing, the reservoir parameters are used to generate a simulation of the field's future and potential production. With this, processing equipment can be correctly sized for the field. The challenge is to find the best layout and combination of subsea processing equipment which yield the highest net present value (NPV).

Manually searching through the different options and layouts is usually slow and expensive. The complexity increases exponentially when more units, locations and parallel trains are considered. Therefore, in this thesis it is proposed to optimize the layout using numerical optimization.

Umeda et al. proposed and developed a method called the superstructure approach to use in the optimization algorithm [3]. The superstructure approach assembles all possible combinations of flow paths and equipment that may be utilized in a given project into a large schematic. From this superstructure an optimizer algorithm chooses what to include and not include to maximize the objective function for the given parameters within the constraints that may apply.

Krogstad used the superstructure approach in his thesis in 2018 to create an optimization model for a production system that considers subsea production and processing. The model uses mixed integer non-linear programming (MINLP) to optimize for the largest net present value (NPV) possible [4]. While this model optimizes the production and processing equipment, there is still improvement to be made regarding reliability and maintenance.

1.2 SCOPE OF THE REPORT

This thesis develops a detailed reliability and availability model for a generic subsea system that contains several subsea processing units. The reliability and availability model provides maintenance costs, intervention costs, uptime considering availability, and production loss due to downtime. The model was integrated with the existing subsea layout optimization model developed by Krogstad, and a study case is analyzed.

The work presented in this thesis is a continuation of the specialization project completed in 2021, where reliability and maintenance aspects of different existing subsea processing layouts were analyzed and compared considering only availability.

Chapter 2.2 and 2.3 are therefore similar to a section from the report "Reliability and Maintenance Analysis of Subsea Processing Configurations" [5], although with some new additions and some changes.

The main objective for this project is:

- ▽ Improve the reliability and maintenance aspects of the subsea production and processing model developed by Krogstad [4]
- ▽ Integration of the reliability and availability model with the subsea layout optimization routine of Krogstad [4]
- ▽ Investigate the potential difference the in layout and NPV with the maintenance implementation

1.3 TOOLS EMPLOYED

To simulate and calculate the results in this report the following tools were employed:

- General algebraic modeling software (GAMS) for the simulations. The version utilized was GAMS 37, with BARON solver.
- Microsoft Excel to compute some initial availability calculations on the equipment. These values were later inserted into the GAMS model. The details about this are mentioned in more detail in Chapter 3. The simulation data was processed in Excel to generate the diagrams and tables presented in the results.

1.4 MAIN CONTRIBUTIONS

The main contributions of this thesis are:

- The total system availability of a subsea processing system using steady-state availability calculations.
- Consideration of onshore spare equipment. This was implemented in the CAPEX cost estimation equations for relevant equipment (multiphase pump, oil pump, compressor unit, and cooler).
- Consideration of a yearly general maintenance cost in the model.
- Consideration of maintenance costs due to the IMR operations required to perform maintenance operations on the subsea equipment.

1.5 LIMITATIONS OF THE WORK

There are several limitations associated with this thesis. These are mainly associated with the accuracy of the data used in the reliability model. Collecting accurate data is very difficult as these are usually not publicly available.

The methodology in calculating the maintenance costs for IMR operations is also simplified, as there are few public available data for both the costs and operation times. The reliability aspects use the steady-state availability method, but the downtime data and mean time to failure (MTTF) are a large uncertainty factor in this work.

Lastly, the optimization model uses static oil, gas, and electricity prices during the entire lifetime. There is no guarantee that these values will be accurate as it is impossible to predict such events. This is a large uncertain factor, and it limits the accuracy of future revenue from the production and also maintenance cost, as these are usually linked in some proportion. During high oil prices, the cost of offshore activities like maintenance and vessel utilization rise, and vice-versa during low oil prices.

2 Theoretical Background

This chapter introduces the concept of subsea processing, and the reliability and maintenance theory applied in this thesis. It also mentions some of the aspects of life cycle costing (LCC), offshore IMR operations and cost estimation used in the model. Reliability and maintenance are important parameters to measure accurately as early as possible due to the potential savings later in the development and operation phases of projects and potential costs associated with later design changes [6].

2.1 SUBSEA PROCESSING

Subsea processing is a concept that is constantly under development and has been firmly established in over the past decade within subsea technology development. Traditional liquid handling has taken place on a processing plant offshore or onshore. Subsea processing seeks to achieve processing and handling of the produced liquid/gas on the seabed to reduce or eliminate the need for a topside facility [2].

Subsea installations have existed since 1985 when the first subsea X-mas tree was installed. In the later years Norway has been on the forefront for development of subsea technology. The new developments saw the introduction of the Ormen Lange field in 2008, a subsea field producing to a processing plant in Nyhamna with no offshore topside facility. The Tordis field has a subsea separator, and the Åsgard field has subsea gas compression systems [7].

There are mainly four types subsea processing applications [8]:

- Multiphase / single-phase boosting
- Gas compression
- Separation processes
- Raw seawater injection

With subsea separation, the liquids can be separated close to the producing wells and reinjected quickly and efficiently wasting less energy by having to pump the fluid all the way to the topside and back. It also allows for effective water handling, and the need for topside water treatment is reduced, thus debottlenecking the processing plant [9].

Subsea boosting and gas compression allows for increased production rates and longer production, by increasing the pressure differential from the well to the receiving facility. This can allow for higher production rates when pressure decline has reduced the natural flow capabilities. By providing longer economically feasible production it is possible to increase the overall recovery of the field. Boosting also allows the fluids to be transported over longer distances to potentially tie into nearby facilities. It also makes it possible to develop and produce low energy fields that would otherwise be unfeasible without artificial lift [4].

Other benefits when considering production with subsea technology are improved flow assurance and HSE-benefits. An increase in flexibility in field development is achieved by reducing the need for modifications and/or facilities on the topside. Also, the environmental impact is reduced alongside the potential risk of explosions and fire [8]. Some of the challenges related to subsea equipment are the requirement for high reliability, specifically the mean time between failure (MTBF), the harsh surrounding environment being saltwater, and the high pressure and temperature design requirement [2].

2.2 RELIABILITY, AVAILABILITY AND MAINTENANCE

This section introduces the general concept of reliability, maintenance, availability, and safety, also denoted as RAMS.

2.2.1 Reliability

The general concept of reliability is the ability of a part or equipment to operate under given conditions over a certain time period. The ISO (1986) defines a systems reliability as “the ability for a system to work under specified environmental and operational conditions for a specified time period” [10].

To ensure that the reliability of equipment meet the given criteria, a reliability requirement is issued to the supplier(s). These requirements are often based on issues the operator of the equipment may encounter during the operation of the equipment. If the supplier(s) does not give a target for reliability, the aim is the highest possible reliability, for the lowest cost [11].

2.2.2 Maintenance and Maintainability

To understand the strategies deployed in the field on operating equipment, first it is important to understand the basic philosophy behind maintenance. Maintenance is defined by ISO (2016) as "A combination of all technical and management actions intended to retain an item or restore it to a state in which it can perform as required" [12].

The maintainability of an equipment part is essential for the equipment's availability alongside the reliability of the equipment. Maintainability is a measure of the ease or difficulty to restore the part into its intended operational state [13].

Maintenance can be divided into two main categories. These are corrective maintenance and preventive maintenance. These main categories can further be divided into subcategories. This is mainly on preventive maintenance, as there are several ways to approach preventive maintenance as opposed to corrective maintenance.

2.2.2.1 Corrective Maintenance

Corrective maintenance is the most basic form of maintenance strategy. The concept is to run the equipment until a failure occurs, this is commonly referred to as run-to-failure. The failure could be a catastrophic failure of the part or simply the part is no longer functioning within the operating parameters [13]. At the time of failure, the failed part will be repaired or replaced according to specified protocol. This type of maintenance will possibly introduce a longer downtime since the maintenance intervention is not planned and might require some logistical effort. This effect will be multiplied when the equipment is offshore and there is no easy way of acquiring special tools or spare parts if they are not already present [14].

There are certain exceptions to this approach. The relative importance of the parts to the overall system integrity and the available redundancy associated with the failed part is some of the considerations when deciding against an immediate action to perform corrective maintenance. The maintenance can be scheduled for a later stage when a better opportunity arises if the part is not critical for the overall integrity or there is enough redundancy in the system to keep it within operating parameters [14].

2.2.2.2 Preventive Maintenance

Preventive maintenance is a form of maintenance where the maintenance operation is planned in advance, and is performed from the basis of one of these measures listed below:

- ∇ Age-based maintenance
- ∇ Condition-based maintenance
- ∇ Clock-based maintenance
- ∇ Opportunistic maintenance

Age-based maintenance is performed when a part has reached a given age. Age in this instance could be operational hours or operational distance as with an engine in a car to name a few. At this time the maintenance operation is performed, whether a failure has occurred or not. Clock-based maintenance is similar to the age-based, where they differ is the clock-based is simply a set calendar time at which maintenance is performed [13].

Condition-based maintenance can also be referred to as predictive maintenance. The aim of this strategy is to continuously monitor the equipment. By doing so gather data of some of the operational parameters and establish the current state of the equipment. When one these parameters is outside of the acceptable operational range, maintenance is performed on the part [13]. This type of operation may also allow for *just-in time* maintenance, extracting as much life as possible out of the equipment while still reducing the downtime to a minimum.

Opportunistic maintenance is a type of maintenance strategy relevant for multi component systems, not suited for systems with only one operating component. The strategy seeks to perform multiple maintenance operations at the same time, thereby achieving higher efficiency of the downtime that is already in place. This is especially effective on production lines or in large plants where a breakdown of a single component in the system calls for a complete shutdown of the facility [15].

2.2.3 Downtime

The downtime can be categorized into two main sections. Unplanned downtime and planned downtime. Unplanned downtime is directly a result of corrective maintenance since it is not a scheduled event. Planned downtime is as with preventive maintenance scheduled in advance, and therefore it is already a planned event.

The planned downtime is better estimated than the unplanned downtime. The unplanned downtime is highly dependent on the cause of failure and failure type the equipment [13].

Mean downtime (denoted MDT) is the average downtime or expected average downtime regardless of the failure type. This can be calculated to increase the accuracy of the true MDT value [13], however for the purpose of this thesis the MDT values are assumed and not based on any calculations, and has a large uncertainty associated with them.

2.2.4 Availability

Availability is the probability of the system to operate within a specified time when required. It could also be expressed as the fraction of time the system is ready to operate within the given operational parameters [16].

The key parameters that affect the availability of a system are MTBF and mean time to repair (MTTR) [13]. The reliability of the system is higher when the MTBF is longer and vice-versa, and the maintainability would be higher at a lower MTTR value and vice-versa.

Steady-state availability is one of the more important factors for some applications when selecting equipment to use in operation [17]. Given the limitations of oil and gas production and processing system design, this thesis will only cover the fundamentals of *series* systems. *Series* in reliability and maintenance relation is a term "borrowed" from electrical engineering to explain systems that will fail with the failure of a single component.

MTTF or mean time to failure is a term used to describe the mean operating/functioning time of equipment before failure [13]. With MDT and MTTF as inputs let j be an index for equipment. As stated earlier, availability is a fraction operational time over total time. This gives an expression for steady-state availability as shown as

$$A_j = \frac{MTTF_j}{MTTF_j + MDT_j} \tag{2.1}$$

It is also possible to express the equipment steady-state availability as a function of *repair rate* and *failure rate*. The failure rate is simply an inverse of the MTTF and describes the number of failures per unit time. The repair rate is the inverse of MDT and describes the number of repairs per unit time. Using j as an equipment index, let λ denote *failure rate*, and μ denote *repair rate* to give steady-state availability as shown in Eq. 2.2

$$A_j \;=\; \frac{\mu_j}{\mu_j + \lambda_j} \tag{2.2}$$

When calculating the steady-state availability of a *series* system, it might be easy to think of the product rule. This could be used approximation when j is small and values of A_j very close to 1. For lower values of A_j or for a large j this method will underestimate the value for system value for A [18].

Assuming the independent steady-state availability of all the equipment comprising a system, the true system steady-state availability can be formulated as

$$A \;= (1 + \sum_{j=1}^{N_j} \frac{1 - A_j}{A_j})^{-1} \tag{2.3}$$

The product rule is the correct way of determining the steady-state availability when equipment availability is based on total system time or total calendar time. This is an unusual method but has been utilized sometimes in the offshore industry. Calculating the steady-state availability as shown in Eq 2.3 requires the equipment availability to originate from actual operational time and actual downtime [18].

2.3 LIFE CYCLE COSTING

Life cycle costing (LCC) is the process of evaluating the different life cycle cost of different options available. The life cycle cost represents the total cost during the life cycle of a project. This is important metric to apply in projects to maximize the economic potential. The decision-makings impact on overall economic gains is greatly diminished later in projects [6]. An example of this is presented in Figure 1.

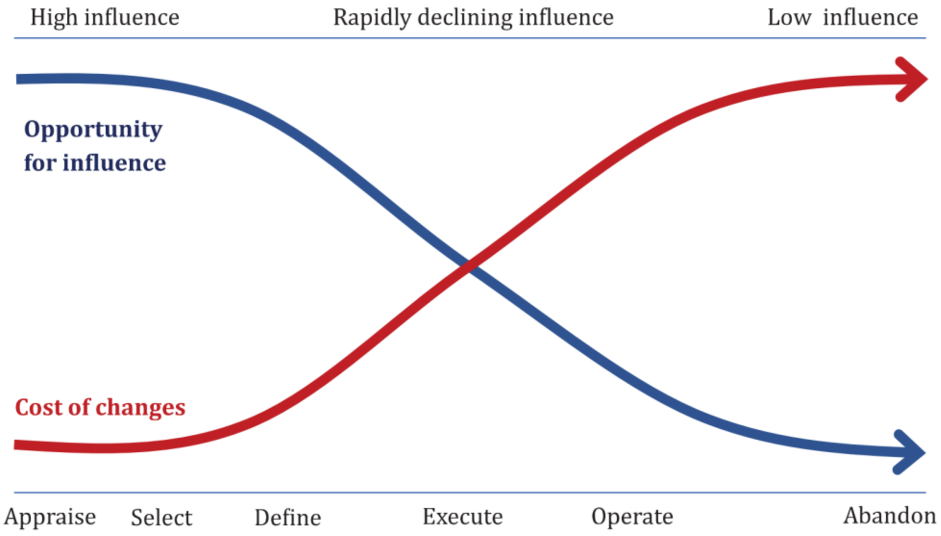

Figure 1 - Opportunity for influence vs cost of change [6]

The earlier a potential change can be realized in a project, the greater the potential of influence the change has to the project itself. Therefore, it is important in subsea field development to find the best solution in the design phase. If the changes were to be made later, larger restrictions would be in place and the cost of making a similar change would be increased.

LCC can also offer better predictability by optimizing the revenues and costs during field development over the lifespan which reduces the operator's economic uncertainty. Management of the LCC is however important to ensure the cost-efficiency potential and to add value to the project [6].

The main factors that affect the total life cost are equipment quality and maintenance strategy. The cheapest upfront equipment cost may not be the best overall solution as the maintenance cost over the lifetime may increase the total cost to several times that of the original investment [19]. Figure 2 illustrates different investment- and operational cost options for a project. In real applications the cost development during the lifetime is not necessarily linear, as it would be affected by many different parameters and changes.

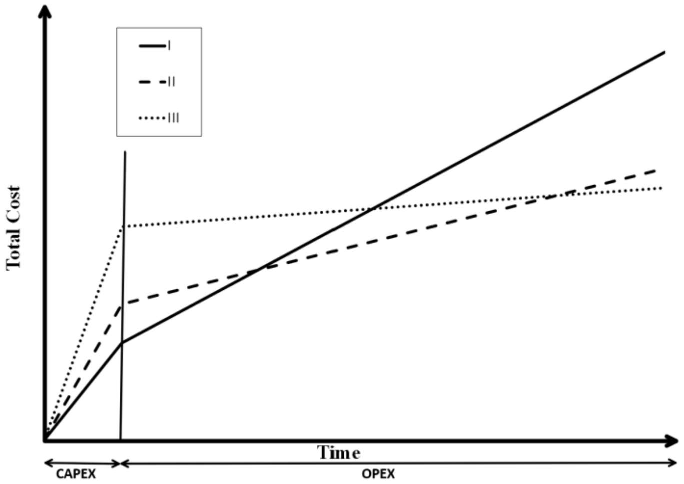

Figure 2 - Example of different LCC options for a project [5]

2.4 MARINE OPERATIONS RELATED TO IMR

When operating offshore especially on the seabed with subsea systems there are several extra stages of planning, complexity and expenses compared to onshore. Four out of the twelve interlinked processes highlighted by API RN-17N mentions availability [11]. One of the most relevant points for subsea production and processing should be to manufacture and design for availability, as mentioned in Chapter 2.1, which can be achieved with very high MTBF.

IMR is crucial to ensure that a system is able to operate safely and within the operational parameters. Subsea systems are operating on the seabed, which is inconvenient for easy access to perform IMR.

Performing subsea IMR operations requires the use of specialized vessels, with lifting cranes, remote operated vehicles (ROV), specialized tools and experienced ROV-operators. To perform a subsea IMR operation as efficiently as possible, planning and preparation are important. The ROV-operators experience is one of the key parameters to enable this, as of today ROV’s require a human pilot to operate. In addition, the weather is a crucial factor as these vessels have specific weather windows to perform these operations [20].

There are several different types of IMR operations, ranging from a simple inspection of the subsea equipment all the way to replacing an entire unit. Subsea systems are designed in such a way that allows for more efficient replacements of smaller modules on certain type of equipment. However, sometimes the entire or a large part of a subsea module must be replaced [14]. Figure 3 is an example of an IMR and survey vessel which can perform small scale lifting operations or inspection/survey mission.

Figure 3 – IMR and survey vessel Edda Flora [21]

The cost related to subsea IMR operations are usually very costly to the operator, due to the extensive planning and complicated tasks. The cost of the vessel itself is also a factor. There are several different types of vessels that can be utilized for IMR operations in different scenarios. Larger vessels are more expensive than smaller ones, but sometimes a small vessel might not have enough equipment or enough lifting capacity to perform the operation at hand. Figure 4 shows an example of a construction vessel, capable of performing heavy lift IMR operations. A short summary of both vessel’s specification sheet is shown in Table 1 below the figure. With the additional deck space and lifting capacity, Edda Freya is able to perform a large variety of installations, replacement and decommissioning operations. On the other hand, Edda Flora has a lower crane capacity and might not be able to perform all the potential lifting operations required, if for example a large compressor unit needs full replacement. This vessel is more capable to perform light interventions and inspection operations. With its smaller size, it would be more economical to use on those missions rather than the larger vessel.

Figure 4 – Construction vessel Edda Freya [22]

Table 1 - Summary of some key features on both vessels [21] [22]

Parameter	**Edda Freya**	**Edda Flora**
Length [m]	149.8	95
Beam [m]	27	20
AHC offshore crane capacity [ton]	600	100
Free deck area [m^2]	2 300	750
Moonpool size [m]	7.2 x 7.2	7.2 x 7.2
Survey ROV [-]	0	1
Work class ROV [-]	2	1

2.5 SHORT INTRODUCTION TO OPTIMIZATION

Since the main aspect of this thesis is to model the RAMS, and not optimalization and the complex theory behind it, the thesis will not cover it in detail. However, in this section some of the basic principles and theory are introduced to give some insight on how the optimization model functions and operate.

Optimization is a valuable tool in decision making to analyze systems. The goal of the optimization is to optimize an objective. This objective can be defined as a quantitative measure of a system’s performance. The objective depends on variables that describe the system’s characteristics. These values are often also constrained or restricted. The goal is to find the value of these variables that gives the optimal objective value. The value for the objective can be income, costs, time, or a combination of quantities that can be represented by a single number [23].

Superstructure optimization is one method used in optimization. The superstructure approach was first proposed and developed by Umeda et al. [3]. Superstructures represent all solutions expected by the designer combined. Considering a superstructure for a subsea processing layout problem, an objective function for the problem needs to be in place for the optimization model to maximize/minimize, like the total system cost, profit or NPV. Mathematical models of each process equipment should be added to the model together as constraints and variables to optimize for the objective [4].

Superstructures can be represented as one of two forms, either state task network (STN) or as state equipment network (SEN) representation. STN-structures declare a set of different tasks in-between various states to convert from a starting material to a finished product, placing different equipment in the slots to perform those specified tasks. SEN-representations use equipment likely to perform tasks in the in order to perform the state change. In the slots of the equipment the tasks are assigned to the unit in the equipment slot [24].

Mixed integer non-linear programming (MINLP) uses both discrete and continuous variables to describe a problem, where the objective function and feasible regions are described by non-linear functions [25]. The superstructure of a subsea processing facility can be expressed as a MINLP problem where the physical equipment is described using discrete integer variables, and the constraints as the continuous variables. These integer variables can be simplified into binary variables, where 0 would indicate an inactive node and 1 an active node for the discrete variables.

Solving these MINLP problems are difficult, and computationally demanding. There are several algorithms used to solve MINLPs, one of them is called the branch-and-bound method [4]. This method breaks down the problem in an integer tree, and then solves each node of this tree. At each node, the solver breaks the problem into non-linear subproblems (NLPs) in order to reach the optimum solution.

NLP problems are defined when one or more functions are non-linear, and all the variables are continuous. These problems are harder to solve than linear optimization problems as they are not necessarily convex, but still doable with quadratic approximations such as sequential quadratic programming (SQP) [4].

A general structure of an MINLP problem takes the following form

$$\begin{cases} \min \quad f(x,y) \\ s.t. \quad h(x,y) = 0 \\ g(x,y) \le 0 \\ x \in X \\ y \in Y \end{cases} \tag{2.4}$$

where $f(x,y)$ represents the objective function, $g(x,y) \le 0$ represents the inequality constraints, $h(x,y) = 0$ represents the equality constraints, x is a vector of continuous variables and y is a vector of integer variables [26].

3 Methodology

This section introduces the optimization model, assumptions made to incorporate the new parameters and equations, new equations, how the existing equations changed with the new additions, and how the different cases were formulated.

3.1 INTRODUCTION TO THE MODEL AND SUPERSTRUCTURE

The methodology for this work will be based on the superstructure proposed by Krogstad [4]. Figure 5 illustrates the subsea layout superstructure. All the flows are represented by the continuous vector x, while the equipment (gravity separator, water treatment, FPSO, pumps, and others) is represented by the binary vector y. A solution to the problem is then represented by the set of optimal flowlines (x), equipment (y), system pressure, and equipment capacity. The most important set of variables is the equipment y (which is referred to as the layout), as this selection is the one that mainly affects the NPV. The other variables are continuous and thus can generate infinitely many solutions around a set of y [5].

Among the set of variable equipment y, there are some fixed equipment that is always present. Those are the subsea gravity separator, oil well, and the water treatment. This is because subsea oil-water separation always is present, and the separated produced hydrocarbons will be boosted to operate the field with sufficient production rates [3].

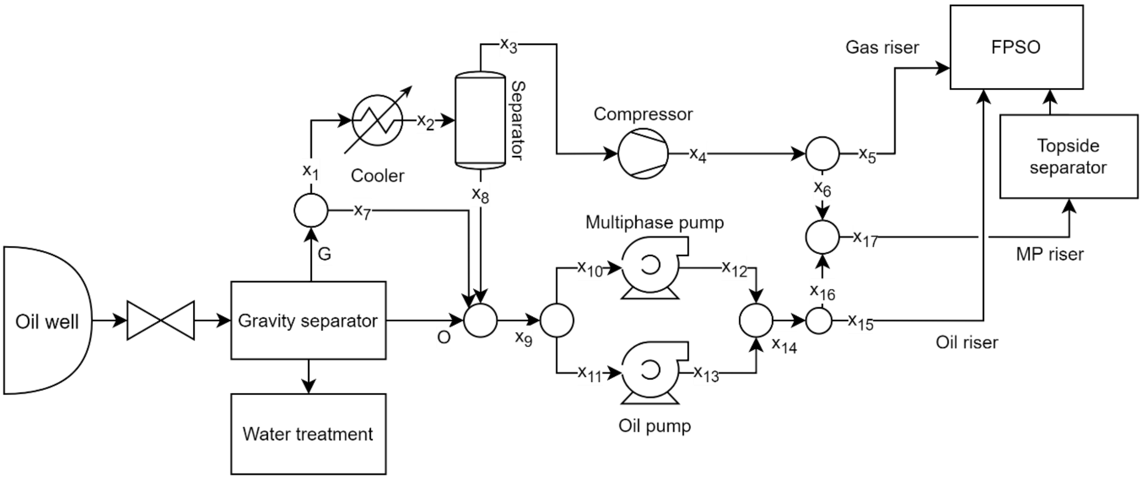

Figure 5 – Superstructure [4]

3.2 ASSUMPTIONS TO THE NEW ADDITIONS IN THE MODEL

To implement the maintenance and reliability aspects to the GAMS model some assumptions had to be made for the purpose of this report. The assumptions made is listed below:

- ∇ Equipment availability can be approximated with the steady-state availability equation expressed in Chapter 2 as Eq. 2.1.
- ∇ The MDT indicates the time at which the processing plant is non-operational i.e., zero production.
- ∇ The equipment downtime is constant and is an approximated value considering both preventive and corrective maintenance operations.
- ∇ The vessel cost is running the entire duration of downtime.
- ∇ There are no bypass flowlines.
- ∇ One yearly inspection per subsea equipment.
- ∇ Common-cause failures are excluded.
- ∇ Cost of maintenance are inflation-adjusted on a yearly basis using a fixed inflation rate.
- ∇ Refurbishment and general maintenance of spare equipment is considered as part the ISBL maintenance cost.
- ∇ A total of 20 years of simulation time is sufficient.

In addition to the assumptions made above, new parameters were introduced to estimate the maintenance cost related to subsea inspections and repairs, and parameters needed to compute the steady-state availability of all the equipment. Table 2 show the parameters contributing to the maintenance cost estimations, while Table 3 show the reliability parameters used in the availability calculations.

Table 2 – Data used in the maintenance equations

Parameter	value	Unit
Large vessel cost	2 000 000	[NOK/d]
Small vessel cost	1 000 000	[NOK/d]
Exchange rate	8.8	[NOK/USD]
Inspection time	12	[h]
Fraction small IMR operations	0.8	[-]
Avg yearly inflation rate	3	[%]
ISBL maintenance factor	5	[%]
Spare part investment cost factor	1.8	[-]

Table 3 - Reliability data used to calculate the input data for the model

Equipment	MTTF [h]	MDT [h]
Cooler	65 700	168
Separator	43 800	24
Compressor	48 180	288
Oil pump	48 180	288
MP pump	35 040	288
Gas transport line	175 200	24
Gas riser	175 200	24
MP transport line	175 200	24
MP riser	175 200	24
Topside separator	70 080	72
Oil transport line	175 200	24
Oil riser	175 200	24

3.3 EQUATIONS AND MODEL PARAMETERS

From the thesis by Krogstad [4] there are two equations and one variable that were modified to include the maintenance and reliability in the subsea processing optimization model. Therefore, the equations that did not change or was of little relevance to the purpose of this thesis are not shown this section. The source code for the optimization model is in Appendix B. The model used in this thesis is an updated version of the model used by Krogstad. It has since then been modified slightly by Sales in his work. The model used in this thesis has modified some equations to use different formulations of some parameters compared to the one originally formulated by Krogstad [27].

3.3.1 Objective Function

As stated earlier the goal of the project was to maximize the NPV. The objective function in GAMS is formulated as described below

$$maximize\ NPV \qquad (3.1)$$

The NPV is calculated as described in Eq. 3.2

$$NPV = \frac{-C_0}{1+r} + \sum_{t=1}^{N_t} \frac{C_t^F}{(1+\ r)^t} \qquad (3.2)$$

In Eq. 3.2 C_0 is the cost of initial investment, also known as capital expenditure (CAPEX), the C_t^F is the cashflow at timestep t and r is the interest rate. Each timestep in this model is equal to one year. This is a slight discrepancy between the different formulations in Krogstad's thesis. This is the NPV formula that is described in the text of the source code, and the one used in this thesis.

3.3.2 New Equations

The new equations introduced used the values described in Table 2 and Table 3. The steady-state availability of the equipment was calculated using Eq. 2.1 as described in Chapter 2.2.4.

In order to implement the steady-state availability equation into the GAMS model, some modifications were made to the steady-state availability equation as described in Eq. 2.3. The modified steady-state availability equation can be seen below as Eq. 3.3.

$$A = (1 + \sum_{j=1}^{N_j} \frac{1 - {A_j}^{y_j}}{{A_j}^{y_j}})^{-1} \tag{3.3}$$

In the modified Eq. 3.3, y_j is the binary variable of equipment j indicating if the equipment is in use, and A is system availability. The model is able freely choose a layout, and therefore the amount of equipment in use will differ and change. Since this model only considers single equipment and not any parallel equipment, the exponent rule can be used. This will also avoid the need to filter out equipment not in use, since anything to the power of 0 is always equal to 1. If the y_j is 0, the nominator is equal to 0, effectively canceling out that term for that specific equipment in a simple and effective way.

To estimate the yearly maintenance cost associated with subsea IMR operations some estimations and simplifications are made. The maintenance cost was calculated based of the failure frequency per year, per equipment. Doing it this way, the maintenance cost is a fixed average value. This allows for simple expressions, though not a perfect solution, but a computationally easy one.

As mentioned in Chapter 2.4, this thesis will distinguish between small and large vessels used in subsea IMR operations. To find a single value to represent the daily cost of an IMR vessel used on all the subsea equipment, the fraction method was utilized. The equation used to describe the vessel cost is described in Eq. 3.4 below

$$DR_{avg} = DR_{sv} \cdot f_{si} + DR_{lv} \cdot (1 - f_{si}) \tag{3.4}$$

Where DR_{sv} is the daily cost of a small IMR vessel, DR_{lv} is the daily cost of a large IMR vessel and f_{si} represents the fraction of IMR operations carried out by small IMR vessels. This equation is calculated using NOK as the currency.

Calculating the yearly maintenance cost associated with subsea IMR operations is done in a per equipment way. This uses inputs such as the MTTF to calculate the yearly failure frequency, and MDT to calculate the vessel costs during downtime for that specific equipment. This is expressed as Eq. 3.5

$$MC_j = \frac{t_{insp}}{24} \cdot \frac{DR_{sv}}{r_{EX}} + \frac{MDT_j}{24} \cdot \frac{DR_{avg}}{r_{EX}} \cdot \frac{8\,760}{MTTF_j} \tag{3.5}$$

Using j as equipment index, $MTTF_j$ represents the equipment's mean time to failure, and MDT_j is mean downtime. Further the t_{insp} represents the duration of a subsea inspection, DR_{sv} is the daily cost of a small IMR vessel, and DR_{avg} is the calculated average daily vessel cost from Eq. 3.4. 8 760 is the number of hours per year and r_{EX} represents the currency exchange rate from NOK to USD.

The total yearly maintenance cost for subsea IMR operations is therefore the sum of the cost of all equipment in use, described as Eq 3.6

$$MC_t^{IV} = \sum_{j=1}^{N_j} MC_j \cdot y_j \cdot (1 + r_{inf})^{(t-1)} \tag{3.6}$$

Here the MC_j is the yearly maintenance cost for equipment j, y_j is the binary variable indicating the state of equipment j, and r_{inf} is the inflation rate. Lastly, t is the timestep.

In addition to the maintenance cost associated with subsea IMR operations, an additional maintenance cost is implemented into the model. This being the inside battery limit (ISBL) maintenance cost. The maintenance cost is usually estimated to be between 3-5 % of the ISBL investment cost [28]. Since this is a subsea processing plant, the maintenance cost based of the ISBL investment is assumed to be 5 % for this project as mentioned in Table 2. Using this the cost of maintenance is formulated as Eq. 3.7

$$MC_t^{ISBL} = f_{ISBL} \cdot C_0 \cdot (1 + r_{inf})^{(t-1)} \tag{3.7}$$

Here f_{ISBL} is the factor of ISBL investment contributing to maintenance, C_0 is the installed cost of all equipment in use, r_{inf} is the inflation factor, and t is the timestep.

The lost revenue is a metric used to describe the lost production due to unexpected downtime in the production and processing system. The lost revenue is included in the cash flow equation highlighted in Eq. 3.2 by the α which is the actual operating hours in a year. Using α_0 as the maximum operating hours per year, the subsea system availability will be the limiting production factor. Isolating the discounted lost revenue allows for comparison between layouts and to investigate the present value at each timestep t. described as Eq. 3.8

$$LR_t = \frac{(\alpha_0 - \alpha) \cdot (O_t \cdot p_{oil} + G_t \cdot p_{gas})}{(1 + r)^t} \tag{3.8}$$

The O_t represents the oil production at timestep t. G_t represents the gas production at timestep t, p_{oil} is the price of oil and p_{gas} is the price of gas and r is the interest rate.

Finding the total discounted lost revenue is simply the sum of lost revenue at each timestep over all timesteps. This can be expressed as Eq. 3.9

$$LR = \sum_{t\,=\,1}^{N_t} LR_t \tag{3.9}$$

3.3.3 Modified Equations and Variables

3.3.3.1 Original Formulations

As mentioned earlier, there are mainly two equations and one variable that will be modified to implement the maintenance and reliability aspects. The first equation, the cashflow equation, originally described as

$$C_t^F = \left(O_t \cdot p_{oil} + G_t \cdot p_{gas}\right) \cdot \alpha - \left(P_t^k + P_t^p + P_t^{MP}\right) \cdot \alpha \cdot p^{el} \tag{3.10}$$

Here the O_t is the oil production and G_t the gas production at timestep t. Oil price is p_{oil}, gas price p_{gas} and p^{el} is the price of electricity. The number of operational hours in a year is represented by α. P_t^k represents the power consumption of the compressor, P_t^p is the pump power, and P_t^{MP} is the power consumption of a multiphase pump. Second, the CAPEX equation, originally described as

$$C_0 = \sum_{j=1}^{N_j} C_j \tag{3.11}$$

In the equation C_j is the investment cost also referred to as the installed cost equipment j. In this equation there is no use of the binary variable y_j to indicate state of the equipment. This is done in the individual cost estimation equations for all equipment and will not be elaborated on any further in this report. To find the equations see Appendix B. Now expanding Eq. 3.11 to include all the terms of C_j to get Eq. 3.12 as shown below

$$C_0 = C_k + C_p + C_{mpp} + C_c + C_{ss} + C_{ts} + C_{fg} + C_{rg} + C_{fm} + C_{rm} + C_{fo} + C_{ro} \tag{3.12}$$

In the equation the cost of all the different equipment is described in Table 4.

Table 4 - Installed cost symbol table

Symbol	Equipment
C_c	Cooler
C_{ss}	Separator
C_k	Compressor
C_p	Oil pump
C_{mpp}	MP pump
C_{fg}	Gas transport line
C_{rg}	Gas riser
C_{fm}	MP transport line
C_{rm}	MP riser
C_{ts}	Topside separator
C_{fo}	Oil transport line
C_{ro}	Oil riser

The last modification from the original model is the α value. This is the value used to indicate the operational hours per year. The α value used here is 8497 h/year and correlates to an availability of approximately 97 %.

3.3.3.2 New Formulations

To update the model to include the new formulations and parameters, the equations described in Chapter 3.3.2 and Chapter 3.3.3.1 are combined, into new formulations before they are introduced to the model.

The updated cashflow is a combination of Eq. 3.6, Eq. 3.7 and Eq. 3.10 resulting in Eq. 3.13 as described below

$$C_t^F = \left(O_t \cdot p_{oil} + G_t \cdot p_{gas}\right) \cdot \alpha - \left(P_t^k + P_t^p + P_t^{MP}\right) \cdot \alpha \cdot p^{el} - MC_t^{ISBL} - MC_t^{IV} \tag{3.13}$$

This equation captures the non-discounted cashflow at timestep t with the revenue generated from production. Operational expenses in the form of power consumption of the subsea boosting, the yearly general maintenance unaffected by availability, and the maintenance cost of subsea IMR operations affected by downtime.

The CAPEX equation is modified to include an additional initial investment of spare parts on critical equipment that could be susceptible to full replacement. These units are the compressors, pumps (single- and multiphase), and possibly the coolers, as these consist of many moving and rotating parts. It is also assumed that it will be cheaper to buy two units simultaneously rather than one up front, and one later in time. Hence why the spare part investment factor, denoted f_{sp} is lower than two. Using Eq 3.12 as a foundation and modifying it to formulate Eq. 3.14

$$C_0 = f_{sp}(C_k + C_p + C_{mpp} + C_c) + C_{ss} + C_{ts} + C_{fg} + C_{rg} + C_{fm} + C_{rm} + C_{fo} + C_{ro} \tag{3.14}$$

Lastly the α value. This will be now referred to as the α_0 value as it now represents a baseline parameter rather than the actual α value. The new α is calculated using a combination of the steady-state availability A, described in Eq. 3.3 and α_0 as described in Eq. 3.15

$$\alpha = \alpha_0 \cdot A \tag{3.15}$$

3.4 FORMULATION OF THE DIFFERENT SIMULATION SCENARIOS

The maintenance and reliability implementation into the GAMS model was done in two stages. The steady-state availability and the intervention-related maintenance cost was calculated in Excel with the data from Table 2 and Table 3, using Eq 3.3 – 3.5. Those results are shown in Table 5 below. The remaining parameters and equations were directly implemented into GAMS, being equations Eq. 3.6 and 3.7, and Eq. 3.13 – 3.15.

Table 5 - Input data used in GAMS

Equipment		**Steady-state availability, A_j**	**Maintenance cost, MC_j**
Symbol	**Description**	**[-]**	**[USD/year]**
j_1	Cooler	0.99745	184 091
j_2	Separator	0.99945	84 091
j_3	Compressor	0.99406	354 339
j_4	Oil pump	0.99406	354 339
j_5	MP pump	0.99185	465 909
j_6	Gas transport line	0.99986	63 636
j_7	Gas riser	0.99986	63 636
j_8	MP transport line	0.99986	63 636
j_9	MP riser	0.99986	63 636
j_{10}	Topside separator	0.99897	107 955
j_{11}	Oil transport line	0.99986	63 636
j_{12}	Oil riser	0.99986	63 636

The different scenarios considered to be of interest were the following,

- ▽ No reliability and maintenance, letting the optimizer find an optimal layout as a baseline of the layout achieving the highest production potential and NPV.
- ▽ Include reliability and maintenance, and let the optimizer find an optimal layout using these restrictions.
- ▽ Consider a fixed layout to see the difference in the results if multiple layouts were found.

In addition to the parameters and changes mentioned above, Table 6 highlights some important parameters of the case-study based on a low-energy synthetic field similar in size to the Goliat field, shown in Krogstad's thesis [4]. The rest of the parameters can be found in the source code in Appendix B.

Table 6 – Additional important simulation data

Parameter	**Value**	**Unit**
Original oil in place	85 000 000	[ton]
Gas-oil ratio	0.06	[ton/ton]
Initial reservoir pressure	90	[bar]
Oil density	844	[kg/m3]
Gas density at S.C.	0.712	[kg/m3]
Distance to FPSO	8	[km]
Water depth	200	[m]
Base operating time	8497	[h/year]
Oil price	57.3	[USD/bbl]
Gas price	2.61	[USD/MMBtu]
Interest rate	0.1	[-]

4 Results

This chapter introduces the results gathered from the simulations performed when running the optimization model based on the different cases mentioned in Chapter 3.4.

4.1 MAIN RESULTS

This section presents the raw data results obtained from running the model.

4.1.1 Ignoring Reliability and Maintenance

The results from a baseline simulation ignoring reliability and maintenance are described in Table 7.

Table 7 - Result when ignoring RAMS

Parameter	Value
NPV [million USD]	2 330.29
CAPEX [million USD]	29.56
Uptime [h/year]	8 497
Availability subsea system [-]	1

The optimal layout of the subsea processing system when ignoring RAMS with the selected set of binary variables shown in Table 8, and an illustration of the layout is presented in Figure 6, referred to as layout A.

Table 8 - Optimal set of binary variables when ignoring RAMS

Variable	Equipment	Value in optimal solution
y1	Cooler	1
y2	Separator	1
y3	Compressor	1
y4	Oil pump	1
y5	MP pump	0
y6	Gas transport line	1
y7	Gas riser	1
y8	MP transport line	0
y9	MP riser	0
y10	Topside separator	0
y11	Oil transport line	1
y12	Oil riser	1

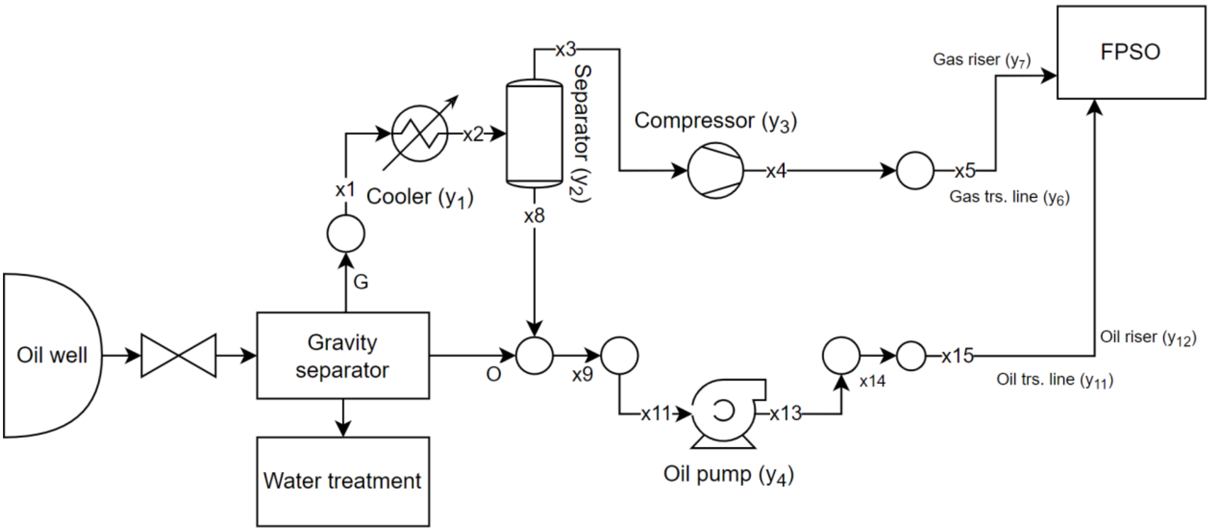

Figure 6 – Illustration of Layout A

4.1.2 Including Reliability and Maintenance

By including reliability and maintenance a new optimal layout of the subsea processing system was found. The selected set of binary variables are shown in Table 9, with an illustration of the layout is presented in Figure 7, referred to as layout B.

Table 9 - Optimal set of binary variables when including RAMS

Variable	Equipment	Value in optimal solution
y_1	Cooler	0
y_2	Separator	0
y_3	Compressor	0
y_4	Oil pump	0
y_5	MP pump	1
y_6	Gas transport line	0
y_7	Gas riser	0
y_8	MP transport line	1
y_9	MP riser	1
y_{10}	Topside separator	1
y_{11}	Oil transport line	0
y_{12}	Oil riser	0

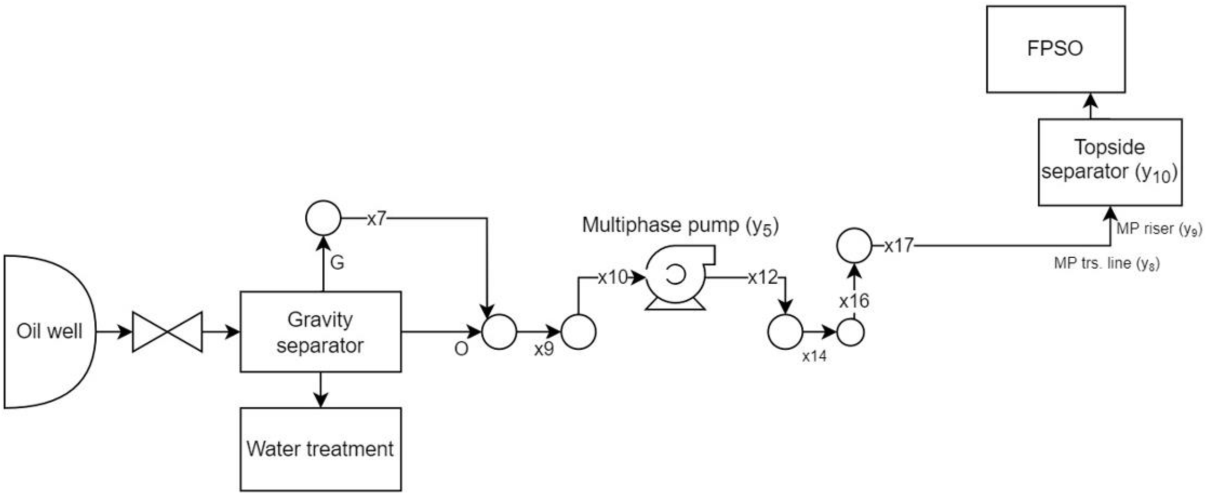

Figure 7 - Illustration of layout B

The results when including reliability and maintenance for both layout A and B are shown in Table 10. The absolute difference in the parameters is shown using Layout A as the baseline. Maintenance costs are the cost in year 1 with no inflation.

Table 10 – Results when including RAMS in both layouts

Parameter	Layout A (Baseline)	Layout B	Absolute difference
NPV [million USD]	2 263.03	2 274.11	11.08
CAPEX [million USD]	29.56	31.46	1.90
Uptime [h/year]	8 366.3	8 416.8	50.5
Availability subsea system [-]	0.9846	0.9906	0.0060
Total discounted LR [million USD]	36.24	22.22	-14.02
MC_{ISBL} [million USD/year]	1.48	1.57	0.09
MC_{IV} [million USD/year]	1.23	0.70	-0.53
Total MC [million USD/year]	2.71	2.27	-0.44

4.2 ADDITIONAL RESULTS

This section presents additional results related to the main results to compare some of the differences in the layouts when including reliability and maintenance and the sensitivity of some parameters.

4.2.1 Sensitivity Analysis

A sensitivity analysis of the new parameters introduced in the optimization model was performed. The solver obtained a solution on each dot in the diagram. Layout B was opted for in all simulations. The results are shown in Figure 8.

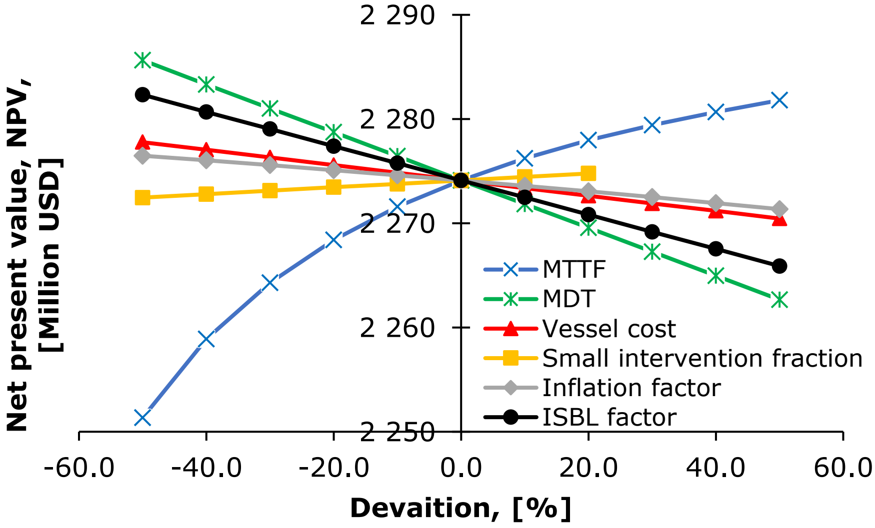

Figure 8 - Sensitivity diagram

Figure 8 shows that MTTF has a non-linear trend, while the other parameters have a linear trend. In addition, the MTTF has the greatest impact on NPV, and MDT is the second most sensitive parameter. The least sensitive parameter is the small intervention fraction. This is only analyzed from -50 % to 20 % since the value of the small intervention fraction can only exist between 0 and 1. For example, incrementing the baseline value of 0.8 by 30 % would result in 1.04, which is above 1.

4.2.2 Lost Revenue

The discounted lost revenue comparison of Layout A and Layout B are shown in Figure 9. Layout A shows a higher value of revenue lost per year over layout B. Higher lost revenue impacts more negatively on the NPV.

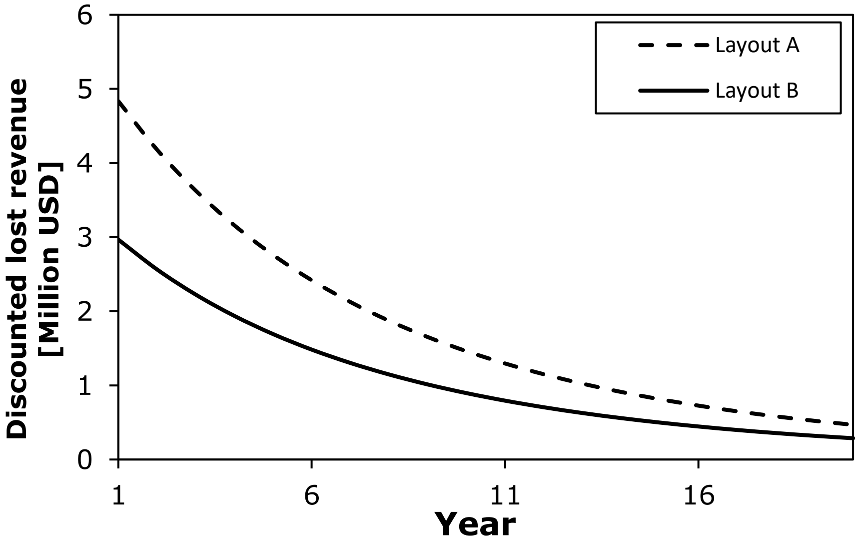

Figure 9 – Discounted lost revenue during the lifetime

4.2.3 Production Profiles

The daily production rate over the lifetime for oil and gas for Layout A and Layout B compared to each other are shown in Figure 10.

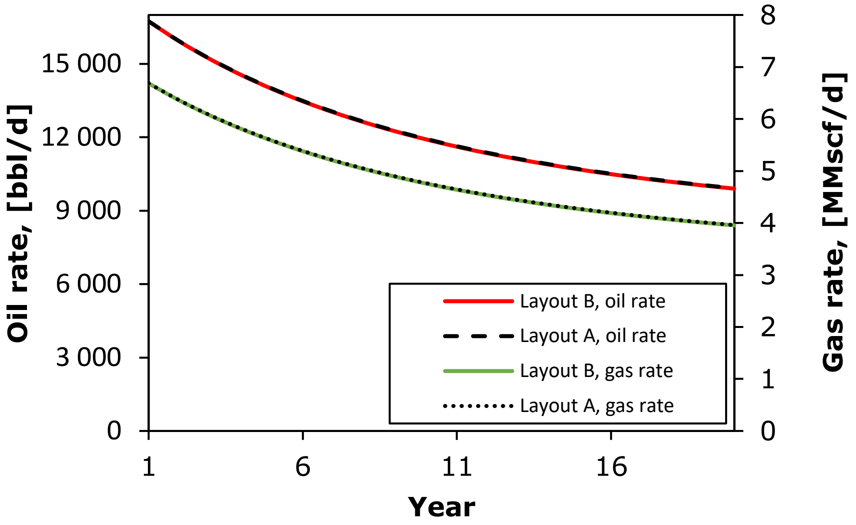

Figure 10 - Production profiles of both layouts

The cumulative production over the field lifetime comparing layout A and layout B is shown in Figure 11.

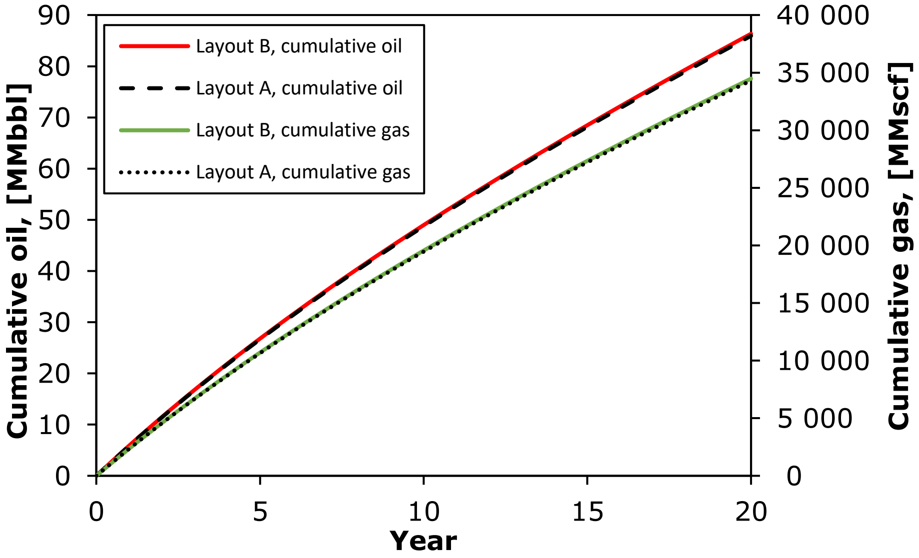

Figure 11 - Cumulative oil and gas production for both layouts

The difference in total production between the layouts over the lifetime of 20 years is 0.41 MMbbl oil and 163.03 MMscf gas with Layout B having the highest production. The relative difference is 0.47 % for the oil produced.

5 Discussion

The results presented from the simulation where there was no reliability and maintenance were used as a baseline to find the best solution for production. The NPV value achieved from this simulation would be unfeasible to achieve due to the assumption that the equipment is available 100 % during operation. The optimal layout found in this simulation was layout A.

When considering reliability and maintenance, a new optimal layout is found. This was layout B. By comparing and including reliability and maintenance in both layouts, the results of the simulations show a difference in the NPV value between the two. The difference in NPV was found to be 11 million USD, where Layout B has the highest NPV of 2 274.11 million USD. By having more equipment in the system, the maintenance required may increase. By increasing the amount of equipment in use, the overall system failure rate is also increased. This in turn also increases the probability of unplanned downtime caused by a failure.

The difference in yearly maintenance cost when considering IMR operations is explained by the amount of subsea equipment in use as this is dependent on the availability and the downtime. The difference in maintenance cost for IMR operations was found to be 0.53 million USD/year. This was mostly affected by the amount of subsea equipment in use since the MTTF values were similar for the majority of equipment in use. The maintenance not affected by the downtime is the ISBL maintenance factor method, which is a factor of the ISBL capital investment. The capital investment for layout A is 1.9 million USD cheaper than layout B. This leads to layout B having 0.07 million USD higher yearly maintenance cost with this metric. The total yearly maintenance cost is still 0.44 million USD/year more expensive for layout A when combining both individual maintenance cost factors. Gathering more accurate data and possibly finding better estimates for the MTTF values could affect the yearly maintenance costs and flip the results or pointing to a new optimum layout. The similarities are a result of lack of available data from trusted sources, as some of the technology is relatively new, such as the subsea gas compression systems.

The sensitivity diagram shown in Figure 8 suggests that the most important factors to consider given their sensitivity are MTTF, MDT, and ISBL maintenance factor.

The MTTF curve is non-linear compared to the other parameters linear trends. The MTTF and MDT values are used in two different equations and affect both the average yearly vessel cost and the availability of that equipment. The remaining parameters are only used in one equation or are a factor that scales linearly. The MDT can be reduced significantly for the equipment with long downtime if preventive maintenance is performed in one of the planned downtime events. During a year, some planned downtime is expected since base operational time per year is only 8497 h/year, 263 hours less than the total amount of hours in a year. This also gives room for opportunistic maintenance, as multiple subsea interventions could take place at the same time, saving costs and reducing overall downtime. By scheduling an IMR operation, the vessel can travel from the base in port to the field while the system is still operating. The downtime would therefore be reduced to equipment maintenance, eliminating the travel time from the total downtime.

Something that is not considered in this thesis is the onshore spare part’s downtime. When a spare part unit is installed in place of a failed unit, the failed unit would be refurbished and repaired. When this unit is restored to a functioning state, it becomes the spare unit. During the refurbishment, no extra spare part would be available in the case of a catastrophic failure of the new in place unit. If such an event would occur, the longevity of the downtime is uncertain as this is not considered. This could happen in the real case and is something that should be risk assessed. During the early years of the field lifetime passthrough/bypass pipes could be fitted to ensure production without the boosting pump/gas compressor. The rate would be reduced if the field is producing outside the plateau production in the decline phase. In late stages, the pressure in the reservoir could have been reduced so much that the reservoir would not be able to produce with natural flow and the production will therefore halt. This is also a factor not considered in this work, as one of the requirements for the field was to use subsea boosting.

Using condition-based monitoring on subsea equipment efficiently allows for better planning of replacement/repair operations. During winter, interventions should be avoided for operations that require long weather windows due to the rougher and more unpredictable sea. Planning to perform these operations to slot in before winter, when an original estimate would be to do it in the middle of the winter, could save days or weeks with waiting on weather. This in turn could save a large amount in lost revenue if the equipment is critical and causes a long halt in production.

The IBSL-maintenance factor is based on processing facilities onshore. Thus, an accurate representation of this cost on a subsea processing system may be difficult. Since the subsea pipelines are a part of the ISBL investment cost, a subsea processing system far away from the receiving facility will have a massively greater investment cost than a nearby system. This would also be true for the water depth. The field used for the case study is a shallow and close to the FPSO. With increased water depth the equipment pressure requirement would be greater, resulting in higher initial cost potentially complicate interventions on the field. With longer distances, pressure drop in the pipes could cause flow assurance problems such as hydrates or wax deposits if the temperature drops too much. Boosting equipment could have a larger pressure delta to keep the production rates high enough, and this would require larger more expensive equipment. Subsea pipelines are usually designed to last the entire lifetime and would require less maintenance than other subsea processing equipment. This could also contribute to artificially inflate the maintenance cost, but the larger sizing could balance it back out somewhat.

With the almost identical production profiles and cumulative production as seen in Figure 10 and Figure 11, it should be noted that the limiting factor may be the reservoir itself, and not the processing equipment limiting the production. The declining production look like an exponential decline, a characteristic curve for reservoirs producing at the production potential. It would be more difficult to estimate the best potential for each layout as the processing system itself is not the limiting factor. This could be why both layouts have almost identical production rate. The lost revenue is therefore just the loss in production caused by downtime compared to the baseline operating time. The availability difference of 0.60 % allows layout B to produce about 50 h/year more, with a total cumulative production of 0.47 % higher than layout A. It would be interesting to see the difference in the production rates where the processing equipment is the limiting factor and investigate if there is any difference in production rates, seeing as the layouts are very different.

There is a difference in the total investment cost between the layouts, as they use different subsea processing equipment, and the total amount of equipment is not the same. It is however interesting that layout B is 1.9 million USD more expensive than layout A. With layout B having less subsea equipment it should be expected to be on a similar cost or cheaper. The subsea compression system is the newest and most expensive boosting solution out of the three options. Alongside this, two trains of single-phase boosting, flowlines, and risers would be expected to be the more expensive solution. This is opposite of the results and bring into question if these cost estimations are accurate. The multiphase pump is only using a fixed cost of 3 million USD, while the rest is using equations to find the cost based on their sizing and flow requirements. With this in consideration, the cost estimates might not be as accurate and will require some modifications.

Another point with the cost estimations is the IMR related maintenance costs. They are among some other parameters very speculative as good data is not easily available to find. Vessel cost is also driven by the market of oil and gas. During periods of high profit margins and increased investments in the industry, the price rises, and in less favorable periods with low profit and little investment the price declines. The cost is in some way proportional to the oil price. In Eq. 3.5 the vessel is assumed to be costing the operator during the downtime period. In reality the vessel will need to travel from the base somewhere in a port to the field. If the vessel is heading to the field for a specified mission, usually the operator is charged for the daily cost during this time. The big uncertainty in this case is that there is no previous knowledge about the distance from the field to the supply base. This in turn would make estimation of the voyage to the field difficult. It is also somewhat compensated on with the pumps, compressor, and cooler MDT being long and the vessel cost applying for the entire duration. During this time the equipment would run through testing before replacement, and testing before being put back into service after replacement. The vessel might not be present the entire duration, but only part of it. Also, it is not certain if every failure is of the severity that would require full replacement, hence the use of the fraction of small-large vessel requirement.

6 Conclusion and Further Work

6.1 CONCLUSION

In this study, a superstructure approach combined with an optimization algorithm was used to determine the best solution to the problem. The optimization model was first developed by Krogstad, however this model only includes CAPEX and power consumption as expenses. The work presented here expanded the model to include reliability and maintenance aspects. Then, a comparison of the difference in parameters and layouts when ignoring and including reliability and maintenance in the optimization model was made.

The method was applied on a case study where three different cases were investigated. One served as the baseline, where no maintenance and reliability were included, in order to find the best layout considering only production. Layout A is then the optimum solution. In the second case the reliability and maintenance were included, and a new optimal layout was found, layout B. Lastly, it was included the reliability and maintenance aspects on layout A to investigate the relative difference in NPV between the different layouts.

When comparing and including reliability and maintenance in both layouts, a difference in NPV of 11 million USD was found, with layout B having the highest. The layout is more reliable, having the same production profile as when not including reliability and maintenance with some negligible differences. This increase in reliability results in uptime increase of 50 h/year, equivalent to an increased system availability of 0.60 %. The lost revenue was drastically reduced compared to layout A, thereby in total layout B was able to generate more revenue in the same time period, as seen by the increased NPV.

The difference in yearly maintenance cost was approximately 0.44 million USD/year, where layout B was the cheaper alternative. The overall capital investment cost of both layout where similar but layout B was found to be 1.9 million USD more expensive than layout A.

6.2 FURTHER WORK

To further improve the accuracy of the model there are several areas that could be improved. The maintenance cost estimation could be improved with better data collection of several key parameters: the downtime, the mean time to failure and the availability-independent maintenance costs. Other potential changes would be to add the opportunity to have different equipment in parallel, either dual operating equipment or potential ready stand-by units. This would require changes to the availability equations and other ways of implementation in GAMS.

The cost estimation of the different subsea processing equipment is also an area for improvement, especially the multiphase pump cost estimation, which also was highlighted by Krogstad in his thesis as it only uses a static cost of 3 million USD per unit.

To fully explore the potential of this model, uncertainties of the parameters introduced in this work need to be reduced. Knowledge about the distance of the field to onshore and offshore facilities is also important. For example, the time for a vessel to reach the field is important not only for the operational cost of the vessel, but also for the overall downtime of the system in the event of a critical system failure. Existing infrastructure may also impact the initial investment cost as the field could be tied into existing infrastructure, saving on the field development investment compared to no existing infrastructure.

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Appendix A Production Profiles

Due the similarities in the production profile and the cumulative production, the data at each timestep is provided in Table A.1 and Table A.2 below to highlight the slight deviation between the two layouts.

Table 11 – Additional data for the production rate for oil and gas

Year	**Oil production [bbl/d]**		**Gas production [MMscf/d]**	
	Layout A	**Layout B**	**Layout A**	**Layout B**
1	16 743	16 738	6.69	6.68
2	15 924	15 915	6.36	6.36
3	15 202	15 190	6.07	6.07
4	14 563	14 549	5.82	5.81
5	13 996	13 980	5.59	5.58
6	13 489	13 472	5.39	5.38
7	13 036	13 018	5.21	5.20
8	12 629	12 611	5.04	5.04
9	12 264	12 245	4.90	4.89
10	11 934	11 915	4.77	4.76
11	11 636	11 617	4.65	4.64
12	11 366	11 348	4.54	4.53
13	11 121	11 103	4.44	4.43
14	10 898	10 881	4.35	4.34
15	10 696	10 679	4.27	4.26
16	10 511	10 495	4.20	4.19
17	10 343	10 326	4.13	4.12
18	10 188	10 173	4.07	4.06
19	10 047	10 032	4.01	4.01
20	9 917	9 902	3.96	3.95

Table 12 – Additional data for the cumulative production

Year	**Cumulative Oil [MMbbl]**		**Cumulative Gas [MMscf]**	
	Layout A	**Layout B**	**Layout A**	**Layout B**
0	0	0	0	0
1	5.84	5.87	2 330.60	2 343.95
2	11.39	11.45	4 547.21	4 572.68
3	16.69	16.78	6 663.37	6 699.93
4	21.76	21.88	8 690.55	8 737.38
5	26.64	26.78	10 638.73	10 695.10
6	31.35	31.51	12 516.41	12 581.72
7	35.89	36.07	14 331.01	14 404.77
8	40.29	40.50	16 089.01	16 170.83
9	44.57	44.79	17 796.10	17 885.63
10	48.73	48.97	19 457.25	19 554.21
11	52.78	53.04	21 076.91	21 181.09
12	56.75	57.02	22 659.01	22 770.19
13	60.62	60.92	24 207.05	24 325.06
14	64.42	64.73	25 724.09	25 848.79
15	68.15	68.48	27 212.95	27 344.21
16	71.81	72.16	28 676.13	28 813.88
17	75.42	75.78	30 115.82	30 259.95
18	78.97	79.35	31 534.01	31 684.49
19	82.47	82.87	32 932.50	33 089.29
20	85.93	86.34	34 312.89	34 475.92

Appendix B GAMS Source Code

This section presents the source code for the optimization model in GAMS.

```
$Title MINLP model.

$onMultiR
$offListing
$offInclude

$OnText
MINLP-model for identifying the optimal set of subsea process units and
production for a single field connected to a FPSO.
CASE I
$OffText

*Defining symbol for end of line comment
$eolcom ->

*Declaring sets
Sets
        t "time horizon [years]" /t1*t20/
        i "superstructure flows" /i1*i17/
        j "equipment" /j1*j12/
        k "index for mass balances" /k1*k13/
        l(k) "subset of mass balance indices with zero-elements on RHS"
        /k2,k3,k4,k5,k6,k8,k9,k10,k11,k12,k13/
        s(t) "years following year 1";

*Defining sets
        s(t) = yes$(ord(t) gt 1);
        alias(tau,t);   -> additional alias set for the time steps.

*Defining parameters for the model
Parameters

*Upper bound for mass flows
        U "upper limit for mass flows [ton/h]" /1000/

*Reservoir parameters
```

```
        d "distance to coast [km]" /8/
        w_d "water depth [km]" /0.2/
        O_IIP "original oil in place [ton]" /85000000/
        p_r0 "initial pressure [kPa]" /9000/
        GOR "gas-oil ratio [ton/ton]" /0.06/
        beta "reservoir pressure decline coefficient [-]" /6000/
        q_ppo0 "maximum initial production potential [ton/h]" /132/
        p_ref "reference pressure [kPa]" /20000/
        -> production potential coefficients [-]
        a_1 /-43.40/
        a_2 /26.04/
        a_3 /-5.97/
        -> maximum production potential coefficients [-]
        b_1 /0.38/
        b_2 /0.6/

*Economic factors
        r "interest rate [-]" /0.1/
        p_bbl "oil price [USD/bbl]" /57.30/
        p_g "gas price [USD/MMBtu]" /2.61/
        alfa_0 "base operating time [h/year]" /8497/ -> 97% of availability
        p_e "electricity price [USD/kWh]" /0.09/
        f_inst "installation cost factor [-]" /4.208/
        f_sub "subsea installation cost factor [-]" /3/
        f_I "scaling economics for inflation factor [-]" /1.1035/
        f_if "inflation rate [-]" /1.03/
        c_1 "subsea separator coefficient [-]" /0.414/
        c_2 "subsea separator coefficient [-]" /0.054/
        d_1 "topside separator coefficient [-]" /0.127/
        d_2 "topside separator coefficient [-]" /0.403/
        m_f "ISBL maintenance cost factor [-]" /0.05/
        -> Equipment size factor table
        f_s_fm "economic size factor for multiphase flowline [-]" /1.00/
        f_s_rm "economic size factor for multiphase riser [-]" /1.70/
        f_s_fo "economic size factor for oil flowline [-]" /0.72/
        f_s_ro "economic size factor for oil riser [-]" /1.1/
        f_s_fg "economic size factor for gas flowline [-]" /0.15/
        f_s_rg "economic size factor for gas riser [-]" /0.5/
        c_b_rigid "base cost for rigid pipe lines [mill USD/km]" /0.230/
        c_b_flex "base cost for flexible pipe lines [mill USD/km]" /2.300/
        C_mpp_coat "coating cost multiphase pipes [mill USD/km]" /0.360/
```

```
        c_o_coat "coating cost oil pipes [mill USD/km]" /0.290/
        c_g_coat "coating cost gas pipes [mill USD/km]" /0.150/

*compressor
        gamma "heat capacity ratio of the gas [-]" /1.557/
        eta_k "compressor efficiency [-]" /0.75/
        T_in "gas temperature at the inlet of the compressor [K]" /300/

*oil pump
        rho_o "oil density [ton/m3]" /0.844/
        eta_p "pump efficiency [-]" /0.75/

*multiphase pump
        eta_mpp "compressor efficiency [-]" /0.6/

*Heat exchanger
        T_LM "cooler logarithmic mean temperature difference [K]" /19.6/
        dT "cooler temperature difference [K]" /2.5/
        Cp_g "Gas heat capacity [J/(kg K)]" /2681/
        U_h "heat transfer coefficient in the cooler [W/(m2 K)]" /20/

*Other factors and constraints
        R_c "universal gas constant [J/(mol K)]" /8.314/
        Mm "natural gas molar mass [kg/kmol]" /16.8036/
        rho_gstd "gas density at standard conditions [ton/m3]" /0.000712/
        -> conversion factors
        bbl_m3 "barrels per cubic meter" /6.29/
        MMBTU_m3 "MMBTU per cubic meter" /0.0354/

*Availability factors

        af(j) "reliability factor [-]"
        /   j1  0.99745,
            j2  0.99945,
            j3  0.99406,
            j4  0.99406,
            j5  0.99185,
            j6  0.99986,
            j7  0.99986,
            j8  0.99986,
            j9  0.99986,
```

```
          j10 0.99897,
          j11 0.99986,
          j12 0.99986
        /

*IMR maintenance cost

    mc(j) "maintenance cost [USD/year]"
        /   j1  184091,
            j2  84091,
            j3  354339,
            j4  354339,
            j5  465909,
            j6  63636,
            j7  63636,
            j8  63636,
            j9  63636,
            j10 107955,
            j11 63636,
            j12 63636
        /
;

Table A(k,i) "mass balance matrix [-]"

      i1   i2     i3   i4   i5   i6   i7   i8   i9   i10  i11  i12  i13  i14  i15  i16  i17
 k1   1    0      0    0    0    0    1    0    0    0    0    0    0    0    0    0    0
 k2   1    -1     0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
 k3   0    0.05   0    0    0    0    0    -1   0    0    0    0    0    0    0    0    0
 k4   0    -1     1    0    0    0    0    1    0    0    0    0    0    0    0    0    0
 k5   0    0      -1   1    0    0    0    0    0    0    0    0    0    0    0    0    0
 k6   0    0      0    -1   1    1    0    0    0    0    0    0    0    0    0    0    0
 k7   0    0      0    0    0    0    1    1    -1   0    0    0    0    0    0    0    0
 k8   0    0      0    0    0    0    0    0    -1   1    1    0    0    0    0    0    0
 k9   0    0      0    0    0    0    0    0    0    -1   0    1    0    0    0    0    0
 k10  0    0      0    0    0    0    0    0    0    0    -1   0    1    0    0    0    0
 k11  0    0      0    0    0    0    0    0    0    0    0    1    1    -1   0    0    0
 k12  0    0      0    0    0    0    0    0    0    0    0    0    0    -1   1    1    0
 k13  0    0      0    0    0    1    0    0    0    0    0    0    0    0    0    1    -1
;

*Defining variables
Positive variables
```

```
        A_c "installed heat transfer area [m2]"
        alfa "overall operating time [h/year]"
        a_total "alpha total [-]"
        C_0 "initial investments [million USD]"
        C_c "cooler cost [million USD]"
        C_fg "gas flowline cost [million USD]"
        C_fm "multiphase flowline cost [million USD]"
        C_fo "oil flowline cost [million USD]"
        c_if(t) "inflated maintenace cost [-]"
        C_k "compressor cost [million USD]"
        C_mpp "multiphase pump cost [million USD]"
        C_p "pump cost [million USD]"
        C_rg "gas riser cost [million USD]"
        C_rm "multiphase riser  cost [million USD]"
        C_ro "oil riser cost [million USD]"
        C_ss "subsea separator cost [million USD]"
        C_ts "topside separator cost [million USD]"
    mc_r "running ISBL maintenance cost [USD/year]"
    mc_i "yearly intervention maintenance cost [USD/year]"
        G(t) "gas production rate [ton/h]"
        O(t) "oil production rate [ton/h]"
        p_in "equipment inlet pressure [kPa]"
        P_k_m "maximum compressor power consumption [ton/h]"
        P_k(t) "compressor duty [kW]"
        P_mpp(t) "multiphase pump duty [kW]"
        p_out(t) "equipment outlet pressure [kPa]"
        P_p_m "maximum pump power consumption [ton/h]"
        P_p(t) "pump duty [kW]"
        p_r "reservoir pressure [kPa]"
        p_s "surface pressure [kPa]"
        q_pp(t) "maximum production potential [ton/h]"
        q_ppo(t) "initial production potential for separator pressure p_s
[ton/h]"
        R_f(t) "recovery factor [%wt]"
        x_cmax "cooler maximum installed capacity [ton/h]"
        x_pmax "maximum oil pump flow capacity [ton/h]"
        x_ssmax "subsea separator maximum installed capacity [ton/h]"
        x_tsmax "topside separator maximum installed capacity [ton/h]"
        x(i,t) "mass flow i [ton/h]"
;
```

```
Binary variables
    y(j) "binary variables for subsea unit installation [-]"
;

Variables
        b(k,t) "RHS for mass balance [ton/h]"
        b1(t) "multiphase pump duty coefficient [kJ/(kg kPa2)]"
        b2(t) "multiphase pump duty coefficient [kJ/(kg kPa)]"
        CF(t) "cash flow [million USD]"
        NPV "net present value [million USD]"
;

*Declaring equations
Equations
*ECONOMIC CONSTRAINTS
        eq1_1 "net present value [million USD]"
        eq1_2 "initial investments [million USD]"
        eq1_3(t) "cash flow [million USD]"

*PRODUCTIVITY CONSTRAINTS
        eq2_1(t) "maximum production potential [ton/h]"
        eq2_2(t) "initial production potential for separator pressure p_s
[ton/h]"
        eq2_3(t) "oil production rate [ton/h]"
        eq2_4(t) "gas production rate [ton/h]"
        eq2_5(t) "recovery factor [%wt]"
        eq2_7(t) "surface pressure [kPa]"
        eq2_8(t) "reservoir pressure [kPa]"

*EQUIPMENT CONSTRAINTS
*Chokes
        eq3_1 "equipment minimum inlet pressure [kPa]"
        eq3_2(t) "reservoir-station choke [kPa]"
        eq3_3 "station-separator choke (no choke) [kPa]"
*Duties
        eq3_4(t) "compressor duty [kW]"
        eq3_5(t) "pump duty [kW]"
        eq3_6(t) "multiphase pump duty [kW]"
        eq3_7(t) "multiphase pump duty coefficient [kJ/(kg kPa2)"
        eq3_8(t) "multiphase pump duty coefficient [kJ/(kg kPa)]"
        eq3_9(t) "maximum pressure gain"
```

```
*Sizing
        eq3_10(t) "maximum compressor power consumption [ton/h]"
        eq3_11(t) "maximum oil pump flow capacity [ton/h]"
        eq3_12(t) "maximum pump power consumption [ton/h]"
        eq3_13 "installed heat transfer area [m2]"
        eq3_14(t) "cooler maximum installed capacity [ton/h]"
        eq3_15(t) "subsea separator maximum installed capacity [ton/h]"
        eq3_16(t) "topside separator maximum installed capacity [ton/h]"

*SUPERSTRUCTURE CONSTRAINTS
        eq4_1(k,t) "RHS for mass balance [ton/h]"
        eq4_2(t) "RHS for mass balance (G) [ton/h]"
        eq4_3(t) "RHS for mass balance (O) [ton/h]"
        eq4_4(k,t) "RHS for mass balance (null) [ton/h]"
        eq4_5(t) "Cooler superstructure requirement"
        eq4_6(t) "Subsea separator superstructure requirement"
        eq4_7(t) "MPP pump superstructure requirement"
        eq4_8(t) "MPP pump superstructure requirement"
        eq4_9(t) "Oil pump superstructure requirement"
        eq4_10(t) "Gas transp. Line superstructure requirement"
        eq4_11(t) "MPP transp. line superstructure requirement"
        eq4_12(t) "Oil transp. line superstructure requirement"
        eq4_13(t) "MPP transp. line superstructure requirement"
        eq4_14 "MPP pump superstructure requirement"
        eq4_15 "MPP pump superstructure requirement"
        eq4_16 "MPP transp. line OR Oil transp. line"
        eq4_17 "MPP transp. line OR Gas transp. line"
        eq4_18 "MPP pump AND MPP transp. Line"
        eq4_19 "MPP transp. line AND MPP riser"
        eq4_20 "MPP transp. line AND Topside separator"
        eq4_21 "Gas transp. line AND Gas riser"
        eq4_22 "Oil transp. line AND Oil riser"

*COST ESTIMATION
        eq5_1 "compressor cost [million USD]"
        eq5_2 "pump cost [million USD]"
        eq5_3 "multiphase pump cost [million USD]"
        eq5_4 "cooler cost [million USD]"
        eq5_5 "subsea separator cost [million USD]"
        eq5_6 "topside separator cost [million USD]"
        eq5_7 "gas flowline cost [million USD]"
```

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        eq5_8 "gas riser cost [million USD]"
        eq5_9 "multiphase flowline cost [million USD]"
        eq5_10 "multiphase riser cost [million USD]"
        eq5_11 "oil flowline cost [million USD]"
        eq5_12 "oil riser cost [million USD]"
        eq5_13(t) "inflation rate [-]"

*RELIABILITY AND MAINTENANCE
        eq6_1 "overall operating time [h/year]"
        eq6_2 "reliability factor [-]"
        eq6_3 "running maintenance cost [USD/year]"
    eq6_4 "yearly maintenance cost for interventions [USD/year]"

*EXCLUDE SOLUTIONS
*    eq7_1 "Exclude solution ID - left side [-]"
*    eq7_2 "Exclude solution ID - left side [-]"
;

*Defining the equations

*ECONOMIC CONSTRAINTS
eq1_1.. NPV =e= -C_0/(1+r) + sum(t,CF(t)/((1+r)**ord(t))); -> Objective
function
eq1_2.. C_0 =e= 1.8*C_c + C_ss + 1.8*C_k + 1.8*C_p + 1.8*C_mpp + C_fg +
C_rg + C_fm + C_rm + C_ts + C_fo + C_ro;
eq1_3(t).. CF(t) =e= (1/1000000)*((O(t)*bbl_m3*p_bbl/rho_o +
G(t)*MMBTU_m3*p_g/rho_gstd)*alfa - (P_k(t)+P_p(t)+P_mpp(t))*alfa*p_e -
mc_i*c_if(t) - mc_r*c_if(t));

*PRODUCTIVITY CONSTRAINTS

*PRODUCTIVITY CONSTRAINTS
eq2_1(t).. q_pp(t) =e= q_ppo(t)*(a_1*R_f(t)**3+a_2*R_f(t)**2+a_3*R_f(t)+1);
eq2_2(t).. q_ppo(t) =e= q_ppo0*(1 - b_1*(p_s/p_ref) - b_2*(p_s/p_ref)**2);
eq2_3(t).. O(t) =l= q_pp(t);
eq2_4(t).. G(t) =e= GOR*O(t);
eq2_5(t).. R_f(t) =e= sum(tau$(ord(tau) le ord(t)),O(tau)*alfa)/O_IIP;
eq2_7(t).. p_out(t) =e= (1.5391E-06*(O(t))**2+0.002749*O(t)+130.4926)*100;
eq2_8(t).. p_r(t) =e= p_r0 - beta*R_f(t);

*EQUIPMENT CONSTRAINTS
```

```
*Chokes
eq3_1.. p_in =g= 5000; -> this can be a function of separator (>3000kPa) or
multiphase boosting (>1500kPa)
eq3_2(t).. p_in =l= p_r(t);
eq3_3.. p_s =e= p_in;
*Duties
eq3_4(t).. P_k(t) =e= x('i3',t)*(R_c*T_in/(Mm*3.6))*(gamma/(gamma-
1))*((p_out(t)/p_in)**((gamma-1)/gamma)-1)/eta_k;
eq3_5(t).. P_p(t) =e= (p_out(t)-p_in)*x('i11',t)/(rho_o*3600*eta_p);
eq3_6(t).. P_mpp(t) =e= 0.273*x('i10',t)*eta_mpp*(b1(t)*((p_out(t)-
p_in)/100)**2+b2(t)*((p_out(t)-p_in)/100));
eq3_7(t).. b1(t) =e= -0.001352667 + (-0.040266667) / (1 + ((p_in/100) /
42.9863)**5.1515);
eq3_8(t).. b2(t) =e= 0.952166667 + (3.856666667) / (1 + ((p_in/100) /
44.678)**3.606);
eq3_9(t).. p_out(t)-p_in =l= 5000;
*Sizing
eq3_10(t).. P_k_m =g= P_k(t);
eq3_11(t).. x_pmax =g= x('i11',t);
eq3_12(t).. P_p_m =g= P_p(t);
eq3_13.. A_c =e= x_cmax*dT*Cp_g/(3.6*U_h*T_LM);
eq3_14(t).. x_cmax =g= x('i1',t);
eq3_15(t).. x_ssmax =g= x('i2',t);
eq3_16(t).. x_tsmax =g= x('i17',t);

*SUPERSTRUCTURE CONSTRAINTS
eq4_1(k,t).. b(k,t) =e= sum(i,A(k,i)*x(i,t));
eq4_2(t).. b('k1',t) =e= G(t);
eq4_3(t).. b('k7',t) =e= -O(t);
eq4_4(k,t)$l(k).. b(k,t) =e= 0;
eq4_5(t).. x('i1',t) - U*y('j1') =l= 0;
eq4_6(t).. x('i2',t) - U*y('j2') =l= 0;
eq4_7(t).. x('i7',t) - U*y('j5') =l= 0;
eq4_8(t).. x('i10',t) - U*y('j5') =l= 0;
eq4_9(t).. x('i11',t) - U*y('j4') =l= 0;
eq4_10(t).. x('i5',t) - U*y('j6') =l= 0;
eq4_11(t).. x('i6',t) - U*y('j8') =l= 0;
eq4_12(t).. x('i15',t) - U*y('j11') =l= 0;
eq4_13(t).. x('i16',t) - U*y('j8') =l= 0;
eq4_14.. y('j4') + y('j5') =e= 1;
eq4_15.. y('j3') + y('j5') =e= 1;
```

```
eq4_16.. y('j8') + y('j11') =e= 1;
eq4_17.. y('j8') + y('j6') =e= 1;
eq4_18.. y('j5') - y('j8') =l= 0;
eq4_19.. y('j8') - y('j9') =e= 0;
eq4_20.. y('j8') - y('j10') =e= 0;
eq4_21.. y('j6') - y('j7') =e= 0;
eq4_22.. y('j11') - y('j12')=e= 0;

*COST ESTIMATION
eq5_1.. C_k =e= (0.49*y('j3') + 0.0168*P_k_m**0.6)*f_inst*f_sub*f_I;
eq5_2.. C_p =e= (-0.00095*y('j4') + 0.00177*P_p_m**0.6)*f_inst*f_sub*f_I +
(0.0069*y('j4') + 0.000206*(x_pmax/(rho_o*3.6))**0.9)*f_inst*f_sub*f_I;
eq5_3.. C_mpp =e= 3*f_inst*f_I*y('j5');
eq5_4.. C_c =e= (0.024*y('j1')+0.000046*A_c**1.2)*f_inst*f_sub;
eq5_5.. C_ss =e= (c_1*y('j2')+c_2*x_ssmax);
eq5_6.. C_ts =e= (d_1*x_tsmax**d_2);
eq5_7.. C_fg =e= (c_b_rigid*f_s_fg + c_g_coat)*d*y('j6');
eq5_8.. C_rg =e= (c_b_flex*f_s_rg + c_g_coat)*w_d*y('j7');
eq5_9.. C_fm =e= (c_b_rigid*f_s_fm + c_mpp_coat)*d*y('j8');
eq5_10.. C_rm =e= (c_b_flex*f_s_rm + c_mpp_coat)*w_d*y('j9');
eq5_11.. C_fo =e= (c_b_rigid*f_s_fo + c_o_coat)*d*y('j11');
eq5_12.. C_ro =e= (c_b_flex*f_s_ro + c_o_coat)*w_d*y('j12');
eq5_13(t).. c_if(t) =e= f_if**(ord(t) - 1);

*RELIABILITY AND MAINTENANCE
eq6_1.. alfa =e= alfa_0*a_total;
eq6_2.. a_total =e=(1 + sum(j,(1 - af(j)**y(j))/af(j)**y(j)))**(-1);
eq6_3.. mc_r =e= m_f*C_0*10**6;
eq6_4.. mc_i =e= sum(j, mc(j)*y(j));

*EXCLUDE BEST SOLUTION
*eq7_1.. sum(j,(2*y(j))**(ord(j)-1)) =g= 0;
*eq7_2.. sum(j,(2*y(j))**(ord(j)-1)) =l= 912;

*STARTING VALUES
p_in.L = 8500; -> AVOID DIVISION BY ZERO.
p_out.L(t) = 13000; -> AVOID DIVISION BY ZERO.
q_ppo.L(t) = 95; -> SPEEDS UP THINGS A LOT.
P_k_m.L = 154;
x_pmax.L = 94;
```

```
*Bounds DICOPT
*C_k.up = 100;
*C_MP.up = 100;

*Generating model
Model mod /all/;

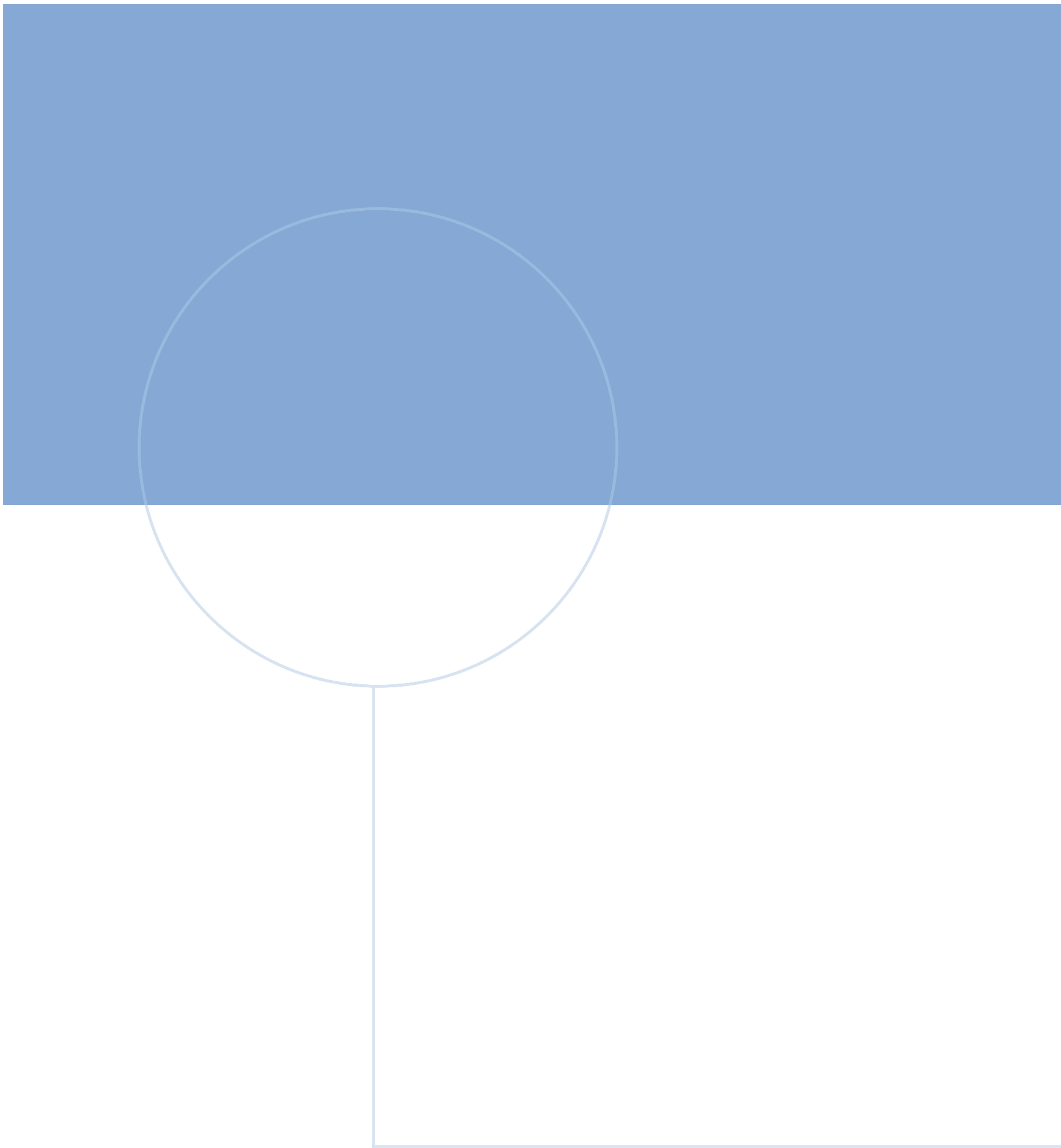
*Setting gap and simulation time limit (172800 = 2 days)
        option optCR = 1E-3;
        option resLim = 172800;

*Choosing subsolvers for MIP and NLP problems
*       option MIP = CPLEX;
*       option NLP = CONOPT;

*Choosing solver for MINLP (BARON or DICOPT)
        option MINLP = BARON;

        option limrow = 0;
        option limcol = 0;

*Solver options (.opt for BARON and .op2 (=2) for DICOPT)
*mod.optfile = 1;
solve mod using MINLP maximizing NPV;
```



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