NTNU – Trondheim
Norwegian University of
Science and Technology

Long Term Scheduling of Major Renewals

Systematic Approach and Financial
Applications

Jon Andreas Folgerø-Holm

Marine Technology
Submission date: June 2014
Supervisor: Ingrid Bouwer Utne, IMT

Norwegian University of Science and Technology
Department of Marine Technology

Preface

This master's thesis is the result of my work in TMR 4930 Marine technology in the 10th semester of the MSc in Marine Technology. The work was carried out in the spring of 2014 at the Department of Marine Technology, Faculty of Engineering Science and Technology at the Norwegian University of Science and Technology. Thanks to my supervisors for helpful guidance, Professor Ingrid Bouwer Utne and Roar Bye, Manager - Operations Strategies and Support at Teekay Petrojarl. Also thanks to my fellow students in office A2.007.

Trondheim, June 10, 2014

Jon Andreas Folgerø-Holm

Summary

Much of the oil and gas installations in the North Sea originate from the booming '80s and '90s, and operators are facing considerable challenges in the management of their ageing assets. Harsh environments combined with tough operating loads make it so that systems must be upgraded, replaced or maintained; preventively or correctively. In many cases, it pays off to renew entire systems at a time, as components belonging to the same systems are exposed to the same operating loads, subject to the same obsolescence issues and are interdependent.

Typically, long term (strategic) plans consist of the same activities as shorter term plans. However, the degree of accuracy and detail is much lower, and they require a greater degree of cross disciplinary coordination. It may be challenging to collect and systematise information from various entities, such as operations management, procurement, material management, suppliers, contractors and legislators.

This study suggests that FPSO contractors, as part of a systematised work process, utilises "Ageing Parameters" as qualitative measures on the deterioration and obsolescence the various systems are subject to. A parameter [0,100] should be established annually for each component to symbolise its condition. The parameter is aggregated hierarchically from component level to system level according to the SFI structure and based on the Technical Condition Index framework by Andersen and Rasmussen (2003). Predefined criticality levels may act as weighting between components and between subsystems. The ageing should then be evaluated continuously using a top-down approach, to find any obvious weaknesses on component level or on subsystem level. Subsequently, if a system renewal, as opposed to minor actions, proves to be appropriate, the optimal time and type of action for this renewal can be decided based on experience and available information. Further on, the activities and their costs may be scheduled and the information utilised financially.

Floating production, storage and offloading vessels (FPSOs) are in many cases not designed to spend their lifetimes on a single field, but to redeploy at end of first contract. When FPSO contractors investigate redeployment opportunities, they need to know as much as possible about future expenditures, to minimise their risk exposure. The cost and time frame of capital replacements are vital in this respect. The renewal activity schedule may be utilised to calculate the discounted cash flow of such activities throughout potential contract periods and along with OPEX estimates, expected revenues, RISKEX etc. form a decision basis for the tender terms.

Depreciation is the difference between an asset‘s acquisition cost and its estimated residual value, more precisely, a way of allocating costs of assets to periods in which they are used. Since vessels consist of systems with various useful lives, the systems (or even components) should be depreciated separately, according to International Accounting Standard 16. By applying the methods from this study, the remaining useful lives of systems should be more accurately estimated compared to current standards in shipping, where depreciation mainly is charged as a constant cost for the vessel as one entity. More accurate depreciation may award companies‘ reduced taxes and increased financial predictability. International Accounting Standard 16 also highlights that obsolescence issues must be accounted for when estimating the residual value of an asset, because they contribute in the diminution of the economic benefits that might be obtained from the asset.

This study has proven that a systematic hierarchy can be established based on SFI tags in computerised maintenance management systems, and that parameters on component level may be aggregated by this hierarchy and the given formulas to a meaningful and robust system parameter. It is also verified that the ageing of the systems can be evaluated systematically and effectively using a top-down approach. However, it has not been verified that the procedure can be implemented in large-scale without taking up to much resources. Even so, the advantages this study has revealed, with regards to depreciation and tendering, could possibly justify the use of resources.

Sammendrag

Mange av olje- og gassinstallasjonene i Nordsjøen stammer fra høykonjunkturene på 80- og 90-tallet, og driftsorganisasjoner opplever derfor store utfordringer med å håndtere aldring av sine anlegg. Hardt vær kombinert med høye produksjonsrater gjør at systemene etter hvert må oppgraderes, byttes ut eller vedlikeholdes; preventivt eller korrektivt. I mange tilfeller, lønner det seg å fornye hele systemer samtidig, da komponentene blir utsatt for de samme belastningene, utdateres samtidig eller er avhengig av hverandre.

Langtidsplaner består typisk av de samme aktivitetene som korttidsplaner, men graden av presisjon og detalj er mye lavere og det kreves en større grad av tverrfaglig koordinering. Det kan være en utfordring å samle og systematisere informasjon fra ulike enheter, som for eksempel, drift, innkjøp, materialhåndtering, leverandører, kontraktører og lovgivere.

Denne studien foreslår at FPSO-kontraktører, som del av en systematisert arbeidsprosess, tar i bruk en "aldringsparameter" som en kvalitativ målestokk på i hvilken grad systemer er utsatt for slitasje eller er utdaterte. En parameter [0,100] settes årlig for hver komponent for å symbolisere dens tilstand. Parameteren blir aggregert hierarkisk fra komponentnivå til systemnivå etter SFI-strukturen. Metoden er basert på rammene fra Technical Condition Index av Andersen and Rasmussen (2003). Fohåndsdefinerte kritikalitetsnivåer brukes som vekting mellom komponenter og mellom undersystemer. Deretter blir aldringen evaluert kontinuerlig og fra toppen av hierarkiet og ned, for å finne åpenbare svakheter på komponentnivå eller undersystemnivå. Videre, dersom det viser seg å være hensiktsmessig å foreta en systemfornyelse, heller en mindre utskiftninger, kan man bestemme det optimale tidspunktet og den optimale løsningen basert på erfaring og tilgjengelig informasjon. Arbeidet og kostnadene blir så innrammet i tidplanen og informasjonen kan utnyttes finansielt.

Flytende produksjons-, lagrings- og lossingsfartøyer (FPSO‘er) blir i mange tilfeller designet for å kunne redeployeres til andre felt ved utgående kontrakt. Når FPSO-kontraktører skal undersøke mulighetene for redeployering, er det helt nødvendig å vite så mye som mulig om fremtidige utgifter, for å minimere sin risikoeksponering. Kostnad og tidramme for de største arbeidene er kritisk i så henseende. Tidsplaner kan benyttes til å beregne diskontert kontantstrøm av større arbeid gjennom potensielle kontraktsperioder. Sammen med OPEX-estimater, forventede inntekter, RISKEX etc. utgjør det beslutningsgrunnlaget for betingelsene i et eventuelt anbud.

Avskrivning er differansen mellom innkjøpskostnaden og restverdien av et anleggsmiddel, eller mer presist, en måte å fordele kostnadene av et anleggsmiddel til de periodene det er i bruk. Siden fartøyer består av mange systemer med ulik levetid, bør systemene (eller til og med komponentene) bli avskrevet hver for seg, ifølge International Accounting Standard 16. Ved å benytte seg av metodene fra denne studien, bør estimatene for gjenværende økonomisk levetid bli mer presise sammenlignet med gjeldende praksis i shipping, hvor avskrivning hovedsaklig blir kostnadsført som en konstant kostnad for fartøyet som en enhet. Mer presis avskrivning kan gi besparelser som redusert skatt og økt finansiell forutsigbarhet. International Accounting Standard 16 trekker også frem at problemstillinger knyttet til utdatering må tas hensyn til når man estimerer gjenværende økonomisk levetid for et anleggsmiddel, fordi det bidrar til reduksjon av de økonomiske fordeler man kunne ha ervervet fra anleggsmidlet.

Denne studien har vist at systematiske hierarkier kan etableres basert på SFI-numre fra datastyrte vedlikeholdssystemer, og at parametre på komponentnivå kan aggregeres ut ifra dette hierarkiet og de gitte formler til en meningsfull og robust systemparameter. Det er også blitt verifisert at aldringen av systemene kan evalueres systematisk og effektivt fra toppen og ned. Imidlertid, har det ikke blitt verifisert at prosedyren kan implementeres i storskala uten å binde opp for mye ressurser. Likevel, fordelene som har blitt avdekket med tanke på avskrivning og anbudsprosess kan muligens rettferdiggjøre den nødvendige ressursbruken.

Contents

List of Figures

List of Tables

Abbreviations

HSE	**H**ealth, **S**afety and **E**nvironment
FPSO	**F**loating **P**roduction **S**torage **O**ffloading
OPEX	**OP**erational **EX**penditures
RISKEX	**RISK EX**penditures
CAPEX	**CAP**ital **EX**penditures
TKPJ	**T**ee**K**ay **P**etro**J**arl
VLTP	**V**essel **L**ife **T**ime **P**lan
FSO	**F**loating **S**torage **O**ffloading
SPM	**S**ingle **P**oint **M**ooring
DP	**D**ynamic **P**ositioning
SFI	a maritime functional subdivision of technical information
L&O	**L**ease **&** **O**peration
AIM	**A**sset **I**ntegrity **M**anagement
HSE	**H**ealth and **S**afety **E**xecutive (a British regulatory institution)
UKCS	**U**nited **K**ingdom **C**ontinental **S**helf
KP4	**K**ey **P**rogramme **4**
AM	**A**geing **M**anagement
NPP	**N**uclear **P**ower **P**lant
SSC	**S**tructures, **S**ystems and **C**omponents
CMMS	**C**omputerised **M**aintenance **M**anagement **S**ystem
KPI	**K**ey **P**erformance **I**ndicator
EUREKA	an intergovernmental research & development organisation
TCI	**T**echnical **C**ondition **I**ndex
RBI	**R**isk **B**ased **I**nspections

AP	**A**geing **P**arameter
RAM	**R**eliability **A**vailability **M**aintainability
FMECA	**F**ailure **M**ode **E**ffect **C**riticality **A**nalysis
NOK	**NO**rwegian **K**rones
DCF	**D**iscounted **C**ash **F**low
IRR	**I**nternal **R**ate of **R**eturn
NPV	**N**et **P**resent **V**alue
POB	**P**ersons **O**n **B**oard
TA	**T**eknisk **A**nsvarlig
P&ID	**P**iping & **I**nstrumentation **D**rawing
MDO	**M**arine **D**iesel **O**il
N/A	**N**ot **A**pplicable
STB	**S**tar**B**oar**D**

Symbols

t	Time, $[hours]$
TC_{Parent}	Technical condition of parent, $[0, 100]$
TC_i	Technical condition of child i, $[0, 100]$
w	Weight of child i, $[0, 100]$
n	Number of child nodes
$AP_{i,W}$	Weighted value of the Ageing Parameter of component i, $[0, 100]$
AP_i	Ageing Parameter of component i, $[0, 100]$
W_i	Weight of component i, $[0, 100]$
$AP_{sbs,j}$	Ageing Parameter of subsystem j, $[0, 100]$
$AP_{j,W}$	Weighted value of the Ageing Parameter of component i, $[0, 100]$
AP_{sys}	Ageing Parameter of the system , $[0, 100]$
$W_{i,j}$	Weight of component i in subsystem j, $[0, 100]$
n_j	Number of components in subsystem j
C_i	Total annual cost in the ith period, $i = 1, 2, 3, ..., n$
M_i	Cost of *maintenance* in the ith period, $i = 1, 2, 3, ..., n$
D_i	Cost of *downtime* in the ith period, $i = 1, 2, 3, ..., n$
F_i	Fixed *operational* cost in the ith period, $i = 1, 2, 3, ..., n$
r	Discount rate
A	Acquisition cost of the system
$Cost_i j$	Cost of activity i in year j, $i = 1, 2, 3, ..., n$, $j = 1, 2, 3, ..., m$
CF_j	Cash flow of all activities in year j added, $j = 1, 2, 3, ..., m$
DCF_j	Discounted value of CF_j, $j = 1, 2, 3, ..., m$
$\sum_{j=1}^{m} DCF_j$	Sum of all discounted cash flows, $j = 1, 2, 3, ..., m$

C_t	Net cash flow over a year t, $t = 1, 2, 3, ..., n$
D	Discount rate
n	Number of years to realisation
D_q	Quarterly depreciable amount
V_R	Residual value
L_R	Residual life

Chapter 1

Introduction

1.1 Background

Health, safety and environmental (HSE) concerns are getting more and more attention in all phases of offshore installation life cycles. To protect people, nature and climate; national and international regulatory bodies impose strict regulations. Alongside tougher commercial market conditions, it makes companies strive to optimise their total operating regime. Maintenance is a key support function in capital intensive businesses and plays an important role in meeting this order (Tsang, 2002). Particularly, the major maintenance jobs and capital replacements are critical. Knowledge of the time frame, workload and cost of such activities can be vital to reach company goals. It is no coincidence that outstanding operators often are recognised by their ability to develop and maintain long term plans (Okstad et al., 2010). Typically, the long term (strategic) plans consist of the same activities as shorter term plans. However, the degree of accuracy and detail is much lower. As time passes, the long term plans convert into medium term (tactical) plans with a higher degree of detail and ultimately into operational plans with a planning horizon in the span of one day up to a year (Okstad et al., 2010).

This thesis focuses on long term maintenance scheduling with particular emphasis on Floating, Production, Storage and Offloading (FPSO) vessels. As much of the remaining offshore oil and gas resources are situated in frontier areas, often with limited infrastructure, the tendency to choose FPSO solutions increases rapidly. These vessels are able to produce, store and offload oil and gas to shuttle tankers, which can carry the petroleum to the needed infrastructure. FPSOs also gives companies the flexibility to start producing in marginal oil and gas fields, as they are more or less mobile. This make the lifetimes of FPSOs not as directly linked to the life of a field as fixed installations. They are, in many cases, not designed to spend their complete lifetime on one single field. Information regarding future renewal activities is particularly crucial when considering redeployments and new commercial opportunities, as these capital expenditures (CAPEX) heavily affect company bottom lines.

Figure 1.1, displays a simplified graphical distribution of a vessel cash-flow. The vessel (could be a tanker conversion or a new build) is acquired on the extreme left side, and after some years, it is upgraded/modified and redeployed.

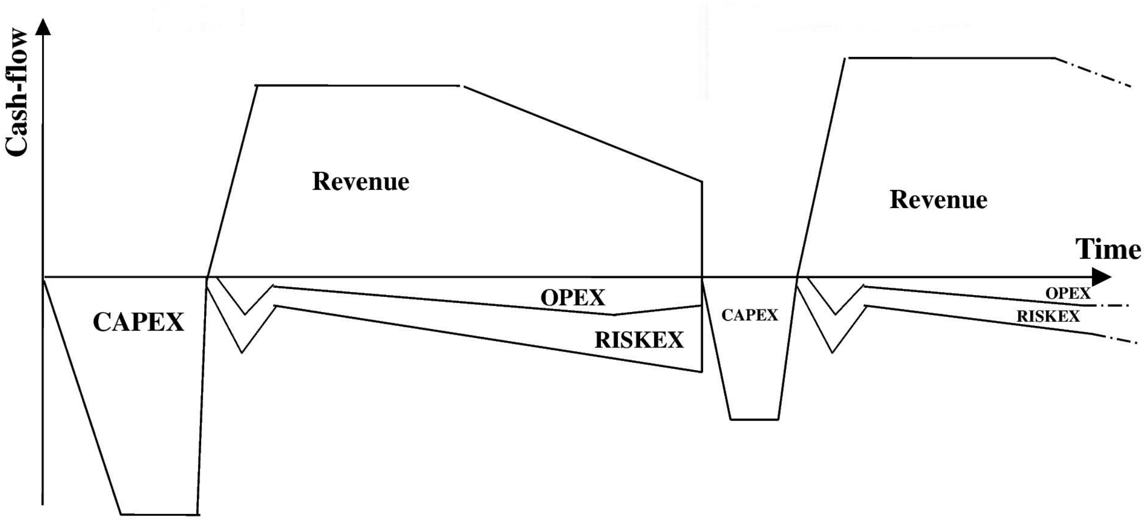

Figure 1.1: Distribution of cash-flow trough vessel lifetime (Bye, 2013)

First of all, the company needs to finance the new asset, meaning it will have high CAPEX. During this period, the vessel is constructed, commissioned and deployed. As all of these are off-hire phases, the company receive no revenues. During the next period, the vessel is (generally) on hire and the company can benefit from its investments. However, OPEX are considerable in this phase and they increase with time (except for in the running-in phase). The is also the case for the average cost of unwanted events, so-called RISKEX. After a certain period, given by the condition of the vessel, it reaches a point where it will need a major upgrade (and perhaps to be redeployed, depending on its contractual status). The company will in this phase receive no revenues from the vessel, but instead have substantial CAPEX. When the vessel is redeployed and production starts, the vessel-specific financial status gets back into a revenue-producing phase.

What is essential to notice from this model, is the significance of the upgrade phases. Needless to say, it is vital for senior management to have as much knowledge as possible of both the time frame and financial extent of these phases.

1.2 Objectives

The primary objective of this study is to develop a systematic approach for FPSO contractors to schedule major renewals on long term basis. It shall also be investigated how this schedule may be utilised in the tender calculations prior to redeployment and in the depreciation of assets.

The subordinate objectives are:

- Investigation and mapping of the decision basis for long term maintenance scheduling.
- Development of a procedure for systematic organisation of the decision basis prior to scheduling.
- Integration of the existing planning tool Vessel Lifetime Plan in the procedure.
- Verification of procedure feasibility.
- Verification of the procedure‘s applicability as decision basis in the tender process.
- Investigation whether the schedule may be utilised in depreciation of assets.

The study is performed in cooperation with global FPSO contractor Teekay Petrojarl. A case study will be used to test and demonstrate the suggested approach.

1.3 Scope and delimitations

The scope of the thesis are the studies ending in the objectives from 1.2, subject to some delimitations. It is meant to discuss operational planning, including how this affect financial decisions, which implies that technical details, inspection methods, maintenance practices etc. are beyond the scope. It is assumed that the reader is familiar with basic maintenance management theory and system reliability theory. The scope is more precisely defined and delimited in the following subsections.

1.3.1 Perspective with regards to time and cost of renewals

Focus is set on major renewals of more or less complete systems, rather than minor maintenance on component level. This implies that from a time perspective, the centre of attention is the strategic long term decisions. From a monetary point of view, Teekay Petrojarl has set a lower limit at 500.000 NOK, for which of the activities that should be registered in their Vessel Lifetime Plan (see Chapter 3). This amount will also somewhat represent the lower limit for the focus area of the activities described in this thesis.

Kelly (2006) classifies maintenance actions by policy characteristics and by organisational characteristics. The former classification distinguishes between preventive actions, corrective actions and modifications. The latter between first line, second line and third line work. This thesis emphasises both corrective actions, preventive actions and modifications. When dealing with renewals of nearly complete systems, will in many cases single actions be fairly combinations of these three. However, the organisational characteristics are another matter.

Daily maintenance jobs, including both preventive routines and minor corrective actions are regarded as first line work. Second line consists of non-routine preventive jobs, sizeable corrective jobs and minor modifications. Third line work deals with the major actions: preventive and corrective, as well as modifications. The type of maintenance jobs addressed here, are those belonging to the third line. They are primarily preventive, condition based decisions and of major significance, either financially or operationally. They represent a long term focus on asset management from a total-cost-of-ownership perspective. For this reason, we can say that they are strategic decisions (Sardar et al., 2006). Figure 1.2 illustrates how these major renewals differ from the minor ones.

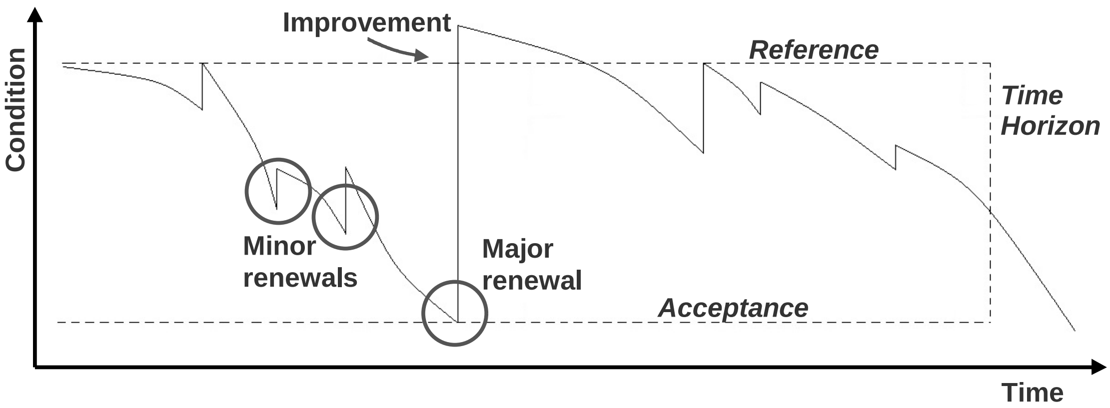

Figure 1.2: The focus in this thesis is on the major overhauls/replacements (Andersen et al., 1998)

1.3.2 Legislative perspective

The thesis touches on ageing management theory. Ageing management is a continuous improvement process and must be distinguished from the process of lifetime extension. Lifetime extension is a procedure to extend the lifetime of an installation and acquire permission to operate a number of additional years (Ramirez and Utne, 2011). The thesis does not address the requirements to such applications, as it would be too extensive, and it is more appropriate to refer directly to the documents (Norwegian Oil and Gas Association, 2012) and (Wintle and Sharp, 2008). However, it is intended that some of the most important topics regarding lifetime extension are given some attention.

Although TKPJ (Teekay Petrojarl) operates vessels both in the North Sea and in Brazilian waters, the focus in this thesis is on the prevailing regulations in the North Sea, i.e in Norwegian and UK waters. This is perhaps most interesting, as these are the strictest and most comprehensive regulations on the matter, and since most of the TKPJ vessels operate in these waters.

1.3.3 Academic perspective

The nature of this study lies in the borderland between technical and financial theory and will hopefully connect these in a meaningful way. However, the primary viewpoint is the technical one, meaning that it will not go very far into the financial side. For instance, the purpose of the case study is to present the procedure for scheduling, with a main focus on the systematisation of information since this probably stands out the most from existing methods, therefore the study will not go far into depreciation and NPV calculations.

The operational and commercial environments used as a basis are adapted to a company operating a medium-large sized fleet of FPSO vessels. However, most principles can be applied to other segments of the offshore oil and gas sector, and some even to other capital intensive businesses. The most essential point that makes the FPSO segment stand out from other parts of the offshore sector, is the mobility, and hence the contractual and operational flexibility.

Chapter 2

Theory

This chapter will start off by briefly explaining the term *asset integrity management*, a term that is increasingly being used, particularly in the oil and gas industry. It, in many ways, forms the basis for companies‘ strive to satisfy their own and their stakeholders‘ demands. Asset integrity management is a very wide term, covering efforts in design, construction, commissioning, operations, modifications and decommissioning phases (Bye, 2013). In the TKPJ management system manual it is defined:

"AIM in TKPJ is the means of ensuring that people, systems, processes and resources which deliver asset integrity, are in place, in use and fit for purpose over the whole life cycle of the asset" (Teekay Petrojarl, 2011).

This thesis focuses on the management of some of these means, with particular emphasis on the actual lifetime of the vessel. Lifetime meaning from the day of hook-up to (and including) the decommissioning. To enlighten the subject further, some examples of management deliverables in asset integrity management are presented (Bye, 2013):

Design phase:

- Maintenance and inspection strategy
- Safety studies
- Design review by verifier/authorities

Construction phase:

- Procurement quality plans
- Inspection and testing record

Commissioning phase:

- Commissioning completion packages
- Third party verification

Operations phase(s):

- Ongoing risk evaluation
- Maintenance and inspection revision
- Third party verification

Modifications phase(s):

- Verification of changes

Decommissioning phase:

- Safety and environmental studies
- Decommissioning strategy

We divide asset integrity into three main categories: design integrity, technical integrity and operational integrity (Ratnayake and Liyanage, 2009). These are in many cases somewhat interrelated. For instance, consider a gas tank system with an inlet valve, an outlet valve, a safety valve and a sensor. The sensor will be triggered if the pressure in the tank reaches a certain value and is connected to a safety valve, which will relieve the pressure. After some years, the management decides that the inlet and outlet valves are going to be replaced by new valves with higher capacity. Before this is done, one needs to assure that the safety valve is dimensioned according to the new valves. In other words, the design specifications need to be assessed according to the new technical requirements. The following notion shows the relationship between the three areas:

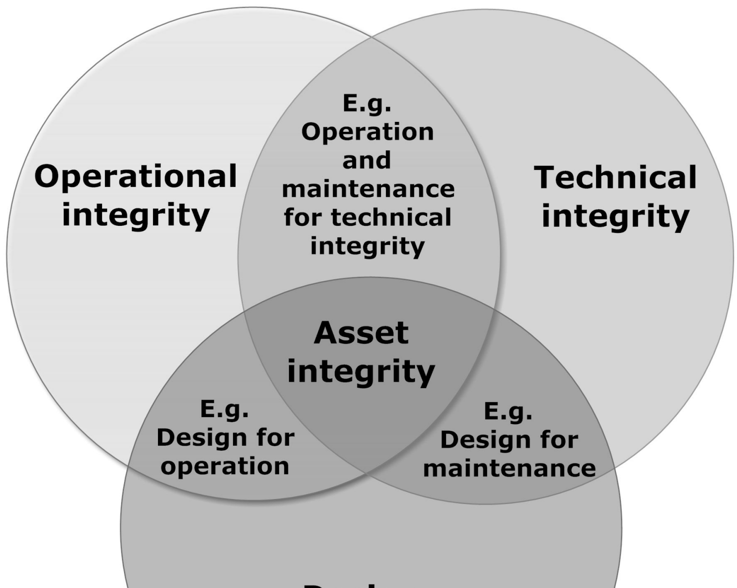

Figure 2.1: Asset integrity (Ratnayake and Liyanage, 2009)

For more on asset integrity management, please see (Ratnayake and Liyanage, 2009) and for technical integrity particularly, (Bale and Edwards, 2000).

2.1 Ageing management

Within the asset integrity domain, one of today‘s trending topics is the management of ageing plants. This goes partiularly for the North Sea oil and gas production, where many of the installations from the booming 80‘s and 90‘s either have reached or are approaching their design limits. HSE, which is the prevailing regulatory body on the UK continental shelf (UKCS), has given the topic great emphasis in their Key Programme 4 (KP4)[1].

To mitigate the risk in ageing offshore systems, there has been an increasing focus on implementing ageing management (AM) systems. Ageing systems may decrease efficiency of process systems, enforce complete plant shut-downs or even pose severe threats to safety . All such reduced performance of critical systems will normally decrease plant profitability. If the management is observing and controlling the ageing process sufficiently, actions can be taken to prevent loss of production and hence; loss of profit. However, mitigating production losses is not the only way of cost saving by ageing management. When it comes to the logistics of modifications and major overhauls, efficient planning and scheduling can award operators huge savings.

Much of the AM knowledge today has been adopted from the nuclear industry, where ageing has been given great concern. The operation of nuclear power plants (NPPs) has many similarities to the offshore industry (very high risk levels, high downtime cost and advanced technology). NPPs are also characterized by having some components that are virtually impossible to replace (Tipping, 2010). All this calls for a well established AM system. According to the International Atomic Energy Agency, predictability is the key to effective AM. To achieve good predictability, one is dependent on having the technical understanding, and doing precise and thorough condition monitoring (Inagaki, 2009). When these efforts are in place, the right decisions and actions can be taken (e.g. preventive maintenance, corrective

[1] Inspection programme aimed at determining the extent to which asset integrity risks associated with ageing and life extension are being managed effectively by duty holders (Health and Safety Executive 2014)

maintenance, modifications or replacements). Additionally, the AM system should be continuously reviewed and improved to achieve the best results (Ramírez, 2013). However, please notice that AM is not only concerned with challenges due to physical degradation, two other areas must also be addressed:

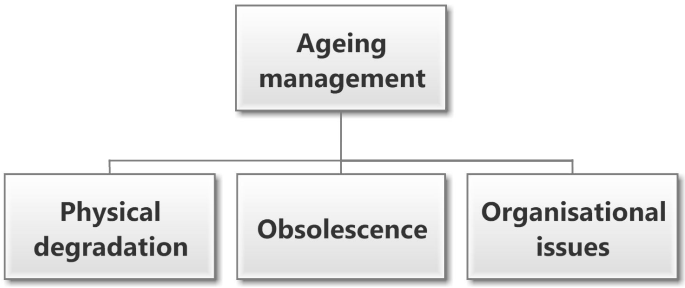

Figure 2.2: Ageing management (Petersson and Simola, 2006)

2.1.1 Physical degradation

As time passes, the physical conditions of SSCs (structures, systems and components) are gradually moving from satisfying conditions towards unsatisfying conditions. Subsurface structures are exposed to sea water, leading to corrosion and fouling. Pumps are subject to thousands of repeated cycles, which may eventually result in fatigue. Pipes are exposed to acidic and corrosive fluids. An overview of the different mechanisms leading to physical degradation can be seen in Figure 2.3.

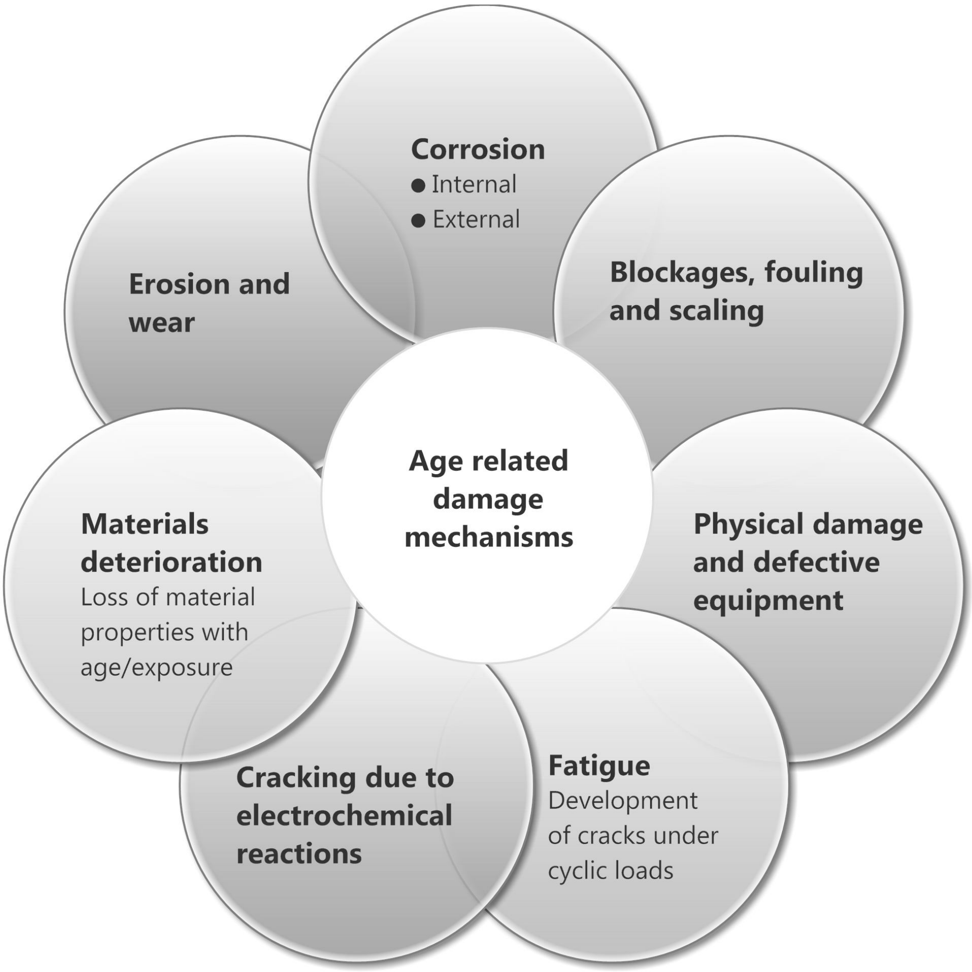

Figure 2.3: Age related damage mechanisms, adapted from (Wintle and Sharp, 2008)

In most cases, there is not one single factor to blame, a failure or degradation is likely to be related to several damage mechanisms. However, as presented in the influence diagram in Figure 2.4, these damage mechanisms are only symptomatic effects of the underlying causes, which may originate from design, fabrication, assembly, maintenance or operating loads (Ramírez, 2013).

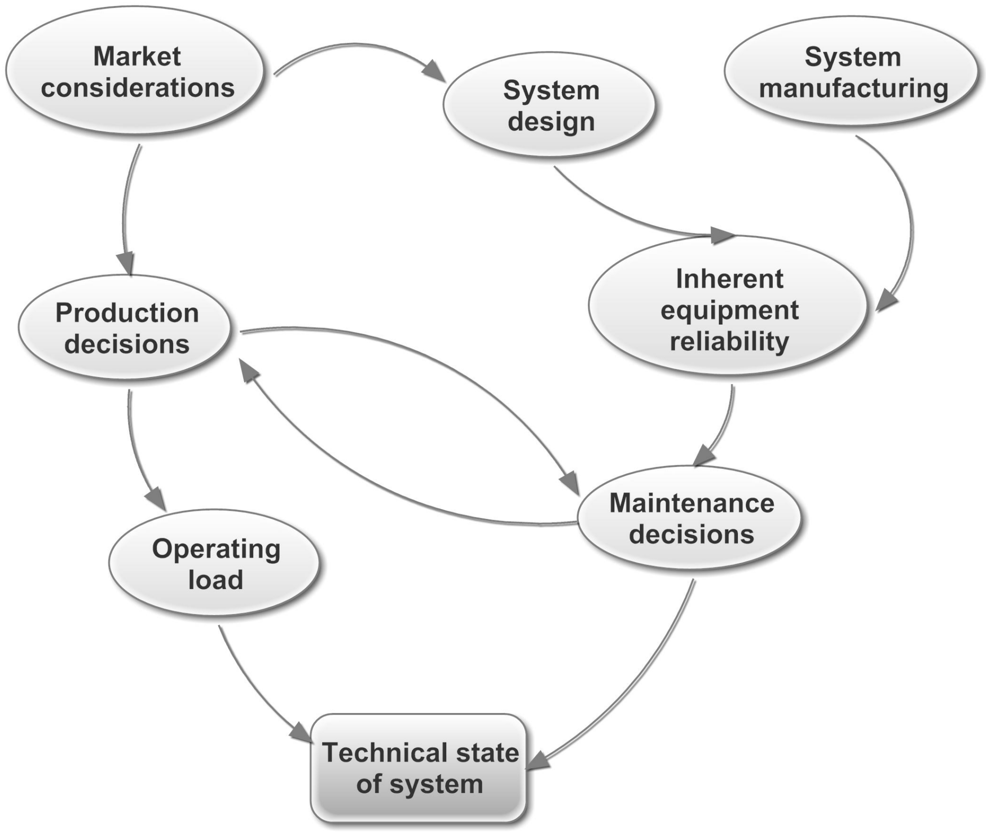

Figure 2.4: Influences on the technical state of a system, adapted from (Murthy et al., 2002)

Ageing models

According to ESReDA[2] (Petersson and Simola, 2006) there are two concepts of physical ageing. The first one is the "reliability-based" concept. This concept is generally applied for active components, as it only considers whether the components are functioning or have lost their function. The second concept however, focuses on the degradation process, which makes it more suitable for passive components.

[2]European Safety, Reliability and Data Association

Reliability-oriented ageing

Active SSCs involve some level of movement, actuation or change in state as they function, and include for instance valves, pumps, generators, circuit boards, power supplies, switches, and batteries (Wintle and Sharp, 2008). The active structures and components are being affected by age related degradation in their functional performance during operation. This effect may be immediate (e.g. failure of power supply or circuit board) or gradual (e.g. progressive reduction in pumping capacity or valve closure time). The service life of these components and systems are normally characterised by three phases. The running-in-phase (called burn-in for electronic components), a maturity phase and the so-called ageing. The failure rate given as a function of time, for this typical service life, is called the bathtub curve and is illustrated in Figure 2.5.

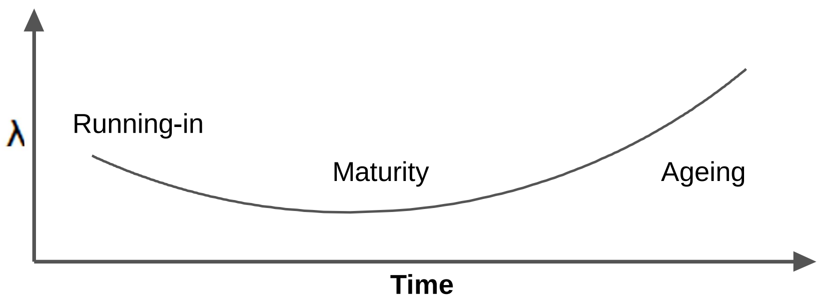

Figure 2.5: The bathtub curve (Petersson and Simola, 2006)

The effect of gradual degradation of an active SSC will in most cases be detectable as the SSC operates to perform its function. Additionally, these SSCs are often subject to a testing, maintenance and/or replacement policy. Active SSCs are therefore excluded from the AM process by the U.S. nuclear industry. This thesis focuses on AM as a planning and decision tool, not only for technical systems, but for the vessels and/or company as a whole. Active components will, on this basis, have to be given attention. Additionally, the level of on-line monitoring may not be as great for offshore installations as for nuclear plants (Wintle and Sharp, 2008).

Flexible, two-parameters distributions such as Weibull, Lognormal Gamma or Beta are widely used to model this type of ageing. Unfortunately, a great deal of failure data is generally needed to determine their parameters in a frequential inference (Petersson and Simola, 2006).

Physically-oriented ageing

This approach focuses on measurable quantities describing the degradation, for instance crack size or corrosion loss of material (Petersson and Simola, 2006). As mentioned, the physically-oriented ageing approach is mainly applied to passive equipment (structures, pipes, pressure vessels etc.) which often is characterised by having a single degradation mechanism and a single failure mode. Condition monitoring and in-service inspections are normally utilized to gather data for the prediction of the ongoing deterioration process (Petersson and Simola, 2006). A common method for generating deterioration models based on condition monitoring results is forecasting using historical records from time series and use of failure mechanism models (Thorstensen, 2008). Thorough knowledge of the actual failure mechanisms and the material properties should be the basis for the selection of life distributions (Rausand and Reinertsen, 1996). However, extensive data is needed to establish this basis and authors disagree on selection guidance. Nonetheless, a preliminary guidance is given by Rausand and Reinertsen (1996) in Table 2.1.

Table 2.1: Recommended life distributions for various types of degradation (Rausand and Reinertsen, 1996)

	Life distribution				
Mechanism	Weibull	Lognormal	Inverse Gaussian	Birnbaum-Saunders	Gumbel
Fatigue (cyclic)		•	•		
Fatigue (cum.)			•	•	
Corrosion (pitting)	•				•
Wear			•		

2.1.2 Obsolescence

As time passes, components and systems become what we in everyday life call "out-of-date". New, better and more advanced technologies are constantly being developed and the strive to achieve higher performance makes it valuable to implement them as they are introduced. Often, operators are left without a choice, because the availability of spare parts changes rapidly and in nearly the same pace as new technology develops. New operational requirements arise, as oil and gas production moves into harsher environments, deeper waters and more remote areas. Additionally, HSE considerations makes authorities and other stakeholders introduce new requirements. Obsolescence is the state where a component, system, practice or service needs to be replaced by the reasons mentioned (Hokstad et al., 2010).

Pecht (2004) argues that the market life cycle of components can be divided into six common stages: introduction, growth, maturity, decline, phaseout and obsolescence. An example life cycle can be viewed in Figure 2.6.

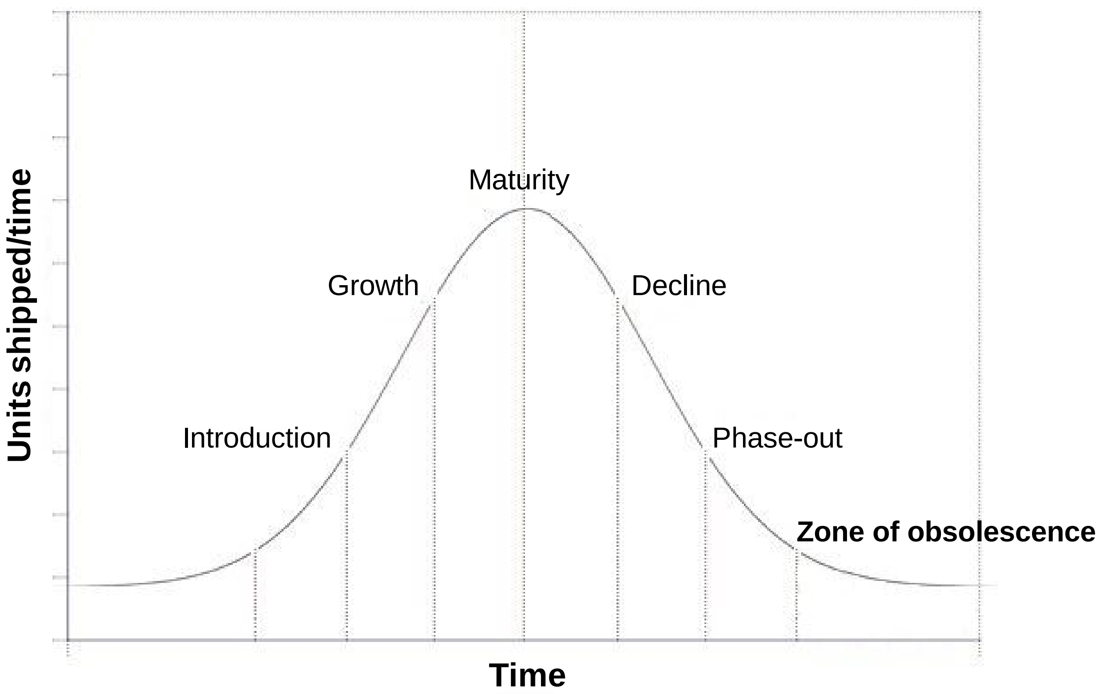

Figure 2.6: Product life cycle stages (Pecht, 2004)

Although this model is built for electronic products, it can be cautiously transferred to other components and systems. Two important differences is that electronic components are generally more standardized (off-the-shelf) and that electronic components generally become obsolete faster than the mechanical ones (Devereaux, 2010). Even so, there is an increasing use of electronic equipment, both in process systems and elsewhere, since tasks can be executed by software, often more accurately, safer and at a lower cost.

2.1.3 Organisational issues

One of the most important steps in the process of managing ageing of offshore installations is thought-through organising of operational teams, onshore as well as offshore. Organisational adjustments are mentioned in most AM articles and reports, both from the authority side and academic side.

Acquiring, maintaining and transferring knowledge

All organisations, from small local companies to huge, international corporations work both strategically and on a day-to-day basis, to maximise knowledge in their organisations. However, it can be challenging to implement and maintain this knowledge in such a way that it can be utilized to strengthen company performance. One key element in the process of managing ageing of SSCs is to maintain specific knowledge of each SSC in the organisation. Wintle et al. (2006) mentions asset registers as a helpful way to retain this knowledge. It does not need to be a vastly detailed document, but a summary list of equipment items with a few key details (e.q. location, function, duty, number of items, remaining life, financial value, decommissioning date) held and regularly updated at site and plant level. Ramirez and Utne (2011) suggests that such documents should be integrated in the existing maintenance management. However, existing computerised maintenance management systems (CMMS) normally concentrate on the present condition of the installation and do not address in a systematic manner the management of ageing (Ramirez et al., 2013).

Establishing interdisciplinary teams with participants from various departments can be a way of transferring knowledge within the organisation (International Atomic Energy Agency, 2009). This way, experts in one area can spread their knowledge to other departments. The benefit comes mainly as increased understanding across the departments, but hopefully also as a more redundant organisation (in the meaning that the organisation will have higher flexibility when personnel resigns, retires or are put to other tasks). This is particularly critical in AM, where local knowledge and understanding of historical issues often are necessary in order to assess and respond to an AM challenge. HSE suggests that the duty holder identifies AM sensitive positions and develop candidate selection criteria for the key integrity assurance positions with effective handover process (Health and Safety Executive, 2009).

Arranging for and encouraging personnel to rotate across different departments, both onshore and offshore is another way of ensuring that key knowledge is shared. Especially swaps from onshore to offshore and vice versa, can prove to become a fruitful measure. This way, onshore personnel can increase their insight of the challenges at sea and offshore personnel can increase their understanding of decisions and priorities made in the onshore organisation.

2.2 Asset information management

Liyanage and Kumar (2003) argue that the changing competitive environment of asset managing organisations along with stricter regulatory requirements, are forcing asset managing organisations to have effective performance management mechanisms for their asset management processes. These information systems should provide a broad base of consistent and logically organised information concerning asset management processes; and second, the availability of real time updated asset related information available to asset life cycle stakeholders (Rondeau et al. 2006).

Two examples of systematic asset information systems follows:

2.2.1 Key performance indicators

Key performance indicators (KPIs) are a common way of measuring and communicating operational or HSE performance in offshore oil and gas companies. However, Lane et al. (2012) states that operators should include KPIs designed to monitor and evaluate effectiveness of AM. They are required to facilitate management oversight, which is essential to ensure that ageing of the offshore installation is being adequately managed (Health and Safety Executive, 2009). Health and Safety Executive (2009) suggests three levels of key performance indication:

- High level - Organisational level
- Medium level - Management level
- Lower level - Operational level

Operators should determine which parameters that are best suited for their installation, such that the changes in performance can be detected. Good value KPIs have the ability to inform on the current status, as well as track and indicate changes over time (Health and Safety Executive, 2009).

2.2.2 Technical condition index (TCI)

The EUREKA[3] project "Ageing Management" ('96-'99) developed a quantitative measure of a plant's technical condition called Technical Condition Index (TCI) (Andersen and Rasmussen, 2003). It is defined as the degree of degradation relative to the design condition. It may take values between a maximum and a minimum value, where the maximum value describes the design condition and the minimum value describes the state of total degradation.

Although TCI measures were developed to quantify a plant's technical condition, it may might as well be applied to the plant's subsystems. This way, a value can be obtained for each system and implemented in the asset information system such that the technical condition can be evaluated along with other information.

The aggregation method to establish a TCI value comprises the following steps:

1. Establish a hierarchy system which represents the actual industrial system. Two principal approaches may be used, either functional breakdown or system breakdown.
2. Assign a weight to each of the objects according to their criticality.
3. Assign relevant input variables, which characterise the objects technical condition (mainly at the bottom level).
4. Based on values of the input variables (e.g. inspection data and monitored variables) the TCI values are then aggregated upwards in the hierarchy.

[3]An intergovernmental organisation for market-driven industrial research & development

The function for the technical condition of a system looks like this:

$$TC_{Parent} = 100 - \frac{\sum_{i=1}^{n} (100 - TC_i) \cdot w_i}{100} \tag{2.1}$$

Where:

TC_{Parent} is the technical condition of parent [0,100]

TC_i is the technical condition of child i [0,100]

w_i is the weight of child i [0,100]

n is the number of child nodes

Chapter 3

Teekay Petrojarl and the Vessel Lifetime Plan

3.1 Teekay Petrojarl

Teekay Petrojarl is the largest FPSO contractor in the North Sea and the fourth largest leased FPSO operator in the global market (Teekay Corporation 2014). Petrojarl ASA entered into a joint venture with international shipping company Teekay in August 2006 and by July 2009 it was fully acquired by Teekay (Reuters 2008). Teekay Petrojarl is headquartered in Trondheim, Norway, and has operational teams in Brazil and UK (Teekay Petrojarl, 2012). Additionally there is a site office in South-Korea supervising the new building. The different vessel-specific operational departments are located at the nearest office to the respective field. A co-ordinate department called Operations Strategies and Support, supports the operational teams (for a closer look at the company organisation, please check Section 3.1.1).

The company owns six ship shaped vessels (one additional vessel, Petrojarl Knarr, is under construction) and three cylindrical units of Sevan type. Six units are placed in the North Sea and three in Brazilian waters. All units are fully owned by Teekay

Petrojarl, and all but one, Hummingbird Spirit, are operated by TKPJ (Teekay Corporation, 2011), for an overview, see Tables 3.1 and 3.2. Figure 3.1 illustrates three different vessel types.

Throughout this study, Teekay Petrojarl is either referred to as TKPJ, the contractor or the duty holder.

Table 3.1: Company fleet(Teekay Corporation, 2011)

Vessel	Type	Waters	Contract	Client	Built
Petrojarl Varg	Ship	Norway	Q3 2016 + (2x3 y.)	Talisman	1998
Petrojarl Banff	Ship	UK	Q4 2014 + (1x4 y.)	CNR Intern.	1998
Petrojarl I	Ship	Norway	Layed-up	-	1986
Petrojarl Foinaven	Ship	UK	Beyond 2021	BP	1996
Petrojarl Cidade R.O.	Ship	Brazil	Aug. 2018	Petrobras	2007
Petrojarl Knarr	Ship	Norway	2020 + (1x14 y.)	BG Norge	2014
Hummingbird Spirit	Cylindrical	UK	March 2016 + (1x1 y.)	Centrica Energy	2007
Piranema Spirit	Cylindrical	Brazil	Oct. 2018 + op.	Petrobras	2007
Voyageur Spirit	Cylindrical	UK	Q3 2017 + op.	E.ON Ruhrgas	2008
Petrojarl Cidade I.	Ship	Brazil	Q4 2021 + (1x6 y.)	Petrobras	2012

Table 3.2: Fleet technical specifications(Teekay Corporation, 2011)

Vessel	Mooring type	Storage cap.	Processing cap.	New/conversion
Petrojarl Varg	Turret	470,000 bbls	57,000 bbl/day	New build.
Petrojarl Banff	Turret	120,000 bbls	95,000 bbl/day	New build.
Petrojarl I	Turret	190,000 bbls	46,000 bbl/day	New build.
Petrojarl Foinaven	Turret	260,000 bbls	140,000 bbl/day	Conversion
Petrojarl Cidade R.O.	Spread (12 lines)	214,000 bbls	45,576 bbl/day	Conversion
Petrojarl Knarr	Turret	800,000 bbls	63,000 bbl/day	New build.
Hummingbird Spirit	Spread (12 lines)	270,000 bbls	30,000 bbl/day	New build.
Piranema Spirit	Spread (9 lines)	250,000 bbls	30,000 bbl/day	New build.
Voyageur Spirit	Spread (12 lines)	270,000 bbls	30,000 bbl/day	New build.
Petrojarl Cidade I.	Spread (16 lines)	650,000 bbls	80,000 bbl/day	Conversion

Figure 3.1: From left: Petrojarl Foinaven (conversion w/turret mooring), Petrojarl Cidade de Rio das Ostras (conversion w/spread mooring) and Voyageur Spirit (new build w/spread mooring)

3.1.1 Company organisation

Teekay Petrojarl is organised based on a simple hierarchical model with the following units (Teekay Petrojarl, 2011):

- Engineering
- Projects
- Operations
- HSE
- HR, IT & Administration
- Finance & accounting
- Commercial & business

The Operations section is split into departments responsible for each of the vessels, plus two supporting departments: Purchasing and Operations support. This is illustrated in Figure 3.2.

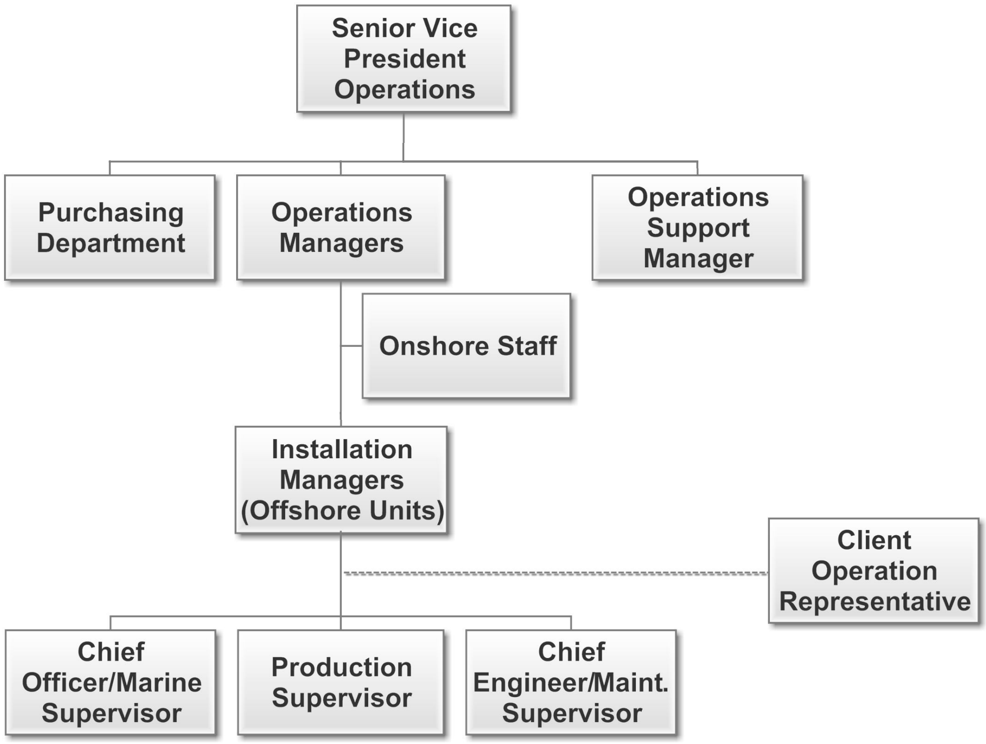

Figure 3.2: Organisation chart for Operations in Teekay Petrojarl (Teekay Petrojarl, 2011)

3.2 FPSO characteristics

FPSO vessels (or units) are floating, moored installations for production, storage and offloading of hydrocarbons. Nearly similar are the FSO vessels, which are not fitted with a topside for processing of oil and gas. FPSOs are typically former tanker vessels which has been refitted with a process plant. Some also have a turret, which is a single point mooring system (SPM), consisting of a hole in the bottom side of the hull and multiple chains, wires and anchors which connects the vessel to the seabed (Paik and K.Thayamballi, 2007). The risers and umbilicals are also connected trough the turret. This allows the vessel to rotate, positioning it towards wind and waves. Figure 3.3 illustrates this type of system.

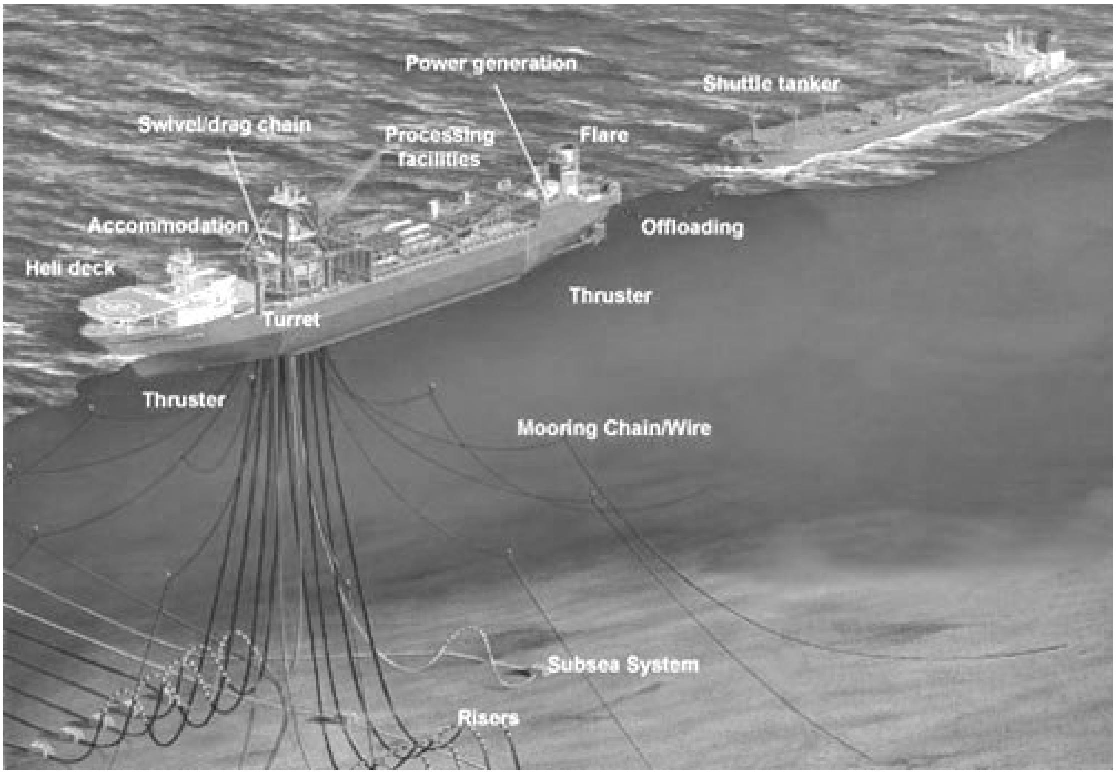

Figure 3.3: FPSO w/Single point mooring system during offloading

A second type is the spread mooring, which is similar to traditional ship mooring in the sense that the vessels are anchored in more than one point and unable to rotate. Third, there are also vessels using dynamic positioning (DP) (Paik and K.Thayamballi, 2007).

As most FPSOs are moored in fixed positions over longer periods of time, they do not necessarily need to be ship shaped. Sevan Marine, a Norwegian company, has patented a cylindrical shaped design. This is geometrically optimised for static operation and the simple shape also means they can be built at lower costs (Teekay Corporation, 2012). However, the vast majority of contemporary FPSOs are ship-shaped, which means that principles for maintenance and inspection in terms of the hull, tanks, marine systems and cargo systems can be based on many years of experience with trading vessels, and especially tankers. Though, the loads and strains they are exposed to, are very different. There are quite a few factors which need to be considered in the projects where trading tankers are converted for production and storage.

There are many benefits from the FPSO solution in marginal field development, the most important ones are listed below:

- **Early deployment**
  FPSOs are constructed in shipyards, which means that process facilities may be integrated at the shipyard. This allows for concurrent activities and shorter project cycle time. Besides, in many cases the topside is installed on existing hulls, allowing for an even earlier "first oil" (Shimamura, 2002).
- **Deep water capability**
  Due to lack of supporting structures or tension legs, the cost of installing FPSOs in deep waters are significantly lower than the alternatives.
- **Mobility**
  FPSO vessels can be relocated rather quickly, which give their owners great commercial flexibility to tender for new contracts when oil reservoirs are depleted.
- **Self-containment**
  Large tanks make the vessels able to store great volumes of oil or gas. Shuttle tankers can therefore be used as the link to shore, which is both a flexible and cheap solution.

- **Crude oil market flexibility**
  When crude oil is transported by pipelines, it often dictates where the oil must be sold, which has negative effects on the selling price. The use of FPSOs and shuttle tankers eliminate some of these constraints (Shimamura, 2002).

3.2.1 Vessel technical build-up

FPSOs are configured somewhat similar to traditional ships. They are systematically coded according to the SFI grouping system[1], but with some amendments. TKPJ's vessels typically have a hierarchical breakdown such as the one below:

1. *Ship General*
2. *Hull*
3. *Subsea and turret based production system*
4. *Process - crude flow/water and gas treatment/laboratory*
5. *Ship equipment - Cargo/life saving/anch. mooring*
6. *Machinery main components*
7. *Systems for machinery main components*
8. *Ship common systems*
9. *Consumables*

From this we can notice that group 3 and 4 are the only ones to separate this from a ship SFI structure. The cylindrical units have an even more ship-like structure with groups 1-8 in this well known configuration plus an extra group: *9 Topside*. This contains all the FPSO-specific systems; such as gas compression trains, water injection plants, well injection equipment and crude flow systems.

[1] An international standard which provides a functional subdivision of technical and financial ship or rig information

3.2.2 The stakeholders

An offshore installation, producing hydrocarbons, is positioned in the center of a vast network of various actors and interests. The owner and daily operator of the vessels, in this case Teekay Petrojarl, is obliged to safeguard these interests and to meet the stakeholders' expectations. The most important ones are:

- **The charterer**
  The charterer of a TKPJ vessel, in most cases an oil company, chooses to lease the operational service to focus on core activities and hence limit its risk exposure (see 3.2.4). By sticking to its core activities; funding, exploring, producing and selling petroleum; it should benefit from the contractors economics of scale (Bloemen, 1997). Contractors have experience with both design and operation of FPSO systems.

  Additionally, there is generally a number of co-owners in an oil field, all of them eager to gain from their investments and to have a say in things.

- **Employees**
  TKPJ is a complex organisation. It is owned by an international shipping company counting approximately 6800 employees (Drøpping, 2013), 1000 of them under TKPJ (Teekay Petrojarl, 2012). A fair share is employed offshore, on various vessels and various shifts. Additionally, the employees are spread among many locations, nationalities, languages and cultures.

- **Society**
  The environmental hazards related to offshore oil production are massive, but well-known. Local communities and national governments set the expectations and provide the guidelines to the industry. Companies are raising their awareness and investments when it comes to these issues as a result of increasing pressure from governments, environmental organisations and media.

- **Vendors**

  Vendors will be affected by company performance, and naturally also by procurement decisions, which make them considerable stakeholders.

- **Shareholders**

  Shareholders will surely be affected by company performance and they have the power to influence top management decisions.

3.2.3 The FPSO market environment

Traditionally on large field developments, the major oil companies build custom designed FPSOs and operate themselves. For smaller fields however, the vessels are normally owned and operated by contractors such as Teekay Petrojarl. This brings economies of scale, as specialised FPSO contractors normally are more experienced and can run their projects and operations more efficiently. However, the FPSO contractor market is very competitive; other major independent FPSO contractors include SBM Offshore NV, BW Offshore, Bluewater, MODEC and Bumi Armada. As of December 2013, there were approximately 174 FPSO units in operation and 38 units in the order books (Teekay Corporation, 2013).

As mentioned previously this chapter, offshore oil and gas production tends to adopt the more marginal reservoirs, deeper waters and more complex field developments. All of these characteristics favour the utilisation of FPSO units. There is thus much reason to believe that the use of such technology will continue to increase.

3.2.4 Contracts between oil company and FPSO contractor

All assets operated by TKPJ are fully owned by the company itself. They are generally leased to oil companies on what is called Lease and Operating (L&O) contracts. These contracts are set for a fixed period plus options to extend. The typical nature of the contract between the two parties is operational lease, meaning that TKPJ is contractually responsible for both making available the physical asset (vessel) and for operating it. This is opposed to financial leasing where the oil companies leases the vessel and not the operational service (Catherine, 2011). Operational lease implies that both the asset risk and operational risk lies with TKPJ, however the oil company will always carry the highest risk, the risk of lost production revenue (R. Bye, pers. comm., 26/11/2013).

The contracts vary significantly from operation to operation with a number of elements involved, some of them based on performance (incentive driven) (R. Bye, pers. comm., 26/11/2013). One variant is that the oil company pays a fixed daily rate for the rental of the vessel (the bare-boat charter) and a daily rate for the operations of the vessel (Catherine, 2011). The operation rate can be in the form of operational cost flow-through with mechanisms for increase due to inflation. A second type is that the contractor invoices a fixed operating fee, incl. the bare-boat element, subject to a revision formula to account for costs inflation during the contract (R.Bye, pers. comm., 26/11/2013). In some contracts, simplified speaking, TKPJ is paid the full rate only if the FPSO is fully available for production. In the case of production losses, the day rate is only partially paid, or in some cases not paid at all. This gives TKPJ strong incentives to avoid production losses, in other words, aiming at operational excellence.

The commercial risk, i.e. the oil price volatility, lies with the oil company (Catherine, 2011). However in some contracts, TKPJ is credited a tariff fee dependant on oil price level (upwards and downwards limited) (R. Bye, pers. comm., 26/11/2013). Risks associated to reservoir performance is typically not directly influencing TKPJ, however it will affect any tariff element and eventually any associated incentive elements.

To sum up; loss of production will in almost all TKPJ L&O contracts sooner or later affect the revenue stream for TKPJ.

3.3 The Vessel Lifetime Plan

3.3.1 Background

In a company such as Teekay Petrojarl (TKPJ), operating complex floating vessels in harsh environments and across national territories, there are vast amounts of asset information to collect, interpret and utilise. The fleet has almost doubled in three years, going from five vessels in 2010 to nine vessels in 2013. Additionally, a vessel will be delivered from Samsung Heavy Industries during 2014. This is a major challenge for the organisation. Previously, key personnel had the ability to somewhat keep track of vessel conditions. Nowadays however, it is very hard (not to say impossible) to obtain a decent overview of fleet integrity. The company is facing major challenges concerning(Drøpping, 2013)(Bye, 2013):

- Harsh environments and challenging operations
- Significant prolongations to expected duration of contracts from extended tail-end production
- Redeployment of units
- Handling of unforeseen events
- Decreasing profit margins

Adding up to this, vessels are operated in different legislative regimes; Brazil, UK and Norway; and as seen in Tables 3.1 and 3.2, the vessels/units vary, both in terms of age and design.

In order to address these challenges, TKPJ is developing an information management system called the Vessel Lifetime Plan (VLTP). The system is intended to gather the most essential information from classification societies, operation and maintenance management (including condition monitoring management systems), engineering, RBI contractors and subcontractors(Drøpping, 2013). The information stored in the VLTP is kept at a system level and only information considered as strategically valuable is entered. The day-to-day maintenance management is covered by other CMMSs. The VLTP is intended to give a clear picture of the state of the vessel. By providing this, it shall be possible to estimate the remaining lifetime of the vessel. It shall also be utilized to plan, schedule and evaluate maintenance, modification, renewal and docking activities, and to estimate the costs of these activities(Bye, 2013). Another challenging issue, given an essential role in the VLTP, is the number of persons on board (POB). As the vessels possesses limited accommodation capacity, the extent of major activities will always need to be carefully estimated and scheduled.

The outputs from the VLTP are also intended to be utilised as input in the company‘s financial models (Bye, 2013). The next chapter looks closer into these opportunities.

3.3.2 Current status

The VLTP has been implemented on Petrojarl Foinaven. This vessel is undergoing a ten year (plus) lifetime extension and subject to extensive upgrade activities (Drøpping, 2013). It is a ship shaped conversion, operating on the UKCS, and a representative example of the TKPJ fleet. The VLTP was developed when the vessel was undergoing life extension study, and focus was very much future-oriented. Contracts were extended and future revenues were evident, meaning that operational managers got recognition for their arguments to prioritise concerns related to vessel ageing. However, 2013 became a financially tough year for TKPJ, experiencing major production issues on Foinaven and one of the newly acquired vessel, Voyageur Spirit. Gaining acceptance for priorities that only become profitable after some years is hard. Due to this, and to lack of ownership in the operational team, the VLTP has not been updated the last year (R. Bye, pers. comm., 05/02/2014).

The system was also partially implemented on Petrojarl 1, but this vessel is currently layed-up and manning minimised. The VLTP is therefore not being updated on

Petrojarl 1 either. Petrojarl Knarr is scheduled for delivery during 2014 and VLTP implementation is in progress, intention is that it will be updated continuously throughout its lifetime. This work has gotten a head start, as the design lifetimes and other information for various systems are far more accessible for newbuilds than for the older vessels.

3.3.3 Structure

The actual database was developed internally in the Microsoft Access software. The interface consist of five main tabs:

- **Activity list**
  List of planned activities sorted by the SFI system. It gives a short description, estimates for earliest and latest activity years, cost estimate and yearly cost distribution for each activity. A screenshot can be seen in Appendix A.
- **Verify new activity**
  Tab where updates can be done and documents added.
- **Estimation**
  Tab where the cost distribution estimates, POB estimates, design lifetime and current lifetime estimate are to be entered. Estimates for workload, number of needed shut down hours, number of needed hot work hours and life extension scope are also entered in this tab. A screenshot can be seen in Appendix A.
- **Budget approval**
  This is where additional budget information is entered: Cost allocation (CAPEX, OPEX or life extension), docking needs (yes or no), priority level (low, medium or high).
- **Realization**
  This tab is currently under development and has not yet any function.

Procedure for implementation of new activities

Once a year, a meeting shall be held to evaluate all production systems, marine systems, utilities systems and structures to identify ageing conditions. Suggested participants are onshore superintendent, chief engineer, production supervisor, TA different disciplines and reliability engineer. After the meeting, the onshore superintendent is responsible for entering the new activities and attach drawings, photos and other documents. The reliability engineer is responsible for updates and verifications in the database on regular intervals.

Chapter 4

A systematic approach

Based on the ageing management theory from Chapter 2, as well as the market and corporate premises in Chapters 1 and 3, this chapter presents a work process for long term scheduling of major renewals. It deals with the total process from condition monitoring to utilisation of schedule output.

The work process is based on the recommended work process in NORSOK Z-008, which can be seen in Appendix B. To make the review more easy-to-follow, it is divided into three main steps and it introduces a fourth:

- **I - Monitor and analyse:** The first step deals with how information is collected and analysed. It represents the lower three nodes from Appendix B.
- **II - Make a decision:** This step emphasises how to optimise decisions based on information obtained in step I. It represents the centre node from Appendix B.
- **III - Schedule:** This step concerns how results from step II are taken further and how the activities are scheduled. It represents the top four nodes from Appendix B.
- **IV - Utilise financially:** This step emphasises some beneficial financial utilisations of the obtained knowledge from the previous three steps.

The following subchapters presents the steps closely, but first, take a look at the work flow in Figure 4.1. It is important to notice that the three framed steps should be done annually, while the rest of the steps form a continuous work process.

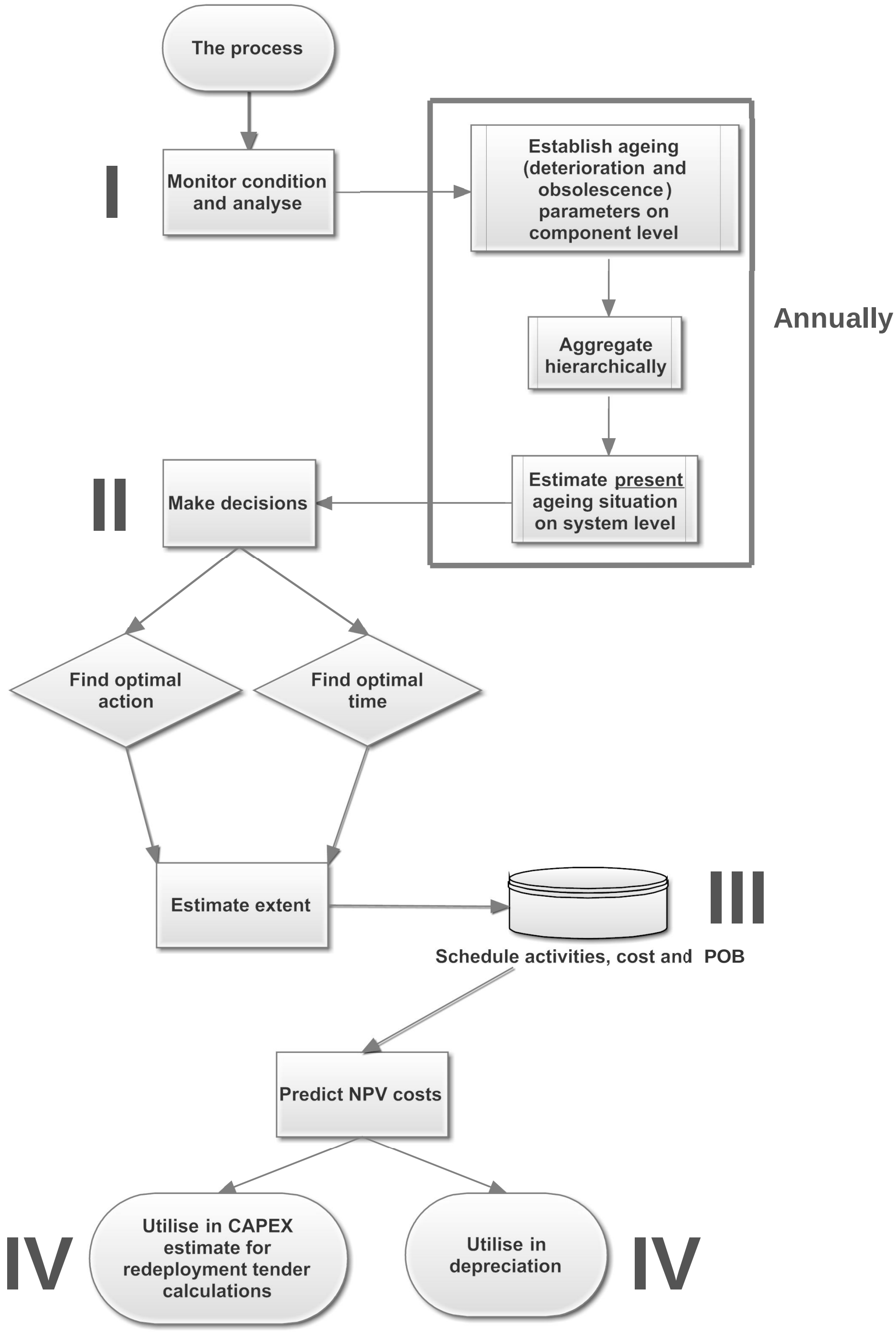

Figure 4.1: The complete process of scheduling system renewals

4.1 Step I: Monitoring and analysis

Arguably the most important aspect in the management of ageing, is information gathering on its progress. By providing the required amount and quality of information, one can optimise life predictions and future actions. However, to evaluate, predict and improve the performance of SSCs, one must also have its historical operating conditions and repair data (Campbell et al., 2011). When data is inadequate one should try to obtain this information by contacting previous owners or designers (Wintle and Sharp, 2008). This experience data needs to be handled appropriately, by expert personnel, both statistically and technically, according to Wintle and Sharp (2008).

There are several ways of performing degradation monitoring, here comes a rough division (Petersson and Simola, 2006):

- **On-line monitoring**
  (e.g. temperature monitoring)
- **Monitoring during maintenance**
  (e.g. taking oil samples)
- **Statistical methods**
  (e.g. trend-spotting)
- **Failure analysis**

As life is extended and greater attention to integrity and performance is required, the scope and frequency of monitoring and testing may need to increase (Wintle and Sharp, 2008). Reduced performance can be signs of incremental trends and actions could be needed, however these trends can also be the case during service life.

It is also essential to gain knowledge on obsolescence. Close interaction between operating departments and procurement/materials management departments is vital. Computerised systems for materials management must be updated continuously by proactive communication with suppliers, developers, premise providers and other market stakeholders.

4.1.1 The Ageing Parameter

To handle this information systematically it is suggested that the contractor introduces a parameter called "Ageing Parameter", based on the framework of TCI, developed by Andersen and Rasmussen (2003) (see Section 2.3.2). It should illustrate all factors relevant in therms of ageing management, which means that obsolescence information must be included along with information on technical condition. As illustrated in the grey-coloured square in Figure 4.1, operation engineers annually establish parameters on component level, based on information from condition monitoring, inspections and other CMMS infromation or by requesting specific information from maintenance-/procurement personnel. The Ageing Parameter can then be established for subsystems and systems by aggregating hierarchically (in spreadsheets or in dedicated software). The vessels' SFI structure may be utilised as the hierarchical structure for this purpose. When this is done, the ageing situation for the system can be analysed by using a top-down approach, to find if there are any obvious weaknesses on component level or on subsystem level.

The equation for the weighted AP of a component (which is based on Equation 2.1) can bee seen below:

$$AP_{i,W} = (100 - AP_{Ageing,i}) \cdot W_i \tag{4.1}$$

Where:

$AP_{i,W}$ is the weighted value of the Ageing Parameter of component *i*

AP_i is the Ageing Parameter of component *i*

W_i is the weight of component *i*

Moving upwards in the hierarchy, the subsystem AP is found by:

$$AP_{sbs,j} = (100 - \sum_{i=1}^{n} AP_{i,W}) \tag{4.2}$$

Where:

$AP_{sbs,j}$ is the Ageing Parameter of subsystem *j*

$AP_{i,W}$ is the weighted value of the Ageing Parameter of component *i*

And finally, the system AP can be calculated by multiplying all subsystem APs by the average weight of its subcomponents and then aggregate:

$$AP_{sys} = (100 - (\sum_{j=1}^{m}(100 - AP_{sbs,j}) \cdot (\sum_{i=1}^{n} W_{ij}/n_j))) \tag{4.3}$$

Where:

AP_{sys} is the Ageing Parameter of the system

$AP_{sbs,j}$ is the Ageing Parameter of subsystem *j*

W_ij is the weight of component *i* in subsystem *j*

n_j is the number of components in subsystem *j*

Criticality and weights

To manage safety- and availability risk, TKPJ has built RAM models for their vessels. One of the steps in this manner is to carry out a Failure Mode, Effect and Criticality Analysis (FMECA). This seeks to identify all possible failure modes of the components, which effects the failure modes will have, and from this, assign criticality levels to all components. Criticality is normally defined as the product of consequences and frequencies of potential failures, however in Teekay Petrojarl (2013), it is defined as the numerical value of the most severe potential consequence of a failure. The equipment subject to evaluation is given a total criticality setting based on the parameter (Safety/health, Environment, Regularity, and Direct Cost) which is considered to be the most severe (Teekay Petrojarl, 2013). Since the levels represent each component‘s importance with regards to the top objectives, they may very well serve as weights in an hierarchical aggregation, as suggested by Andersen and Rasmussen (2003) for the TCI. Criticality levels in TKPJ are either:

- H(1) - High
- M (2) - Medium
- L (3) - Low
- N/A - No criticality

These levels need however to be converted to weights. In this context it is worth noticing that the ratio between levels are not necessarily linear. The levels have been assigned to components according to the consequences which occur when the component:

- loses its intended function, or
- function is greatly reduced, or
- malfunctions

How TKPJ has grouped these consequences and which criticality they are assigned can be seen in Appendix C (Teekay Petrojarl, 2013). They are, as mentioned, defined according to the following categories: safety/health, environment, availability and direct cost. Obviously cost is the parameter which most straight-forwardly can be converted to weights. Failures of SSCs with potential direct cost <= 500.000 NOK are considered by TKPJ to be N/A. SSCs with potential >= 500.000 NOK are considered Low and potential >= 2.000.000 NOK are considered Medium. The High criticality level is not given any monetary value, but is defined as an event which is severely threatening to safety of the installation. Based on this, it is suggested that the four levels are weighted by values 0, 0.15, 0.30 and 0.90 respectively. This is summarised in Table 4.1.

Table 4.1: Conversion from criticality to weighting

Criticality level	Consequence	Weighting
N/A	<= 500.000 NOK	0
3 - Low	>= 500.000 NOK	0.15
2 - Medium	>= 2.000.000 NOK	0.30
1 - High	Severely threatening	0.90

Component level AP definitions

When operation engineers are going to assign a value for each component‘s Ageing Parameter, there will always be uncertainty and subjectivity to some extent. It may not be entirely clear what is the design condition of the component or there may lack information on the present condition, either technically- or obsolescence-wise. It will also be somewhat subjective how each employee emphasise the information obtained. All this will depend on the knowledge and experience each has. It is thus important to define the different intervals of ageing from 0 to 100. At the same time, the definitions need to be open and unspecific enough to cover a wide range of components. It goes without saying that the accuracy when it comes to the AP to represent the actual ageing condition on component level will not be extremely precise. However, on system level and upwards, this should be more or less evened out. One can certainly say that the AP represents the organisation‘s subjective image of the present condition of the vessel. Nevertheless, it will hopefully provide a more systematic and realistic picture than what one would have without such an approach.

It may be beneficial to define more precisely for the highly critical components, as these affect the aggregated AP‘s to a far greater extent than what is the case of the ones belonging to the medium, low or N/A categories. One may divide these components into different categories across the function of their systems. E.g. may safety valves and instrumentation be two such groups that are assigned each their specific definitions.

4.2 Step II: Decision-making and prioritising

According to NORSOK Z-008, a method for prioritising should be in place. It is worth noticing that system AP‘s are already prioritised prior to this step, as they are weighted by criticality. In this respect should those system renewals which will result in the greatest improvement of AP already have been given the greatest emphasis. However, from this point on, there must be performed thorough evaluation on what needs to be done, and not least, when it should be done.

Prior to any multi-criteria decision-making there are a handful of questions that should be asked. Some of them are:

- Which information is available?
- Which information is relevant, and which is not?
- Is the information reliable?

When these are answered, whether it is done systematically or not, the two most important parameters may be evaluated: time and action.

4.2.1 Optimal time

As systems age, maintenance actions will have to increase in complexity and frequency. Possibly adding to the cost of maintenance itself, are the downtime costs from both preventive and corrective actions. However, as time passes, the systems are depreciated and capital costs decrease accordingly. The decision of when to perform a system renewal will therefore be a trade-off between increasing operational costs and decreasing capital costs. Decision makers need to ask themselves, which is closest to maintenance objectives: cost minimisation or availability maximisation (Campbell et al., 2011)? The classical approach to maintenance optimisation is to estimate an optimal interval for maintenance of single components. In multi-component systems, such as a compressor train, there are dependencies between maintainable components. The total downtime may then be reduced if components are maintained simultaneously and share common set-up costs (Okstad et al., 2010)

The renewal of a specific system is performed rarely, sometimes never, and often only once or twice, during a vessel lifetime. These systems consist of numerous components, both passive and active, some of them mechanical and some electronic. The natures of these components give them totally different failure rates and the system structure gives them different criticality levels, which means that maintenance needs to be performed at individual points in time. However, after some time, due to deterioration or obsolescence, it may be beneficial to modify, overhaul or replace the total system. The ideal time of renewal will be a decision considering the ageing of the most critical, costly and maintenance-intensive components and subsystems. This is graphically displayed in Figure 4.2.

The total annual cost of a single system will be a function of the maintenance cost, the downtime cost, the fixed operational cost, the acquisition cost and the discount rate. Equation 4.4 assumes the scrapping value/resale value to be zero.

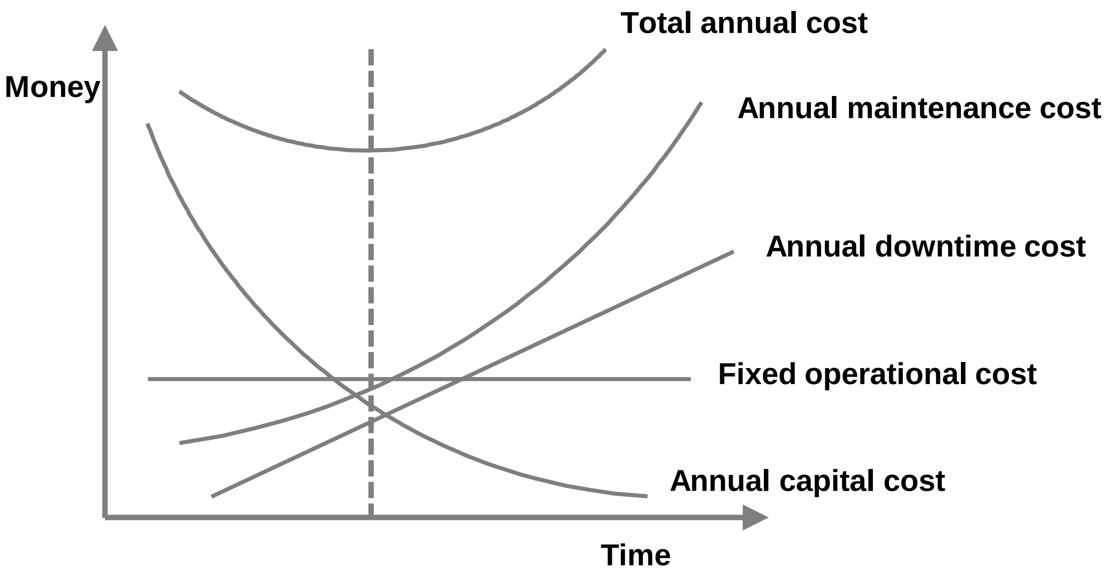

Figure 4.2: Optimising the time of renewal by total cost minimisation (Campbell et al., 2011)

$$C_i = M_i + D_i + F_i + rA(1-r)^i \tag{4.4}$$

Where:

C_i is the total annual cost in the ith period, $i = 1, 2, 3, ..., n$

M_i is the cost of maintenance in the ith period, $i = 1, 2, 3, ..., n$

D_i is the cost of downtime in the ith period, $i = 1, 2, 3, ..., n$

F_i is the fixed operational cost in the ith period, $i = 1, 2, 3, ..., n$

r is the discount rate

A is the acquisition cost of the system

4.2.2 Optimal action

Asset renewal processes are information intensive and require the asset managing organisation to take into consideration various options available in terms of full asset renewal, upgrade, or substitution. It follows an articulated evaluation process to arrive at an information based quality decision (Haider, 2013). The decision needs to take into consideration a number of issues, here are some examples:

- Cost of rehabilitation versus replacement
- Possible increases in residual life following different treatment options
- Probability and consequences of failure if renewal is not performed
- Capital investment requirements and options
- Future annual and periodic maintenance and operating costs following rehabilitation or replacement
- Justifications for any premium being paid for increased level of service

HSE, the British regulatory institution, suggests a procedure and a range of alternatives to address ageing, see Figure 4.3:

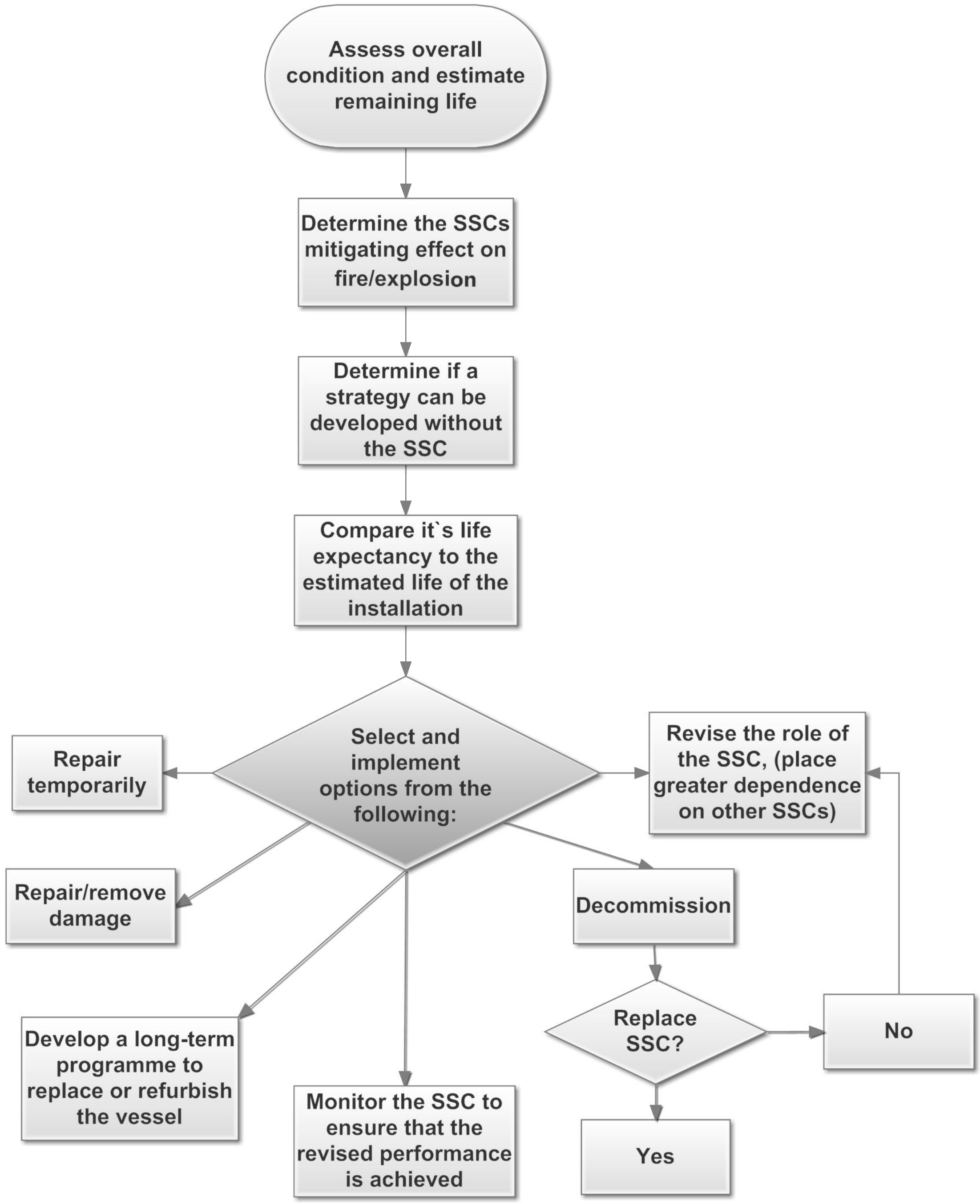

Figure 4.3: Determination of actions to address ageing, adapted from (Health and Safety Executive, 2009)

4.3 Step III: Scheduling

In this step, the decisions made in Step II are implemented in the Vessel Lifetime Plan. This part does not differ appreciably from what is the intended procedures of the VLTP today. For a walk-through of these procedures, please read Chapter 3.

4.4 Step IV: Financial applications

4.4.1 Utilisation in in the tender process

When FPSO contractors are looking into business opportunities, a tremendously important stage, is the calculation and preparation of tender. As much information as possible regarding market situations and outlooks, legislative terms, as well as the condition of the company's financial and physical assets, need to be on the table. This section focuses on how physical asset information can be utilised to optimise a tender offer, hence minimise risk and maximise profit. Perhaps the vessel‘s condition will make a redeployment unprofitable? Will the vessel need an extensive modification/renewal program to perform satisfactory during a new contract period? The tender procedure can be seen in Figure 4.4, please notice the CAPEX and OPEX node.

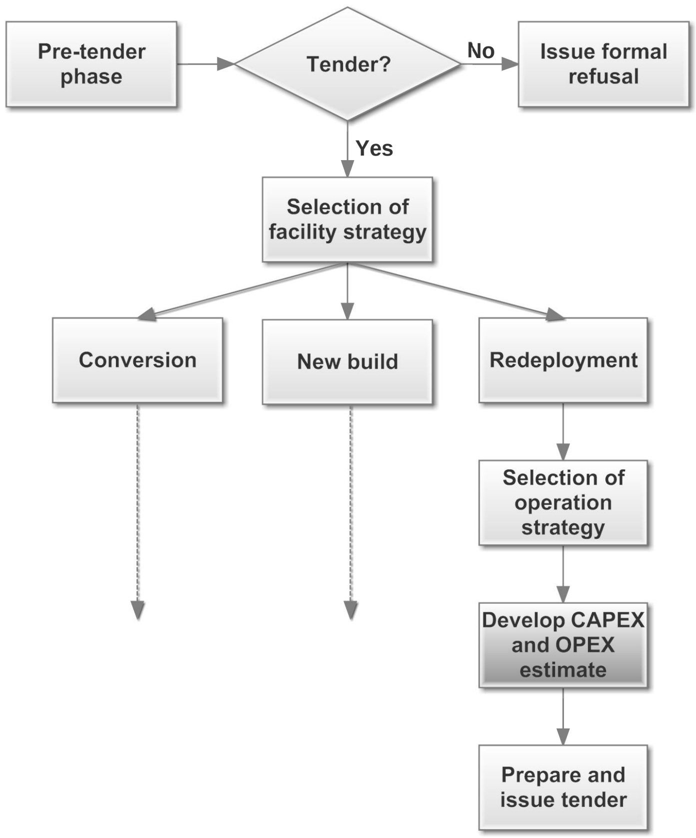

Figure 4.4: The tender process in Teekay Petrojarl simplified, the complete process can be viewed in Appendix D

Teekay Corporation (2013) highlights the redeployment risk of FPSO units in their annual reports, given the vessels lack of alternative uses and significant fixed costs. FPSO units typically require substantial capital investments prior to being redeployed to a new field and production service agreement. Ongoing agreements will expire or they may even be terminated prior to their expiration under specific circumstances. Idle time prior to commencement of new contracts or potential inability to deploy vessels at acceptable rates may have adverse effects on operating results.

Major activity cost estimates

The traditional approach used by FPSO contractors for pricing lease contracts is to apply the Discounted Cash Flow (DCF) method. This cost driven approach is based on the cost estimates of capital expenditure required to provide the FPSO at the given requirements and on estimates of operational expenditures required to operate the FPSO at the needed availability throughout the contract (Catherine, 2011). FPSO Contractors' management fix the target level of Internal Rate of Return (IRR) the new contract should achieve. Then the day-rate is calculated to reach the target. A shortened work process diagram of this TKPJ procedure can be seen in Figure 4.4.

When the physical and financial extent of the renewal activities has been estimated and implemented in the VLTP, a strategic renewal budget can be set up. This budget serves as input to the mentioned DCF calculations. The method classically cumulates all costs within each year. They will then be discounted according to the year they fall due and the given discount rate, as in the traditional NPV method, see Figure 4.5.

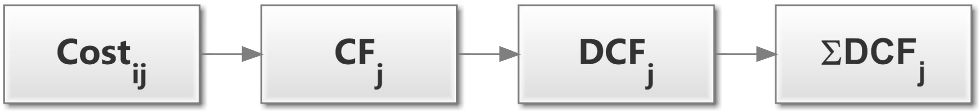

Figure 4.5: The procedure of discounting and adding up costs

Where:

$Cost_{ij}$ is the cost of activity i in year j, $i = 1, 2, 3, ..., n$, $j = 1, 2, 3, ..., m$

CF_j is the cash flow of all activities in year j added, $j = 1, 2, 3, ..., m$

DCF_j is discounted value of CF_j, $j = 1, 2, 3, ..., m$

$\sum_{j=1}^{m} DCF_j$ is the sum of all discounted cash flows, $j = 1, 2, 3, ..., m$

The net present value of cash flows in years $t = 1, 2, 3, ..., m$ is found by Equation 4.5. The sum of all these discounted yearly cash flows must consequently be balanced against the terms, rates and risks in a tender offer.

$$NPV = \sum_{t=0}^{n} C_t/(1 + D)^n \quad (4.5)$$

Where:

C_t is the net cash flow over year t, $t = 1, 2, 3, ..., m$

D is the discount rate

n is the number of years to realisation, $n = 1, 2, 3, ..., k$

4.4.2 Utilisation in depreciation

Deprecation is the difference between an asset‘s acquisition cost and its estimated residual value. The residual value is defined as the estimated amount that a vessel would currently obtain from disposal of the vessel after deducting the estimated costs of disposal, if the vessel was already of the age, and in the condition, expected at the end of its useful life (PriceWaterhouseCoopers, 2005). The international accounting standard *IAS 16 - Property, plant and equipment* (International Accounting Standard 16), states that if the estimated residual value of a vessel falls, the additional depreciation charge should be spread over the remaining useful life of the vessel. This means that the vessel and its technical systems will be continuously depreciated over their useful life to their residual value. According to Deloitte Shipping and Ports Group (2011), the judgements made for useful lives and residual values should be revisited at each reporting date or at least annually. When the estimated useful life or estimated residual value for a vessel changes for any reason, this change should be accounted for prospectively. However, repairs and day-to-day maintenance is considered part of the operating costs and should not be depreciated, replacement costs of major components and complete systems must be.

The International Financial Reporting Standards (IFRS)

IFRS are international accounting standards published by IASB (International Accounting Standards Board). "It has rightly been described as the biggest change in accounting for the last 25 years" (PriceWaterhouseCoopers, 2005). One of the IFRS standards, *IAS 16 - Property, plant and equipment* is particularly relevant for FPSO contractors such as TKPJ.

Since vessels consist of systems with different useful lives, the systems (or even components) should be depreciated separately, according to International Accounting Standard 16. This must be done when the replacement cost is significant in relation to the total cost of the vessel. When a system is replaced during the vessel's life, the cost of the replacement must be added to the vessel's carrying amount and the remaining unamortised amount (if any) is written off.

IAS 16 §56 also clearly highlights that obsolescence issues; whether it origins from technical-, commercial- or legislative reasons; must be accounted for when estimating the residual value of an asset, because they contribute in the diminution of the economic benefits that might be obtained from the asset.

The straight-line method

Various methods can be used to allocate the depreciable amount of asset systematically through its useful life (International Accounting Standard 16). Methods include the straight-line method, the diminishing balance method and the units of production method. The first one is the simplest and most commonly used method, and is also the one that is used in TKPJ. This method results in a constant charge over over the useful life, if the vessel's residual value does not change. If the estimated useful life of a vessel, system or component is reduced, it will increase the constant quarterly depreciable amounts.

$$D_q = \frac{A - V_R}{L_R} \tag{4.6}$$

Where:

D_q is the quarterly depreciable amount

A is the acquisition cost

V_R is the residual value

L_R is the residual life

The Ageing Parameter should contribute positively in this respect. If the company utilises this parameter actively in their estimates of useful lives of systems or major components, it may get a more accurate vessel residual lifetime. This may entail advantages such as reduced taxes and increased financial predictability.

By applying the methods described in this chapter, the present conditions of the various systems should be more accurately established compared with current standards in shipping. It is worth noticing that in the FPSO business, judgements for remaining useful lives tend to be driven by the remaining reserves associated with the oil field (KPMG, 2012). This may be correct in some cases, but frequently it is not.

Depreciation in Teekay Petrojarl

In Teekay, depreciation is calculated on a straight-line basis over a vessel's estimated useful life, less an estimated residual value (Teekay Corporation, 2013). Depreciation is calculated using an estimated useful life of 20 to 25 years for FPSO units, commencing the date the vessel is delivered from the shipyard. Estimates of future cash flows involve assumptions about future charter rates, vessel utilization, operating expenses, dry-docking expenditures, vessel residual values and the remaining estimated life of the vessels. TKPJ estimates of operating expenses and dry-docking expenditures are based on historical operating and dry-docking costs and their expectations of future inflation and operating requirements. The remaining estimated lives of Teekay vessels used in the estimates of future cash flows are consistent with those used in the calculations of depreciation (Teekay Corporation, 2013).

According to Teekay Corporation (2013), vessel capital modifications include the addition of new equipment or can encompass various modifications to the vessel that are aimed at improving or increasing the operational efficiency and functionality of the asset. This type of expenditure is amortized over the estimated useful life of the modification. Minor repairs and preventive maintenance are in TKPJ, as in most companies expensed as incurred.

A substantial portion of the costs incurred during dry docking are capitalized and amortized throughout the equipment's estimated useful life, which typically is from the completion of a dry docking or intermediate survey to the estimated completion of the next dry docking.

Teekay Corporation (2013) further states that: "If the remaining useful life of the vessel is unknown or it turns out to be erroneous, it forces the company to impair its value on our financial statements and it may need to recognize a significant charge against its earnings." This underlines the importance of keeping a clear picture of the vessels ageing process.

Chapter 5

Case study

This chapter will go through an example, utilising the suggested approach from Chapter 4. The purpose of the case study is to demonstrate, test and evaluate the long term scheduling of major renewals procedure, with a main focus on the Ageing Parameter and its hierarchical aggregation, since these parts stands out the most from prevailing methods in TKPJ and the industry in general. Voyageur Spirit will be used as a case example, because it is a fairly new unit, with accessible drawings, system descriptions and other documentation. Also, for the same reason, Voyageur Spirit may be a natural candidate if TKPJ wishes to implement the suggested procedure. The systems onboard Voyageur Spirit are not yet experiencing much ageing issues, but rather run-in failures. However, as performing assessments of its condition, both in terms of degradation or obsolescence, will have an extent beyond the scope of this case study, this is irrelevant. The key answers from this case study, should be whether or not it is possible to determine system boundaries, establish reasonable system hierarchies, obtain components' criticality values and utilise this information to establish Ageing Parameters for each of the systems. The next two sections describes the case vessel and the case scenario.

5.1 Vessel description

Voyageur Spirit is a cylindrical shaped floating, production, storage and offloading unit. It is operating on the Huntington field in the UK North Sea on a Q3 2017 contract with E.ON UK. The hull was built at Chinese shipyard Yantai Raffles and transported by heavy-lift vessel to Keppel Verolme, Netherlands, where the topside was integrated. It commenced production in August 2009 and went ashore for a capacity upgrade the following year.

Voyageur Spirit was the world's third cylindrical FPSO unit, after the Teekay owned sister units, Piranema Spirit and Hummingbird Spirit.

5.2 Scenario

In this thought scenario, Voyageur Spirit is at the end of her present contract, which terminates the third quarter of 2017. Present time is set to the beginning of 2017. The field owner, E.ON Ruhrgas has decided not to exercise their option on Voyageur Spirit. TKPJ is now using its market intelligence to look for new contract opportunities in the North Sea. They recently received a Request for Tender from a major oil company on FPSO operation and lease on another UK North Sea field. The anticipated length of the contract is seven years, from Q1 2019 to Q4 2025. The company‘s Department of Commercial and Business Development (CBD) has reviewed and screened the tender. Subsequently, the management has chosen to prepare a tender for redeployment of Voyageur Spirit, which means that the tender terms, market conditions, commercial and technical statistics, CAPEX estimates and OPEX estimates are reviewed closely. To see more precisely how this procedure goes in TKPJ, please see Figure 4.4, or check Appendix D for the most comprehensive overview.

With this as a backdrop, the following chapter presents two of Voyageur Spirit's systems: the fuel oil purification system and the bilge system. Further, their ageing conditions are assessed, the needed renewal actions are chosen and NPVs of the renewal activities are estimated. It is demonstrated how this information can be utilised in depreciation of the asset, as well as in the CAPEX estimates of the "ongoing" redeployment tender calculations.

Since much of the work, especially that which belongs to Step II (Decision-making) must be performed by a team of experienced operation engineers and procurement personnel, these parts will for this case study be only hypothetical. However, they are based on information from similar type of work (from the VLTP) and are intended to be realistic. The discount rate is set to 7 % and the Ageing Parameters (on component level) are given more or less random (but realistic) values to fit the illustrative and investigative purposes.

5.3 Fuel oil purification system

5.3.1 System description and input data

The fuel oil purification system purifies the marine diesel oil on its way from the settling tanks to the service tanks. The purpose is to provide that the fuel oil entering the main engines does not contain water or fines, which can damage the engine (M. C. Ford, 2012). The system set-up consist of two independent parallel trains.

Dirty oil enters the two centrifugal purifiers via oil heaters (not considered part of the system). The data for the two purifiers are given in Table 5.1.

Table 5.1: Purifier systems data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
MDO purifier	702.020.01	2 - Medium	0.3	80
MDO purifier	702.020.02	2 - Medium	0.3	100

Each of the purifiers are connected to highly critical emergency stops. Input data for the emergency stops can be seen in Table 5.2.

Table 5.2: Emergency stops data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
Emergency stop	702.601.01	1 - High	0.9	100
Emergency stop	702.601.02	1 - High	0.9	100

Water is collected in a sludge tank and the purified oil continues to the service tank. Data for the sludge tank may be seen in Table 5.3.

Table 5.3: Sludge tanks data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
MDO collection tank	702.034.01	3 - Low	0.15	80

Pressure is provided by two pumps, each controlled by pressure indicators on the inlets and outlets. Data for the former are displayed in Table 5.4, and for the latter in Table 5.5.

Table 5.4: Purifier pumps data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
Purifier pump	702.001.01	2 - Medium	0.3	90
Purifier pump	702.001.02	2 - Medium	0.3	90
Purifier pump control	702.001.01-A01	3 - Low	0.15	50
Purifier pump control	702.001.02-A01	2 - Medium	0.3	90
Purifier pump motor	702.001.01-M01	2 - Medium	0.3	100
Purifier pump motor	702.001.02-M01	2 - Medium	0.3	100
Emergency stop	702.001.01-S01	1 - High	0.9	100
Emergency stop	702.001.02-S01	1 - High	0.9	80

Table 5.5: Pressure indicators data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
PI - pump 01 inlet	702.084.05-PI	3 - Low	0.15	100
PI - pump 01 outlet	702.084.06-PI	3 - Low	0.15	60
PI - pump 02 inlet	702.084.07-PI	3 - Low	0.15	90
PI - pump 02 outlet	702.084.08-PI	3 - Low	0.15	100

In addition, the system has two junction boxes, which are considered non-critical. Their data an be seen in Table 5.6.

Table 5.6: Junction boxes data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
Junction box	702.616.01	N/A	0	100
Junction box	702.616.02	N/A	0	80

P&IDs (production and instrumentation drawings) and system hierarchical breakdown of the complete fuel oil purification system can be seen in Appendix E.

5.3.2 Estimation of the Ageing Parameter and judgements

To establish the Ageing Parameter for the complete technical system, the Ageing Parameters are aggregated hierarchically as presented in Chapter 3. Components found to have low criticality in TKPJ‘s FMECA are given 0.15 weights, medium critical components 0.3 and high critical components 0.9. The subsystems are not given criticality values in the FMECA and they are for this purpose therefore weighted as the average of all criticality values of their subcomponents. All levels are then aggregated according to Equations 4.1, 4.2 and 4.3. The Ageing Parameter for the fuel oil purification system is found to be 81,7. This value indicates that the system is clearly affected by ageing, since the value is well below the design value of 100. However, an immediate and comprehensive renewal would not be necessary. It is probably more appropriate to overhaul/replace one or more of the components or subsystems. From the excel sheet (enclosed zip-file) it is easy to see which subsystems contribute the most to the downward adjusted parameter. In this case, we see that the purifier pumps have an AP of 65,5. This is by far the lowest value of the subsystems. By looking on component level, we can see that this subsystem have two high-criticality components. One has an AP of 100 and there has therefore not been reported any ageing effects. The other however, *Emergency Stop for Purifier Pump 2*, has an AP of 80, see Table 5.4 (not to be confused with the emergency stops for the purifiers in Table 5.2). Given the weight of this component, it affects the total system AP heavily, even though its AP is as high as 80. By renewing it, one would enhance the system integrity considerably. From adjusting the calculations in the spreadsheet, a complete renewal of the emergency stop will make the system AP go from 81,7 to 89,5. This is a satisfying solution in the medium term. However, in some years it will probably be beneficial to make more of a complete system renewal. This decision must be based on the theory and methods presented in Section 4.2. When optimal time and action is decided, the next step will therefore be an estimation of the time and cost of such an upgrade. This decision will rely heavily on company experience and expert judgement. As mentioned previously, it is not a matter of calculating the exact cost, nor determining a precise time, as this would be almost impossible in a long term view. A thorough qualified estimate would be beyond the scope of this case study, such that the estimates used here are only for illustrative purposes.

It is assumed that the purifier pumps and all their subcomponents, as well as the MDO purifiers, the MDO collecting tank and the pressure indicators will have to be changed. The cost is assumed to be 5 million NOK (an amount which is, for the purpose of this case study, loosely based on the cost of similar renewals from the real VLTP of Petrojarl Foinaven). The replacement is planned 5 years from present time (which is set at Q1 2017) and estimated to be finished within one year, such that the costs are distributed within 2022. The work is assumed to add two persons to the POB over a time frame of six months. The schedule is presented in Table 5.7.

Table 5.7: F.O. purification system renewal schedule

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025
Cost [million NOK]	0	0	0	0	0	**5**	0	0	0
POB [extra persons]	0	0	0	0	0	**2**	0	0	0

5.4 Bilge system

5.4.1 System description and input data

The bilge system‘s purpose is to discharge and filter water that collects in the bottom compartments of the ship, below the waterline. Principally, the system is segregated from the ballast system, however, the two systems are cross-linked and pumps can be run interchangeably (White, 2008). According to DNV (2011), dry compartments shall be connected to the bilge system. It shall be capable of discharging water if the lower compartments are flooded, e.g. due to moderate hull damage or fire fighting. It is thus a fundamental principle that the bilge system is given at least the same capacity as the fire fighting system. It shall also have at least two parallel bilge pumping units, to provide sufficient redundancy.

The bilge system of Voyageur Spirit has been installed with three pumping units (P&ID drawings and system hierarchical breakdown may be seen in Appendix E). One of them handles bilge from the pump room, one from below the accommodation area and one from the pump engine room. The firstly mentioned discharges water to an open drain tank, while the latter two lead to the bilge water tank. Sludge and drainage water from other systems are also collected in this tank, before it's all discharged to the slop tanks by the bilge sludge pump.

Each pumping unit starts with a filter, the input data for these three filters can be seen in Table 5.8.

Table 5.8: Bilge water filters data (Star Information System, 2014)

Component	**SFI**	**Criticality**	**Weight**	**Ageing Parameter**
Filter - bilge pump inlet	803.020.01	N/A	0	70
Filter - bilge pump inlet	803.020.02	N/A	0	70
Filter - bilge pump inlet	803.020.03	N/A	0	70
Filter - bilge pump inlet	803.020.04	N/A	0	70

After the filters, there are ball valves (in the pump room unit, the ball valve is controlled by level switches, see drawings in Appendix E). Table 5.12 gives the data for the ball valves. Subsequently and prior to the bilge pump there is a non-return valve. Input data for all the non-return valves in the bilge system can be seen in Table 5.9.

Table 5.9: Non-return valves data (Star Information System, 2014)

Component	**SFI**	**Criticality**	**Weight**	**Ageing Parameter**
Non-return valve	803.261.01	3 - Low	0.15	100
Non-return valve	803.261.03	3 - Low	0.15	90
Non-return valve	803.261.06	3 - Low	0.15	90
Non-return valve	803.261.08	3 - Low	0.15	60
Non-return valve	803.261.11	3 - Low	0.15	80
Non-return valve	803.261.14	3 - Low	0.15	100
Non-return valve	803.261.16	3 - Low	0.15	100
Non-return valve	803.261.21	3 - Low	0.15	95

Each of the three parallel bilge system units has one bilge pump, Table 5.10 lists their input data.

Table 5.10: Bilge pumps data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
Bilge pump	803.001.01	N/A	0	90
Bilge pump	803.001.02	N/A	0	100
Bilge pump	803.001.03	N/A	0	80

There is also a non-return valve after each of the bilge pumps, and from this on, the piping continues to either the open drain tank or towards the bilge water tank. The open drain tank is not considered part of the bilge system. Data for the bilge water tank can be seen in Table 5.11.

Table 5.11: Bilge sludge tanks data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
Bilge water tank	803.031.01	2 - Medium	0.3	90

At the inlet of the bilge water tank there are non-return valves and ball valves. For ball valves data, see Table 5.12.

Table 5.12: Ball valves data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
Ball valve	803.274.02	3 - Low	0.15	90
Ball valve	803.274.05	3 - Low	0.15	100
Ball valve	803.274.07	3 - Low	0.15	100
Ball valve	803.274.09	3 - Low	0.15	90
Ball valve	803.274.10	3 - Low	0.15	100
Ball valve	803.274.15	3 - Low	0.15	80
Ball valve	803.274.17	3 - Low	0.15	80
Ball valve	803.274.18	3 - Low	0.15	100
Ball valve	803.274.19	3 - Low	0.15	100
Ball valve	803.274.20	3 - Low	0.15	100
Ball valve	803.274.22-X	3 - Low	0.15	90
Ball valve	803.274.24	3 - Low	0.15	100
Ball valve	803.274.25	3 - Low	0.15	100

At the outlet of the bilge water tank, there are two ball valves, and subsequently there is a sludge pump. This discharges the sludge through a non-return valve and a ball valve (controlled by a limit switch) to the slop tanks. Input data for the sludge pump is displayed in Table 5.13.

Table 5.13: Bilge sludge pumps data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
Bilge sludge pump	803.027.01	2 - Medium	0.3	85

On multiple locations in the system, level switches monitor the water levels, for data, see Table 5.14.

Table 5.14: Instrumentation data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
Level switch HH	803.084.01	1 - High	0.9	100
Level switch H	803.084.02	1 - High	0.9	100
Level switch HH	803.084.04	1 - High	0.9	100
Level switch H	803.084.05	1 - High	0.9	100
Level switch H	803.084.07	1 - High	0.9	95
Level switch H	803.084.09	1 - High	0.9	100
Level switch HH	803.084.11	1 - High	0.9	95
Level switch H	803.084.15	1 - High	0.9	100

The piping data is displayed in Table 5.15.

Table 5.15: Bilge system piping data (Star Information System, 2014)

Component	SFI	Criticality	Weight	Ageing Parameter
From below accom.	803.220.01	2 - Medium	0.3	100
To bilge water tank	803.220.02	2 - Medium	0.3	80
From pump room	803.220.03	2 - Medium	0.3	90
From pump room STB	803.220.04	2 - Medium	0.3	80
To open drain tank	803.220.05	2 - Medium	0.3	100
From pump engine room	803.220.06	2 - Medium	0.3	100

5.4.2 Estimation of the Ageing Parameter and judgements

The AP for the bilge system is aggregated in the same manner as for the fuel oil purification system and the calculations shows that the bilge system is subject to fairly extensive ageing. Most importantly, there has been a step change in filter technology and to comply with future environmental regulations, the bilge water filters will need to be changed in few years. A typical obsolescence issue. They are therefore given AP‘s of 70 each, which heavily affects the system AP (see Table 5.8 and the Excel-sheet enclosed in zip-file). Along with ageing of the other components (mainly deterioration) it makes the system AP only 60,0. Based on the principles in Section 4.2, it is decided to renew the filters plus most of the pumps and valves. Additionally, some of the piping needs to be replaced. Altogether, this is considered to be a fairly large renewal and the cost is estimated to a total of 15 million NOK, 10 million falls due in 2018 and 5 million in 2019. It is also estimated that three extra persons must be added to the number of POB as long as the work progresses. A schedule for costs and POB can be seen below in Table 5.16.

Table 5.16: Bilge system renewal schedule

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025
Cost [million NOK]	0	**10**	**5**	0	0	0	0	0	0
POB [extra persons]	0	**3**	**3**	0	0	0	0	0	0

5.5 Aggregated NPV cost for the contract period

The total renewal schedule is obtained by joining the cost distributions of both system renewals. Then the cash flows in each year are found, which is a simple task, since there is only two renewal activities scheduled (when this procedure is performed for a complete vessel, there will obviously be several amounts that must be added up to obtain the cash flow for each year). The cash flows are then discounted according to Equation 4.5. Finally, the discounted cash flows for the contract period are added up and the total net present value is found to be 17.28 million NOK (see Table 5.17 and the Excel-sheet). This amount may, along with the other CAPEX estimates, the OPEX estimates, expected revenues, RISKEX etc. form a decision basis for the tender terms.

Table 5.17: Discounted cash flow schedule

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025	Total
CF [million NOK]	0	**10**	**5**	0	0	**5**	0	0	0	**20**
DCF [million NOK]	0	**9.35**	**4.37**	0	0	**3.56**	0	0	0	**17.28**

The POB schedule is also obtained by joining the schedules for each activity. See Table 5.18 below.

Table 5.18: Schedule for extra number of persons on board

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025
POB [extra persons]	0	**3**	**3**	0	0	**2**	0	0	0

5.6 Depreciation

As described in Section 4.4.2, residual lives should be estimated on system level and include obsolescence issues along with degradation. Renewal activities has now been scheduled for the bilge system and the fuel oil purification system, by evaluation of their APs. If we assume that the residual lives cease at the last day of renewal, their residual lives are three years (bilge system) and six years (fuel oil purification system) respectively. By assuming that the estimated lifetimes at the time of acquisition are 15 years (estimated lifetimes may in most cases be obtained from suppliers) and that the residual values have not changed, the new depreciable amounts have increased $15/3 = 5$ times and $15/6 = 2.5$ times respectively. These amounts can then be written off over the remaining lifetimes, by the straight-line method and award company savings. The straight-line method is explained in Section 4.4.2 and Equation 4.6.

Chapter 6

Discussion

Chapter 4 presented a systematic approach for long term scheduling of major renewals. It was based on theory from Chapter 2 and on the corporate basis from Chapter 3. The approach was demonstrated and tested in Chapter 5. The following chapter discusses the applicability of the approach according to the results from the case study and theory.

The suggested approach provides a picture of the present condition of the system. Actually, as Ageing Parameters only are assigned annually, at worst, it describes the condition one year ago. This is obviously not optimal. By looking at the degradation pattern obtained from condition monitoring, it is possible to predict the future degradation, as described in Section 2.1.1. However, in a system (such as the bilge system from the case study), there are components and subsystems having completely different degradation patterns. Some are active components (such as the bilge pumps) and some are passive components (the piping). Some are electronic (the level switches) and some are mechanical (the valves). Additionally, systems consist of multiple parallel paths, where some are subject to greater loads than others. Due to these reasons, it is not usual to build degradation models for these systems and hence predict future degradation.

The type of renewals emphasised in this thesis are complete system renewals, in the sense that condition, function and criticality of all the system‘s components are evaluated and together form a decision basis. However, this does not necessarily mean that the complete system should be renewed concurrently, but rather that all parts of the system are interdependent in some way.

The methods described are meant to give management a holistic view of the vessel‘s condition and be able to make strategic decisions. It focuses therefore only on the present condition of systems and do not try to predict future ageing. Component level monitoring, prediction and (potential) renewal must be done parallelly and continuously (at least for the critical components).

As described in Section 2.2.1, good value KPIs have the ability to inform on the current status, as well as track and indicate changes over time. As the Ageing Parameters are updated annually, they are able to both inform on current status and indicate changes over time, at least in a long term sense.

One might argue that the information stored in the schedule will be too subjective as Ageing Parameters are numerical, but are converted from qualitative information by various individuals. Each person will interpret the obtained information differently and emphasise it according to their own experience. The interpretation of information from existing CMMSs (computerised maintenance management systems), material management systems, condition monitoring and inspections may therefore always be a source of error. However, it should be counteracted, if the background, purpose, build-up and definitions of the Ageing Parameters are well known to everyone that are given the responsibility to evaluate this information and utilise it to estimate Ageing Parameters.

When planning in the long term, there will always be some degree of uncertainty. As illustrated in Figure 2.4, several factors influence the technical state of a system. Market conditions, operating load, degradation pattern and maintenance backlog are some examples. These may be hard to predict. On these grounds, and considering the use of resources in planning, lots of decisions need to be based on experience and subjective judgements. This is unfortunate of course, but is something one have to accept when planning far ahead. From the case study it has been verified that the hierarchical aggregation of the Ageing Parameter, allows information to be systematically sorted. It provides a realistic picture of the state of the total system, given that the Ageing Parameters on component level are correct. Systematic information tend to make better decision basis than its alternative, and the suggested approach will therefore enhance the quality of decisions.

Another part of the suggested procedure that may cause error, is the conversion from criticality to weighting. Section 4.1.1 mentioned that the relationships between the different criticality levels not necessarily are linear. This means e.g. that if components classified as Low are weighted to 0.15 and Medium components are 0.30, High components must not necessarily be 0.45. The High category is defined as severely threatening to safety. In an offshore oil and gas context, this can mean enormous value. If all stakeholder costs are included, the cost of potential scenarios may be billions of dollars. However, in most scenarios belonging to this category, the entailed costs would be much, much lower. Nevertheless, the High category must clearly be heavily weighted. This study chose 0.90 relative to 0.3 and 0.15 for Medium and Low, and perhaps even this weighting is too low. However, by trial and error in the spreadsheet during the work with the case study, this weighting turned out to have the best fit. Larger ratios between High and the other levels were attempted, but it made the other components negligible in the hierarchical aggregation, which would make a false impression of the system condition. Teekay Petrojarl‘s definitions of the criticality levels can be seen in Appendix C.

The case study demonstrated that judgements for optimal time and action of future renewal activities may be well founded by Ageing Parameters. The parameter does not only provide a picture of the total system‘s condition, but also for subsystems and components. Therefore may weaknesses easily be detected and judgements optimised to raise the integrity of the system in the most efficient way. The renewal of the emergency stop in the fuel oil purification system clearly demonstrated this feature, as it raised the system Ageing Parameter from 81,7 to 89,5.

When it comes to the redeployment tender calculations, it does not represent a completely new methodology for utilisation of long term scheduling in Teekay Petrojarl. CAPEX estimates are already natural parts of the risk evaluation prior to a tender offer. Nonetheless, the case study has been utilised to test if and how the suggested approach may be utilised in such estimates, which proved to be feasible.

This study has also investigated whether the suggested approach may be utilised in depreciation. It is in this area it has shown to be the most interesting. International Accounting Standard 16 states that depreciation should be charged on system level. The suggested procedure provides the systematic foundation for estimation of residual lives of systems and not complete vessels, which is the prevailing approach in the industry. The case study demonstrated how these estimates may be based on the activity schedule.

It is also interesting to see that the standard highlights the inclusion of obsolescence in the residual life estimations, as it contributes in the diminution of the economic benefits that might be obtained from the asset. Inclusion of obsolescence issues is the main feature that distinguishes the Ageing Parameter from the Technical Condition Index, which it was originally inspired by.

Chapter 7

Conclusions and recommendations for further work

7.1 Conclusions

This study has investigated the challenges operators face regarding their ageing assets. It has been examined through literature study what influences ageing and how it should be dealt with. It has been determined that obsolescence may be just as vital as deterioration in this respect. This type of information must thus be included in a systematic indicator, such as the Ageing Parameter.

Parts of the suggested work process have been tested and verified in Chapter 5. The procedure contains some elements that are already well-known and established in Teekay Petrojarl, as well as in the business, such as condition monitoring, major activity schedules and CAPEX estimation. The new elements are the integration of the Ageing Parameter and the financial applications. These are therefore emphasised in the case study. Their feasibility has been verified in the meaning that it is proven that a systematic hierarchy can be established based on SFI tags from the computerised maintenance management system. It has been verified that parameters on component level may be aggregated by this hierarchy and the given formulas to a meaningful and robust system parameter. It is also verified that the ageing of the systems‘s can be evaluated systematically and effectively using a top-down approach. However, it has not been verified that the procedure can be implemented in large-scale without taking up to many resources. FPSO vessels consist of numerous such technical systems and it may be resource-draining to go through all components annually. Even so, the advantages this study has revealed could possibly justify the use of resources.

7.2 Recommendations for further work

This investigation has, based on theory and legislation, developed a work process for scheduling of major renewals in the long term. It does not go very deep into details and there is much that needs to be done before such a procedure may be introduced. First of all, it must be established a working group to look at the definitions of different intervals of the Ageing Parameter. Ergo, it must be defined which conditions and situations that corresponds to the different values of the parameter. The definitions must obviously be rather open to fit all kinds of components. There should be a set of definitions for obsolescence and a set for deterioration. Preferably, to avoid misjudgements, there should be sets of definitions for the different groups of components according to their nature. Examples of such groups may be: Instrumentation, passive mechanical components, active mechanical components and complex components.

Although the use of Excel proved to be adequate for the case study, it may benefit TKPJ to develop their own software to aggregate, store and evaluate the Ageing Parameters. As a part of this work, system breakdowns (such as the ones developed for the case study, seen in Appendix E) needs to be established according to information in CMMS or in drawings.

Roles and responsibility need to be allocated in the operational organisations. It is recommended that a person in each operational unit is given the responsibility of process ownership[1] with regards to the establishment and annual update of Ageing Parameters.

To be able to utilise the described methods, other departments (besides Operations) needs to be informed and involved. Finance and Accounting must be involved in the implementation of this procedure, so that it may be fitted to depreciation utilisation and Commercial and Business must be involved to fit it to their tender process.

[1]Process owner: Person who is responsible for a process to achieve its objectives at all times. The process owner has the necessary authority to affect all process inputs (Lederkilden)

Bibliography

T. M. Andersen and M. Rasmussen. Aging management: Monitoring of technical condition of aging equipment. In *ICMES*, pages 238–241. International cooperation on marine engineering systems, 2003.

T. M. Andersen, T. A. Thorstensen, and M. Rasmussen. Decision support in short term and long term maintenance planning using condition montoring information. *IEE Conference Publication*, pages 45–52, 1998.

E. Bale and D. Edwards. Technical integrity - an engineer‘s view. *Engineering Management Journal*, 10(2):88–94, April 2000.

A. Bloemen. FPSO lease versus ownership: decision factors, contracting strategies, future trends. In *OTC*, pages 223–2226. Offshore Technology Conference, 1997.

R. Bye. Asset integrity management of FPSOs. PPT presentation, January 2013.

J. Campbell, A. K. S. Jardine, and J. McGlynn. *Asset management excellence*, volume 2. CRC Press, 2011.

G. Catherine. Analysis of options in FPSO contracts. Master's thesis, Université Paris - Pantheon-Sorbonné, 2011.

Deloitte Shipping and Ports Group. IFRS for shipping - Accounting for owned vessels by shipping companies. Report, 2011.

J. E. Devereaux. Obsolescence: A systems engineering and management approach for complex systems. Master's thesis, Massachusetts Institute of Technology, 2010.

DNV. Rules for classification of ships. Machinery and systems, 2011.

M. Drøpping. Maintenance and operational excellence. PPT presentation, April 2013.

A. Haider. *Information Systems for Engineering and Infrastructure Asset Management*, volume 1. Springer Gabler, 2013.

Health and Safety Executive. Guidance on management of ageing and thorough reviews of ageing installations. HSE, 2009.

Health and Safety Executive 2014. KP4-Programme. http://www.hse.gov.uk/offshore/ageing/kp4-programme.htm. Viewed 09/02/2014.

P. Hokstad, S. Håbrekke, R. Johnsen, and S. Sangesland. Ageing and life extension for offshore facilities in general and for specific systems. SINTEF Technology and Society, 2010.

T. Inagaki. Proactive management of ageing for nucelar power plants. International Atomic Energy Agency, 2009.

International Accounting Standard 16. *Property, Plant and Equipment*.

International Atomic Energy Agency. Ageing management for nuclear power plants. Safety Guide No. NS-G-2.12., 2009.

A. Kelly. *Managing Maintenance Resources*. Elsevier Ltd., 2006.

KPMG. Impact of IFRS: Shipping. Report, 2012.

A. Lane, J. Saunderson, D. Ritchie, I. Hannah, D. May, and N. Pickering. Guidance on the management of ageing and life extension for UKCS oil and gas installations. Oil and Gas UK, 2012.

Lederkilden. Dictionary. http://www.lederkilden.no/oppslag/ordliste/prosesseier. Viewed 04/06/2014.

J. P. Liyanage and U. Kumar. Towards a value-based view on operations and maintenance performance management. *Journal of Quality in Maintenance Engineering*, 9(4):333–350, 2003.

M. C. Ford. A masters guide to using fuel oil onboard ships. ABS Report, 2012.

D. N. P. Murthy, A. Atrens, and J.A. Eccleston. Strategic maintenance management. *Journal of Quality in Maintenance Engineering*, 8(4):287–305, 2002.

NORSOK Z-008. *Risk based maintenance and consequence classification*.

Norwegian Oil and Gas Association. 122 - Recommended guidelines for the assessment and documentation of service life extension of facilities. Norsk Olje og Gass, 2012.

E. Okstad, J. Vatn, and R. Bye. Maintenance management and optimization of FPSOs. In *European safety and reliability conference*, pages 592–598. ESREL, 2010.

J. K. Paik and A. K.Thayamballi. *Ship-shaped offshore installations : design, building, and operation*. Cambridge University Press, 2007.

M. Pecht. *Parts selection and management*. Wiley, 2004.

L. Petersson and K. Simola. Ageing of components and systems: an ESReDA working group report. ESReDA, 2006.

PriceWaterhouseCoopers. Full steam ahead with IFRS. Report, 2005.

P. Ramirez and I. Utne. Challenges due to aging plants. *Process Safety Progress*, 30(2):196–199, 2011.

P. Ramirez, I. Utne, and C. Haskins. Application of systems engineering to integrate ageing management into maintenance management of oil and gas. *Systems Engineering*, 16(3):329–345, 2013.

P. A. Pérez Ramírez. *Ageing management and life extension of technical systems*. PhD thesis, Norwegian University of Science and Technology, 2013.

R.M.C. Ratnayake and J.P. Liyanage. Asset integrity management: sustainability in action. *International Journal of Sustainable Strategic Management*, 1(2):175–203, 2009.

M. Rausand and R. Reinertsen. Failure mechanisms and life models. *International Journal of Reliability, Quality and Safety Engineering*, 3(2):137–152, 1996.

Reuters 2008. Teekay announces acquisition of remaining shares of Teekay Petrojarl ASA. http://uk.reuters.com/article/2008/07/09/idUS204770+09-Jul-2008+MW20080709. Viewed 29/01/2014.

G. Sardar, N. Ramachandran, and R. Gopinath. Challenges in achieving optimal asset performance based on total cost of ownership. In *Engineering Asset Management*, pages 54–63. World Congress on Engineering Asset Management (WCEAM), 2006.

Y. Shimamura. FPSO/FSO: State of the art. *Journal of Marine Science and technology*, 7(-):59–70, 2002.

Star Information System. Voyageur Spirit. CMMS, 2014.

Teekay Corporation. Vessel fact sheets. TKPJ, 2011.

Teekay Corporation. FPSO business update and knarr project. PPT presentation, June 2012.

Teekay Corporation. Annual report 2013. Form 20-F, 2013.

Teekay Corporation 2014. Floating production storage and offloading. http://www.teekay.com/business/fpso/default.aspxt. Viewed 12/02/2014.

Teekay Petrojarl. Management system manual (MSM). Internal document, August 2011.

Teekay Petrojarl. 2012 sustainability report. TKPJ, 2012.

Teekay Petrojarl. Operations manual Voyageur Spirit . Internal document, 2013.

T. A. Thorstensen. *Lifetime profit modelling of ageing systems utilising information about technical condition*. PhD thesis, Norwegian University of Science and Technology, 2008.

P. G. Tipping. *Understanding and mitigating ageing in nuclear power plants : materials and operational aspects of plant life management (PLiM)*. Oxford: Woodhead Publishing, 2010.

A. H. C. Tsang. Strategic dimensions of maintenance management. *Journal of Quality in Maintenance Engineering*, 8(1):7–39, 2002.

M. F. White. *Marine Engineering Systems*, volume UK-08-04. Department of Marine Technology, NTNU, 2008.

J. Wintle and J. Sharp. Requirements for life extension of ageing offshore production installations. Petroleum Safety Authority, 2008.

J. Wintle, P. Moore, N. Henry, S. Smalley, and G. Amphlett. Plant ageing - management of equipment containing hazardous fluids or pressure. Health and Safety Executive, 2006.

Pictures: Figure 1.3[2], Figure 3.1 [3] [4] [5]

[2]www.teekayoffshore.com
[3]www.teekay.com
[4]www.remontowa.pl
[5]www.solstadcrew.com

Appendices

ID	Status	SFI	Category	SFIName	Tagnr	Description	Earliest	Latest
249	Accepted	41	Process	PROCESS FLOW TRAIN 1 (A)		Painting Program6 Y program	2009	2015
151	Accepted	44	Process	WATER TREATMENT SYSTEM / PWRI	Piping	Replace all piping due to internal corrosion.More detailed in	2011	2015
193	Accepted	66	Machinery Main Component & ICSS	GENERATORS FOR POWER PLANT		Program for onshore change out/repair all 8 generators du	2011	2015
228	Accepted	81	Ballast, bilge, fire fighting, ESD, PSD, HIF	EMERGENCY ALARMS- FIRE FIGHTINGS AND ES		Deluge piping main deck to be replaced.Started in 2008 - o	2008	2013
225	Accepted	80	Ballast, bilge, fire fighting, ESD, PSD, HIF	BALLAST AND BILGE SYSTEM	Piping	Piping around pumps have internal corrosion, many spools	2014	2015
200	Accepted	72	Utility	COOLING WATER - SEA & FRESH WATER SYST		Seawater system - sea chest: port and starboard main se	2011	2011
250	Accepted	41	Process	PROCESS FLOW TRAIN 1 (A)		Services required to painting program, see act. ID 249	2009	2015
153	Accepted	44	Process	WATER TREATMENT SYSTEM / PWRI	Piping	Open Drain piping - no regular inspection program today. D	2011	2011
139	Accepted	43	Process	GENERAL - GAS COMPRESSION AND GAS TRE/	04-C-003	Replace machinery protection system(GE fanuc) due to ob	2012	2015
172	Accepted	53	Cargo, lifesaving, mooring, lifting, naviga	MOORING AND ANCHORING EQUIPMENT (INCLU		Mooring system to be replaced in 3-4 years	2013	2014
245	Accepted	25	Hull	TURRET CONSTRUCTION		Repair turret from findings from fatigue review	2015	2017
198	Accepted	69	Machinery Main Component & ICSS	ENGINE/PROSESS/DECK CONTROL - ICSS (SIEM		Woodward Control and monitoring system - Upgrade of sy	2011	2012
163	Accepted	46	Process	RELIEF AND FLARE SYSTEM / CLOSED DRAIN	6"-DC-15	Replace remaining piping not beeing part of replacement pi	2013	2014
194	Accepted	66	Machinery Main Component & ICSS	GENERATORS FOR POWER PLANT		Preparation and installation work for generators change oi	2011	2015
138	Accepted	43	Process	GENERAL - GAS COMPRESSION AND GAS TRE/	04-C-003	Dry gas seal problem issue - too short lifetime	2011	2013
136	Accepted	43	Process	GENERAL - GAS COMPRESSION AND GAS TRE/	Gas com	Replace gas injection line(to swivel)	2012	2014
104	Accepted	24	Hull	HULL - FORE PART		Need for fatigue analysis of fore part.	2014	2016
182	Accepted	61	Machinery Main Component & ICSS	MANOUVERING MACHINERY	MP-TTE0:	Thruster replaced in 2009, due to internal leakages. Can e:	2015	2016
192	Accepted	64	Machinery Main Component & ICSS	STEAM & BOILER PLANT		BMS system, Control & burner System: New system to be	2011	2012
165	Accepted	50	Cargo, lifesaving, mooring, lifting, naviga	CRUDE OIL STORAGE AND DISCHARGE SYSTEI		Metering - ObsolenceFlow computer to be replaced 2011	2012	2012

Figure A.1: VLTP interface - Major activity plan

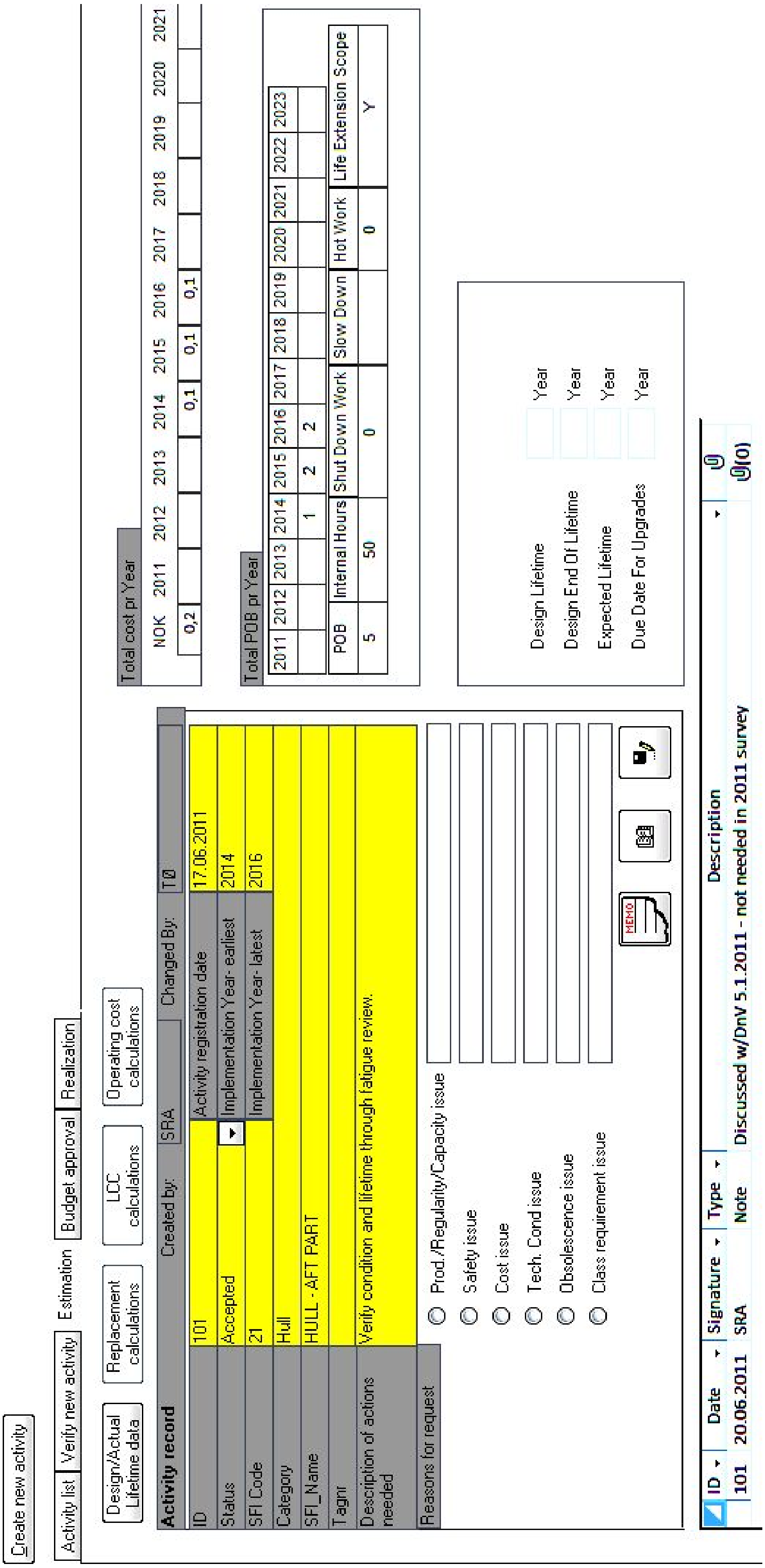

Figure A.2: VLTP interface - POB and cost estimations/calculations for activities

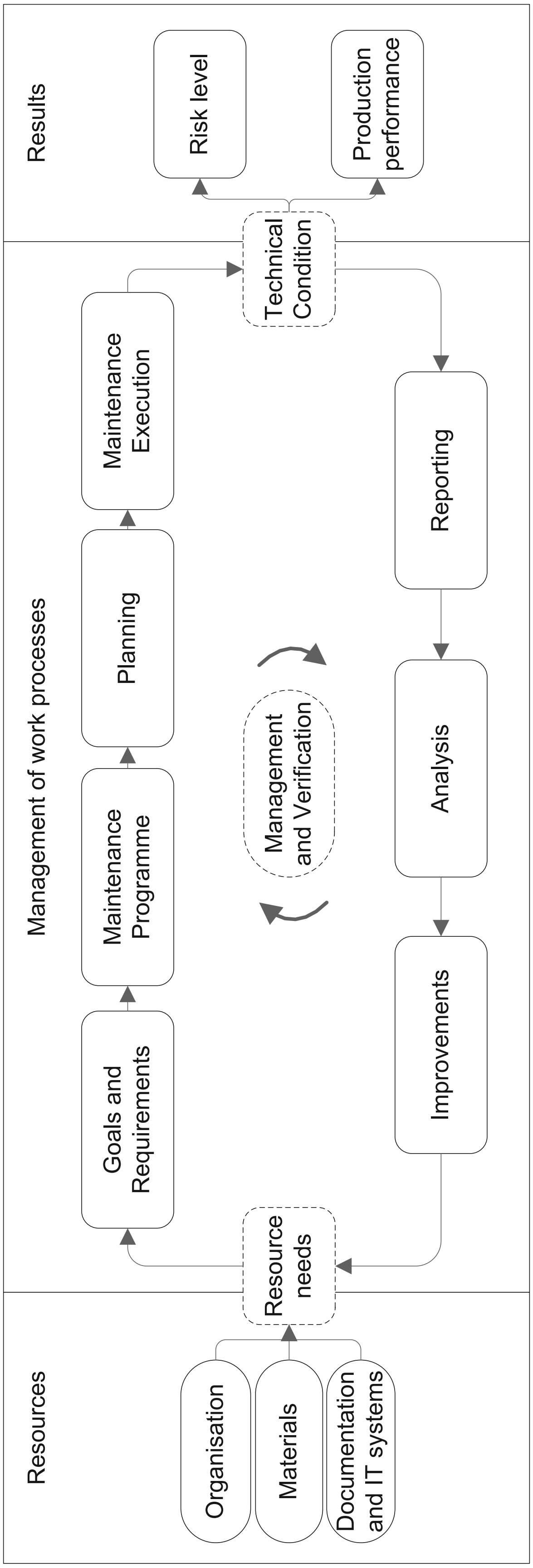

Figure B.1: Maintenance management process according to NORSOK Z-008

	N/A (ingen kritikalitet)	L (lavt kritikalitet)	M (medium kritikalitet)	H (høy kritikalitet)
Sikkerhet / Helse	Ubetydelige følger	Utstyr / systemsvikt som kan forårsake svekkelse eller er medvirkende til å svekke sikkerhetsbarrierer og som dermed fører til: • Personskade som behandles ombord eller mindre helseskade	Utstyr / systemsvikt som kan forårsake svekkelse eller er medvirkende til å svekke sikkerhetsbarrierer og som dermed fører til: • Medisinsk behandlingsskade Hendelse som alvorlig truer deler av installasjonens sikkerhet	Utstyr / systemsvikt som kan forårsake svekkelse eller er medvirkende til å svekke sikkerhetsbarrierer og som dermed fører til: • Død / alvorlig personskade med permanent invaliditet Hendelse som alvorlig truer installasjonens sikkerhet Utstyr er del av barrierefunksjon.
Ytre miljø	Ubetydelige følger	Utstyr / systemsvikt som kan forårsake: Utslipp av substanser som ikke fører til alvorlig skade på miljøet. Typisk ikke-forurensende oljer, kjemikalier eller gasser.	Utstyr / systemsvikt som kan forårsake svekkelse eller er medvirkende til å svekke sikkerhetsbarrierer og som dermed fører til: • Utslipp av substanser som fører til betydelig skade på miljøet. Typisk: Olje > 1 m^3 Kjemikalie gruppe I > 10 m^3 Kjemikalie gruppe II (PLONOR) > 1000 m^3	
Effekt på regularitet	< eller = 8 timer	Utstyr / systemsvikt som kan forårsake tap av produktivitet og derav inntektstap i mer enn 8 timer.	Utstyr / systemsvikt som kan forårsake produksjonsstans i 48 timer eller mer	
Direkte kostnad	< eller = 500,000 NOK	Utstyr / systemsvikt som kan forårsake en kostnad på 500,000 NOK eller mer, for å gjenopprette funksjonalitet. Kostnaden inkluderer alle materialkostnader, arbeid og transport, men inkluderer ikke inntektstap som følge av produksjonsstans.	Utstyr / systemsvikt som kan forårsake en kostnad på 2 000 000 NOK eller mer, for å gjenopprette funksjonalitet. Kostnaden inkluderer alle materialkostnader, arbeid og transport, men inkluderer ikke inntektstap som følge av produksjonsstans.	

Figure C.1: Criticality matrix (Teekay Petrojarl, 2013)

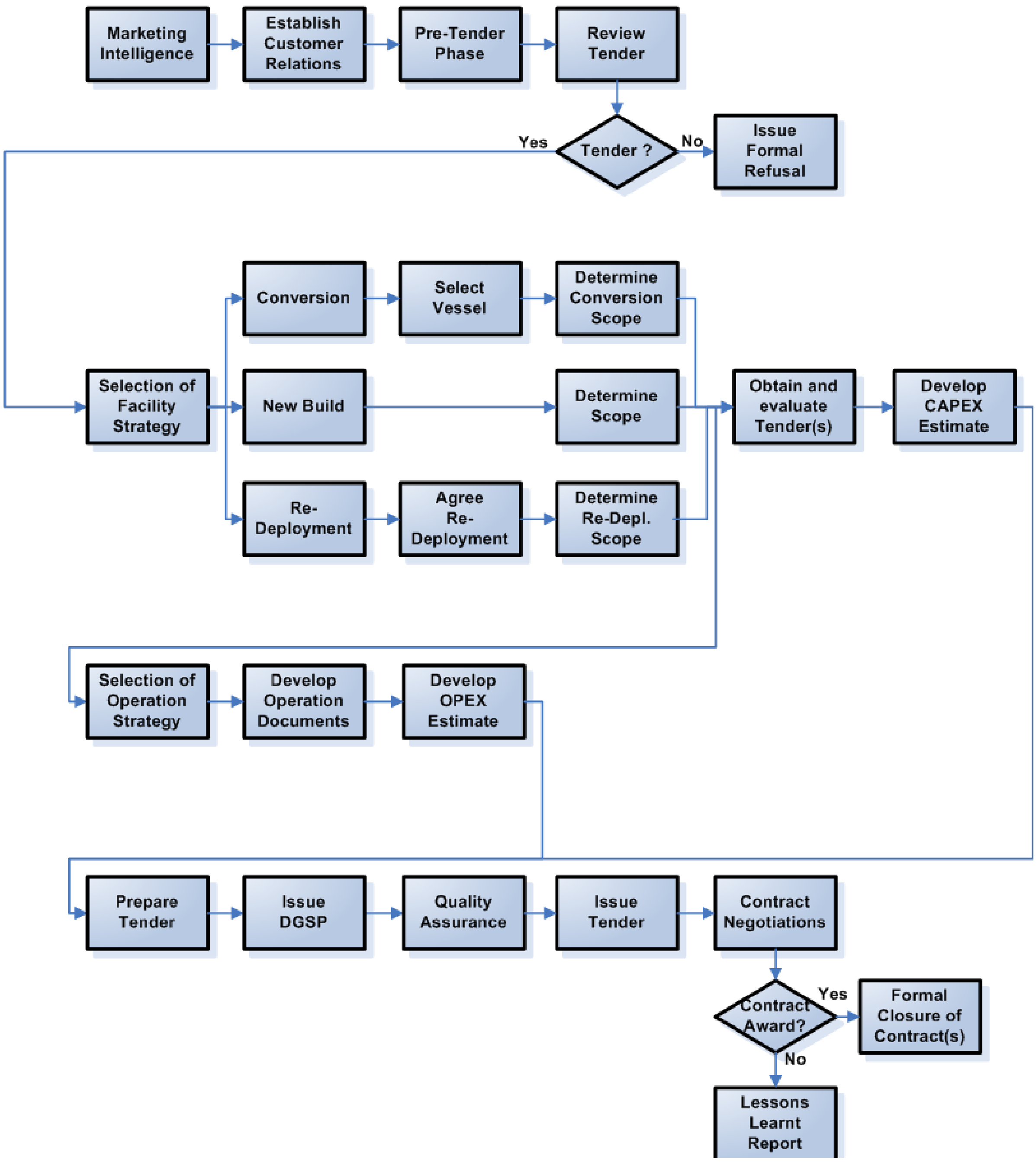

Figure D.1: The complete tender process in Teekay Petrojarl
(Teekay Petrojarl, 2011)

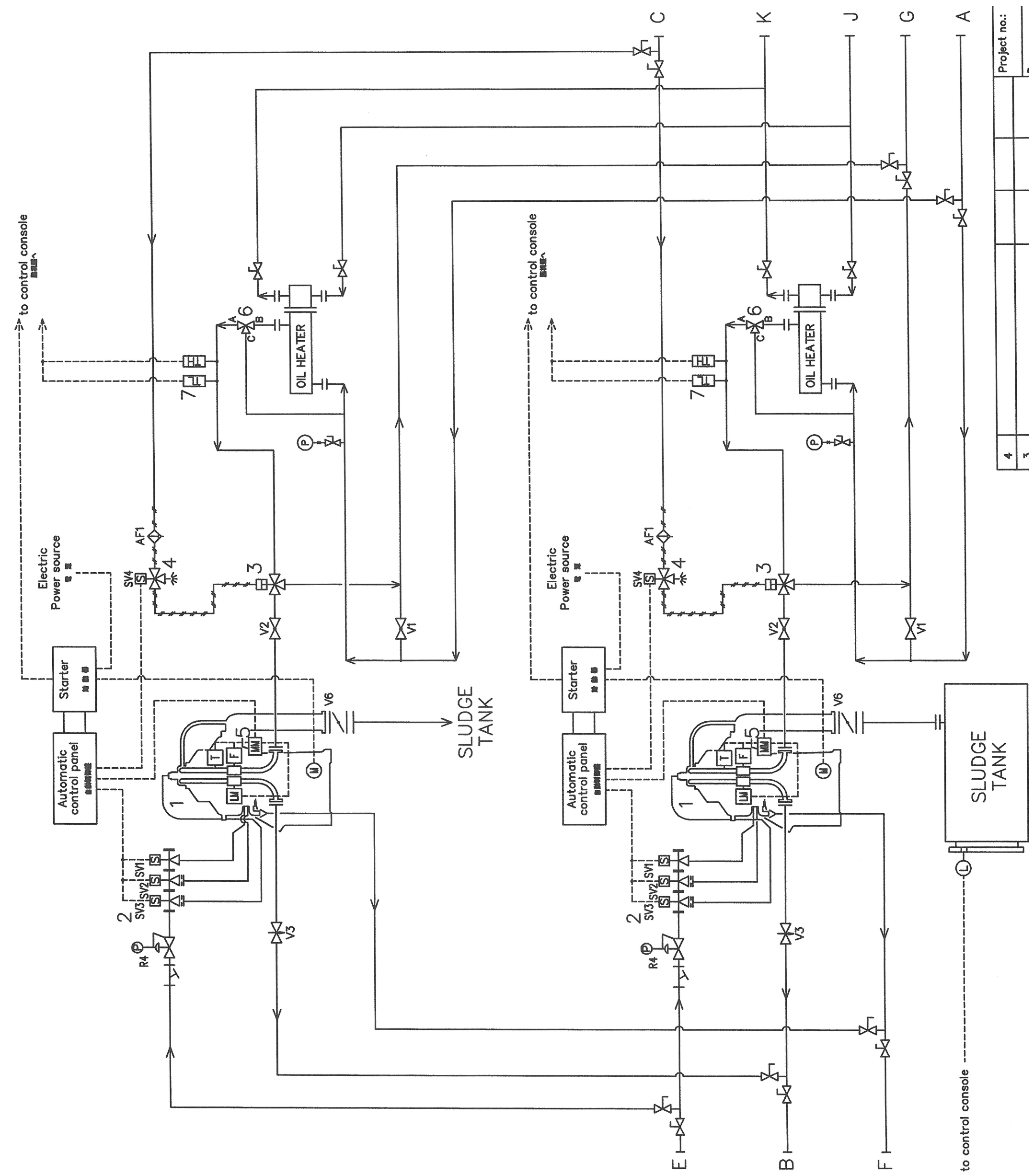

Figure E.1: P&ID of the fuel oil purification system

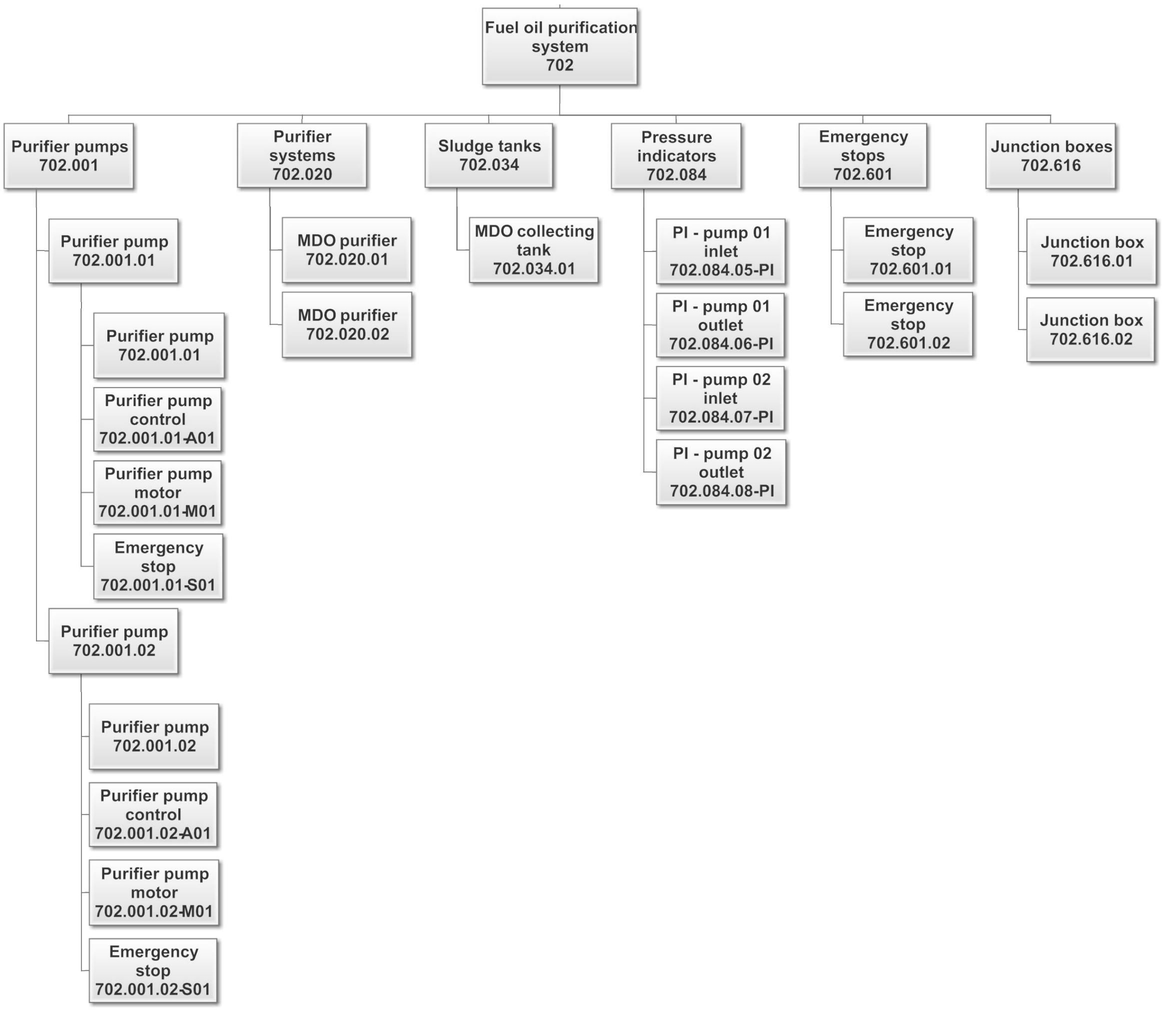

Figure E.2: Systematic breakdown of the fuel oil purification system, established from SFI grouping (Star Information System, 2014)

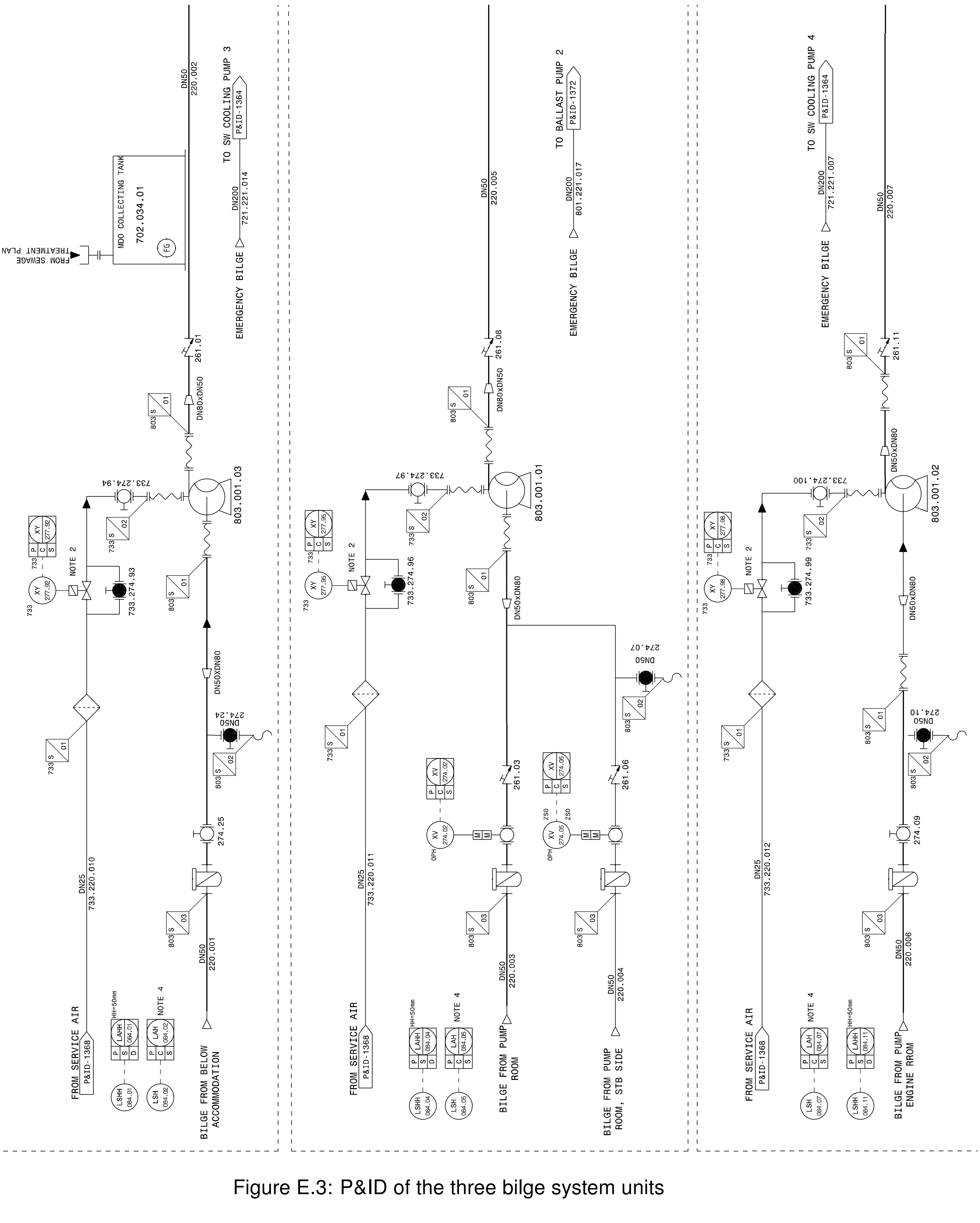

Figure E.3: P&ID of the three bilge system units

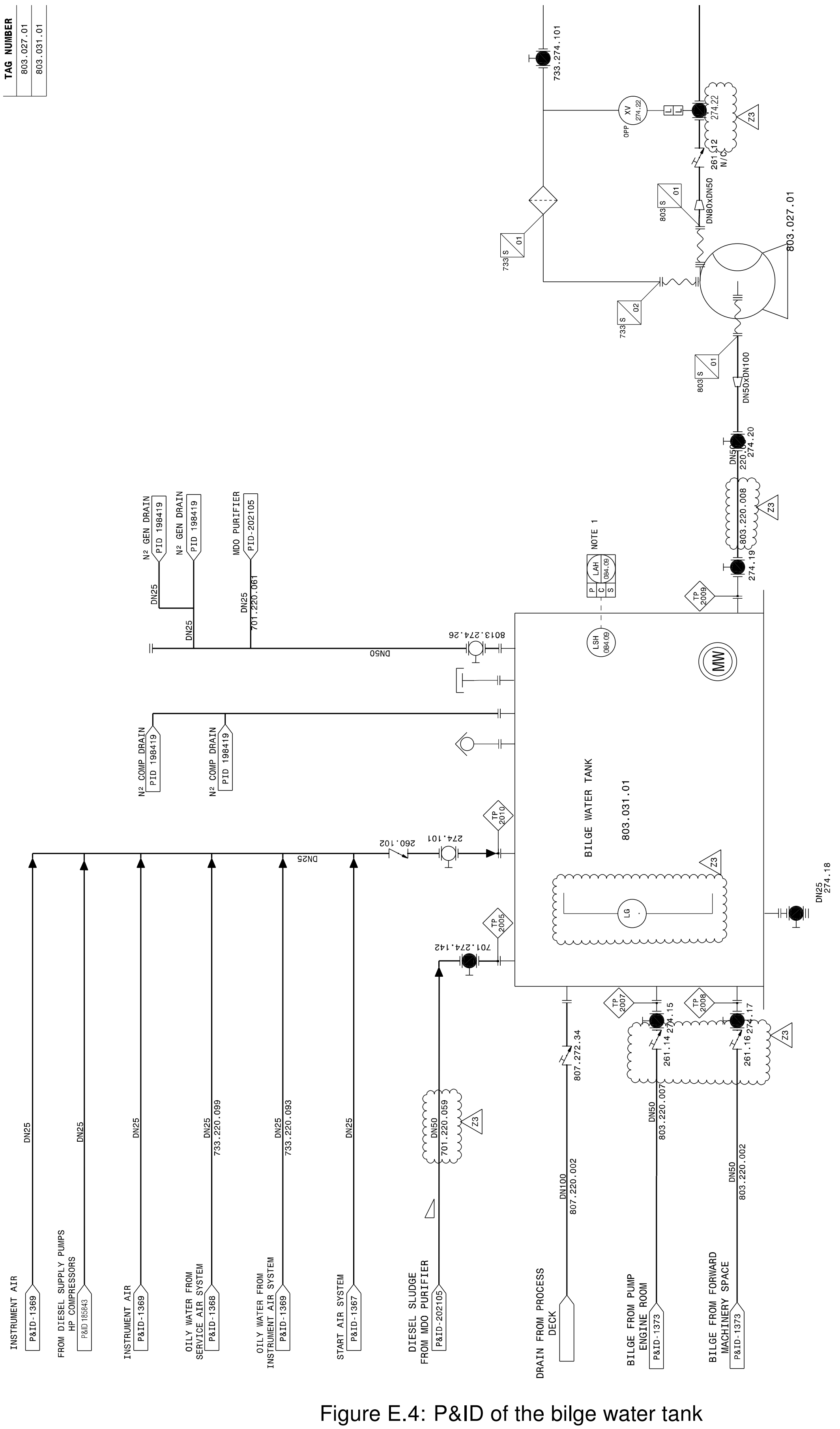

Figure E.4: P&ID of the bilge water tank

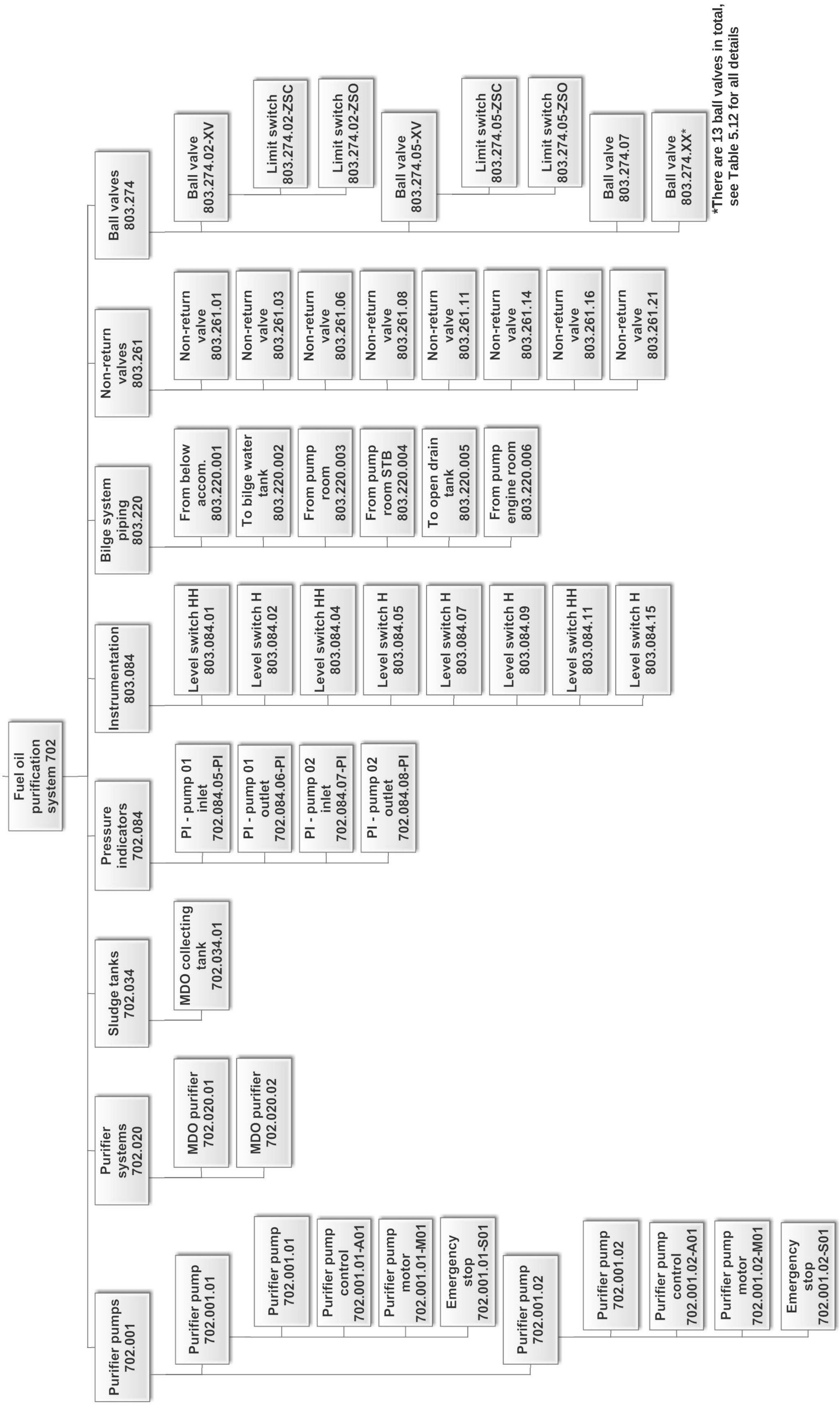

Figure E.5: Systematic breakdown of the bilge system, established from SFI grouping (Star Information System, 2014)