NTNU – Trondheim
Norwegian University of
Science and Technology

Production Assurance and Life Cycle Cost Evaluation of Offshore Development Projects in the Conceptual Design Phase

Liaoyi Wang

Reliability, Availability, Maintainability and Safety (RAMS)

Submission date:	June 2012
Supervisor:	Marvin Rausand, IPK
Co-supervisor:	Øystein Eriksen, Aker Solutions Bjørnar Langelo, Aker Solutions

Norwegian University of Science and Technology
Department of Production and Quality Engineering

RAMS
Reliability, Availability,
Maintainability, and Safety

Production Assurance and Life Cycle Cost Evaluation of Offshore Development Projects in the Conceptual Design Phase

Liaoyi Wang

June 2012

THESIS

Department of Production and Quality Engineering

Norwegian University of Science and Technology

Supervisor 1: Marvin Rausand

Supervisor 2: Øystein Eriksen

Supervisor 2: Bjørnar Langelo

NTNU
Faculty of Engineering Science and Technology
Department of Production and Quality Engineering

Date
2012-01-12

Our reference
MAL/LMS

MASTER THESIS
2012
for
stud. techn. Liaoyi Wang

REGULARITY AND LIFE CYCLE COST EVALUATION OF OFFSHORE DEVELOPMENT PROJECTS IN CONCEPT PHASE

(Regularitets- og levetidskostnadsvurdering av et offshore utviklingsprosjekt i konseptfasen)

RAM analyses are normally performed as part of concept studies, to evaluate the overall production availability of the installation/field development. Several tools/methods for life cycle cost (LCC) evaluations exist, but they tend to be too time-consuming and complicated to use in concept studies with a short execution schedule. Hence, a RAM/LCC model suitable for use in typical offshore engineering concept studies should be developed.

The objective of this master thesis is to develop method for regularity and life cycle cost evaluation of offshore development projects in concept phase. The thesis should conclude with a proposed method/tool suitable for use in concept selection and systems development phase (short execution time). An AkerSolutions FPSO concept (ongoing concept study) can be used as a representative test case.

As part of this project thesis the candidate shall:

1. Evaluate previous work and existing methods/tools for RAM/LCC evaluations.
2. Establish a Miriam Regina RAM model for an FPSO concept (test case).
3. Perform a RAM analysis of the system/equipment configuration chosen as base case for the FPSO concept.
4. Based on the result from the RAM analysis, propose alternative system/equipment configurations to be further evaluated (RAM/LCC).
5. Perform RAM analysis for alternative configurations.
6. Develop method for life cycle cost evaluation (CAPEX, OPEX, REGEX).
7. Perform life cycle cost evaluations for base case and alternative configurations.
8. Discuss the uncertainties related to the obtained RAM/LCC results.

9. Give recommendations for further studies.

Following agreement with the supervisors, the various points may be given different weights.

Within three weeks after the date of the task handout, a pre-study report shall be prepared. The report shall cover the following:

- An analysis of the work task's content with specific emphasis of the areas where new knowledge has to be gained.
- A description of the work packages that shall be performed. This description shall lead to a clear definition of the scope and extent of the total task to be performed.
- A time schedule for the project. The plan shall comprise a Gantt diagram with specification of the individual work packages, their scheduled start and end dates and a specification of project milestones.

The pre-study report is a part of the total task reporting. It shall be included in the final report. Progress reports made during the project period shall also be included in the final report.

The report should be edited as a research report with a summary, table of contents, conclusion, list of reference, list of literature etc. The text should be clear and concise, and include the necessary references to figures, tables, and diagrams. It is also important that exact references are given to any external source used in the text.

Equipment and software developed during the project is a part of the fulfilment of the task. Unless outside parties have exclusive property rights or the equipment is physically non-moveable, it should be handed in along with the final report. Suitable documentation for the correct use of such material is also required as part of the final report.

The student must cover travel expenses, telecommunication, and copying unless otherwise agreed.

If the candidate encounters unforeseen difficulties in the work, and if these difficulties warrant a reformation of the task, these problems should immediately be addressed to the Department.

The assignment text shall be enclosed and be placed immediately after the title page.

Deadline: June 11th 2012.

Two bound copies of the final report and one electronic (pdf-format) version are required.

Supervisor at NTNU:
Marvin Rausand
Phone: 73 59 25 42
E-mail: marvin.rausand@ntnu.no

Supervisor at Aker Solutiona:
Øystein Eriksen
Phone: +47 67527757
E-mail: Oystein.Eriksen@aksersolutions.com

Bjørnar Langelo
Phone: +47 22946160
E-mail: Bjornar.Langelo@akersolutions.com

**DEPARTMENT OF PRODUCTION
AND QUALITY ENGINEERING**

Per Schjølberg
Associate Professor/Head of Department

Marvin Rausand
Responsible Supervisor

Preface

This Master thesis is part of my master program in RAMS at the Norwegian University of Science and Technology (NTNU). The project is carried out in cooperation with the Technical HSE Department at Aker Solutions, Fornebu. The thesis has been carried out from February 2012 till June 2012 partly at Fornebu and partly in Trondheim, Norway.

RAM analysis is used to assess system availability in the oil and gas industry. By performing RAM analysis in the conceptual design phase, it provides the opportunity for system optimization before entering into the detailed engineering phase. Together with LCC analysis, the selected solution is balanced between regularity and expenditure. However, the conceptual design phase is rather short, and therefore a simple model must be established to conduct the two analyses. This thesis is aimed at proving the feasibility of performing both RAM and LCC analyses of offshore projects in the conceptual design phase.

To better understand the thesis, it is assumed that the reader has some background in reliability. Previous knowledge from the book *"System Reliability Theory: Models, Statistical Methods, and Applications"* by Marvin Rausand and Arnljot Høyland is recommended.

Trondheim, 2012-06-10

Liaoyi Wang

Acknowledgment

First, I would like to thank Professor Marvin Rausand, from the Department of Production and Quality Engineering at NTNU. He suggested me to write the thesis in cooperation with Aker Solutions. Throughout the cooperation, I have learned many practical things from the company which lay the foundation for my future career. When I was in Trondheim, we had a meeting once a week, every time he gave me valuable feedback and fresh inputs. I was very inspired by his dedication and well motivated to produce a better job. Professor Raudsand also taught me about the report writing program, Latex. I found Latex is helpful and saved me a lot of time in formality.

I would also like to thank my manager Linda Fløttum and my supervisors Øystein Eriksen and Bjørnar Langelo from Aker Solutions. They proposed such an interesting topic and involved me in their ongoing project. During my thesis, all of them have continuously supported me to achieve the predetermined goal. Under their help, I gained deeper insights about the topic and actually enjoyed the process of learning. Whenever I had questions, they tried to help me even though they were very busy themselves. I appreciate their precious time on contribution to my thesis.

L.W.

Summary and Conclusions

RAM analysis is used to assess system availability in the oil and gas industry. As the concept *design for reliability* is getting attention throughout various industries, RAM analysis has become a mandatory delivery in the conceptual design phase. LCC analysis aims at predicting acquisition cost and ownership cost during the project life cycle. Since the ownership cost is derived from operation and maintenance, which can be potentially much higher than the acquisition cost, so that quantifying the ownership cost is the main objective of a LCC analysis. Combing RAM and LCC analyses in the conceptual design phase helps the trade-off between maximizing regularity and minimizing expenditure before entering into the detailed engineering phase. However, the conceptual design phase is rather short, and therefore a simple model is a key to the feasibility of performing the two analyses. An ongoing project from Aker Solutions has been carried out in this thesis as a case study to perform both RAM and LCC analyses.

The analytical and the simulation approaches are the two common approaches to RAM analysis. In general, the analytical approach is rigid by using predefined formulas. It may be easy to apply in the conceptual design phase, but rather weak at handling large and complex systems. In contrary, the simulation approach is more flexible and capable. By simulating, more detailed and accurate results can be generated. Several software tools have been developed for both approaches. They are briefly discussed with pros and cons. Rather than saying one tool is superior to the other, it is more important to know which tool to use in the specific application. Since Aker Solutions has close cooperation with Statoil, Miriam Regina is used in Aker Solutions to perform the simulation approach.

A number of LCC-related standards have been developed. Although many theoretical issues have been discussed, a complete LCC analysis is hardly found in the literatures. This may be due to confidential issues, lack of practical guidance and knowledge limitation in the project's early phase. Considering the variance of different projects, it is somehow unrealistic to develop a universal method for LCC analysis. In this thesis, a six steps procedure is illustrated with explanation of each step. Based on the NORSOK standards, an Excel spreadsheet is established, and demonstrated in the case study.

Sensitivity analysis offers the possibility of comparing alternative solutions. By incorporat-

ing sensitivity analysis into RAM and LCC analyses, the alternative solutions are examined related to both regularity and cost dimensions. Usually, in the conceptual design phase, the sensitivity analysis is used to reveal the impact of changes in the component configuration or process design, which in turn guide system optimization.

Uncertainties are found in three areas, parameter, model and completeness. It is however impossible to quantify uncertainties. In order to reduce uncertainties, it is important to obtain reliable data, use appropriate model, and document assumptions.

In the case study, by using Miriam Regina, RAM analysis provides the production availability and ranks the subsystems/components according their criticality. LCC analysis is applied with the Excel spreadsheet, which calculates the acquisition cost and the ownership cost for the proposed options. Through the case study, the feasibility of performing RAM and LCC analyses in the conceptual design phase has been proved.

Contents

Preface . . . i

Acknowledgment . . . ii

Summary and Conclusions . . . iii

1 Introduction **2**

1.1 Background . . . 2

1.2 Objectives . . . 4

1.3 Limitations . . . 4

1.4 Structure of the Report . . . 5

2 RAM Analysis **6**

2.1 RAM Analysis in Design . . . 6

2.2 Approaches of RAM Analysis . . . 7

2.2.1 Analytical Approach . . . 7

2.2.2 Simulation Approach . . . 9

2.3 Software Tools for Analytical Approach . . . 11

2.4 Software Tools for Simulation Approach . . . 12

2.4.1 Miriam Regina . . . 12

2.4.2 MAROS . . . 14

2.4.3 ExtendSim . . . 16

3 The Practice of the Simulation Approach **18**

3.1 General Procedure . . . 18

3.2 Inputs . . . 19

3.2.1 Failure Events . . . 19
3.2.2 Failure and Repair Data . . . 20
3.3 Simulation . . . 22
3.4 Sensitivity Analysis . . . 22
3.5 Handling of Uncertainty . . . 23

4 LCC analysis 25
4.1 Background . . . 25
4.2 LCC Analysis in Design . . . 26
4.3 Procedure of LCC Analysis . . . 28
4.3.1 Problem Definition . . . 29
4.3.2 Cost Elements Definition . . . 29
4.3.3 System Modeling . . . 30
4.3.4 Data Collection . . . 31
4.3.5 Cost Profile Development . . . 31
4.3.6 Evaluation . . . 32
4.4 Applications of LCC Analysis . . . 32

5 Case Study 33
5.1 Introduction . . . 33
5.1.1 Scope of Work . . . 33
5.1.2 Objectives . . . 33
5.1.3 Steps . . . 35
5.2 System Description . . . 35
5.3 RAM Analysis . . . 36
5.3.1 Assumptions . . . 36
5.3.2 Critical Subsystems/Components Selection . . . 38
5.3.3 Alternative Solutions in Gas Lift Compressor . . . 38
5.3.4 Reliability Block Diagrams . . . 38
5.3.5 Inputs . . . 39
5.3.6 Results . . . 40

5.3.7 Uncertainties 41
5.4 LCC analysis 42
5.4.1 Cost Elements Identification and Calculation 43
5.4.2 Result 46
5.5 Conclusion 46

6 Summary **50**
6.1 Summary and Conclusions 50
6.2 Discussion 52
6.3 Recommendation 52

A Acronyms **54**

B Definitions **56**

Bibliography **58**

Chapter 1

Introduction

1.1 Background

Reliability, availability and maintainability (RAM) analysis, also referred to as production assurance/availability analysis or regularity, has been applied in many industries, such as aerospace, nuclear power and process industries.

RAM analysis determines the system availability, which in turn can be used to optimize design configuration, maintenance schedule, and logistic planning. Generally, a system is broken down into a number of subsystems. To simplify the model, only the critical subsystems and components are analyzed. The availability is calculated and the critical items are ranked according to their influence on the unavailability. In this way, RAM analysis provides the opportunity to optimize the system through changing components or choosing alternative configurations. Alternative configurations, maintenance and logistic rules can be further investigated by sensitivity analysis. RAM analysis can be carried out by an analytical approach or by the simulation. The former uses approximation formulas, while the latter is more capable in terms of modeling complex systems.

Life cycle cost (LCC) analysis is based on RAM analysis and aims at considering cost issues of designs. Figure 1.1 illustrates that the combination of RAM and LCC analyses facilitates the trade-off between maximizing availability and minimizing financial expenditure.

As defined in Appendix B, LCC does not only cover *acquisition cost*, but also *ownership cost*. *Acquisition cost* is the capital expenditure called CAPEX, and *ownership cost* includes OPEX and

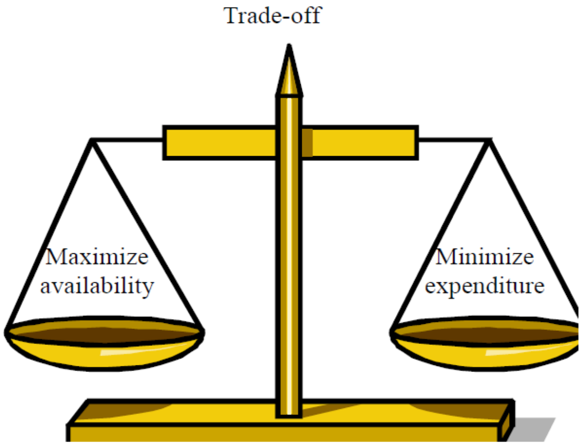


Figure 1.1: Contribution of RAM and LCC analysis

REGEX which are derived from operation, maintenance and lost production throughout the project life cycle. As illustrated by the iceberg in figure 1.2, the *ownership cost* is often much higher than the *acquisition cost*. From past experience, *ownership cost* takes up 60% to 80% of the total LCC. SAE ARP4293 (1992) says that the percentages of *ownership cost* for a fighter aircraft and for a basic trainer aircraft are 53% and 91%, respectively. A main objective of LCC analysis is thus to quantify the *ownership cost*. To reach this purpose, a thorough LCC analysis must involve RAM analysis, economic analysis, and risk analysis to gain deep insights of the system.

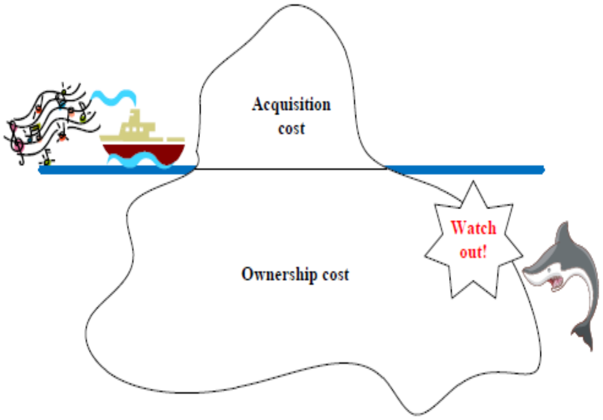


Figure 1.2: Acquisition vs ownership cost (Dangel, 1969)

In the past, the conceptual design phase mainly focused on engineering designs that must fulfill standards or specific requirements. As a high level of RAM is expected during the project life cycle, the concept *design for reliability* is formed. RAM analysis is most important to perform in the conceptual design phase. Combining RAM analysis and LCC analysis, it assists decision-making in capital investment, design optimization, and maintenance scheduling. In this thesis, the methodologies for the two analyses are briefly discussed. An Aker Solutions' ongoing project is used as a case study to demonstrate the feasibility of RAM and LCC analyses in the conceptual design phase.

1.2 Objectives

The main objective of this thesis is to develop a model for RAM and LCC analyses of offshore development projects in the conceptual design phase. To meet this objective, the following activities are identified:

1. Describe the methodology and approaches used in RAM analysis
2. Review existing software tools of RAM analysis, and investigate pros and cons of each tool
3. Illustrate the procedure of performing RAM analysis in Aker Solutions
4. Perform RAM analysis on an Aker Solutions' project, as a case study
5. Perform sensitivity analysis for the alternative system configuration
6. Describe LCC analysis and its procedure
7. Establish a feasible model for LCC analysis
8. Perform LCC analysis on the same project of Aker Solutions using the proposed model

1.3 Limitations

Only Miriam Regina is investigated by actual application. The presentations of other RAM analysis software tools are based on literature search and reviews.

In the case study, the limitation of the RAM analysis is lack of proper data. The OREDA hand-hook is the main data resource where the failure rates and the active repair times are obtained.

For the pre-repair and the post repair time, expert judgment is used. From the client's feedback, the data should be adjusted to better suit this project. However, the process of data estimation is still on-going, the presented RAM analysis is thus a preliminary version.

The procedure of LCC analysis is introduced but the application is not thoroughly studied. For the LCC analysis in the case study, it is not possible to acquire cost data for operation, preventive maintenance and transportation, etc. Due to time limitation, OPEX is not examined into details.

1.4 Structure of the Report

In this thesis, the following tasks are performed and structured as below.

Chapter 2 describes two common approaches of RAM analysis. Various software tools for each approach are introduced in section 2.3 and 2.4 with pros and cons.

Chapter 3 presents a procedure of the simulation approach used in Aker Solutions with the software Miriam Regina. The purpose of sensitivity analysis is discussed in section 3.4, and the uncertainty handling is elaborated in section 3.5

In chapter 4, a six steps procedure is proposed for LCC analysis. Each step with its sub activities is further discussed in section 4.3.

Chapter 5 is a case study which demonstrates the method of performing RAM and LCC analyses in the conceptual design phase.

In the end, chapter 6 sums up the findings with discussions and recommendations.

Chapter 2

RAM Analysis

RAM analysis is a mature availability assurance activity for safety critical systems in aerospace and nuclear power industries. For the process industries (e.g., oil and gas, power plants), RAM analysis is rapidly developing and becomes a mandatory deliverable for the conceptual design phase. This chapter introduces two common approaches and the supportive software tools of RAM analysis.

2.1 RAM Analysis in Design

Design for reliability expresses the importance of performing RAM analysis in the conceptual design phase. Figure 2.1 illustrates that during the whole project life cycle, the conceptual design phase is the ideal time to perform RAM analysis. It provides the chance to optimize the system before entering into the detailed engineering phase. Once the engineering phase is started, it will become too costly and unfeasible to make significant changes.

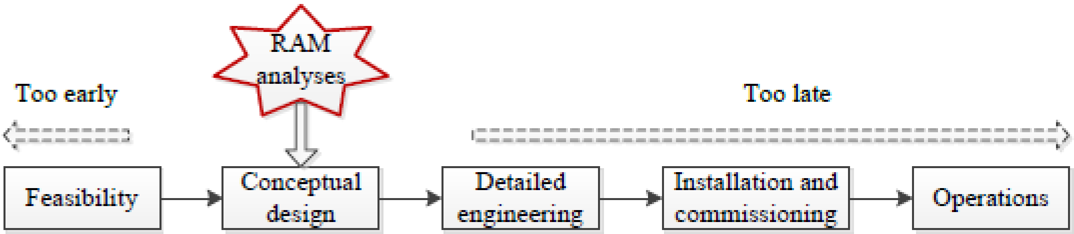


Figure 2.1: RAM analyses in a project lifetime

NORSOK Z-016 (1998) states that the objective of the feasibility phase is to find both technically and economically feasible development options. Some preparation activities of RAM analysis are, for example,

- define the scope and boundary of the work
- define the need for sensitivity analysis

When it comes to the conceptual design phase, the goal is to select the most preferred design, and outline the operation and maintenance strategies. RAM analysis is thus an effective tool to serve this purpose. It assesses availabilities of all the proposed options, and gives details of each option regarding components' contribution to the unavailability. In this way, a valuable guidance is generated for system optimization. During the process of RAM analysis, it is essential to involve engineers from different disciplines. The accuracy of results requires high level of consultancy and engagement.

However, the dilemma is that the conceptual design phase is rather short, and the RAM analysis is time consuming. Limited information in the project's early phase may also impose difficulties to determine parameters and the estimated data are often with high uncertainties. An appropriate and easy model is thus the foundation of *design for reliability*.

2.2 Approaches of RAM Analysis

Analytical approach and simulation approach, are the two common approaches of RAM analysis. Rather than saying one approach is superior to the other, it is more important to understand them and use the most relevant approach to the specific situation. This section gives a brief discussion of the two approaches and their advantages and disadvantages.

2.2.1 Analytical Approach

According to Hokstad (1989), the asymptotic calculations and Markov analysis are the typical analytical techniques.

Asymptotic calculations

The asymptotic calculations are the calculations deploying steady state approximation formulas. It is a mechanic way to calculate availability based on reliability and maintenance (RM) parameters. The availability of every subsystem, A, can be calculated as,

$$A = \frac{MTTF}{MTTF + MDT} = \frac{1}{1 + \lambda \cdot MDT}$$

where MTTF is the mean time to failure, MDT is the mean down time and λ is the failure rate.

The overall system availability is calculated as the combination of the availability of each subsystem. Since the approximate formula is based on a lot of assumptions, so that the application is to some degree restricted. It is assumed that repairs are taking place immediately after failures, and the repaired item is as good as new. For safety critical systems, the formula is incapable to treat undetected failures. Due to its simplicity in application, asymptotic calculations are natural to be used in the conceptual design phase. A lot of projects carried out in Aker Solutions are performed with this approach using an Excel spreadsheet.

Two shortages of asymptotic calculations are discussed as follows.

- The formulas are valid on the assumption that the operating conditions are stationary. When the project starts, the availability is usually equal to 1.0. It may take some years until the stationary condition is reached. Thus, the asymptotic method is only suitable for long life cycle projects.
- Multiple repairs may reduce the accuracy of results. For subsea production systems, the multiple repair is a typical maintenance strategy. If two or more failures occurred, individual repairs will not start immediately after each failure. Instead, they will wait to carry out together in the same maintenance interval. In this case, the actual waiting time (mobilization time) would be shorter than the predefined MDT for the individual component.

Markov Analysis

Markov analysis is perhaps the most popular technique among all the analytical techniques. Different from the asymptotic calculations, Markov analysis is capable to model maintenance strategies, such as comparing vessel mobilization criteria.

The exposed limitations of Markov analysis are (Hokstad, 1989):

- All relevant time periods are assumed to be exponentially distributed. For subsea production systems, past experience has shown that exponentially distributed MDT does not affect much of the result. However, it may cause significant deviation if MTTF does not follow the exponential distribution.
- The computing time is longer than that of the asymptotic approach. It is certainly depend on the size and complexity of the system. For large systems, Markov analysis becomes clumsy, and simulation might be a better approach.
- In order to reduce the computing time, system stages are often refined and the least probable stages are eliminated. For example, the stage in which all the components are failed. Simplifying the stages may generate a conservative result, but do not have severer impact.

Overall, Markov is suitable for small and medium sized systems in the project development phase where detailed results are requested.

2.2.2 Simulation Approach

The simulation approach is referred to as the Monte Carlo simulation (Mitrani, 1982). It is primarily used for modeling stochastic behavior of dynamic systems. Such systems are influenced by "random events", like failures, repairs or planned inspections. In order to save simulation time, it only takes the critical components into account. For the case study in chapter 5 as an example, the production insignificant components are excluded. RM parameters (e.g., failure rate, active repair time) are used to define the states of each component. Various combinations of each component's states further determine the system states. A typical simulation procedure is shown in figure 2.2.

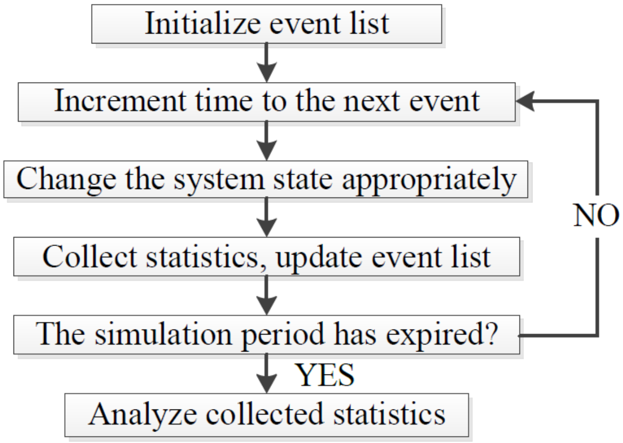


Figure 2.2: The procedure of RAM analysis using the Monte Carl simulation, (Kawauchi and Rausand, 1999)

The *"event list"* includes all "random events" which creates a realistic scenario over the system life cycle. The time at which an event occurs or the duration of the event is determined by generating a random number, which is substituted for a cumulative distribution function of the time of the event. Throughout the simulation process, new events are taking place while the last events are discarded from the list. In this way, the *"event list"* keeps track of the next event and the system state is updated accordingly. After the life cycle scenario has been repeated a number of times (normally 300 times for offshore development projects), the availability is calculated. The uncertainty derived from simulation depends on the number of replications, the more replications run, the more stable the result is. The large number of replications will increase the computing time.

Compared to the analytical approach, the simulation approach is very flexible and capable of modeling complex systems and treating different factors, including

- weather conditions (influencing repair time)
- production profile
- maintenance philosophy

Production profile defines production rate along with the project life cycle. By considering production of each operation year, the obtained results are time dependent and reflect the real production availability. By including all these factors, the simulation approach can establish more accurate models for specific systems. If a detailed RAM study is required, only the simulation approach is satisfied. However, the informative output is based on a large amount of inputs. The process of collecting data can be time consuming, and sometimes difficult because of limited data resource and high uncertainties, e.g. This may be a severer weakness of the simulation approach using in the conceptual design phase.

2.3 Software Tools for Analytical Approach

Computer based RAM analysis is becoming an integral part of system optimization. The deterministic model allows compare the reliability of alternative solutions in a systematic way. Various software tools of the analytical approach have been developed, such as

- UNIRAM
- WinRAMA
- SUBMARK and SUBCALC

UNIRAM (unit reliability and maintainability) was originally developed by the Electric Power Research Institute (EPRI) to apply in the power generation industry. It was intended to calculate the availability of individual units, later it has been proved sufficiently for the system level as well. The programming codes in UNIRAM enable more rigorous RAM assessment than previous approaches.

UNIRAM assumes that the assessed system has several capacities between 0 to 100%. Depending on the operating conditions, each operating condition is defined as a state with the associated capability. The operation condition contains the information of which components are functioning, which are failed. Based on RM data of each component, the probability of the system staying at each state is calculated, thereby a time dependent result is obtained in accordance with operating conditions.

As a result, UNIRAM can provide

- each capacity level with the corresponding probability and duration

- the ranking of unavailability contributors
- sensitivity analyses
- uncertainty effects from RM data

Apart from the power generation industry, UNIRAM has been extended to wide applications, such as chemical and petrochemical plants, transportation systems and weapon systems, (Witt, 1990) (EPRI, 1991).

WinRAMA calculates flow analytically using the RBD method. It was developed by DNV Industry AS. Same as UNIRAM, WinRAMA provides the system capacity level with the corresponding probability and the operation duration.

SUBMARK and SUBCALC were developed by the SERA program to assess reliability of oil/gas subsea production systems (SSPS). SUBMARK adopts the Markov approach, and SUBCALC is based on asymptotic formulas. The SERA program has also created a simulation program called SUBSIM, it is cooperated with fields operations simulation program (FOSP) by Shell.

2.4 Software Tools for Simulation Approach

So far, a number of commercial simulation tools have been developed and used in various industries. In this section, Miriam Regina, Maros and Extendsim are discussed. Miriam Regina is further used in the case study in Chapter 5.

2.4.1 Miriam Regina

Miriam Regina (Miriam is the first version) is a well known simulation tool developed in 1980s by Electronic Data Systems corporation (EDS) in close cooperation with Statoil. Originally, it was intended to model RAM performance of offshore facilities, later on, the flexibility enables Miriam Regina to apply in other industries as well.

Methodology

The methodology used in Miriam Regina is a combination of the flow network approach and the Monte Carlo simulation.

The flow network is a reliability dependent block diagram. Different from the actual process block diagram, the flow network represents the throughput of the system production line. When the throughput of each subsystem/component changes, the overall throughput will change accordingly. These changes, are in fact partially deterministic, for instance, the user can specify when they happen. The model itself contains a lot of information, for example, the boundary of the modeled system, storage for buffering and maintenance rules of individual elements.

As the Mote Carlo simulation presented in 2.2.2, Miriam Regina generates discrete random events (failures, repairs, etc.) to simulate a realistic scenario for the system over its life cycle.

Key Features

The flow network is built by reliability block diagrams (RBDs), see figure 2.3. It is composed with boundary points (triangle), process stages containing items (square) and storage units (circle). Arrows are drawn to link all the elements together.

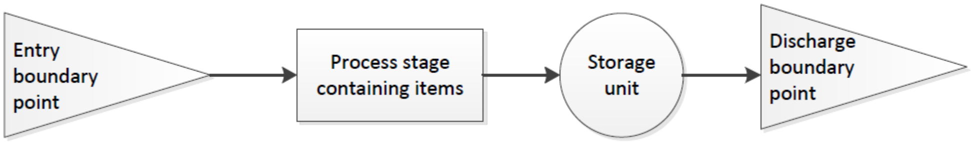


Figure 2.3: Network elements

All networks must contain at least two boundary points (entry and discharge), one process stage. The process stage can be a specific item or a subsystem with several items in parallel/series configuration. For each item, the following entries must be determined:

- Configuration, i.e., 1×100%, 2×50%
- MTTF and MDT
- Production capacity

Other information can also input to Miriam Regina, such as the production profile, maintenance strategy including resources planning and preventive schedules. The more inputs entered, the more detailed results will get.

Once the model is validated successfully, the following items need be specified to start simulation:

- Simulation length: the life cycle of the system
- Number of replications: the more replications, the higher accuracy of the result
- Output reports: a variety of reports can be chosen depending on requirements

Both the input parameters and the output reports can be exported to Excel. Among the output reports, the variability report is the one showing production availability per replication and blaming contributors to unavailability. Playback function is unique to Miriam Regina, which is used for network flow check, see what has happened during the simulation.

Advantages

Miriam Regina enables the user to model the operational performance of continuous process plants in terms of equipment availability, production capability and maintenance resource requirement.

Due to the advanced simulation approach, Miriam Regina is able to

- handle multiple flows
- record production availability results for several boundary points
- change capacities of the network through simulation
- handle time depend variations in production and demand through modeling the production profile

2.4.2 MAROS

Maintainability availability reliability operability simulation (MAROS) is a simulation tool developed by Jardine dn Associates Ltd. The methodology used in MAROS is similar to Miriam Regina with both the flow network and the Morte Carlo simulation.

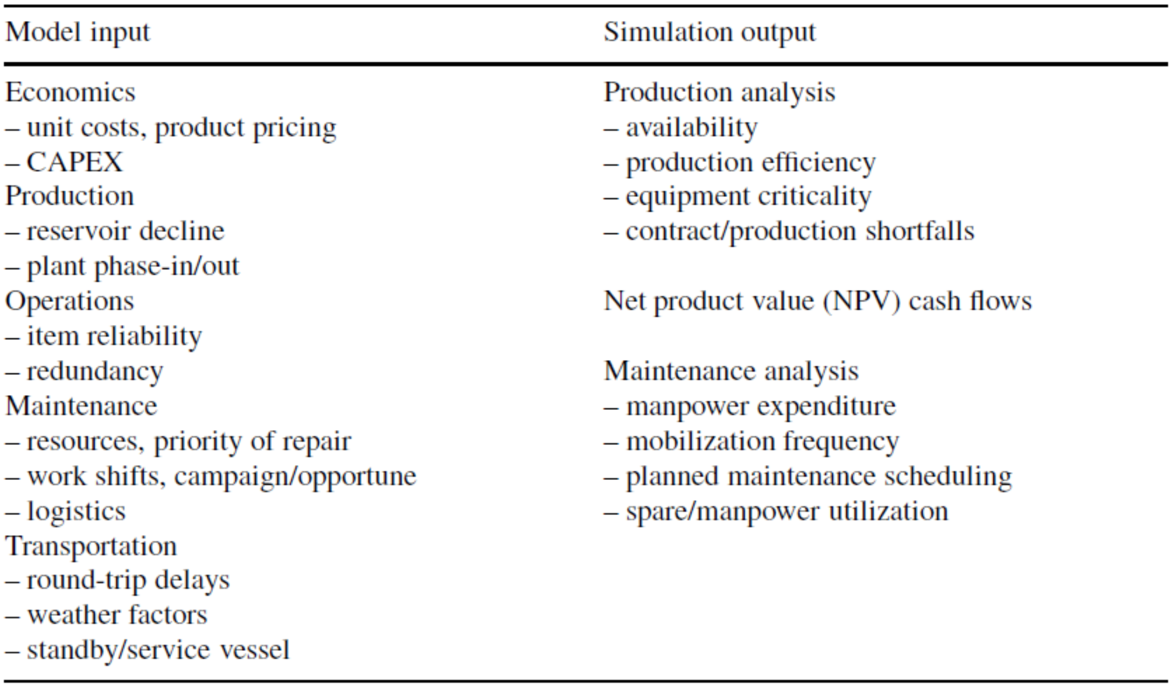
Total asset review and optimization (TARO) is another simulation tool developed upon MAROS. Besides all the functions of MAROS, TARO is capable in terms of

- handling multi-product or multi-stream flow
- performing detailed maintenance analysis down to the skill make-up of repair crews
- supporting more detailed OPEX profiles

Key Features

The main input and output of MAROS are summarized in table 2.1.

Table 2.1: Main input and simulation output of MAROS (Chang et al., 2010)



Model input	Simulation output
Economics	Production analysis
– unit costs, product pricing	– availability
– CAPEX	– production efficiency
Production	– equipment criticality
– reservoir decline	– contract/production shortfalls
– plant phase-in/out	
Operations	Net product value (NPV) cash flows
– item reliability	
– redundancy	Maintenance analysis
Maintenance	– manpower expenditure
– resources, priority of repair	– mobilization frequency
– work shifts, campaign/opportune	– planned maintenance scheduling
– logistics	– spare/manpower utilization
Transportation	
– round-trip delays	
– weather factors	
– standby/service vessel	

From the input entries, it can be seen that MAROS is able to treat economic data. In such a way, LCC analysis and RAM analysis are combined in one program. Compared to other simulators, MAROS is unique in providing optimization opportunities with both availability and profitability dimensions at the same time.

Advantages

MAROS is capable to model a wide variety of complicated components, system behaviors, and operational and maintenance philosophies. Meanwhile, by incorporating LCC analysis, MAROS allows to maximize economic return with high level of confidence throughout the decision making process.

An updated version of Maros has been released by DNV Software Custer Portal. The new version has made the following improvement,

- better user experience, save time when establish models
- better scheduling actives, increase quality control ability

2.4.3 ExtendSim

ExtendSim (first known as Extend) has been used in chemical processing, pharmaceuticals, consumer product manufacturing, food manufacturing, mining, and the oil and gas industry. For a chemical plant (Sharda and Burry, 2008), as an example, one application of ExtendsSim is to improve operations by identifying the relationship between the critical subsystem and the production loss. ExtendSim was not the first “drag and drop” simulation program, but it was the first graphical simulation tool to embody the concept of modeling components as objects (Krahl, 2009).

Key Features

According to Krahl (2009), two unique features of ExtendSim are illustrated as below,

Discrete rate model

ExtendSim has a variety of technologies for simulation modeling, including continuous, discrete event, discrete rate, and agent-based system. Among them, discrete rate modeling combines the rate-based capabilities of continuous models in an event-based environment. It is especially useful to simulate high-speed and/or high-volume processes that have flows, rates, events, constraints, storage capacity, and routing. Discrete rate modeling eliminates the rounding errors caused by mismatches between discrete events and continuous time steps and it runs a lot faster than discrete event models. Accurate answers are quickly achieved (Damiron and Nastasi, 2008).

Database

An ExtendSim model is created by adding blocks to a model worksheet, connecting them together, and entering the simulation data. Each type of block has its own functionality, icon, and connections. The source code for all of these blocks is available and can be viewed or modified by the end user. Blocks can be created from existing blocks or created from scratch.Each instance of a block has its own data. ExtendSim includes a relational database for organizing and centralizing simulation information. The use of a database in a model allows the modeler to separate the data from the model structure. This database has become a core feature in ExtendSim models. Generally, the ExtendSim model begins with the conceptualization of the database. Once the database design has been completed, the model is built to support the data organization. This approach creates a scalable and well organized model.

Advantages

Advantages of ExtendSim are found as follows:

- Every technology covered in ExtendSim can handle certain types of systems, which enables ExtendSim have a wide range of applications.
- The block is defined by codes, thus ExtendSim can construct a flexible model which suits better for the specific system
- Discrete rate is unique in its implementation and capabilities. The rate based model is easier to construct and faster to run.
- By feedback loops, calculations in ExtendSim preserve mass balance when flows are merged or diverged.

Chapter 3

The Practice of the Simulation Approach

Aker Solutions has a lot of experience on performing RAM analysis. This Chapter illustrates the core practice of the simulation approach used in Aker Solutions.

3.1 General Procedure

Based on previous projects, a general procedure of RAM analysis is shown in figure 3.1.

First, the full operation picture of the system should be studied from the system description, the process drawings and master equipment list (MEL), etc. The MEL is a list of all the components, categorized into subsystems.

In order to simplify the RAM analysis, FMECA is often carried out prior to modeling. The purpose of FMECA is to select critical components from the MEL. In section 5.2.1, FMECA is referred to as performance and operability review workshop (POR).

Since the whole production line is analyzed, the RAM analysis should engage a multi-disciplinary engineering team representing all operational aspects, including mechanical, electrical, process and maintenance. A high level of collaboration is thus required during the analysis process. The collaboration is facilitated by the RAM analyst.

The key inputs are RM data of each component. RM data can be obtained from an existing database, previous studies, or expert judgments. The accuracy of results highly depends on the quality of data and assumptions made during the analysis. In some cases, failure modes, maintenance modes, and sensitivity parameters are taken into account to support a complete

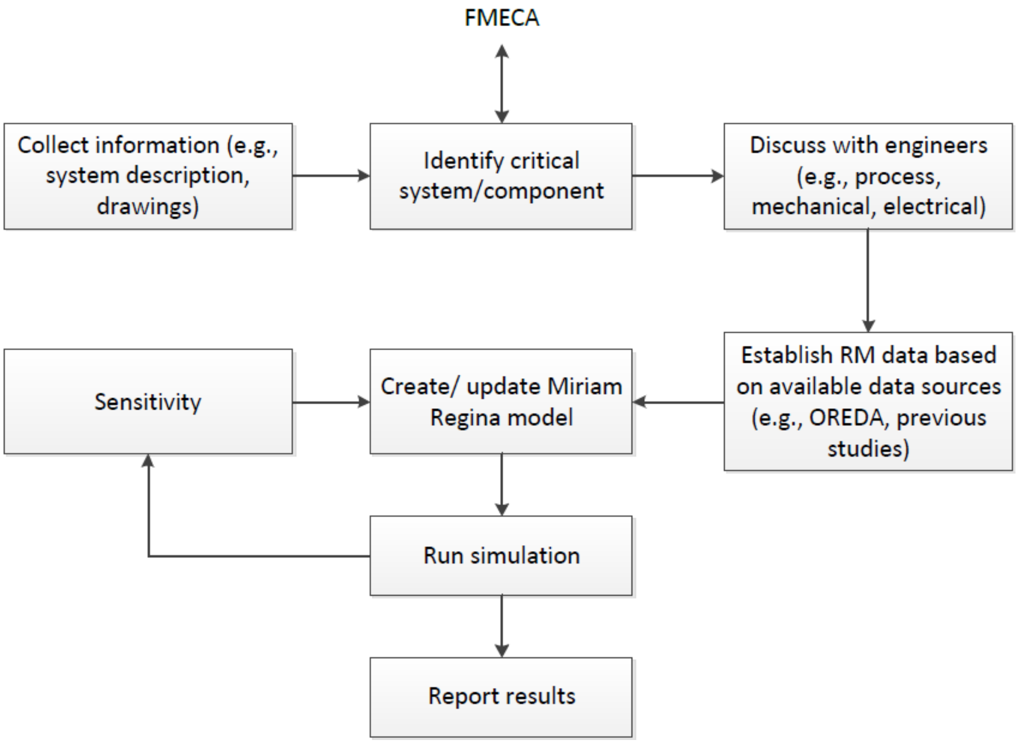


Figure 3.1: General procedure of RAM analysis, adapted from Aker Engineering (2008)

risk profile.

After the components and the associated RM data are ready, reliability block diagram (RBD) are established in Miriam Regina. If the model is validated successfully, the simulation will start running with hundreds of replications.

The model (RBD and data) can be further adjusted to conduct sensitivity analysis. In the end, the results of RAM analysis is generated through different types of reports.

3.2 Inputs

Failure events are the causes leading to production loss. The RM data which determine failure events, are thus basic inputs to RAM analysis.

3.2.1 Failure Events

Figure 3.2 illustrates the system performance associated with a failure event. The production rate indicates the system performance. The component failure rate is a parameter showing how often a failure happens. The system downtime includes full mobilization time, active repair time and preparation for start-up. Parts of run-down time and ramp-up time are also the system downtime. Normally, ramp-up time is longer than run-down time, particularly for valves.

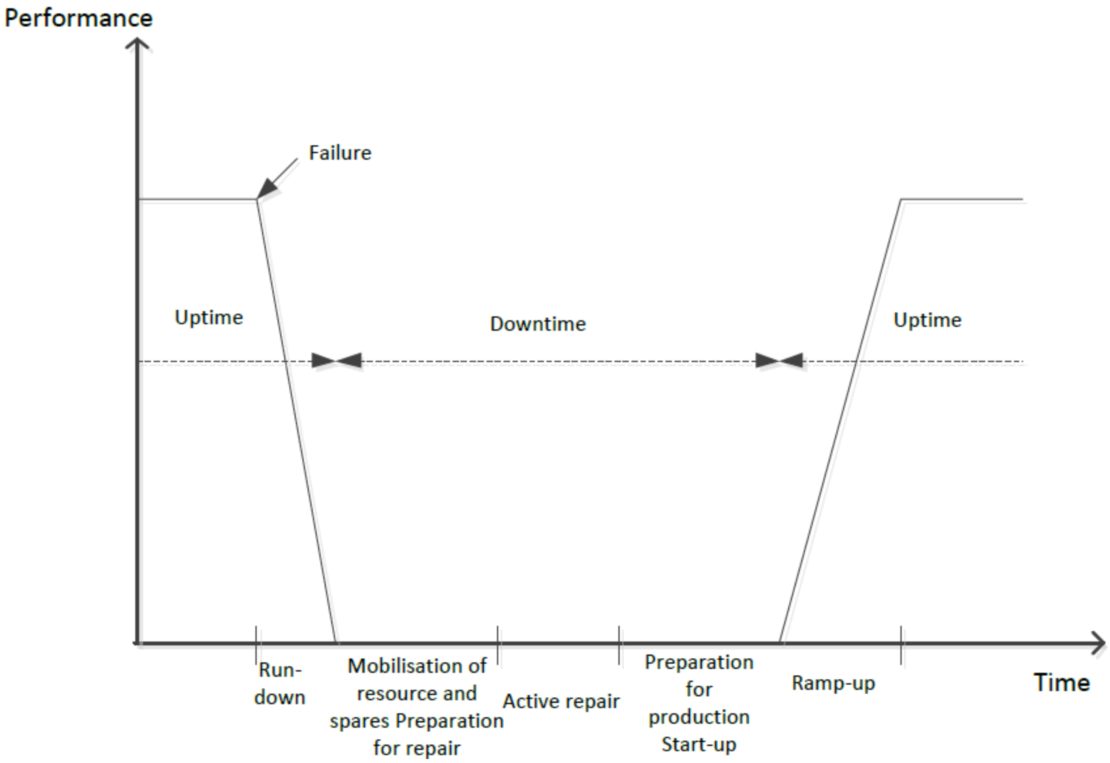


Figure 3.2: Illustration of downtime associated with a failure event, (ISO 20815, 2008)

All parameters illustrated in figure 3.2 are the inputs to RAM analysis. Note that for mobilization time, it is very project dependent and with high uncertainties. Expert judgment must be carried out for data determination in the specific application..

3.2.2 Failure and Repair Data

Failure and repair data can be found in several sources:

- The OREDA handbook (Oreda, 2009)
- Nonelectronic Parts Reliability Data (Denson et al., 1995)
- Availability Analysis Handbook for Coal Gasification and Combustion Turbine based Power Systems (Arinc Research Corporation, 1985)

The RM data for the same component may vary significantly in different sources. This is because the data are depend on operation conditions, the observation size and duration. The proper data source lays the foundation for the quality of final results. However, uncertainties are existing in the RM data.

The OREDA handbook is the most used data source in the oil and gas industry. It collects data for a large variety of components and systems used in offshore projects. Until now, several editions of the OREDA handbook have been issued, the 5th edition in 2009 is the most recent one. Additionally, a computerized database is available, but only to the OREDA participants.

The useful data for RAM analysis in OREDA are the failure rate and the active repair time. OREDA provides both failure rate with regard to calender time and operation time. In RAM analysis, the operational time dependent data is used. In order to enter into Miriam Regina, the failure rate needs converted to MTTF. Since the MDT does not only include the active repair time, thus additional determination of mobilization time, ramp-up time, etc, are required.

Assumptions regarding on the RM data are presented as below.

Constant Failure Rate

The real failure rate, as the function of time, is commonly illustrated by the bathtub curve shown in figure 3.3.

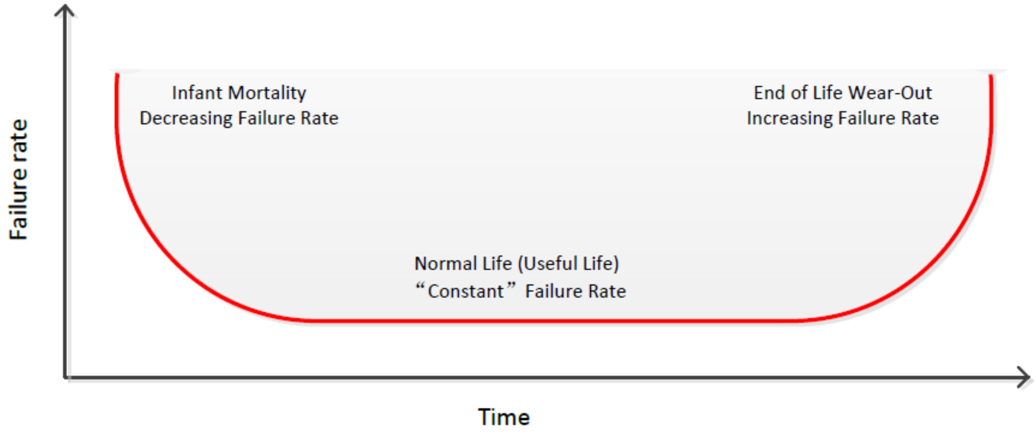


Figure 3.3: The bathtub curve

In RAM analysis, it is considered adequate to assume that the failure rate is constant. This implies all “infant mortalities” and wear-out failures are disregarded. A life cycle is limited to the useful lifetime of the project. Thus, the MTTF is specified as exponentially distributed in

Miriam Regina .

"As good as new" policy

The assumption “as good as new” implies that the maintenance activities have the ability to restore the component to an “as good as new” state. This allows to disregard the possibility of wear-out failures. Due to the implementation of a commissioning period and the assumption of “as good as new”, it is reasonable to use the same data for the entire life cycle and the assumption of a constant failure rate.

3.3 Simulation

Miriam Regina establishes models by using RBDs. It should be noted that the RBD does not represent the actual process arrangement, but rather depicts the reliability dependent relations which will cause production interruption. By performing FMECA, the production critical components are selected to be modeled.

To imitate the life cycle scenario, the simulation period for one replication is the expected life cycle of the system. After running a sufficient number of replications, the result is generated.

Advanced blaming is an unique feature of Miriam Regina. Whenever the throughput in the model is below the demand value at a discharge boundary point, the loss is attributed (blamed) to the items in the model that are currently in a failed state. Based on the production loss, the contribution from the failed components are calculated. The blaming report lists all the items in the model and their contribution to the system unavailability. Basically, the oil company is always concerned about the most critical components. For this purpose, the list of unavailability contributors is an effective indicator.

3.4 Sensitivity Analysis

Sensitivity analysis is used to investigate the impact of changes from RM data, system configuration and maintenance strategies. Both the analytical and simulation approaches are applicable to perform sensitivity analysis.

Usually, in the conceptual design phase, the main purpose of sensitivity analysis is to select the optimal system configuration. From the previous projects in Aker solutions, sensitivity analysis is carried out to compare the alternative design against the base design. For example, the Luno project conducts a sensitivity analysis to determine the influence of two compressor trains compared to one compressor train. In the Gjøa project, the sensitivity analysis reveals the effect of which flaring is included in the high pressure mode from the 3rd stage separator.

3.5 Handling of Uncertainty

According to NORSOK Z-016 (1998), the uncertainties occurring in RAM analysis shall be discussed and if possible quantified.

In fact, it is impossible to quantify the overall uncertainty. However, what can be done is to keep the uncertainties in mind throughout the whole analysis process, quantify what it is possible to quantify, and document the effort on the uncertainty reduction (Rausand, 2011). In such a way, it is clear to the decision-maker how the result is generated based on the available information.

The sources of the uncertainties are complex, they can be improper models, non-relevant data or limited knowledge of operation conditions. NUREG 1855 (2009) attributes the uncertainties to

- Parameter
- Model
- Completeness

Parameter uncertainties result from their interdependence with modeling assumptions (Parry and Winter, 1981), lack of statistically significant data (Apostolakis, 1978), expert opinion and rarity of modeled events (Apostolakis, 1990), (Apostolakis and Mosleh, 1979). In RAM analysis, the RM data should be obtained from the most relevant data source and may be adjusted according to the specific system. In any database, the quality of RM data is affected by the number of observed installations and reported failure events, and the duration of observation time.

Model uncertainties are unavoidable. This is because models themselves are simplifications of the real system. To minimize this type of uncertainties, it is important to know the existing models and use the most appropriate one. Uncertainties from simulation is expressed as a measure of the spread of this distribution by standard deviation. From previous reports of Aker Solutions, the only quantified uncertainty is from simulation.

Completeness uncertainties represent uncertainties derived from inexplicit risk pictures of the assessed system (NUREG 1855, 2009). Simplification may limit the scope of the analysis, and few resources are also problems for a thorough study. Usually, assumptions are made for the system boundary definition, model construction and data assessment. Thus, the RAM results must be seen along with all the assumptions.

Chapter 4

LCC analysis

4.1 Background

LCC analysis was developed to support procurement cost management in the U.S. Department of Defense (White and Ostwald, 1976). Till now, it has been widely used in the military sector as well as in the construction industry (Woodward).

LCC is the sum of the total life cycle costs, including initial investment and expenditure occurring during the product life cycle. However, the initial investment is in many cases the primary and sometimes the only criteria in purchase decisions. One of the difficulties of performing a proper LCC analysis is the lack of standards and data (Lindholm and Suomala, 2005).

Several standards have been developed for LCC analysis

- IEC 60300-3-3 (1996)
- SAE ARP4293 (1992) and SAE ARP4294 (1992)
- NORSOK O-CR-001 (1996) and NORSOK O-CR-002 (1996)
- ISO 15663 (2000)

The IEC 60300-3-3 (1996) introduces the basic concept and a general six steps procedure of LCC analysis, but it does not explain details when it comes to practical application. SAE ARP4293 (1992) focuses on the cost analysis considering cost elements, estimating techniques and other factors that have an impact on LCC. Some application issues, such as simulation, cost estimating relationships (CER) and top-down/bottom-up approaches are also discussed. SAE ARP4294 (1992) is intended to guide LCC analysis for aerospace propulsion systems.

NORSOK standards are developed by the Norwegian offshore oil and gas industry. NORSOK O-CR-001 (1996) is a LCC standard for systems and equipments in general, while NORSOK O-CR-002 (1996) is for oil production facilities. Both standards define cost elements in details and provide a spreadsheet as a model to calculate LCC. Compared to the other standards, the NORSOK standard is the most practical one. After 2000, the NORSOK standards are replaced by ISO 15663 (2000). The ISO standard suits best for offshore facilities, but may be extended to other industries.

4.2 LCC Analysis in Design

LCC analysis can be carried out in all phases of a product life cycle to support decision making. However, the earlier the cost picture is depicted, the better the product will be in terms of balancing performance, reliability, maintenance support and other goals against life cycle costs (IEC 60300-3-3, 1996).

According to White and Ostwald (1976), the LCC is the sum of all expenditure spend in support of the product from its concept development, manufacture to its operation till decommission. The costs occurring during the operational phases can be many times more than the initial costs (Woodward). Past experience has proven that up to 70 - 90% of the LCC is possible to be predicted in the conceptual design phase. From the perspective of both clients and suppliers, the purpose of performing LCC analysis in the conceptual design phase are illustrated as below, (Barringer and Weber, 1996).

- Affordability studies- measure the impact of a system or project's LCC on long term budgets and operating results.
- Source selection studies- compare estimated LCC among competing systems or suppliers of goods and services.

- Design trade-offs- influence design aspects of plants and equipment that directly impact LCC.

Figure 4.1 depicts the relationship between the commitment and the actual expenditure, as well as the associated evaluation uncertainty throughout the development phases of a program (SAE ARP4293, 1992). The fast increased commitment cost in the early phases shows that LCC analysis is more powerful to minimize the overall LCC in the early phases than the later. It is believed that 80% of the LCC is allocated by decisions made within the first 20% of the life of the product (Kawauchi and Rausand, 1999). The uncertainty level of LCC estimation varies according to the program development. Obviously, in the concept studies, the uncertainty level is rather high, then gradually reduced after more information is available.

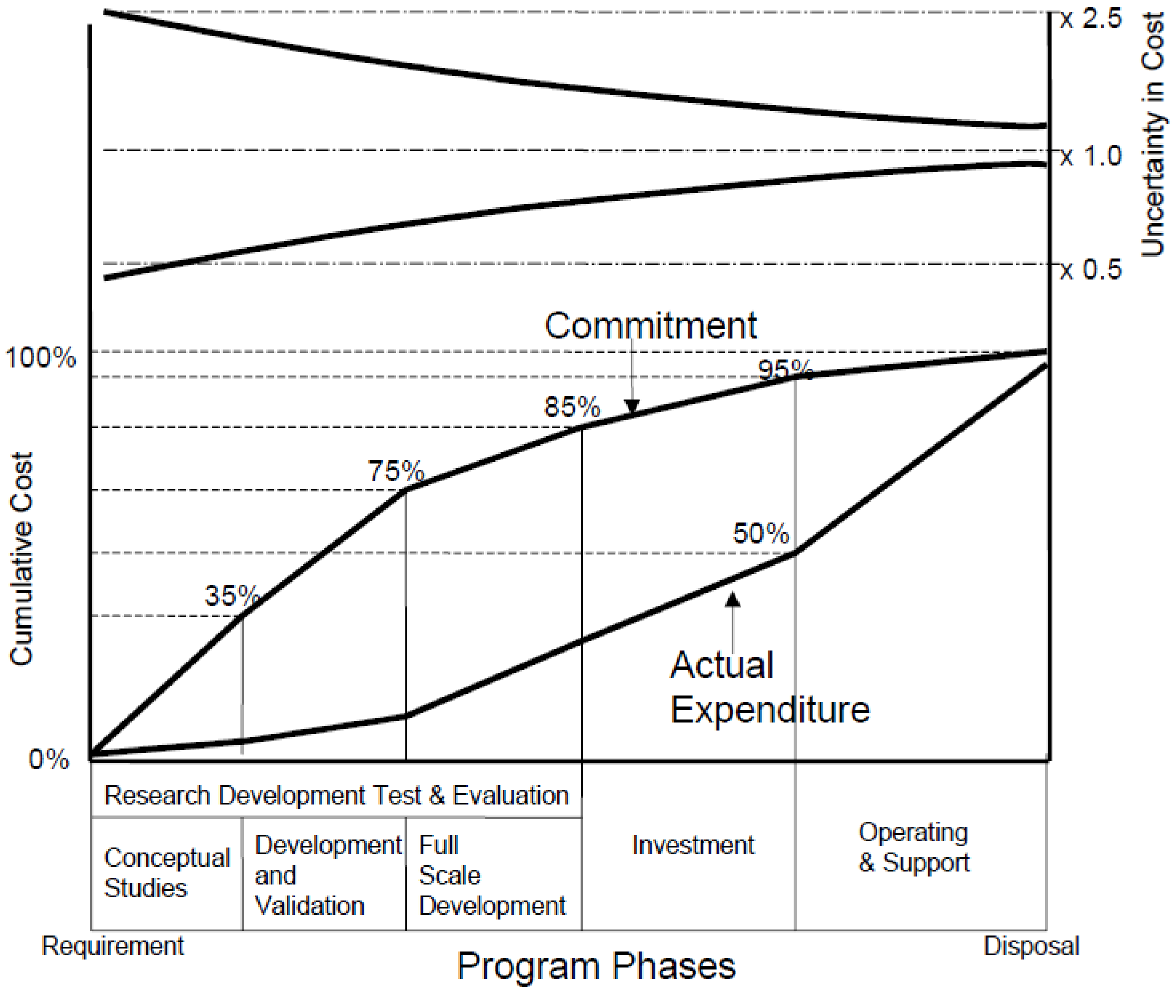


Figure 4.1: An example of influence of program phases on LCC, (Kawauchi and Rausand, 1999)

Overall, it is important to perform LCC analysis in the conceptual design phase. In order to reduce uncertainties, as much information as possible should be collected to produce a reliable result.

4.3 Procedure of LCC Analysis

Many procedures of LCC analysis have been proposed by different authors for a range of purposes. Although these procedures vary depending on different system properties, the main principles are more or less the same. The six basic steps are identified here with sub-activities, see figure 4.2.

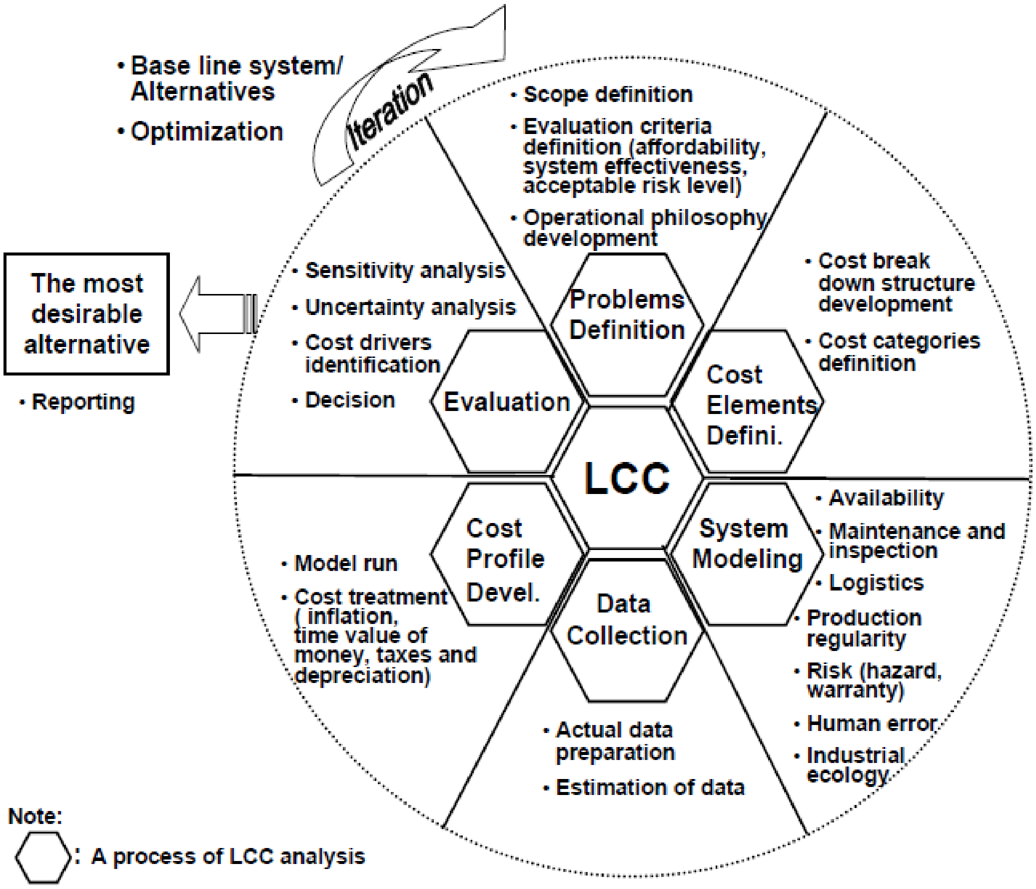


Figure 4.2: A LCC concept map (the six basic steps and the associated sub-activities), (Kawauchi and Rausand, 1999)

By performing RAM analysis, problems definition and system modeling have been touched upon. In this sense, LCC analysis is a collective analysis including many types of analysis. Apart from RAM analysis, it may include risk analysis, environmental analysis, maintenance management, etc. According to Kawauchi and Rausand (1999), each step is further elaborated as follows.

4.3.1 Problem Definition

As the first step of LCC analysis, the objective of the problem definition is to lay a basis for the following steps. It can be discussed from the three activities listed below.

Scope definition is to illustrate the scope, the objective and the assumptions of LCC analysis. For any system, it is important to outline a clear picture to be analyzed, including the system boundary, the considered characteristics, and in which life cycle phase the analysis is carried.

Evaluation criteria used in the last step "evaluation" is necessary to be defined in the first step. The criteria should describe which factors the LCC is evaluated against, so that the most optimal option is selected by trade-off between these factors. One suggested criterion is the balance between cost and effectiveness (Clarke, 1990), (Lydersen and Aaroe, 1989). Effectiveness can be further specified according to specific requirements, such as availability, and product quality.

Operational philosophy directly influences the system performance and the cost supporting such operations. Thus, if it is concerned by the product owner, the operation and maintenance plan should be specified, for example, the interval of overhaul inspection and the capacity of maintenance resources.

4.3.2 Cost Elements Definition

In order to identify all cost elements, (IEC 60300-3-3, 1996) recommends to develop a cost breakdown structure (CBS). This approach allows to find costs by three dimensions, life cycle phase, product/work breakdown structure, and cost categories.

Various cost categorizes have been suggested. However, due to different types of systems, the cost category is only a guideline, and has to be tailored for the specific application. For offshore development projects in the conceptual design phase, the costs elements are defined from (Aaroe, et al, 1996)

- Acquisition cost (CAPEX)
- Operating cost (OPEX)
- Cost of deferred production (REGEX)

In Hokstad, et al (1998), the cost category is somewhat similar to this one, but introduces another cost element in parallel with the above three, which is called *hazard cost* (RISKEX). RISKEX may be included, depends on the available information and if it is concerned in the phase when LCC analysis is performed.

4.3.3 System Modeling

Except from the acquisition cost which can be obtained directly, other costs often need to be quantified by modeling. Models are introduced in the following, but details is not described.

Maintenance and inspection modeling

Maintenance and inspection planning has a great impact on the system performance. Mean time between maintenance, maintenance man hour rate, turnaround time, as well as other related factors will mainly influence OPEX.

Logistics modeling

The elements covered by logistics can be, storage capacity, personnel and facility transportation, etc. The logistic support directly affect maintenance activities, for example, the sufficient spare parts storage on site, the less repair time is required, thus the less cost is spent on repairing, but higher cost to support the spare parts on board.

Production regularity modeling

Here the production regularity modeling is identical to RAM analysis. It is intended to quantify REGEX. REGEX is thus calculated by the production unavailability of the system (the result from RAM analysis) and the loss of production rate. If the unavailability of the system is high, REGEX is considerable compared to other elements in LCC.

Risk (hazard,warranty) modeling

Risk means the combination of the frequency and consequences of the accident. To evaluate RISKEX, the consequences will be all converted to a cost unit. For the oil and gas industry, many specific risk analysis methods have been developed.

Besides the above modelings, other modeling can be added depend on the actual requirement of LCC analysis.

4.3.4 Data Collection

In order to run the modelings, data must be collected. For RAM analysis, as an example, RM data are recorded in many resources. However, for other types of data, such as operation, maintenance and cost, few data is accessible to the public. In most cases, the analyst has to consult the manufacturer to get internal data. If the quality of data is poor, expert judgment or estimation has to be used. Some estimation methods have been proposed, for more details see SAE ARP4293 (1992).

4.3.5 Cost Profile Development

One of the main objectives of LCC analysis is an affordbility analysis considering a long term financial planning. In the affordability analysis, a cost profile over the life cycle is key information showing the cost of different design options throughout the system life cycle. The cost profile is achieved through running cost models developed in a LCC analysis with input data.

Since LCC takes into account future costs, the time-value of money needs to be discounted to present value especially if the life of the asset is long. Equation is used to cost discounting,

$$NPV = \sum_{n=0}^{T} C_n (1+X)^{-n}$$

where,

NPV is the net present value of future cash flows
C_n is the nominal cash flow in the nth year
n is the specific year in the life cycle costing period
X is the discount rate
T is the length of the time period under consideration, in years

In fact, interest rate, exchange rate, and inflation may also taken into account. However, it is difficult to determine these factors. If they are not proper defined, it may have serious impact on the accuracy of the LCC results.

4.3.6 Evaluation

In this step, both base case and the alternative should be evaluated by the criteria defined previously. If none of the option is satisfied, the system should be further modified and analyzed. If required, sensitivity analysis is used to examine the impact of changes in input parameters and identify the high-cost contributors. Based on the results of all the options, the most optimal design is selected considering by a large range aspects, from operation, maintenance, to economic issues.

4.4 Applications of LCC Analysis

Korpi and Ala-Risku have reviewed several published LCC analysis case studies, and found there is no perfect LCC application. It seems difficult to perform a full LCC analysis as suggested in the literature or standards, some common problems are that these case studies

- covered fewer parts of the whole life cycle
- estimated the costs on a lower level of detail
- used cost estimation methods based on expert opinion rather than statistical methods
- were content with deterministic estimates of life cycle costs instead of using sensitivity analyses

Although many procedures have been created for LCC analysis, it is still lack of a practical model for application systematically. This thesis develops an Excel spreadsheet based on the NORSOK standards and the past experience of Aker Solutions. This simple model is considered to be sufficient in the conceptual design phase, which is utilized in the case study in section 5.4.

Chapter 5

Case Study

5.1 Introduction

In cooperation with Aker Solutions, RAM and LCC analyses are performed on an ongoing offshore project as a case study.

5.1.1 Scope of Work

Figure 5.1 illustrates the process of system optimization. In this case study, RAM and LCC analyses are carried out in the conceptual design phase. The alternative solution is proposed by the process engineer, thus the selection of the alternative solution based on constrains is not in the scope of this study.

5.1.2 Objectives

The RAM analysis is intended to assess the production availability of the system. The production uncritical subsystems/components are thus not taken into account. By running the simulation model with Miriam Regina, an overall production availability as well as unavailability contributors on both subsystem and component levels should be generated.

The LCC analysis is performed to compare the base case and the alternative solution in terms of economic issues. Due to limited time and resources, only the cost categories, CAPEX, OPEX, and REGEX are calculated. Other costs, such as RISKEX, tax and emission are not included.

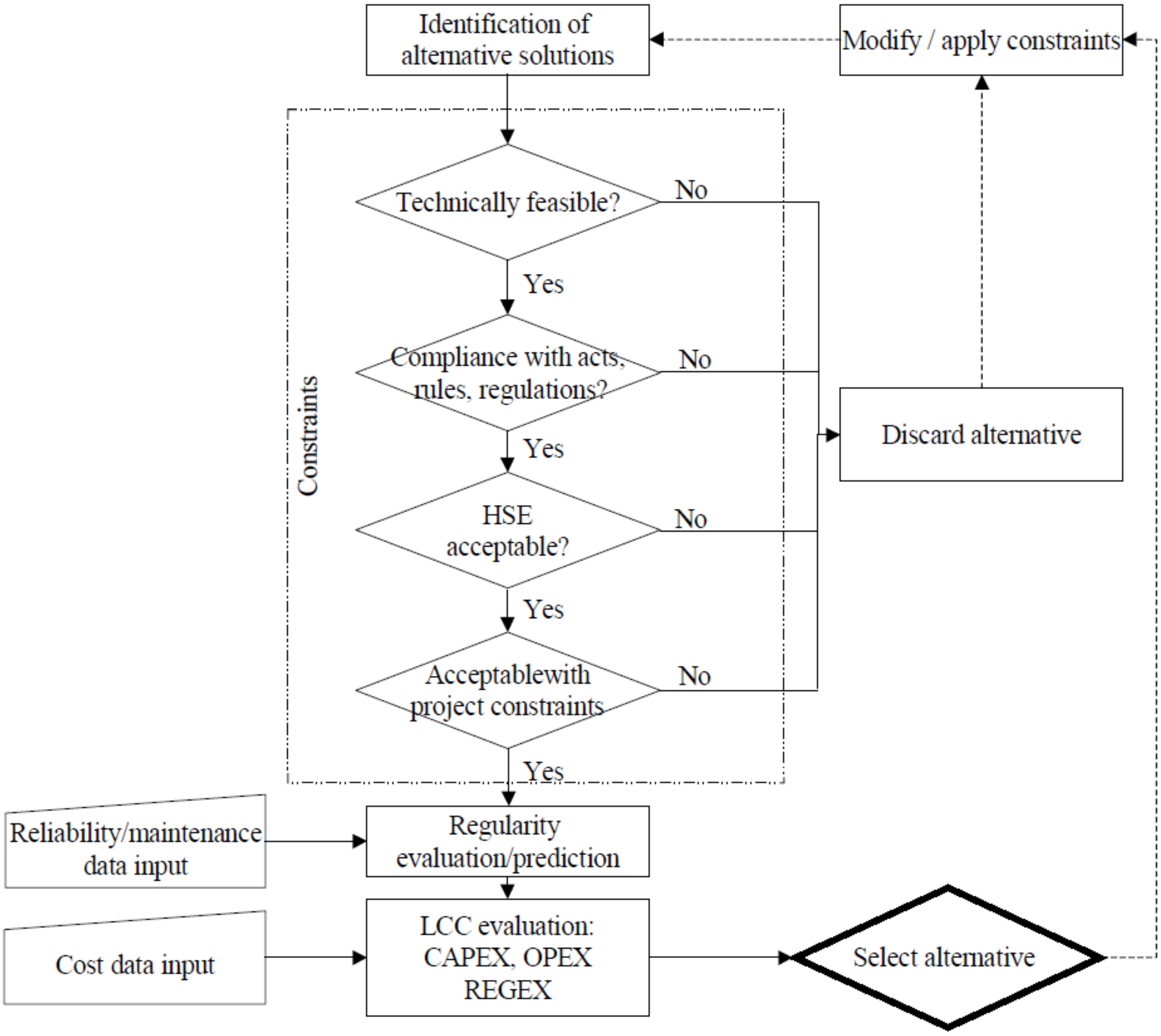


Figure 5.1: Optimization process (NORSOK Z-016, 1998)

As a result, the outputs of RAM and LCC analyses should be able to select the best solution with regards to regularity and cost.

The overall objective of this case study is to demonstrate the procedure of RAM and LCC analyses and prove the feasibility of performing these two analyses in the conceptual design phase.

5.1.3 Steps

The case study is conducted by the steps as below. The key steps and assumptions are presented in the following sections

	Step 1: System description
RAM analysis	Step 2: Production critical subsystems/components selection (POR/FMECA) Step 3: Set up the reliability block diagram (RBD) in Miriam Regina Step 4: Collect RM data Step 5: Validate and simulate Step 6: Sensitivity analysis Step 7: Report and result Step 8: Identify the cost categories
LCC analysis	Step 9: Identify the cost elements of each category Step 10: Collect data Step 11: Calculation and discounting Step 12: Compare savings between alternative solutions
	Step 13: Conclusion

5.2 System Description

A sketch of the system topside process is shown in figure 5.2. The production is derived from four wells split on two templates. Two production flowlines are routed to the FPSO, one from each template. The well fluid is separated in oil for storage, gas for injection or export (dependent of drainage strategy) and produced water to specifications.

Oil is stabilized in a two stage separation train. Water is removed from the oil in the 1st stage separator and finally in an electrostatic coalescer downstream the 2nd Stage Separator. The produced oil is pumped to storage in the floating production storage and offloading (FPSO) tanks via the crude oil cooler. The produced water is treated to specification in a hydro-cyclone and compact flotation unit (CFU). The produced water is injected together with treated seawater into the reservoir to enhance oil recovery.

Gas from the separators is recompressed and dried in a tri-ethylene glycol (TEG) column. Dry gas is used as fuel gas for the turbine driven power generators. Remaining gas is either exported to the Åsgard transport pipeline or up to 0.6 MSm^3/d of gas is circulated downhole to aid reservoir fluid flow. This gas is compressed to a higher pressure than the exported gas.

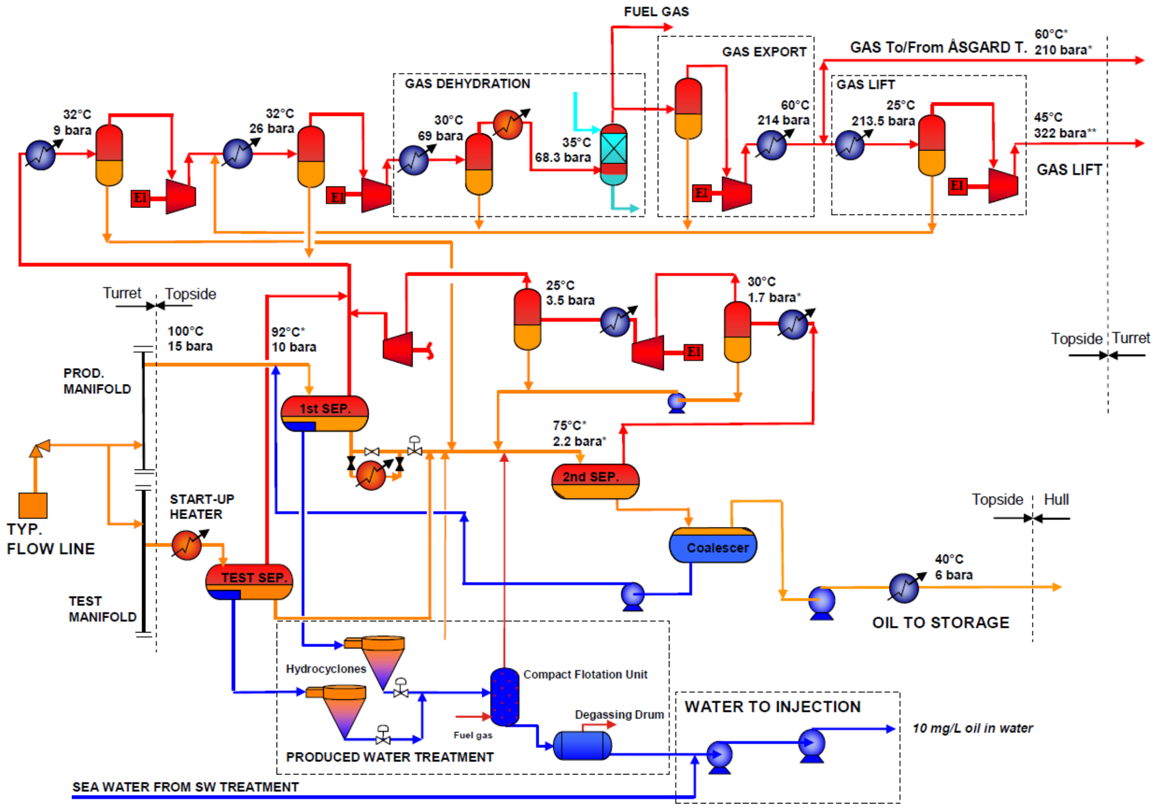


Figure 5.2: A sketch of the topside process

5.3 RAM Analysis

The boundary of RAM analysis is the 1st separator on the upstream side and the safety valves for crude and gas export on the downstream side. The battery limits can also be seen in assumptions in section 5.3.1, and Appendix C.

Furthermore, a sensitivity study is defined to determine the influence of two gas lift compressors (2 × 50%) compared to one compressor (1 × 100%) to the production availability. The Monte Carlo simulation is run by the software tool Miriam Regina.

5.3.1 Assumptions

The main assumptions are shown in table 5.1. Component specific assumptions regarding RM data are documented in Appendix E.

Table 5.1: Assumptions

ID	Assumptions
1	Reliability data from the OREDA-2009 handbook is used as a basis for this study.
2	Only failure modes classified as critical are considered in the analysis. It is assumed that degraded and incipient failures will be repaired on next opportunity, and will not impact the production.
3	The unavailability contribution from process transmitters, manual valves, check valves and flanges is assumed to have negligible impact on production, and are thus omitted in this study. It is assumed that process transmitters can be replaced on next opportunity, or without disrupting the production.
4	The assumption as good as new is used for failure events. This assumption implies that all maintenance operations have the ability to restore the production at a state which is as good as new.
5	Constant failure rates are assumed for all equipment included. All equipment is assumed to have an exponentially distributed lifetime.
6	No seasonal variations are considered.
7	It is assumed that the water injection has no influence on the production.
8	It is assumed that the oil export pipeline is 100% available and hence it does not affect the production availability.
9	The MEG system is critical for start-up, but does not affect the production availability at regular production, and will not be a part of the analysis.
10	Constant weather conditions all year is assumed.
11	Metering packages are assumed 100% available.
12	Planned testing, revision shutdowns and preventive maintenance are not considered.
13	The effect of changes in production profile and capacities over the lifetime is not considered (i.e. only average system availability estimated based on fixed 100% production rate).

5.3.2 Critical Subsystems/Components Selection

A performance and operability review (POR) workshop is carried out to identify the production critical subsystems/components from the MEL. The POR serves the same purpose as FMECA in figure 3.1. The selected components are shown in the entire MEL in Appendix C.

Additionally, the POR also helps in model establishment and data estimation particularly when no relevant data is available. The POR workshop is participated by personnel from Aker Solutions, covering disciplines of process, electrical, mechanical, safety and maintenance.

5.3.3 Alternative Solutions in Gas Lift Compressor

The gas lift process is to lift oil or water from wells artificially to ensure production from low pressure reservoir. To support the gas lift process, the gas lift compressor is normally consist of two or three stages of compression and are driven by a common driver. In this project, it is unclear about the actual production loss when the gas lift compressor fails. However, the process engineer states that at least in the first three years, the gas lift compressor will not influence much on production due to sufficient pressure in the reservoir. This means the low water cut implies a lower specific gravity of the well flow compared to later in the field life. Instead of full production loss, the reduced production in case of the gas lift compressor failure tells the production remains quite good even without gas lifting.

In this case study, different designs of the gas lift compressor are investigated. For the base case $(1 \times 100\%)$, if the gas lift compressor fails, it will cause 25% of the production unavailability. And for the sensitivity $(2 \times 50\%)$, the production will be reduced to 90% if one out of the two compressors fails.

5.3.4 Reliability Block Diagrams

The RBDs for both production and utility are established in Miriam Regina, see figure 5.3 and 5.4.

Some process stages indicate components, and the others indicate subsystems within parallel/series structured components inside. All the modeled items and their configurations are shown in Appendix C and D.

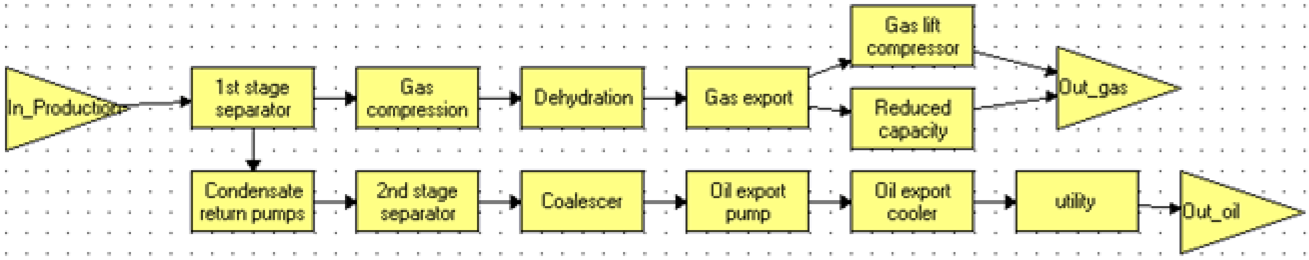


Figure 5.3: Production reliability block digram

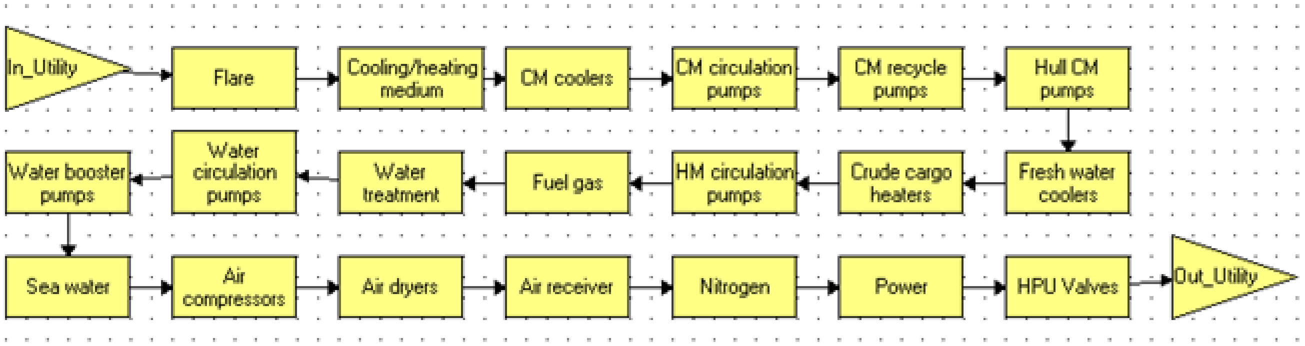


Figure 5.4: Utility reliability block diagram

The *reduced capacity* process stage in paralleled with the *gas lift compressor* process stage realizes the assumption of reduced production when the gas lift compressor fails. For the base case, if the 1 × 100% gas lift compressor is failed, the *reduced capacity* will support 75% of the availability. For the sensitivity, 2 × 50% gas lift compressors are included in the *gas lift compressor* process stage and 40% of the production is given to *reduced capacity*. If one out of the two compressor is failed, the unit will then provide 90% of the production.

5.3.5 Inputs

The RM data (failure rate and active repair time) are mainly obtained from OREDA. Pre-repair time and ramp-up time are determined by expert judgment through POR. Assume that no total replacement is required for the complex components and there is sufficient indicator of the critical failure where only parts of the component need to be repaired. The data dossier is available in its entirety in Appendix E.

- Pre-repair times have been set to 2 hours for components where spare parts are assumed to be available onboard at any time.

- Pre-repair times have been set to 12 hours for components where the acquisition may take long time.
- Ramp-up time have been set to 5 hours for all the equipments, but half of the ramp-up time is assumed to be downtime.

5.3.6 Results

When the model is validated successfully, the simulation is ready to generate the results. Without considering planned maintenance, a simulation over 20 years of 300 replications has been run. The result shows for the base case (1 × 100% gas lift compressor), the production availability is 93.01% with a standard deviation 0.02%. And for the sensitivity (2 × 50% gas lift compressors), the production availability is 93.10% with a standard deviation 0.03%.

The results are based on the assumptions listed in section 5.3.1 and the input data in Appendix E. Due to production profile is not considered, the estimated availability is based on fixed 100% production rate.

Main Contributors to the Production Unavailability

The contributors to the production unavailability per equipment type are shown in figure 5.5. The percentage expresses the contribution of each equipment type to the overall unavailability.

From figure 5.5, it is visible that the centrifugal compressors with 52.56% are the largest unavailability contributors. The vessels and electric motors are13.63% and 10.26%, respectively. Furthermore, the heater exchangers and the reciprocating compressor contribute 5.82% and 4.30%, respectively, to the unavailability. Equipments that are not shown in figure 5.5 have minor impacts on the production unavailability.

Figure 5.6 shows the main contributors to the unavailability per item. The five compressors (including electric motors and frequency converters) are the main contributors.

Figure 5.7 illustrates the main contributors to the unavailability per system. System 23 (Gas compression and re-injection), 27 (Gas export), 20 (Separation and stabilization), 24 (Gas treatment), and 80 (Main power high voltage) are the main contributors to unavailability. Note that the gas lift compressor is included in the system 27.

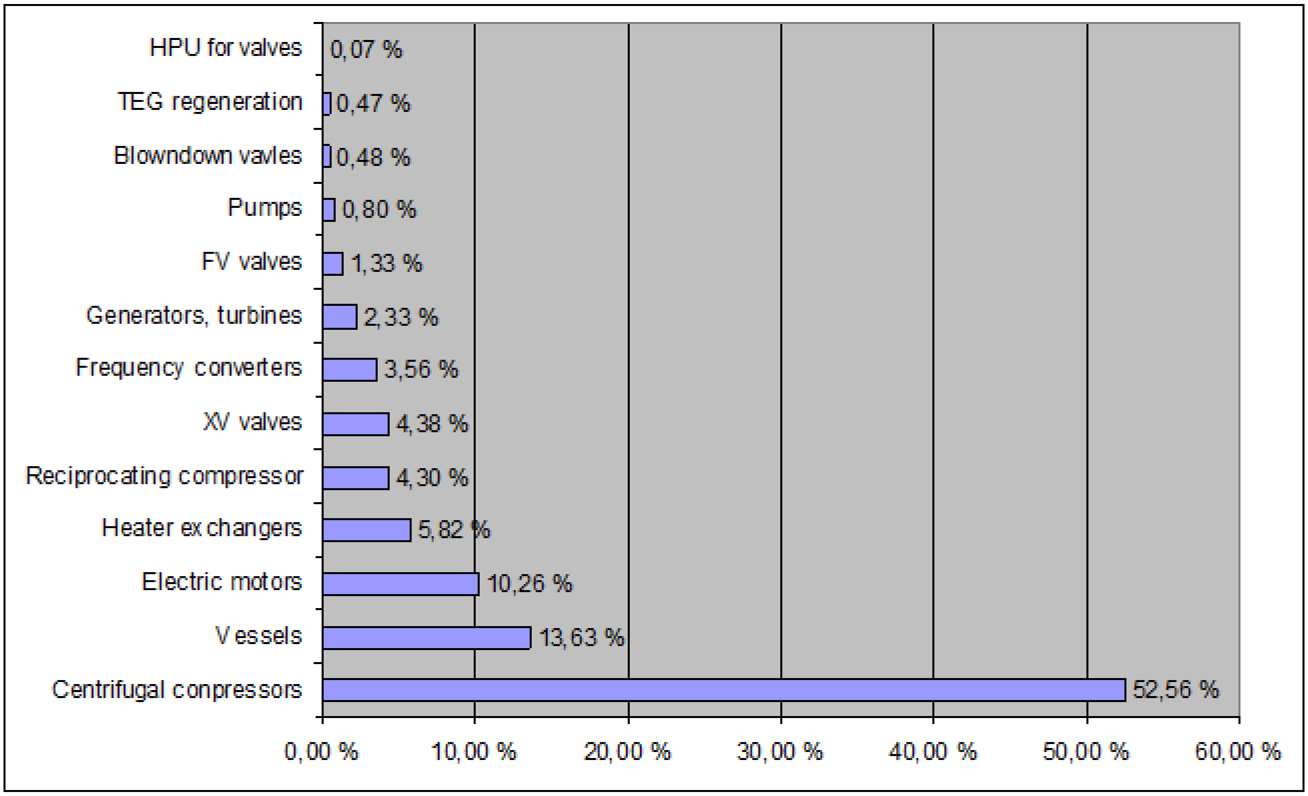


Figure 5.5: Main contributors to unavailability, per equipment type

5.3.7 Uncertainties

As presented in section 3.5, uncertainties are derived from parameter, model and completeness. Accordingly, uncertainties associated with this RAM analysis are found in these three area.

Parameter uncertainties. For some items, the RM data recorded in OREDA have a poor statistical basis. In this case, data of a similar equipment type or from previous studies are used for these items. For the data that are not recorded in OREDA, such as the pre-repair time and the ramp-up time, expert judgment is taking place. More details about the RM data are seen in Appendix E.

Model uncertainties. Miriam Regina is used to carry out the Monte Carlo simulation. The simulation uncertainty is quantified, and expressed by the standard deviation. In this RAM analysis, 300 replications result in the standard deviation of 0.02%. As the availability is based an average of all the replications, the availabilities can be regarded as normally distributed . By increasing the number of replications, the standard deviation of the results will be reduced.

Completeness uncertainties. This type of uncertainties are from the refined risk picture of

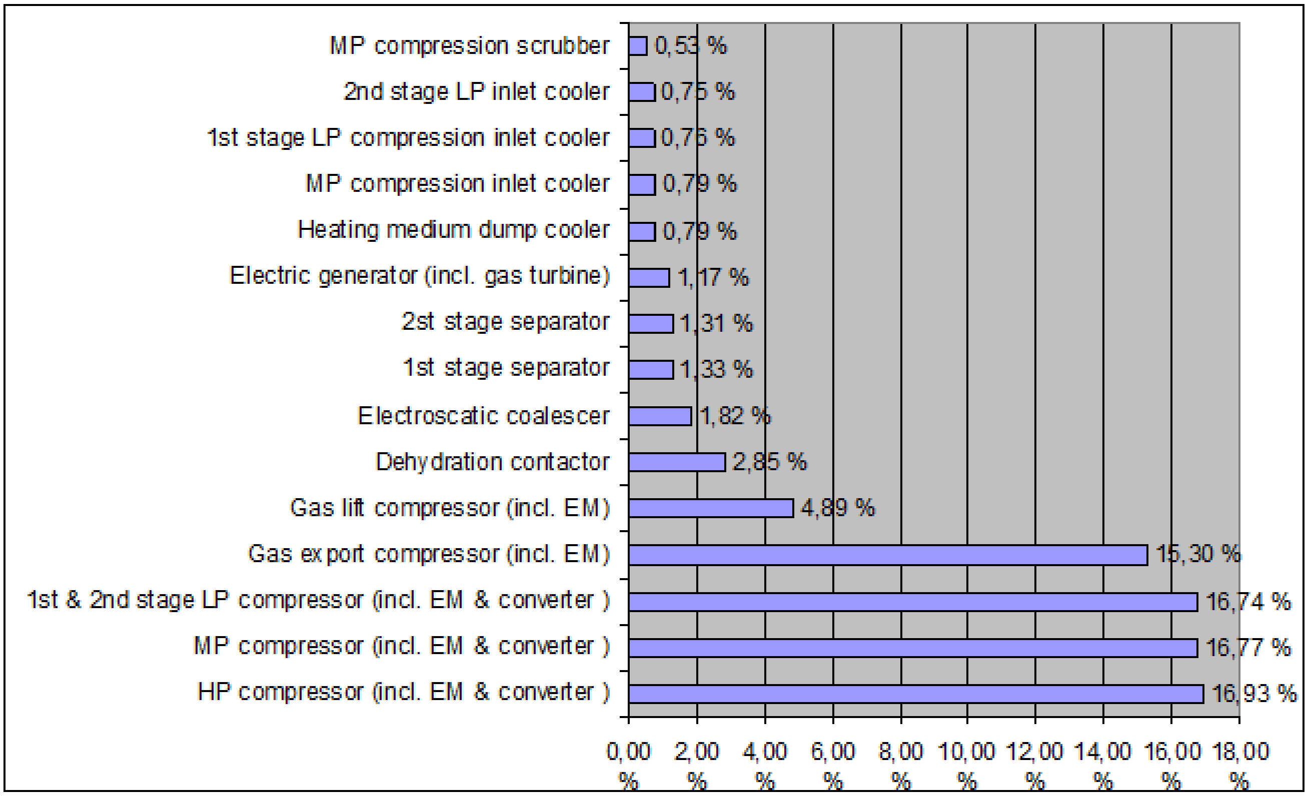


Figure 5.6: Main contributors to unavailability, per item

the system while modeling. By selecting the critical subsystems/components and simplifying the RBDs, the model is feasible to be simulated but brings risks of completeness at the same time. The completeness related uncertainties are documented in the assumptions in section 5.3.1.

5.4 LCC analysis

The RAM analysis lays the foundation for the LCC analysis to further examine the proposed solutions in terms of costs.

Two options of the gas lift compressor are studied, option 1 is the configuration of 1×100%, and option 2 is 2×100%. It is noted the option 2 is different from the alternative solution, 2×50%, in the RAM analysis. This is because the 2×50% configuration is considered not as efficient as 2×100%. Due to limited conditions, the RAM analysis could not be updated, while the LCC analysis is carried out for the newly suggested solution. The inconsistent alternative solutions

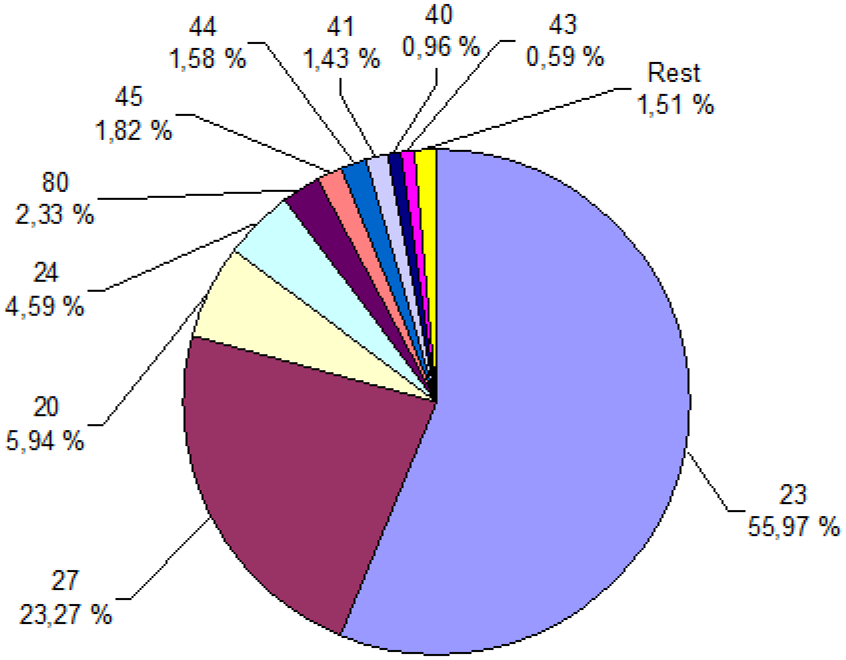


Figure 5.7: Main contributors to unavailability, per system

.

in both analyses have brought a series of issues for this case study: REGEX of the option 2 is calculated based on the production availability of 2×50%, and it is impossible to select the final solution. However, the purpose of this case study is to demonstrate the method rather than getting the actual result.

Assumptions and description of the LCC analysis are shown in table 5.2.

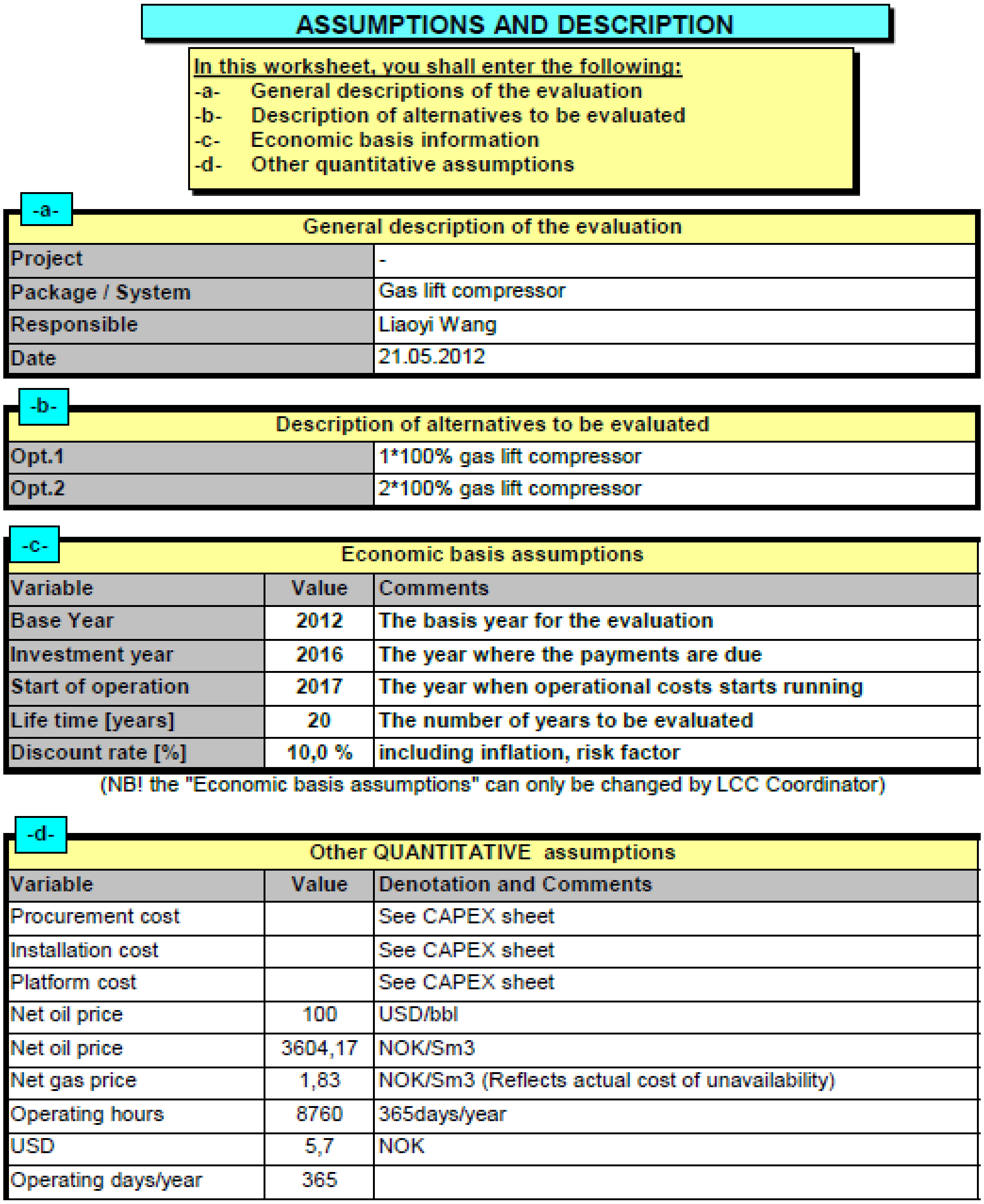
5.4.1 Cost Elements Identification and Calculation

Since the LCC analysis is carried out in the conceptual design phase, the cost categories, CAPEX, OPEX and REGEX are taken into account. Other costs such as RISKEX, tax and emission costs are thus not included. Adapted from NORSOK O-CR-001 (1996), a Excel spreadsheet is used for cost calculation and result summary, which is presented as follows.

CAPEX

CAPEX is calculated based on the total weight of both the equipment (gas lift compressor) and the associated items, for each option. The weight calculation is illustrated in table 5.3.

Table 5.2: Assumptions and description



ASSUMPTIONS AND DESCRIPTION

In this worksheet, you shall enter the following:
-a- General descriptions of the evaluation
-b- Description of alternatives to be evaluated
-c- Economic basis information
-d- Other quantitative assumptions

-a-

General description of the evaluation	
Project	-
Package / System	Gas lift compressor
Responsible	Liaoyi Wang
Date	21.05.2012

-b-

Description of alternatives to be evaluated	
Opt.1	1*100% gas lift compressor
Opt.2	2*100% gas lift compressor

-c-

Economic basis assumptions

Variable	Value	Comments
Base Year	**2012**	**The basis year for the evaluation**
Investment year	**2016**	**The year where the payments are due**
Start of operation	**2017**	**The year when operational costs starts running**
Life time [years]	**20**	**The number of years to be evaluated**
Discount rate [%]	**10,0 %**	**including inflation, risk factor**

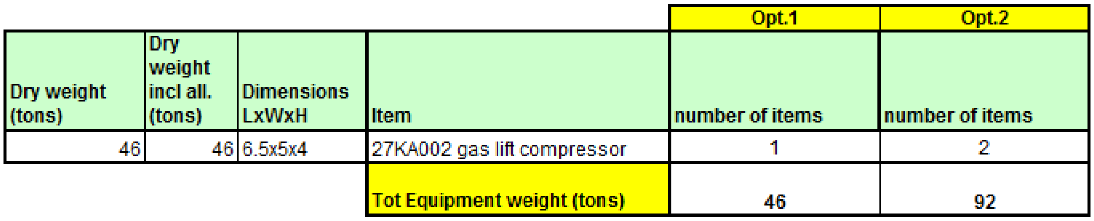
(NB! the "Economic basis assumptions" can only be changed by LCC Coordinator)

-d-

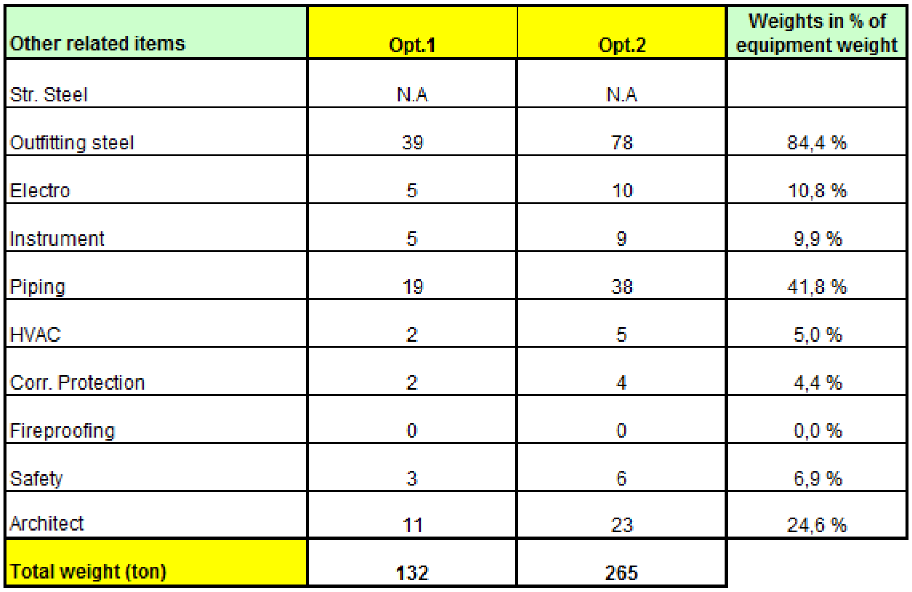
Other QUANTITATIVE assumptions

Variable	Value	Denotation and Comments
Procurement cost		See CAPEX sheet
Installation cost		See CAPEX sheet
Platform cost		See CAPEX sheet
Net oil price	100	USD/bbl
Net oil price	3604,17	NOK/Sm3
Net gas price	1,83	NOK/Sm3 (Reflects actual cost of unavailability)
Operating hours	8760	365days/year
USD	5,7	NOK
Operating days/year	365	

Table 5.3: Weights of the equipment and the associated items



				Opt.1	Opt.2
Dry weight (tons)	**Dry weight incl all. (tons)**	**Dimensions LxWxH**	**Item**	**number of items**	**number of items**
46	46	6.5x5x4	27KA002 gas lift compressor	1	2
			Tot Equipment weight (tons)	**46**	**92**



Other related items	Opt.1	Opt.2	Weights in % of equipment weight
Str. Steel	N.A	N.A	
Outfitting steel	39	78	84,4 %
Electro	5	10	10,8 %
Instrument	5	9	9,9 %
Piping	19	38	41,8 %
HVAC	2	5	5,0 %
Corr. Protection	2	4	4,4 %
Fireproofing	0	0	0,0 %
Safety	3	6	6,9 %
Architect	11	23	24,6 %
Total weight (ton)	**132**	**265**	

The identified cost elements of CAPEX are procurement, fabrication & installation, commissioning, management process & engineering, logistics and company & contingency. Since the gas life compressor is an individual equipment, thus there is no hook-up cost. The cost of as built documentation is included in engineering cost. Assume man hour rate of installation is 900 NOK, and of engineering is 1100 NOK. Other related parameters are given by Aker Solutions. Table 5.4 shows how the costs are generated and the sum of CAPEX in the investment year 2016, for the two options are 98 151 290 NOK and 196 302 581 NOK, respectively.

OPEX

The calculation of OPEX is very coarse here. Aker Solutions normally assigns 5% of CAPEX on the average to OPEX, which including the passive components, such as bulk. For the gas lift compressor, 10% of CAPEX is assigned to OPEX. The sum of OPEX in the investment year 2016, for the two options are 9 815 129 NOK and 19 630 258 NOK, respectively.

REGEX

The production profile is obtained for 20 operation years, from 2017 to 2036. The cost caused by deferred production is the combination of the unavailability and the production of each year. The costs occurring during the operation years are discounted to the investment year 2016, with the discount rate 10%, see table 5.5. The sum of REGEX in the investment year 2016, for the two options are 2 563 935 560 NOK and 2 530 923 514 NOK, respectively.

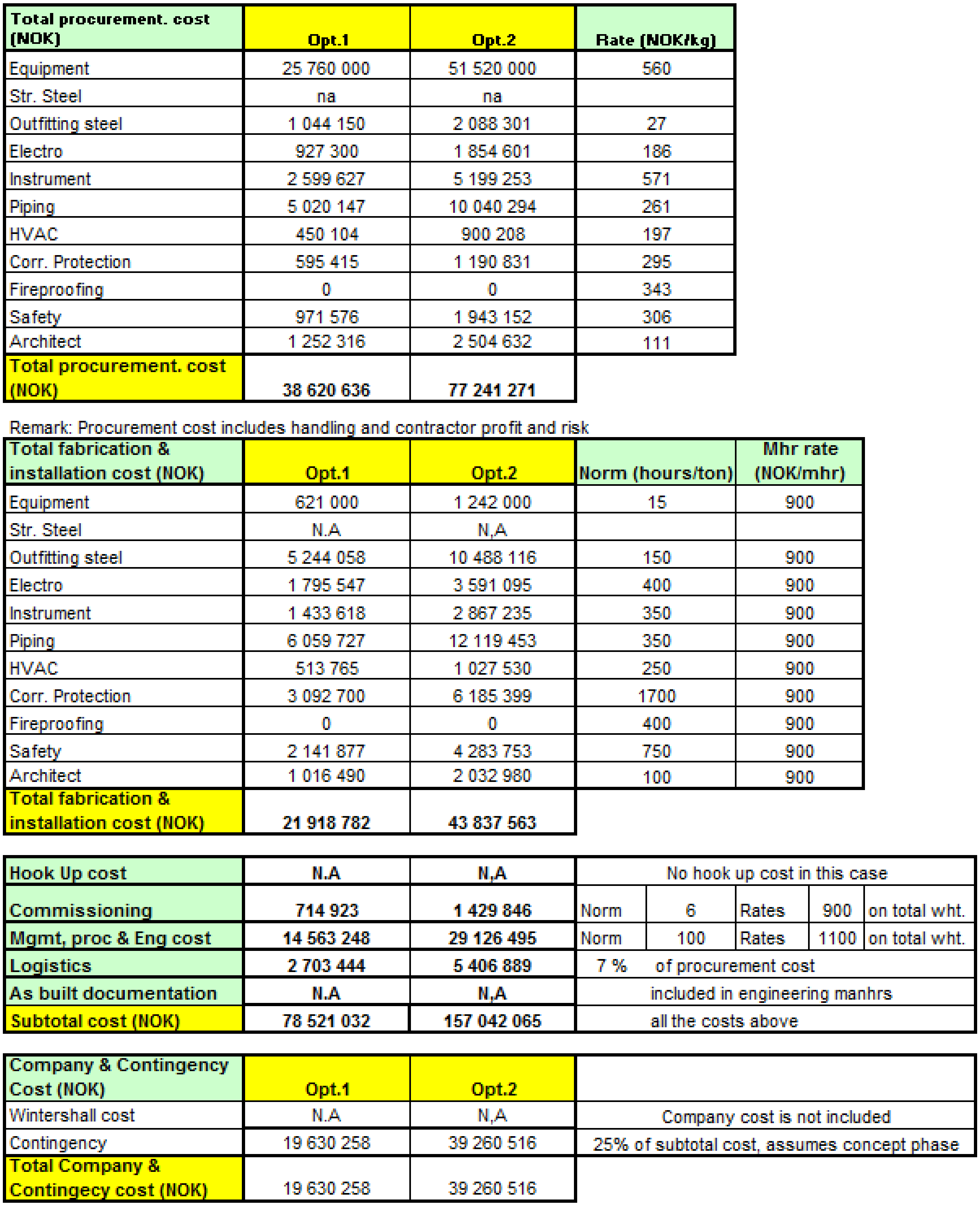
5.4.2 Result

All the cost elements are finally summarized and discounted to the base year 2012, with the discount rate 10% (table 5.6). Summing up CAPEX, OPEX, and REGEX, the result shows that the option 1 is 40 730 471 NOK cheaper than the option 2.

5.5 Conclusion

The objective of the RAM analysis is reached that the production availability is produced and the most critical subsystems/components are ranked according to their influence on the avail-

Table 5.4: Costs calculation of capex



Total procurement. cost (NOK)	Opt.1	Opt.2	Rate (NOK/kg)
Equipment	25 760 000	51 520 000	560
Str. Steel	na	na	
Outfitting steel	1 044 150	2 088 301	27
Electro	927 300	1 854 601	186
Instrument	2 599 627	5 199 253	571
Piping	5 020 147	10 040 294	261
HVAC	450 104	900 208	197
Corr. Protection	595 415	1 190 831	295
Fireproofing	0	0	343
Safety	971 576	1 943 152	306
Architect	1 252 316	2 504 632	111
Total procurement. cost (NOK)	**38 620 636**	**77 241 271**	

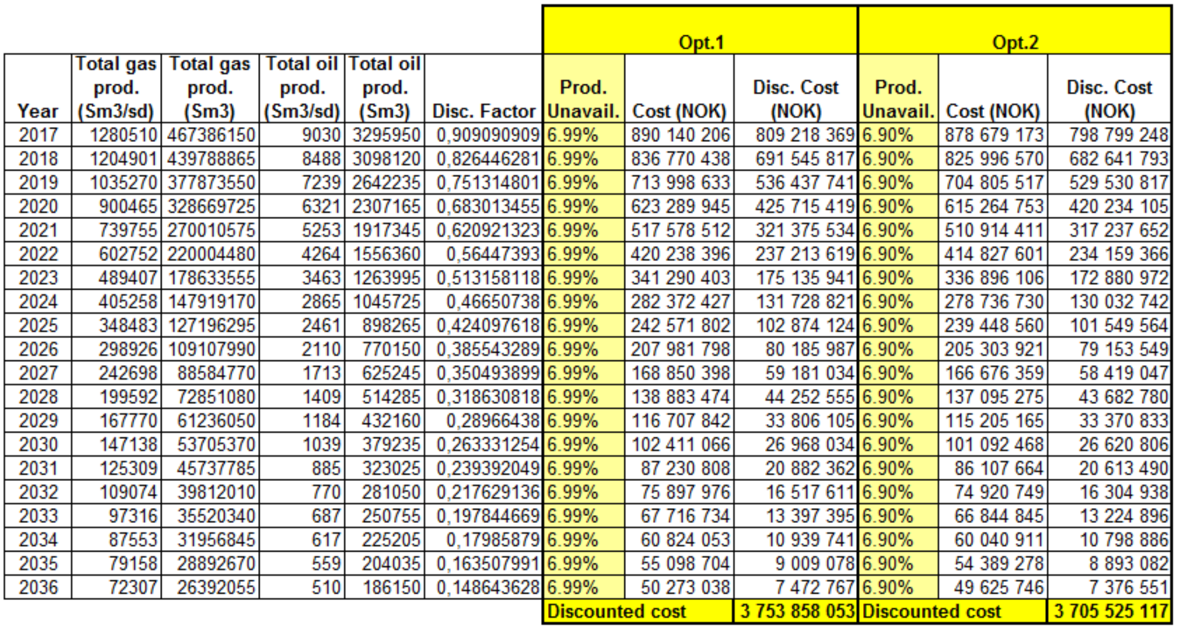
Remark: Procurement cost includes handling and contractor profit and risk

Total fabrication & installation cost (NOK)	Opt.1	Opt.2	Norm (hours/ton)	Mhr rate (NOK/mhr)
Equipment	621 000	1 242 000	15	900
Str. Steel	N.A	N,A		
Outfitting steel	5 244 058	10 488 116	150	900
Electro	1 795 547	3 591 095	400	900
Instrument	1 433 618	2 867 235	350	900
Piping	6 059 727	12 119 453	350	900
HVAC	513 765	1 027 530	250	900
Corr. Protection	3 092 700	6 185 399	1700	900
Fireproofing	0	0	400	900
Safety	2 141 877	4 283 753	750	900
Architect	1 016 490	2 032 980	100	900
Total fabrication & installation cost (NOK)	**21 918 782**	**43 837 563**		

Hook Up cost	**N.A**	**N,A**	No hook up cost in this case				
Commissioning	**714 923**	**1 429 846**	Norm	6	Rates	900	on total wht.
Mgmt, proc & Eng cost	**14 563 248**	**29 126 495**	Norm	100	Rates	1100	on total wht.
Logistics	**2 703 444**	**5 406 889**	7 %	of procurement cost			
As built documentation	**N.A**	**N,A**	included in engineering manhrs				
Subtotal cost (NOK)	**78 521 032**	**157 042 065**	all the costs above				

Company & Contingency Cost (NOK)	Opt.1	Opt.2	
Wintershall cost	N.A	N,A	Company cost is not included
Contingency	19 630 258	39 260 516	25% of subtotal cost, assumes concept phase
Total Company & Contingecy cost (NOK)	19 630 258	39 260 516	

Table 5.5: Costs calculation of REGEX



						Opt.1			Opt.2		
Year	Total gas prod. (Sm3/sd)	Total gas prod. (Sm3)	Total oil prod. (Sm3/sd)	Total oil prod. (Sm3)	Disc. Factor	Prod. Unavail.	Cost (NOK)	Disc. Cost (NOK)	Prod. Unavail.	Cost (NOK)	Disc. Cost (NOK)
2017	1280510	467386150	9030	3295950	0,909090909	6.99%	890 140 206	809 218 369	6.90%	878 679 173	798 799 248
2018	1204901	439788865	8488	3098120	0,826446281	6.99%	836 770 438	691 545 817	6.90%	825 996 570	682 641 793
2019	1035270	377873550	7239	2642235	0,751314801	6.99%	713 998 633	536 437 741	6.90%	704 805 517	529 530 817
2020	900465	328669725	6321	2307165	0,683013455	6.99%	623 289 945	425 715 419	6.90%	615 264 753	420 234 105
2021	739755	270010575	5253	1917345	0,620921323	6.99%	517 578 512	321 375 534	6.90%	510 914 411	317 237 652
2022	602752	220004480	4264	1556360	0,56447393	6.99%	420 238 396	237 213 619	6.90%	414 827 601	234 159 366
2023	489407	178633555	3463	1263995	0,513158118	6.99%	341 290 403	175 135 941	6.90%	336 896 106	172 880 972
2024	405258	147919170	2865	1045725	0,46650738	6.99%	282 372 427	131 728 821	6.90%	278 736 730	130 032 742
2025	348483	127196295	2461	898265	0,424097618	6.99%	242 571 802	102 874 124	6.90%	239 448 560	101 549 564
2026	298926	109107990	2110	770150	0,385543289	6.99%	207 981 798	80 185 987	6.90%	205 303 921	79 153 549
2027	242698	88584770	1713	625245	0,350493899	6.99%	168 850 398	59 181 034	6.90%	166 676 359	58 419 047
2028	199592	72851080	1409	514285	0,318630818	6.99%	138 883 474	44 252 555	6.90%	137 095 275	43 682 780
2029	167770	61236050	1184	432160	0,28966438	6.99%	116 707 842	33 806 105	6.90%	115 205 165	33 370 833
2030	147138	53705370	1039	379235	0,263331254	6.99%	102 411 066	26 968 034	6.90%	101 092 468	26 620 806
2031	125309	45737785	885	323025	0,239392049	6.99%	87 230 808	20 882 362	6.90%	86 107 664	20 613 490
2032	109074	39812010	770	281050	0,217629136	6.99%	75 897 976	16 517 611	6.90%	74 920 749	16 304 938
2033	97316	35520340	687	250755	0,197844669	6.99%	67 716 734	13 397 395	6.90%	66 844 845	13 224 896
2034	87553	31956845	617	225205	0,17985879	6.99%	60 824 053	10 939 741	6.90%	60 040 911	10 798 886
2035	79158	28892670	559	204035	0,163507991	6.99%	55 098 704	9 009 078	6.90%	54 389 278	8 893 082
2036	72307	26392055	510	186150	0,148643628	6.99%	50 273 038	7 472 767	6.90%	49 625 746	7 376 551
						Discounted cost		3 753 858 053	Discounted cost		3 705 525 117

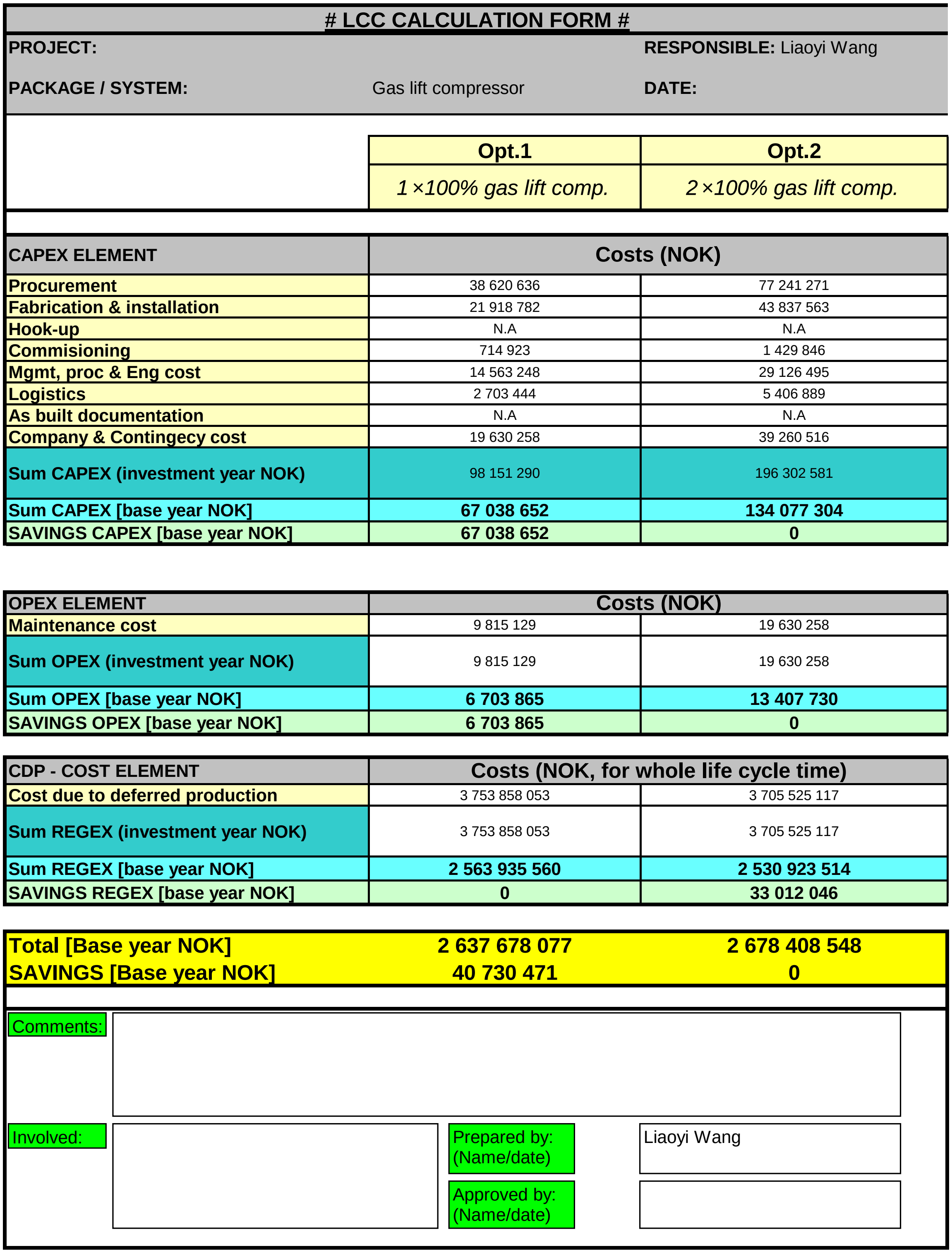
ability.

In the base case (1 × 100% gas lift compressor), 93.01% of the production availability is relatively low. The client requires to update the RAM analysis with the adjusted RM data. From the variety report, the gas lift compressor including the electric motor contributes to 4.89% of the unavailability. The sensitivity analysis further investigates the alternative design of the gas lift compressor (2 × 50%). It is shown that the production availability is not increased significantly by introducing redundancy to the gas lift compressor.

Therefore, an another configuration of 2×100% is suggested. Together with 1 × 100%, the two options are studied in the LCC analysis. CAPEX, OPEX and REGEX are calculated for each option. The result shows that the 2×100% configuration costs less in REGEX, however the 1 × 100% configuration saves more money in terms of CAPEX and OPEX.

Although, due to different alternative solutions in the two analyses, the final optimal solution is not able to selected. The overall objective of this case study is realized, which is to demonstrate the feasibility of performing the RAM and LCC analyses in the offshore project conceptual design phase through software tools.

Table 5.6: Result of the LCC analysis



LCC CALCULATION FORM

PROJECT:		**RESPONSIBLE:** Liaoyi Wang	
PACKAGE / SYSTEM:	Gas lift compressor	**DATE:**	

	Opt.1	**Opt.2**
	1 ×100% gas lift comp.	*2 ×100% gas lift comp.*

CAPEX ELEMENT	Costs (NOK)	
Procurement	38 620 636	77 241 271
Fabrication & installation	21 918 782	43 837 563
Hook-up	N.A	N.A
Commisioning	714 923	1 429 846
Mgmt, proc & Eng cost	14 563 248	29 126 495
Logistics	2 703 444	5 406 889
As built documentation	N.A	N.A
Company & Contingecy cost	19 630 258	39 260 516
Sum CAPEX (investment year NOK)	98 151 290	196 302 581
Sum CAPEX [base year NOK]	**67 038 652**	**134 077 304**
SAVINGS CAPEX [base year NOK]	**67 038 652**	**0**

OPEX ELEMENT	Costs (NOK)	
Maintenance cost	9 815 129	19 630 258
Sum OPEX (investment year NOK)	9 815 129	19 630 258
Sum OPEX [base year NOK]	**6 703 865**	**13 407 730**
SAVINGS OPEX [base year NOK]	**6 703 865**	**0**

CDP - COST ELEMENT	Costs (NOK, for whole life cycle time)	
Cost due to deferred production	3 753 858 053	3 705 525 117
Sum REGEX (investment year NOK)	3 753 858 053	3 705 525 117
Sum REGEX [base year NOK]	**2 563 935 560**	**2 530 923 514**
SAVINGS REGEX [base year NOK]	**0**	**33 012 046**

Total [Base year NOK]	**2 637 678 077**	**2 678 408 548**
SAVINGS [Base year NOK]	**40 730 471**	**0**

Comments:			
Involved:		Prepared by: (Name/date)	Liaoyi Wang
		Approved by: (Name/date)	

Chapter 6

Summary and Recommendations for Further Work

6.1 Summary and Conclusions

RAM analysis is used to assess the system availability and identify the most critical components. By performing RAM analysis in the conceptual design phase, it provides the opportunity for system optimization before entering into the detailed engineering phase.

Two approaches of RAM analysis, the analytical approach and the simulation approach, have been discussed. The analytical approach calculates the availability by predefined formulas based on RM data. Due to its simplicity, it may be easy to apply in the conceptual design phase, but not able to handle complex systems and give detailed results. For the simulation approach, it is powerful in terms of taking weather conditions, production profile and maintenance philosophy into account. However, the large number of inputs may be difficult to obtain and the process of collecting data can be time consuming.

Several software tools are described with pros and cons for each approach. Rather than saying one tool is superior to the other, it is more important to know which tool suits best to the specific application. Since Aker Solutions has close cooperation with Statoil, the simulation tool Miriam Regina is mainly discussed and utilized in this thesis. The procedure of performing the simulation approach in Aker Solutions is illustrated using Miriam Regina.

The uncertainties of RAM analysis are usually derived from parameter, model, and completeness. It is impossible to fully quantify uncertainties. In order to reduce uncertainties and produce the most reliable result based on available information, it is essential to use qualified data, choose a proper model, and document all assumptions.

LCC covers both *acquisition cost* and *ownership cost*, where the latter can be considerably higher than the former. To quantify the *ownership cost* is thus the main objective of LCC analysis. By conducting LCC analysis in the conceptual design phase, it enables the engineer to design for cost benefit. However, the limited knowledge and data in the project's early phase lead to results with high uncertainties. Thus, a good timing is the key for LCC analysis, which should allow feasibility in system optimization and assure a reliable result at the same time.

A number of LCC-related standards have been developed. Although many theoretical issues have been discussed, a full practice of LCC analysis is hardly found in the literature. This may be due to the confidential issues, lack of practical guidance and knowledge limitation in the project's early phase. Considering that projects are different, it is somehow unrealistic to develop an universal method for LCC analysis. Based on various procedures, a basic six steps procedure is introduced. Each step and its associated sub-activities are also presented.

An Excel spreadsheet is developed for LCC analysis. The spreadsheet is adapted from the NORSOK standards and is a rather simple and easily managed model. By using this spreadsheet, LCC analysis is conducted as follows: (i) identify the cost categories, (ii) collect data and calculate, (iii) discount the cost, (iv) summarize the saving.

By combining RAM and LCC analyses, it facilitates the trade-off between maximizing regularity and minimizing expenditure. An ongoing project from Aker Solutions is used as a case to perform RAM and LCC analyses in the conceptual design phase. From the RAM analysis, the production availability is generated and the unavailability contributors are ranked according to their criticality. CAPEX, OPEX, and REGEX are calculated for the proposed options in the LCC analysis. REGEX is the cost caused by deferred production and based on the RAM analysis.

Sensitivity analysis provides the possibility to compare the alternative solutions. In this case study, the sensitivity analysis has been carried out for both RAM and LCC analyses to select the optimal configuration of gas lift compressor. Unfortunately, the analyzed configurations are not the same in the two analyses, and it is therefore failed to judge the best solution by both regularity and expense dimensions. However, through the case study, the feasibility of conducting RAM and LCC analyses in the conceptual design phase has been proved using the software tools.

6.2 Discussion

In Aker Solutions, the simulation by Miriam Regina has been used in many projects in the detailed engineering phase. For the conceptual design phase, the analytical approach is often applied using Excel spreadsheet. Since the simulation approach is flexible and capable of handling complex systems, it does make sense to introduce this approach in the conceptual design phase. However, considering that the conceptual design phase is short, it is necessary to know the requirements of the project. If the analytical approach is not satisfying, the simulation approach should then be used. This means that the simulation approach may not be the first priority in terms of performing RAM analysis in the conceptual design phase.

Regarding RM data, the case study adopts the data from the OREDA handbook. According to the feedback from the client, data needs to be adjusted. Thus, in order to save time in modeling, it is wise to keep communication with the client during the process of data collection.

For simplicity, the RAM and LCC analyses are not throughly conducted in the case study. For example, the production availability is assessed based on a fixed 100% production rate. With Miriam Regina, it is possible to take the production profile into account and give a time dependent result. For OPEX, instead of taking percentage from CAPEX, it is possible to obtain data of detailed cost elements from the manufacturer.

6.3 Recommendation

Due to limited time and resources, some important issues are not covered in this thesis. Recommendations for further work are presented as follows:

- RAM analysis is built upon a lot of assumptions. The incorrect result will certainly mislead the engineers. Thus, the confidence of RAM analysis needs to be proven.
- With the simulation approach, RAM analysis is capable to outline better maintenance and

logistic strategies. The guidance in maintenance and logistics planning needs to be practiced.

- Although RAM analysis is intended to assist in system optimization, the actual impact in decision-making is not clear. This thesis recommends to document the interaction between the RAM analysis and the system feedback to see if RAM analysis is useful.
- When discounting the future cost to the present, the issue is how to treat the extreme significant accident with low probability. If this type of cost is discounted, the present cost is going to be very small. Whether extra concern is needed to prevent a catastrophe, is need to be studied to support the decision-making.

Appendix A

Acronyms

FMECA	Failure mode, Effect and Criticality Analysis
FPSO	Floating production storage and offloading
HPU	Hydraulic Power Unit
KO	Knock Out
LCC	Life cycle cost
MDT	Mean Down Time
MTBF	Mean Time Between Failures
MEG	Mono-Ethylene Glycol
MEL	Master Equipment List
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NPV	Net Present Value
OREDA	Offshore Reliability Data
PFD	Process Flow Diagram

POR Performance and Operability Review

RAM Reliability, Availability and Maintainability

RBD Reliability Block Diagram

RM Reliability and Maintainability

TEG Tri-Ethylene Glycol

UFD Utility Flow Diagram

Appendix B

Definitions

☞ CAPEX: capital expenditure, usually associated with all expenditure up to and including commissioning.

☞ Failure: Termination of the ability of an item to perform a required function (ISO 20815, 2008). *Typical failure modes are External leakage (e.g. separators), Fail to start on demand (e.g. pumps), Fail to close on demand (e.g. valves).*

☞ Failure mode: effect by which a failure is observed on the failed item (ISO 20815, 2008).

☞ FMECA: detailed task identifying failure modes and effects of failures locally and globally for each item.

☞ Life cycle: Time interval between a product's conception and its disposal (IEC 60300-3-3, 1996).

☞ Life cycle cost (LCC): cumulative cost of a product over its life cycle (IEC 60300-3-3, 1996).

☞ Maintainability: the probability that a given active maintenance action for an item under given conditions of use can be carried out within a stated time interval, when the maintenance is performed under stated conditions and using stated procedures and resources (IEC 60050-191).

☞ NPV: net present value is used to provide visibility of the overall discounted expenditure over the life of an option, it is the discounted total of all expenditure.

☞ OPEX: operating expenditure, covering the in service phase of an assets life from start of production to and including disinvestment or redeployment

☞ Preventive maintenance: the maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item (IEC 60300-3-3, 1996).

☞ Production availability: the ratio of production to planned production, or any other reference level, over a specified period of time (ISO 20815, 2008).

☞ Production performance: capacity of a system to meet demand for deliveries or performance (ISO 20815, 2008). *Production availability, deliverability, or other appropriate measures can be used to express production performance.*

☞ Reliability: the probability that an item can perform a required function under given conditions for a given time interval (IEC 60050-191).

Bibliography

Aaroe, et al (1996). Subsea hipps development study, part 8: Overall economic evaluation. *SINTEF Safety and Reliability*.

Aker Engineering (2008). Miriam regina course.

Apostolakis, G. E. (1978). Probability and risk assessment: The subjective view point and some suggestions. *Nuclear Safety, 19(3)*, pages 305–315.

Apostolakis, G. E. (1990). The concept of probability in safety assessment of technologicl systems. *Science*, 250:1359–1367.

Apostolakis, G. E. and Mosleh, A. (1979). Expert opinion and statistical evidence: An application to reactor core melt frequency. *Nuclear Science and Engineering*, 70:135–149.

Arinc Research Corporation (1985). *Availability Analysis Handbook for Coal Gasification and Combusion Turbine-bases Power System.* Prepared for Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, California 94304.

Barringer, H. and Weber, D. (1996). Life cycle cost tutorial. In *Fifth International Conference on Process Plant Reliability*, page 58, Houston, Texas.

Chang, K. P., Chang, D., and Enrico, Z. (2010). *Application of Monte Carlo Simulation for the Estimation of Production Availability in Offshore Installation.* Spinger Series in Reliability Engineering.

Clarke, J. D. (1990). Life cycle cost: An examination of its application in the united states, and potential for use in the australian defense forces. *Thesis of M.S, Naval, Postgraduate School.*

Damiron, C. and Nastasi, A. (2008). Discrete rate simulation using linear programming. Technical report, Institute of Electrical and Electronics Engineers, Inc.

Dangel, R. (1969). Integrated logistic support (ils) implementation in the naval ship system command. *ASE 6th annual technical symposium*, pages 1–25.

Denson, W., Chandler, W. C., Clark, A., and Jaworski, P. (1995). *Nonelectronic Parts Reliability Data*. Reliability Anlaysis Center, PO Box 4700 Rome, NY 13442-4700.

EPRI (1991). Availability cost optimization methodology. *Electric Power Research Institute*, (TR - 100225).

Hokstad, P. (1989). Reliability prediction of subsea oil/gas production systems. (STF75 A89038).

Hokstad, et al (1998). Life cycle analysis in railway systems. *SINTEF Safety and Reliability*.

IEC 60050-191. *International Electrotechnical Vabulary*. International Electrotechnical commission.

IEC 60300-3-3 (1996). Life cycle costing.

ISO 15663 (2000). Petroleum and natural gas industries - life cycle costing.

ISO 20815 (2008). Petroleum, petrochemical and natural gas industries - production assurance and reliability management.

Kawauchi, Y. and Rausand, M. (1999). Life cycle cost (lcc) analysis in oil and chemical process industries.

Korpi, E. and Ala-Risku, T. Life cycle costing: a review of published case studies. Technical report, Helsinki University of Technology, Department of Industrial Engineering and Management, P.O. Box 5500, FIN-02015 TKK, FINLAND.

Krahl, D. (2009). Extension advanced technology: discrete rate simulation. In *Process of the 2009 Winter Simulation Conference*, Imagine That, Inc. 6830 Via Del Oro, Suite 230, San Jose, CA 95119, USA.

Lindholm, A. and Suomala, P. (2005). Learning by costing: Sharpening cost image through life cycle costing? In *The 7th Manufacturing Accouting Research Conference*, Tamere, Finland.

Lydersen, S. and Aaroe, R. (1989). Life cycle cost prediction handbook, computer-based process safety systems. *SINTEF Safety and Reliability*.

Mitrani, I. (1982). Simulation techniques for discrete event systems. *Cabridge University Press*.

NORSOK O-CR-001 (1996). Life cycle cost for systems and equipment.

NORSOK O-CR-002 (1996). Life cycle cost for production facility.

NORSOK Z-016 (1998). Regularity management & reliability technology.

NUREG 1855 (2009). Guidance on the treatment of uncertainties associated with pras in risk-informed decision making.

Oreda (2009). *Oreda, Offshore Reliability Data Handbook*, volume 1, Topside Equipment. 5th edition.

Parry, G. W. and Winter, P. W. (1981). Characterization and evaluation of uncertainty in probabilistic risk analysis. *Nuclear Safety, 22(1)*, pages 28–42.

Rausand, M. (2011). *Risk Assessment, Theary, Methods, and Applications*. Jogn Wiley & Sons, Inc.

SAE ARP4293 (1992). Life cycel cost - techniques and applications.

SAE ARP4294 (1992). Data formats and proactices for life cycle cost information.

Sharda, B. and Burry, S. A. (2008). A discrete event simulation model for reliability modeling of a chemical plant. Technical report, Institute of Electrical and Electronis Engineers, Inc.

White, G. and Ostwald, P. (1976). *The life cycle cost of an item is the sum of all founds expended in support of the item from is conception and fabrication through its operation to the end of its useful life*, volume 57 of *Management Accounting*.

Witt, J. (1990). Unisam - an extension of uniram for spares optimization. *A technical pater presented in 17th Inter-ram Conference for the Electric Power Industry*.

Woodward, D. *Life cycle costing - theory, information acquistion and application*, volume 15. International Journal of Project Mangament.