

CRANFIELD UNIVERSITY

ISAAC ANIMAH

MANAGING LIFE EXTENSION PROCESS FOR SAFETY CRITICAL
ELEMENTS ON OFFSHORE OIL AND GAS INSTALLATIONS

SCHOOL OF WATER, ENERGY AND ENVIRONMENT

PhD

Academic Year: 2014 - 2017

SUPERVISORS: DR. MAHMOOD SHAFIEE AND DR. NIGEL SIMMS
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ABSTRACT

Life extension (LE) of Safety Critical Elements (SCEs) is one of the hottest topics in the offshore Oil and Gas (O&G) industry today. Although LE is considered as the most appropriate alternative among the end of life management strategies (EOMLS), there are still several challenges confronting asset managers during LE phase of operation. Key among these challenges includes; lack of integrated technical and economic approach to assess the current health conditions of SCEs for LE, over reliance on expert knowledge and experience for selecting the most suitable LE strategy and the lack of suitable approach to integrate all LE decision making elements for effective operations of SCEs.

To overcome these challenges, this research aimed at developing an integrated decision making framework to use for managing LE process for SCEs found on offshore O&G installations. In order to overcome the first challenge, a techno-economic framework which integrates technical and economic assessment procedures for condition assessment of SCEs is developed. Furthermore, approaches based on Life Cycle Cost Benefit (LCCB) concept and Multi Criteria Decision Making (MCDM) method are subsequently proposed to overcome the challenge of lack of suitable methodology for selecting the most appropriate LE strategy. Lastly, a proposed multi-stage remanufacturing architecture capable of integrating all LE decision making elements is developed. These decision making models have been developed and analysed using data from literature review, expert opinion, review of company internal documents as well as data from manufacturers of SCEs in the offshore O&G industry.

The models are validated with a number of real life case studies which involves water deluge system, industrial air compressors and three phase separation systems to ascertain their efficacy. The outcome of validation processes indicates that these decision making models provide cost effective solutions to overcome the three key LE challenges outlined in this study. This research has added to the scientific understanding of this research area through creation of

novel decision making models to support LE phase of operation in the offshore O&G industry.

Keywords: Life Extension (LE), Offshore Oil and Gas (O&G), Safety Critical Elements (SCE), Techno-economic, Asset Management.

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LIST OF ABBREVIATIONS

ABAO	As Bad As Old
ACM	Annual Cost Method
AFMEA	Ageing Failure Mode And Effect Analysis
AGAN	As Good As New
ALARP	As Low As Reasonably Possible
ALRC	Asset Loss Risk Cost
ANN	Artificial Neural Network
ATEX	Atmosphere Explosibles
BBN	Bayesian Belief Network
BCR	Benefit Cost Ratio
BIPV	Building Integrated Photovoltaics
BLP	Bridge Linked Platform
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CBR	Cost Benefit Ratio
CEN	Committee For Standardization
CIM	Condition Index Matrix
CMM	Capability Maturing Model
CPC	Containment And Process Control
CRA	Corrosion Resistance Alloy
DBN	Dynamic Bayesian Network
EC&I	Electrical Communication & Instrument
EDRC	Environmental Damage Risk Cost
EHI	Equipment Health Index
EOLMS	End Of Life Management Strategies
FCP	Flexible Composite Pipe
FEA	Finite Element Analysis
FFE	Fire Fighting Equipment
FMEA	Failure Mode Effect Analysis
FPSO	Floating Production And Storage Offloading
FSO	Floating Storage And Offloading
FSU	Floating Storage Unit

GAIA	Geometrical Analysis for Interactive Aids
GoM	Gulf Of Mexico
HAZOP	Hazard & Operability Analysis
HHLRC	Human Health Loss Risk Cost
HSE	Health and Safety Executive
HVAC	Heating, Ventilation and Air Conditioning
IROR	Internal Rate Of Return
ISO	International Standard Organisation
KPI	Key Performance Indicator
LCC	Life Cycle Costing
LCCB	Life Cycle Cost Benefit
LEM	Life Extension Measure
LNG	Liquefied Natural Gas
LTO	Long Term Operation
NCS	Norwegian Continental Shelf
NGO	Non-Governmental Organisations
NPD	Norwegian Petroleum Directorate
NPV	Net Present Value
OEM	Original Equipment Manufacturer
OPEX	Operating Expenditure
OSPAR	Oslo And Paris Convention
P&ID	Piping and Instrumentation Diagram
PFEER	Prevention Of Fire, Explosion And Emergency Response
PHM	Prognostic Health Management
PLRC	Production Risk Loss
PM	Preventive Maintenance
PoF	Physics of Failure
PSA	Probabilistic Safety Assessment
PSD	Process Shut Down
PRV	Process Relief Valve
QRA	Quantitative Risk Assessment
RCM	Reliability Centred Maintenance
RFL	Remaining Field Life

RISKEX	Risk Expenditure
ROCOF	Rate Of Occurrence Of Failures
RPN	Risk Priority Number
RUL	Remaining Useful Life
RUL	Remaining Useful Life
SADT	Structured Analysis And Design Technique
SCE	Safety Critical Elements
SIM	Structure Integrity Management
SSC	Structure, System And Components
SW	Sea Water
TRC	Total Risk-Cost
UKCS	United Kingdom Continental Shelf
DSM	Decision support method

LIST OF SYMBOLS

Symbol	Description	Symbol	Description
α	relative importance of history score	T_o	time for crack initiation
$\alpha - 1$	relative importance of health score	T_G	time for crack growth to critical path
$B(t)$	benefits	CAP_o	capital expenditure
$C(t)$	cost	$C_o(t)$	operational expenditure
A_D	equipment damage area	$C_M(t)$	maintenance cost
C_A	asset loss cost per unit area	$C_R(t)$	risk expenditure
N_D	number of people	$C_a(t)$	annualised capex
C_H	cost associated with each fatality	i	interest rate
A_{ED}	environment damage area	C_{INST}	installation cost
C_{ED}	cost of environmental damage per unit area	C_{INST}^{lab}	labour cost during installation
C_{SC}	surface clean-up cost	C_{INST}^{dt}	downtime cost due to installation
C_p	production rate per day	C_{INST}^L	logistics cost
T_d	expected downtime	$L_{RT/d}$	labour rate/day
T_A	actual thickness measured during inspection	Mh^{INST}	total man-hours for installations
T_R	design thickness without corrosion allowance	N_{INST}	number of installation team
ΔK	stress intensity	C_{PL}	production loss cost
C and m	material properties	N_D	number of days
a_1	initial crack size	EHI	equipment health index
a_{cr}	critical crack size	C_{REM}	cost of remanufacturing
T_f	time to failure	CF_{CM}	carbon footprint due to cm

C_{FM}	fixed maintenance cost	CF_{PM}	carbon footprint due to pm
C_{CM}	corrective maintenance cost	CF_{REM}	carbon footprint due to remanufacturing
C_{PM}	preventive maintenance cost	C_{FC}	cost of fatalities
$\lambda(t)$	failure rate	PA	production availability
Mh^{FM}	man-hour time for fixed	C_p	value of unit of production
Mh^{CM}	man-hour time for corrective maintenance	β	scale parameter
Mh^{PM}	man-hour time for preventive maintenance	η	shape
C_{AD}	cost of asset damage	X	fraction of time
λ_j	frequency j -type accident	C_d	Cost of disposal
C_{CM}^{dt}	downtime cost due to CM		

1 INTRODUCTION

1.1 Ageing Offshore Oil and Gas Infrastructure

The ages of some installations in different energy industries have exceeded their original design lives and these installations are still operating due to the additional economic value to companies. This has resulted in savings to asset owners by delaying the construction of new installations as well as decommissioning of older assets. In the North Sea, the United Kingdom Continental Shelf (UKCS) has the oldest average ages of installations (26 years), this is followed by the Netherland (24 years), Norway (24 years) while Denmark has the youngest average ages of installations (Decom North Sea and Scottish Enterprise, 2014). For example, Stacey et al. (2008) and Stacey (2011) reported that almost half of the fixed offshore O&G installations operating in the North Sea exceeded their original design life of 20-25 year in 2003. The age distribution of fixed installations in the UKCS and Norwegian Continental Shelf (NCS) by the year 2003 is illustrated in Fig.1-2. In light of this, Tveit et al. (2014) suggested that this trend is likely to continue due to the rise in offshore O&G activities across the globe with majority of installations in their maturity stage.

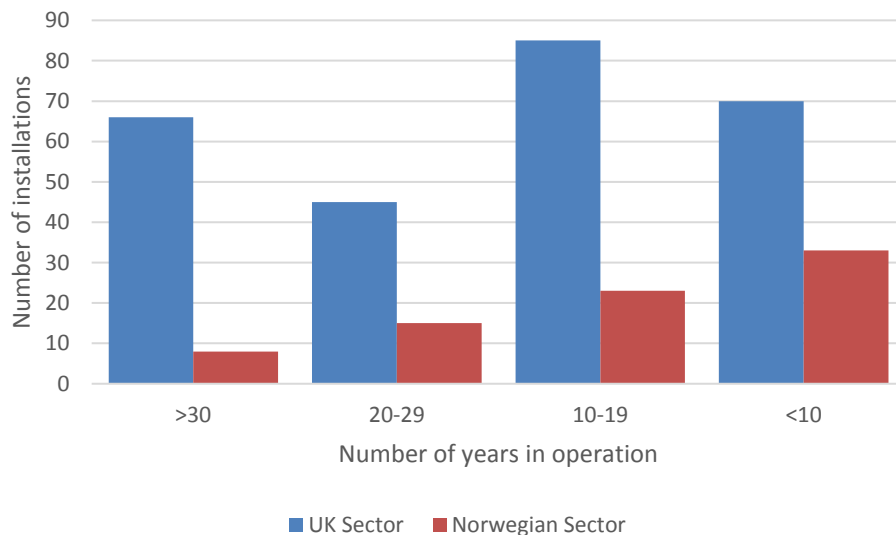


Figure 1-1 Ages of offshore installations in the UK and Norwegian sector of the North Sea in 2003 (Gerhard Ersdal, 2005).

In the offshore O&G industry as time passes, the physical assets gradually deteriorate in strength and this is referred to as an ageing process (Willis and Schrieber, 2013). Ageing has been defined as the condition of a plant and how it changes over time (Horrocks et al., 2010; Wright, 2011). However, the concept of ageing may not necessarily mean old age but rather the uncertainty about asset condition and how that is changing over time (Wintle et al., 2012). Willis and Schrieber (2013) classified ageing phenomenon into chronological ageing, cumulative service, abnormal event stress and technical obsolescence.

Assets operating under harsh conditions suffer various types of degradation largely caused by either environmental or operational agents (IEEE, 2006). Examples of environmental ageing agents includes vibration, temperature, pressure, humidity or simply passing of time while operational agents includes heating from electrical or mechanical loads, stresses and abrasive wearing (IEEE, 2006). Corrosion, erosion, fatigue and wear are examples of physical ageing mechanisms that may indicate the condition and age of an asset. These ageing mechanisms poses health and safety risk for many energy infrastructure.

Asset managers are confronted with several challenges when managing ageing offshore O&G facilities. These challenges can be classified as technical and human or organisational. The technical challenges are related to material degradation and key amongst these challenges includes limited amount of ageing related data, lack of understanding of ageing mechanisms, failure causes and failure modes of different facilities operating on offshore O&G installations, inability to apply appropriate physical degradation models to their corresponding failure mechanisms for analysis and insufficient use of semi-quantitative tools for assessing the current health conditions of SCEs. The lack of workforce with the appropriate competence and knowledge to manage ageing and LE process of offshore O&G facilities is the main human or organisational challenge.

The offshore O&G platforms contains assets which are critical to support production, enhance environmental protection (Environmental critical assets)

and ensure safety of assets as well as personnel (SCEs). However, one of the critical assets that suffer from varying forms of physical ageing mechanisms at the end of original design life are the SCEs (See Fig.1-4 & 1-5).



Figure 1-2 Corrosion of bolted connections (Wintle and Sharp, 2008)



Figure 1-3. Corrosion of valve (Wintle and Sharp, 2008)

“SCEs are any parts of an installation and plant (including software programs) whose failure causes or contribute substantially to a major accident or purpose of which is to prevent or limit the effect of major accident” (Dhar, 2011; Paterson, 2011; Stacey et al., 2008). SCEs are crucial in maintaining the safety

of installations, personnel and the environment, as well as improving production during LE phase of operation. Therefore, in order to continue operating existing installations while meeting regulatory standards such as NORSOK-N-006, NORSOK U-009, NORSOK Y-002 and ISO/TS 12747, there must be an effort to address the phenomenon of extensive degradation of SCEs that may have occurred at the end of original design life.

In order to comply with safety requirements contained in the standards outlined above during LE phase of operations of SCEs found on offshore O&G platforms, this thesis proposes decision making models such as techno-economic framework, life cycle costing benefit (LCCB) model, multi-criteria decision making (MCDM) model and multi-stage remanufacturing architecture to support LE management of ageing SCEs on offshore O&G installations. These enabled the development of systematic and structured frameworks for managing SCEs during the LE phase of asset lifecycle.

1.2 Life Extension Process

The topic of LE is currently a hot issue in the offshore O&G, renewable energy and nuclear power plant industries. This EOLMS is employed when an asset reaches the end of its original design life and provided the asset is economically and technically viable, the life is further extended. Long term operation, life prolongation and extension of service life are some of the terminologies used interchangeable with LE. LE is carried out with the objective of implementing engineering and administrative actions to restore ageing asset to optimal performance level while improving company's economics without compromising safety (Shafiee et al., 2016). Restoration of ageing asset to optimal performance level involves several industrial activities to halt or reduce degradation rate, reduce frequency of downtime, minimise impact of obsolescence and improve workforce safety.

LE decision making process considers economic, technical and organisational factors. LE delivers benefits such as increased production (oil , electricity etc.), low levelised cost of energy, saving investors from high CAPEX involved in

constructing new facility, sustaining jobs, reducing CO₂ emissions, and reducing financial risk compared to risk of investing in greenfield project. Also, in some countries due to highly restrictive regulations on construction of new infrastructure, companies use LE as means to avoid phasing out existing infrastructure.

Examples of fields whose lives have been extended in the offshore O&G industry includes Ekofisk 2005 until 2015, Asgard C 2005 until 2018, Ula 2005 until 2028, Statfjord A 2007 until 2028, Valhall QP, 2007, until 2010, Valhall PCP and DP 2007 until 2015, Hod 2008 until 2028, Norpipe oil 2008 until 2028, Veslefrikk A & B 2009 until 2020 (Ersdal and Selnes, 2010). In recent times, the Norwegian Petroleum Directorate (NPD) has given BP the opportunity to extend the life of the Tambar field until January 1, 2022.

In the UKCS, requirements for LE are handled by the Health and Safety Executive (HSE) offshore division. The Key Performance Indicator 3 (KP3) and Key Performance Indicator 4 (KP4) were some of the initial attempt by HSE to address the issues of ageing asset integrity and LE (HSE, 2009, 2010, 2012). The KP3 programme was introduced by the HSE for the period 2004 – 2007, primarily to focus on ageing asset integrity (Stacey, 2011) whilst the KP4 programme introduced in 2010 was essentially to address issues of LE. The HSE interim report on KP4 suggested that the industry reacted very well with the programme by demonstrating considerable understanding of LE concepts (HSE, 2012). However, the report recommended that in order to fully meet regulatory requirements, duty holders must ensure that installations long term integrity plan anticipate and manages degradation and its consequences associated with LE of SCEs.

Similarly in Norway, LE requirements and activities are under the control of Petroleum Safety Authority (PSA) ([Http://www.psa.no/aging-and-life-extension/category1032.html](http://www.psa.no/aging-and-life-extension/category1032.html)). They are responsible for issuing licence, ensuring standardisation, developing LE guidelines and building a knowledge base. PSA contribution for addressing issues of ageing and LE includes a comprehensive report on ageing and LE for specific and general equipment on offshore O&G

installations (Hokstad et al., 2010). Also, Norsok standard U-009 has been developed for LE of subsea system (i.e. Christmas tree, manifold template etc.) while Norsok standard Y-002 is for LE of transportation systems (i.e. pipelines) (Norsok, 2011, Norsok, 2010). However, in order to satisfy LE requirements and standards while simultaneously minimising cost and not compromising on safety, it is critical for stakeholders to concentrate effort on how SCEs on ageing installation can be managed properly during LE phase of operation. This is because properly managed SCEs ensures availability, reliability and functionality of an entire plant throughout its lifecycle and is also considered as a cost - effective means of managing ageing installations (IAEA, 2006).

Although, some scientific works have been carried out by both practitioners and scholars with respect to LE (Ramírez and Utne, 2011), there are still some challenges regarding managing SCEs during LE phase of operation. Håbrekke et al. (2011) in a study reported that safety related systems have received little attention in relation to LE management compared to other facilities operating in the offshore O&G industry. Also, while reviewing literature a lot of research has been done in the nuclear industry on LE of safety related assets (for more see Asmolov et al., 2014; Ballesteros et al., 2014; Ramuhalli et al., 2012; Saldanha and Frutuoso E Melo, 2012) while it is relatively new to the offshore O&G industry. The nuclear power plant industry has developed a comprehensive framework for managing ageing structures, systems and components (SSC) for LE, which is being used by nuclear energy companies all over the world (IAEA, 2009). In principle, when asset manager takes the decision to extend the service life of safety related assets, they need to be based on a structured decision making process involving expertise from different departments in the industry. This ensures better understanding of assets condition, asset risk to the environment and the economic implications of the extended operations of the asset. Furthermore, considering that field reserves are depleted during the LE phase of operation, there is the need to apply robust decision making process to account for the impact of uncertainties such as cost and technical conditions.

A brief description of LE concepts is illustrated using the bath curve in the next section.

1.2.1 The Concept of Life Extension

The well-known bathtub curve is used to describe the concept of LE. Fig.1-6 shows a classic bathtub curve for equipment lifecycle. The bathtub curve is an ideal curve of failure rate of a system with multicomponent versus operating time. Based on the failure rate, different life stages can be described for equipment lifecycle.

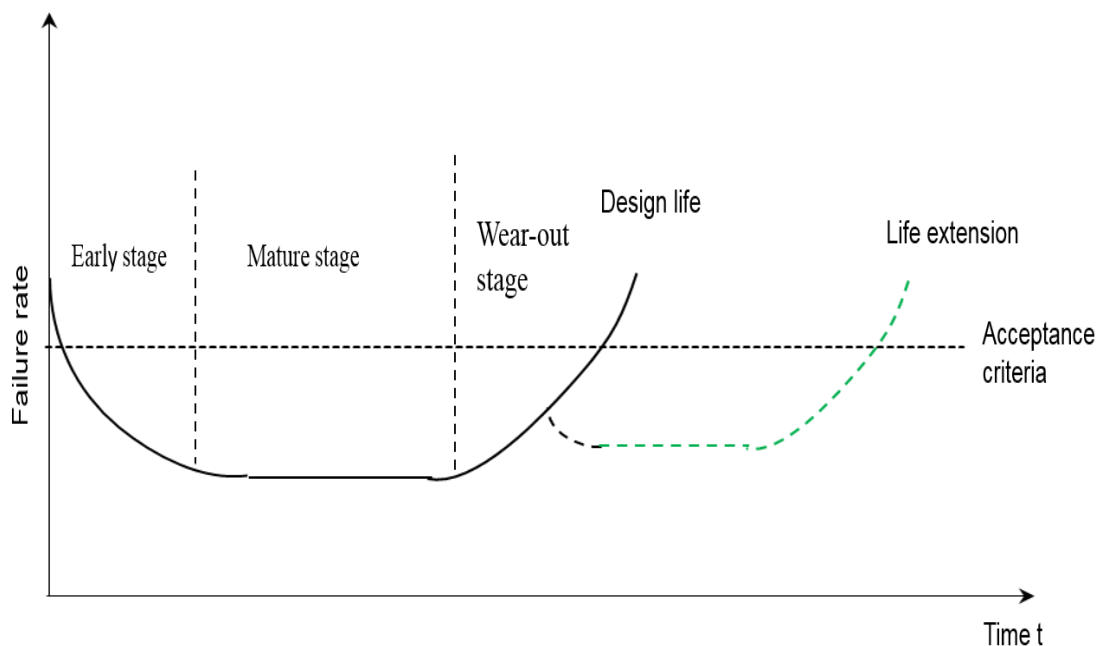


Figure 1-4. Classic bathtub curve

Equipment having this failure rate function is likely to experience a decreasing failure rate in the early life stage (infant mortality). The failure rate of equipment at the early life stage may be due to reasons such as material flaws, incorrect assembling, incorrect installation and poor component design etc.

The mature stage is the most useful and productive stage of every equipment lifecycle. At this stage the equipment is reliable, predictable and has a constant failure rate. Exponential distribution is usually used to model the probability of failure and reliability models at this stage of asset lifecycle.

The wear-out stage indicates that the equipment is approaching the end of life, where accumulated damage from the previous two stages of the equipment lifecycle appears as an increasing failure rate. At this stage of equipment lifecycle, more proactive inspection and maintenance approaches are required. In light of this accumulated damage, asset managers are still encouraged to extend the service lives of their installations. Thus, LE phase of operation mainly focuses on the operations beyond the wear-out stage of equipment lifecycle, represented by the green dotted line in Fig.1-4.

However, during LE phase of operation the failure rate of the equipment further increases due to global ageing effect such as corrosion, erosion, fatigue and wear, which means that asset managers are likely to increase the frequency of preventive maintenance (PM) actions. However, to successfully extend the operational lives of SCEs beyond the wear out stage while meeting safety and other regulatory requirements, asset managers are required to undertake some critical measures beyond the task of increasing the frequency of PM actions.

1.3 Problem Statement

The funding for this doctoral research was provided by Ministry of Energy, Ghana. The mandate of the ministry is to regulate activities in the energy sector of Ghana including conducting research. The main purpose for this doctoral research is to develop LE management framework for SCEs (e.g. static and rotating machinery) operating beyond their original design life and subsequently demonstrate how the proposed framework can be applied to effectively manage SCEs during LE phase of operation in the offshore O&G industry in Ghana and the UK.

This research topic is of extreme importance to the offshore O&G industry, because over the past decades, many offshore O&G installations are ageing and required LE in order to sustain production. Hence, the research topic continues to attract the attention of both practitioners and scholars in the reliability and asset management community. Reasons such as increased demand in O&G product, remaining reserves at the end of original field life, lack

of capital investment capacity on the part of asset managers and restrictive regulations in some jurisdictions which prevent companies from building new installations have been identified as the key motivation for LE in the offshore O&G industry. However, one of the essential requirements for securing LE approval is to ensure that the SCEs continue to deliver high level of service in a safe and cost-effective manner beyond original design life. One of the plausible means of satisfying this requirement is through the use of integrated decision making models by stakeholders.

However, literature review confirmed that in the past, decision regarding LE was often made using subjective principles, expert judgement and accumulated experience of engineers and inspectors (Shafiee and Animah, 2017). Decisions based on the above mentioned approaches are full of errors and uncertainties. Hence, in an attempt to minimise the reliance on expert's judgement and experience of engineers for LE decision making in the offshore O&G industry, some frameworks were developed to help asset managers assess the viability of their assets for extended operations. However, these frameworks tend to answer technical question only or economic questions only (for more see, Galbraith et al, 2005; Hokstad et al., 2010; Liu et al., 2014). While these frameworks may be convenient for managing LE process of SCEs, they are with some draw backs. First, decision making tends to skew to one side, sometimes leading to incorrect conclusions and recommendations. Second, these frameworks are industry specific and may lack applicability outside the industry from which they originate. Therefore, one vital motivation for this research is how to successfully integrate technical and economic decision making processes to support LE management of SCEs in the offshore O&G industry.

Furthermore, interactions with industrial experts confirmed literature findings that there exists no approach which integrates technical and economic assessment processes simultaneously, hence making the use of accumulated knowledge and experience of engineers very popular in the offshore O&G industry.

Also, from literature review as well as consultations with industrial experts in the offshore O&G industry, selection of suitable LE strategy is overly centred on accumulated knowledge and experience of engineers. However, this approach often result in very little added value for operators during LE phase of operation and the motivation at this stage is to develop systematic and structured processes to assist asset managers select the most suitable LE strategy.

The projected growth in the expected numbers of offshore O&G installations requiring LE further enhances the importance of having this integrated decision making framework during LE phase of operation.

1.4 Research Aim and Objectives

1.4.1 Aim

The lack of integrated technical and economic approach to assess the condition of SCEs for LE, over reliance on expert knowledge and experience for selecting the most suitable LE strategy and the lack of suitable approach to integrate all LE decision making elements for effective operations of SCEs during LE phase of operation led to the aim of this thesis. Hence, the aim of this research is to:

Develop LE management framework which is integrated for screening and prioritisation, condition assessment, remaining useful life estimation, risk analysis and cost-benefit analysis for SCEs in the offshore O&G industry.

1.4.2 Objectives

In order to explore and achieve the aim, a number of objectives are proposed:

1. To review state-of-the-art of LE in the offshore O&G industry, in order to gain in-depth understanding of existing works and identify gaps in this research area.
2. To understand current practices, identify key LE decision making challenges and learn good practices from other industries.
3. To develop a qualification framework which integrates technical and economic assessment processes to support LE feasibility assessment of SCEs.

4. To develop processes based on life cycle cost benefit (LCCB) approach and multi-criteria decision making (MCDM) method to select the most suitable LE strategy using both quantitative and qualitative data.
5. To propose a multi-stage remanufacturing architecture that integrates all LE decision making elements for effective management of SCEs.
6. To verify and validate the proposed decision making models using real life cases in the O&G industry.

The key research questions for the study are as follows:

1. How can factors that influence LE decision making process be identified and classified within the scope of the offshore O&G industry?
2. How can asset managers trust that their existing SCEs can operate satisfactorily beyond the end of original design life through the use of an integrated technical and economic assessment framework?
3. How can asset managers ensure that suitable LE strategy selection is not based on entire experience and judgement of experts and engineers?
4. How can asset managers integrate all LE decision making elements for smooth operation of SCEs during LE phase in the offshore O&G industry?

1.5 Thesis Assumptions

In order to achieve the aim and objectives of this research, the following assumptions are made:

1. SCEs considered in this thesis include containment and process control (CPC) systems, process safety systems, fire and gas (F&G) detection systems and active and passive firefighting systems.
2. SCEs are assumed to be operating beyond original design life with increasing failure rate due to ageing effects such as corrosion, wear and fatigue.
3. Time-to-failure of SCEs during LE of period follows Weibull distribution.

1.6 Key Research Contributions

This research has extensively contributed to increasing the understanding about managing SCEs on offshore O&G installations during LE period of operation. From literature review as well as interactions with industrial experts, the thesis revealed a lack of comprehensive framework incorporating screening and prioritisation process, condition assessment, remaining useful life (RUL) estimation and cost benefit analysis as a means to manage SCEs on offshore O&G installations during LE phase of operation. The thesis has further introduced concepts in relation to LE management that enabled the development of a techno-economic decision making model to support the management of ageing SCEs beyond original design life. The key contributions of this research is summarised below:

- This research has identified and classified key factors that influence LE decision making process in the offshore O&G industry, which hitherto were fragmented, making decision making regarding LE more complicated. This classification framework has the ability to reduce the complexities involved in LE decision making process.
- As results of this research, a novel framework which integrates technical and economic assessment processes has been developed to provide a systematic approach to support LE feasibility assessment of SCEs. The framework was validated with case studies involving SCEs operating on both offshore O&G and non-offshore O&G installations.
- This research developed both LCCB and MCDM decision making models, which provides systematic processes to help asset managers' select the most suitable LE strategy among wide range of alternatives.
- This research used multi-agent model to decompose the overly complex and centralised LE decision making process to ensure that each agent responsible for smooth operation of SCEs during LE phase of operation know their responsibilities, when to acts and when to interact and communicate with other agent.

1.7 Research Methodology Adopted

This research focused on addressing the challenges facing the offshore O&G industry in managing SCEs during LE phase of operation. The research combines theoretical and practical applied research methods in developing appropriate solution to the challenges associated with management of SCEs during LE phase of operation. Systematic literature review and interactions with industrial experts provided the rationale regarding the decision to adopt this research methodology. Due to the type of data expected to be collected for this research, inductive and deductive research category were applied in this research. The systematic literature review and engagement with experts were applied to gain in-depth and contextual understanding on how to develop a comprehensive framework for managing SCEs during LE phase of operation in the offshore O&G industry. The strategy enabled generalisation of the framework to other industries. The proposed methodology for the research was conducted in four stages as shown in Fig.1-7.

The first stage focused on gaining in-depth understanding of LE concept in relation to the offshore O&G industry. A detailed systematic literature review was conducted covering topics such as factors influencing LE decision making process, types of assets, LE assessment methods, LE strategies, RUL approaches, software tools and regulations for LE analysis. Keyword searches were conducted for these terms. Based on the research objectives, the research adopted exploratory research purpose considering both qualitative and quantitative research design. The qualitative research approach was solely used for interaction with industrial experts. Semi-structured interviews facilitated the elicitation of information from experts' for capturing current practices and challenges related to LE management of SCEs in the offshore O&G industry.

The purpose of the second stage was to collect data and generate ideas. A research protocol was developed to capture current practices and challenges associated with LE phase of operation in the offshore O&G industry. Consultation with industry involved seven seasoned experts with wealth of experience in managing LE projects in the offshore O&G industry. Capturing

current practices involved conducting a semi-structured interview with all the experts. Questions were developed before the interview section and these questions were validated with one of the experts, supervisors and colleague PhD researchers. The main benefit of the semi-structured interview was the flexibility it provided in eliciting information from the experts. Current practices captured from systematic literature review were compared to those realised from industrial experts. The semi-structured interview questions were also framed to capture the challenges experienced in applying current practices, linking these challenges to the challenges already captured from literature to generate ideas. The survey involved 23 experts with several years of experience in the offshore O&G industry. Out of the 23 experts used in the survey, seven responses were received and this represented 30.4% response rate. The data were then analysed using the Mindjet software in order to identify similarities and differences in experts' responses.

The full list of the questions can be found in APPENDIX A.1. This provided a deeper understanding of challenges captured in literature as well as those captured from industrial experts. About a total of seventy-five minutes of interview were conducted involving the experts. The experts had diverse and rich background in the offshore O&G industry including structural engineers, HSE consultant, safety case consultant, operators, scholars and representative from regulatory institutions with over 20 years of experience in handling LE projects. These backgrounds of the experts were considered sufficient for capturing current practices and challenges. Other data collection techniques such review of publicly available publications in the form of companies' magazines and information found on leading LE support companies' websites were used to triangulate the data acquired. Audio interviews were recorded, transcribed and organised into maps with analysis software tool called Mindjet. Similarities and differences between various responses were identified to ascertain convergence and divergence in the collected data to enable the author further identified gaps and challenges from expert's perspective.

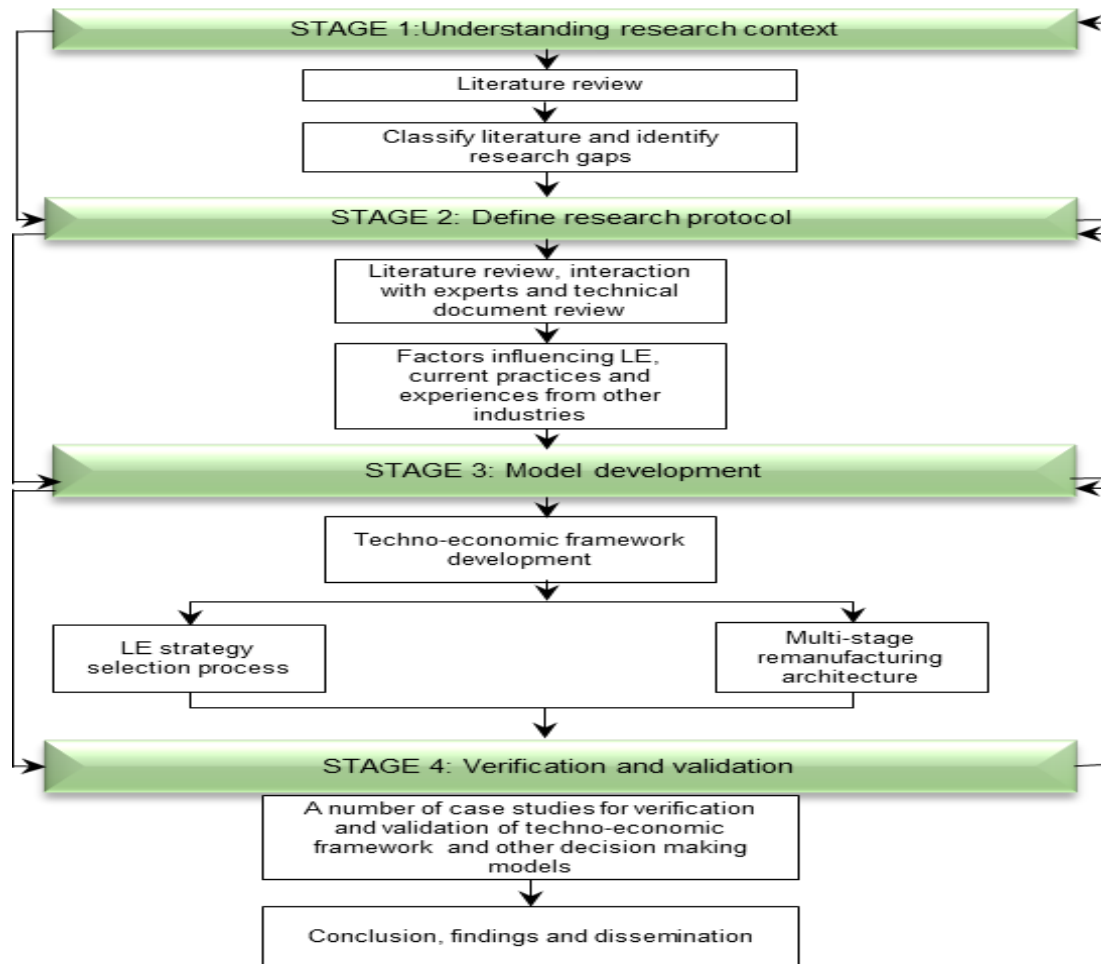


Figure 1-5. Research process adopted

The third stage focused on developing decision making models to support LE process of SCEs in the offshore O&G industry. The gaps, challenges and ideas generated during literature review and the results of stage two of the research methodology provided us with good understanding of LE practices in the offshore O&G industry and determined the scope for the decision making models. These models are supposed to present solutions to identified gaps and challenges. The models were developed with lessons from stages one and two of the research methodology.

The fourth stage of the research methodology involved validation of the proposed models with real life case studies. For example, at this stage of the research, the initial proposed techno-economic framework was subjected to several months of rigorous iterative process with support from literature in order

to finalise the framework. Total of 7 meetings were used to go through each step of framework to ensure logical sequence and reasoning.

The key strength of this research methodology is driven by the data collection methods adopted. These methods includes interview, survey, review of companies internal documents and literature review to gather information from different sources to compare and contrast in order to get deeper understanding and perspective of LE in the offshore O&G industry.

1.8 Thesis Structure

Based on literature review in Chapter 2 and consultation with industrial experts in Chapter 3, the activities that led to the achievement of the research aim and objectives are outlined.

In chapter 2, an account of existing literature in the research context is presented. In the author's effort to present critical content analysis and achieve comprehensive review of relevant topics in this research area, a systematic literature review approach was adopted. A classification framework with attributes such as LE decision making influencing factors, types of assets, LE assessment methods, LE strategies, RUL approaches, software tools and regulations for LE analysis were proposed with the principal objective of discussing the strength and weakness of existing literature leading to the identification of gaps and also highlighting research trends considering each attribute of the classification framework.

Chapter 3 presents the current practices and challenges facing stakeholders in the offshore O&G industry during LE phase of operation. This chapter also provide the details of interactions with industrial experts. Finally, LE lessons learned from other industries such as nuclear power plants, electrical transmission and distribution, transportation and wind energy are presented.

In chapter 4, factors influencing LE decision making process in the offshore O&G industry has been categorised using an appropriate classification framework. Based on the classification framework, results from experts'

interactions and findings from literature review, a techno-economic model, which integrates technical and economic assessment processes to support LE feasibility assessment of SCEs is developed.

Chapter 5 focuses on selecting suitable LE strategy by developing both qualitative and quantitative approaches. This is because during LE phase of operations, selection of suitable LE strategy is overly centralised on expert judgement and accumulated experience of engineers and inspectors.

In Chapter 6, a multi-stage remanufacturing architecture is proposed to integrate all elements involved in LE decision making to ensure smooth coordination and communication among LE decision making agents. Also, the multi-stage remanufacturing architecture is used to decentralise decision making during LE phase of operation.

In Chapter 7, the thesis is synthesised and the key research findings and its implications are discussed.

Finally, in Chapter 8, the conclusions are presented, describing how the aim and objectives of the research have been attained. The key research contributions are outlined together with research limitations and future work directions.

2 LITERATURE REVIEW

2.1 Introduction

This Chapter presents the review of LE literature exclusive to the O&G industry. The objective is to provide a better understanding of the state-of-the-art in this research area, identify existing research gaps and highlight trends.

2.2 Review Methodology

For the purpose of this research, a comprehensive investigation has been carried out in order to identify publications related to the research area of LE in the offshore O&G industry. The author adopted a systematic literature review approach to ensure research objectivity and replicability. Evidence that support LE should be a peer reviewed journal article, conference proceedings, technical reports, University dissertation, book chapters and must describe the issue of LE associated with the offshore O&G industry. In this research, the author systematically screened and reviewed scientific publications from the following databases: Scopus, ISI Web of science and Google scholar search engines. The author also reviewed publications in Onepetro, IEEE Xplore, Knovel and American Society of Mechanical Engineers (ASME) digital collection relevant to LE. The methodology for literature review was more comprehensive as it covers keywords, abstracts and paper titles search. Keywords and phrases were used to identify the papers that potentially contained information relevant to LE in the offshore O&G industry. The primary keywords used for the search included *life extension* and *ageing*. Other search terms were also combined with the primary keywords for further search. Examples of such terms are degradation, obsolescence, safety critical elements, technical health, maintenance etc. Publications that covered topics that were not specifically related to LE in the offshore O&G industry were not included in the review.

2.3 Selection Process and Evaluation of Papers

A total 75 publications were identified to have studied LE in the offshore O&G industry and each of the publication was reviewed and classified according to a

process agreed upon by the author and the supervisory team. The processes involved four stages: (i) online database search, (ii) initial classification of papers by the researcher, (iii) independent verification of initial classification by supervisors and (iv) the final verification by researcher and supervisors. If there was doubt about the classification of a paper, the paper is then discussed and a decision is subsequently made on the suitable classification for the paper.

2.4 Distribution of Scientific Publication

The author reviewed a total of 115 publications and 75 out of the 115 publications were classified according to the classification framework in Fig. 2-5 because they have conducted LE studies exclusive to the offshore O&G industry. The resulting literature comprises 10 journal articles (13.4%), 58 conference papers (77.3%), 5 technical reports (6.7%), 1 Doctoral dissertation (1.3%) and book chapter (1.3%) respectively. Fig.2-1 shows the distribution of scientific publications considered in the systematic review. As can be seen in Fig 2-1, large amount of publications have appeared in conference proceeding compared to journal articles and book chapters. Thus, there is an urgent need to raise the awareness in this research area to attract attention of researchers in publishing scientific works in peer-reviewed journals. Also, out of the 10 journal publications, Journal of Loss Prevention in Process Industry and Reliability and Systems Engineering has provided the highest number of publications in this area of study

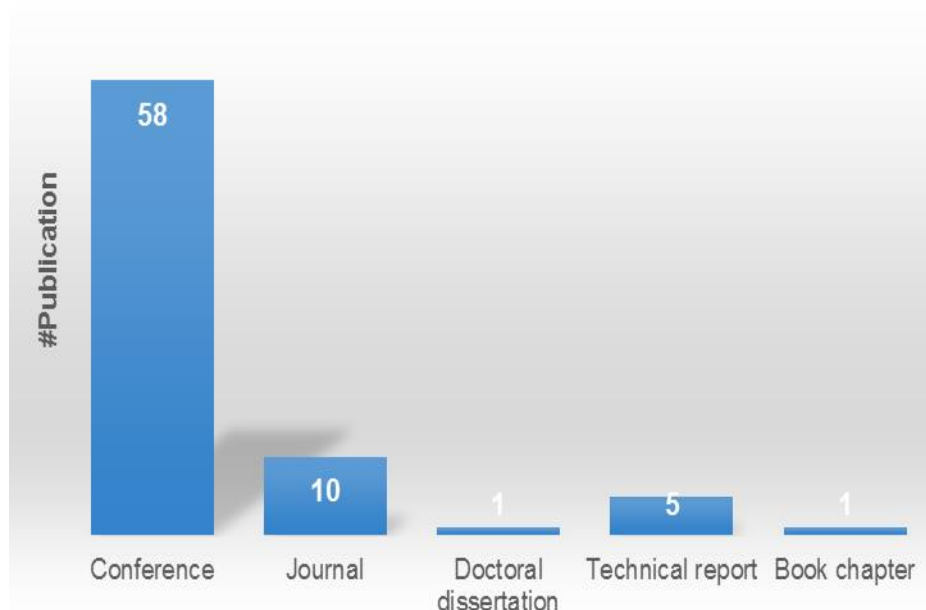


Figure 2-1. Distribution of scientific publications consider in the systematic review

As shown in Fig.2-2, the number of scientific publications increased between the periods of 2011-2016. Publications declined in 2012 and picked up again in 2013. The period 2011 and 2016 recorded the highest number of publications, which indicates that more publication could be expected in the next coming years.

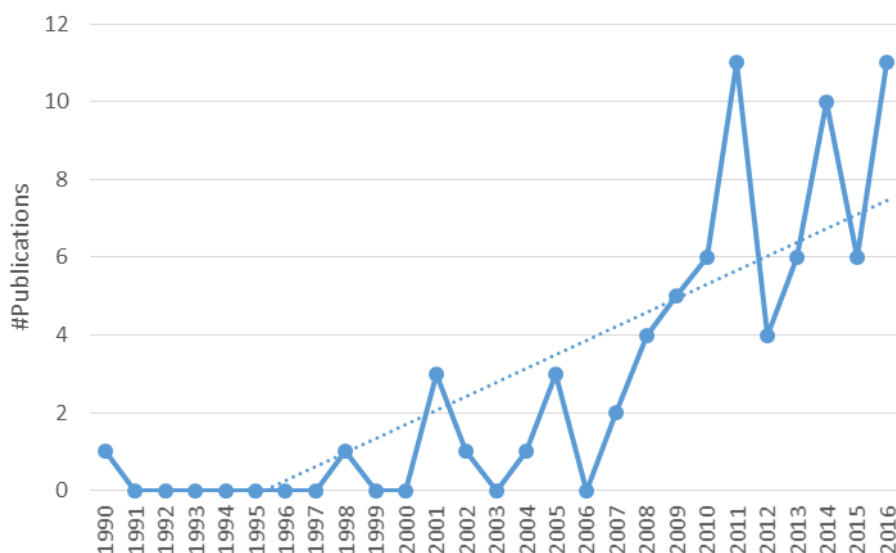


Figure 2-2 Number of publication per year (last updated 2016)

2.5 Most Influential Publications

As shown in Fig.2-3, the most cited and influential authors within the research area of LE in the offshore O&G industry are presented. A doctoral dissertation published by Ersdal (2005) is the most influential publication with 55 citations in Google scholar. It is followed by Hokstad et al. (2010) from SINTEFF with 19 citations by Goggle Scholar, Galbraith et al (2005) with 12 citations in Google scholar, Ramírez and Utne (2015) with 12 citation in Google scholar, Ramírez and Utne (2011) with 9 citation in Google scholar, Tveit et al. (2014) with 9 citations in Google scholar and Ersdal and Hörnlund (2008) with 8 citations in Google scholar. It has emerged that the most cited and influential authors and papers are based in Norway and UK.

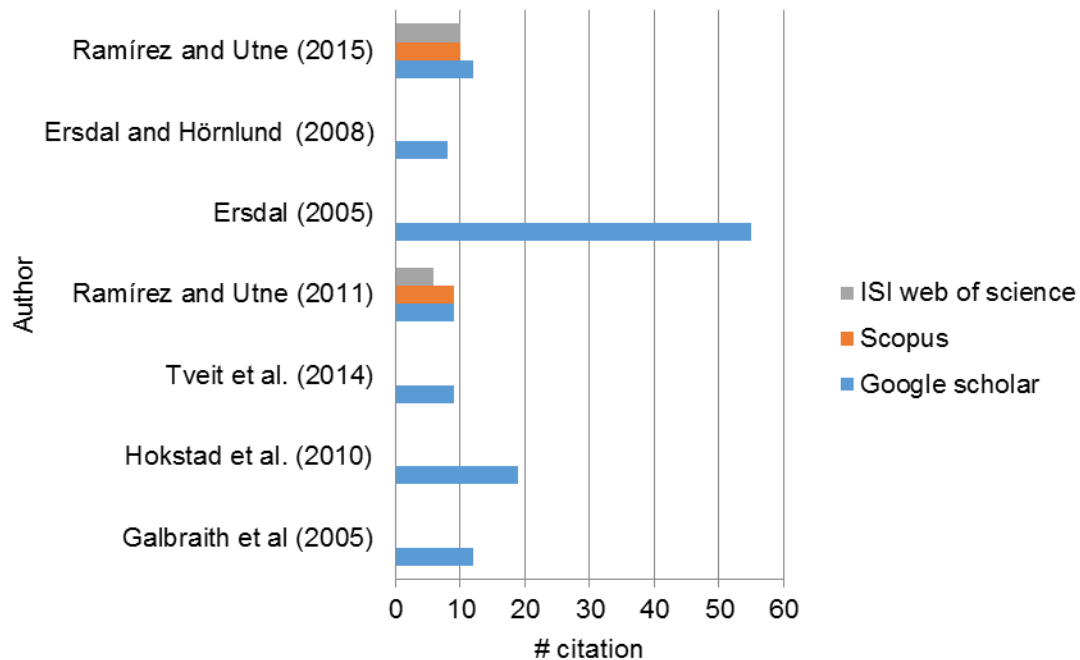


Figure 2-3 Most cited authors (last updated 04/03/17)

2.6 Publication by Countries

As can be seen Fig.2-4, the UK appears to be leading in the number of publications and keenly followed by Norway. Both countries account for a total of 89% of publications in this research area with the rest of countries accounting for 11%.

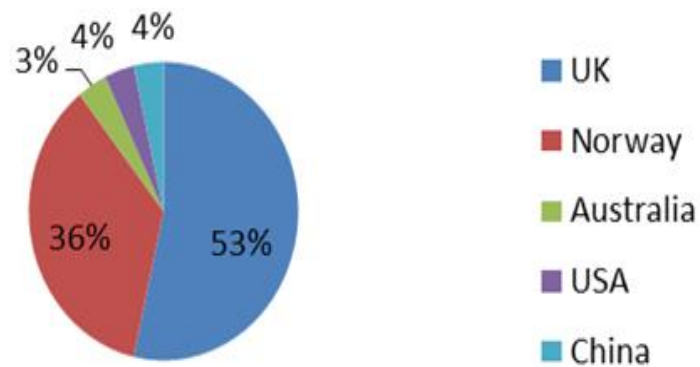


Figure 2-4: Publication by country (last updated 04/03/17)

2.7 Classification Framework

In order to classify published literature, each paper was reviewed and thoroughly analysed to identify relevant areas of application or issues they aimed to address. The classification framework illustrated in Fig.2-5, covers broad areas of issues that must be taken into account when undertaking LE programme.

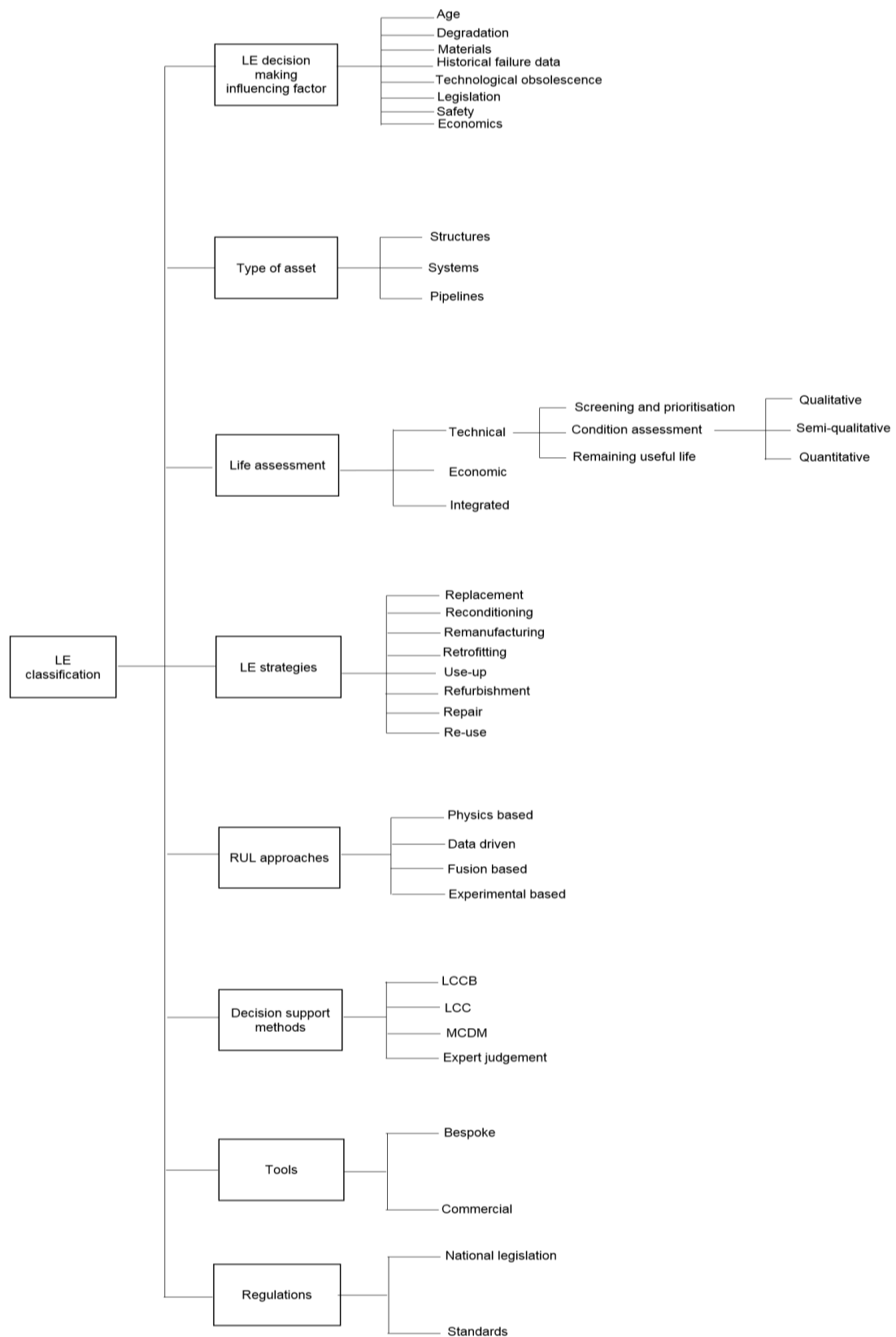


Figure 2-5 Classification framework

The framework classifies available publications according the following attributes:

1. LE decision making influencing factors (Age, degradation, materials, historical failure data, technological obsolescence, legislation, safety and economics).
2. Type of assets (structures, systems and pipelines).
3. LE assessment techniques (technical, economic and integrated).
4. LE strategies (replacement, repair, reconditioning, remanufacturing, retrofitting, re-use, use-up and refurbishment).
5. RUL approaches (Physics based, data driven, fusion based and experimental based approaches).
6. Tools (Bespoke and commercial).
7. Regulations (Standards and National legislation).

2.8 Classification Results

Based on careful content analysis and review of available publications, the result of each attribute belonging to the classification framework is reported below.

2.8.1 LE Decision Making Influencing Factors

LE decision making in the offshore O&G industry is critical and therefore decision makers must be aware of decision making influencing factors in order to make the correct decisions. The consequences of not considering these factors into LE decision can expose both platform and personnel to health and safety risk. The factors considered during LE decision making are reviewed as follows:

2.8.1.1 Age

The age of an installation and its equipment is one of the factors that influences LE decision making process in the offshore O&G industry (Denney, 2012). Age can refer to calendar age or usage intensity. Offshore O&G installations are built for a period between 20-25 years (Hudson, 2008; Stacey, 2011; Tveit,

Sivertsen and Hernaes, 2014). It should be noted that not all equipment operating on an installation have the same life span. According to Tveit et al.(2014) equipment such as subsea and topside processing facilities are designed for 10-15 years; while other equipment ages depend on running hours or usage intensity. Ages of systems on platforms often give indication of the level of degradation and the condition of the asset.

2.8.1.2 Degradation

The offshore O&G industry, like other industries (such as rail transportation, nuclear, bridges and construction, shipping, aviation, automotive etc.) suffers varying levels of degradation. Degradation is the top ranked driver for LE in the North Sea (Stacey et al., 2001; Stacey, 2008; Nabavian and Morshed, 2010; Denney, 2012; Russell and Keith, 2014). Therefore, understanding the impact of degradation mechanisms could confirm whether equipment can continue to operate within their original safety margins during LE period of operation or some remedial actions must be implemented to enable operations during LE phase of operation. Hauge and Onshus (2006) classified degradation into reliability oriented degradation and physically oriented degradation. Reliability oriented degradation refers to failure that has occurred in a system (loss of function) while physically oriented degradation refers to slow continuous process of degradation of equipment properties (Hauge and Onshus, 2006). Wintle and Sharp (2008); Palkar and Markeset (2012) and Ramírez et al. (2013) categorised degradation or ageing into three main groups as illustrated by Fig.2-6 below.

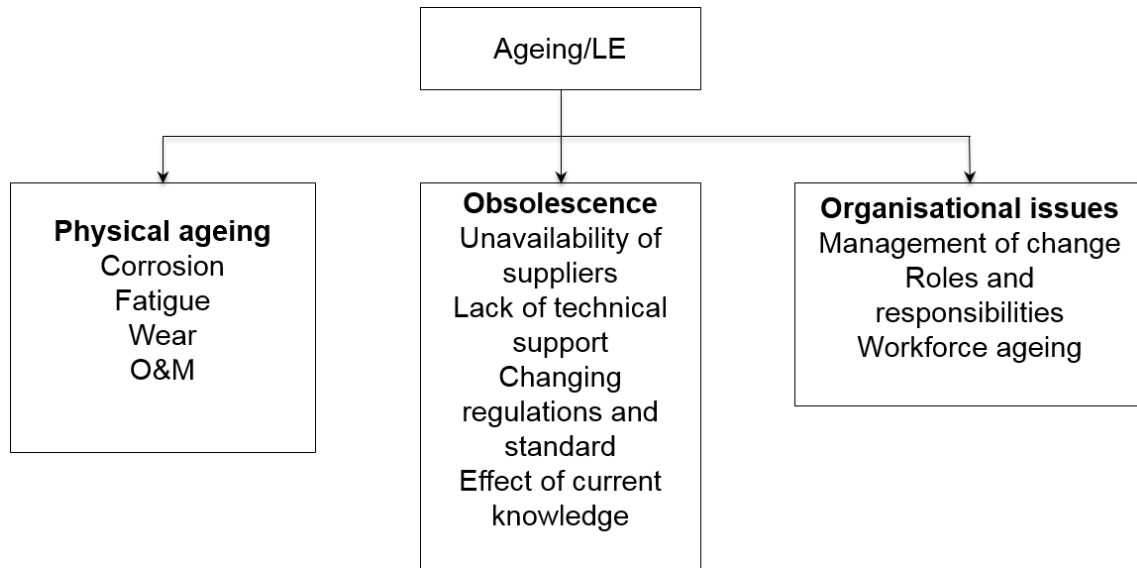


Figure 2-6 Aspect of ageing management for LE

Physical degradation deals with deterioration of equipment/component parts due to environmental or operational effects. Corrosion, fatigue, wear and erosion are typical examples of physical degradation mechanisms that negatively impact the integrity of offshore O&G installations. Horrocks et al. (2010) also stated that from 1980-2006 a total of 96 major accidents were captured in the Europe Union (EU) major accident report which was due to physical degradation process. Veritas (2009) identified physical degradation in the offshore O&G industry, as time-dependent failures, which are mainly corrosion, wear and fatigue. Ramírez and Utne (2011) discussed the challenges of degradation in the offshore O&G industry in relation to LE phase of operation. The discussions on physical degradation process in the offshore O&G industry has focused on metals, since they dominate the industry. However, efforts should be made to study degradation process of concrete, composite and other new materials being introduced into the industry.

On the other hand, obsolescence in offshore O&G industry occurs when there is rapid technological advancement, unavailability of suppliers, lack of technical support from manufacturers and lack of compliance with rapidly changing industry regulations and standards while human and organisational issues deal with ageing workforce, roles and responsibilities and competence of personnel involved in LE activities (Hokstad et al., 2010; Ramírez and Utne, 2011;

Ramírez et al., 2013). However, this study focuses on addressing LE challenges related to physical degradation of SCEs and lessons would be learnt from other categories of degradation when required.

Also, organisational issues such as defining the roles and responsibility of LE team members, transfer of knowledge and work force ageing are some of the factors that can accelerate the degradation of offshore O&G installations. Palkar and Markeset (2012) indicated that majority of the current administrative and operational workforce in the upstream sector of the offshore O&G industry are ageing together with the installations which poses challenges for LE planning. Therefore, during LE phase of operation asset managers must ensure that organisational issues, knowledge and data are adequate, current and of good quality. Also, the capabilities and skills of the workforce to support LE management process should not be disregarded.

2.8.1.3 Knowledge of Materials

Structures, systems and components (SSCs) operating on offshore O&G installations are made of many materials. Knowledge of material behaviour in the offshore environment is of great importance during LE decision making process. This is because recommendations for equipment modification (e.g. by welding and fabrication) during LE phase of operation is largely based on understanding of different material behaviours within the offshore environment. Materials in the offshore O&G environment suffer various forms of degradations impacting on installation's integrity, thereby influencing LE decision making (Lancaster, 1997; Chakrabarti, 2005). In-depth knowledge of material behaviour may assist engineering team to adopt state of the art modification techniques during LE phase of operation. Also, understanding of material specifications and properties could contribute to improvement of installation's integrity and performance during LE phase of operation.

2.8.1.4 Historical Failure Data

Historical failure data are useful for risk assessment and development of age-dependent reliability models to support LE decision making process (Lundteigen and Rausand, 2006; Veritas, 2009; HSE, 2012). Historical failure data assist

engineering teams to make judgement on reliability improvement of plants specific parts and plan maintenance activities during the extended period of operation.

Failure data can be grouped into generic and non-generic data. Generic failure rate data are established failure rate data with high degree of confidence within many industries. LE assessment teams need to decide if generic data are appropriate for their assessment. In situations where generic failure rate data is deemed inappropriate, then further work is required to determine specific plant part failure data, which are referred to as non-generic failure data.

The offshore O&G industry lack good quality data to support LE decision making process. Hokstad et al. (2010) reported that the offshore O&G industry lacks data with high degree of confidence to support LE decision making process. The following literature sources were identified to contain some level data that can support LE decision making process in the offshore O&G industry (Veritas, 2009; Hokstad et al., 2010; HSE, 2010). Beerens et al. (2006) identified a number of databases, where generic historical failure data for pressure vessels and piping could also be obtained for analysis with respect to LE decision making process.

Other forms of data could be acquired from other industries with similarities to the offshore O&G industry for purposes of LE assessment (e.g. nuclear power plant and electrical transmission and distribution industries). Historical failure data can relate to degradation processes, failure mechanisms and repair process at the component level or the interconnections between the different components at the system level (Barabadi, et al., 2015). LE assessment requires failure data with a high degree of confidence as inputs to make useful decisions.

2.8.1.5 Technological Obsolescence

Technological obsolescence is one of the key decision making constraints in the entire lifecycle of an offshore O&G platform (Jonathan Lewis et al., 2009; Strouse et al., 2014; Akbar et al., 2015). LE may result in the modernisation and

upgrading of installation's facilities, leading to better performance and availability of equipment. Ensuring modernisation or upgrade during LE phase of operation requires introduction of new technologies (i.e. replacing analogue system with digital systems) to achieve the required performance and availability. However, majority of platforms reaching LE phase did not consider the issue of integrating existing and new technologies at the design stage of the installation life. Saul (2006) discussed the impact of technological advancement in relation to LE in the offshore O&G industry. Strouse et al. (2014) discussed the challenges of managing obsolescence in the offshore O&G industry and subsequently provided best practices and tools to manage subsea systems obsolescence. Belshaw (2015) addressed challenges of obsolescence management during LE phase of operation and suggested offshore site visit and detailed design studies of equipment as the appropriate means of assessing the obsolescence levels of SCEs during LE period of operation. Lewis et al. (2009) utilised risk based approach to assess obsolescence of ageing control and presented proactive obsolescence management procedures for subsea systems. However, review of literature indicates that few studies have researched on obsolescence management during LE phase of operation.

2.8.1.6 Legislative Changes

Legislations, regulations, standards, codes and guidelines are dynamic and therefore change over time. Legislations in the offshore O&G industry have evolved over the last two decades, with each country trying to institute best practice to achieve higher levels of safety (OGP, 2010). For example, the UK after the Piper Alpha incident moved from the prescriptive nature of regulation to the safety case regime which is more proactive with Norway having similar approach (Sefton, 1994). These changes may not be limited to national legislation but extends to international regulations. HSE requirements under the ATEX (Atmosphere Explosibles) directive by European Union (EU) and UK regulation PFEER (Prevention of fire, explosion and emergency response) poses a challenge for duty holders during LE process. Duty holders in the UK sector of the North Sea should comply with PFEER as part SCE management. This means that existing SCEs in hazardous locations before the PFEER came

into force must demonstrate compliance to PFEER regulation at the LE phase of operation and this may require modification and redesign of these elements.

According to Wright (2007) ATEX Directive 94/9/EC requires that new mechanical equipment to be installed in areas with high flammability potential must comply with similar standards already applied to Electrical Communication & Instrument (EC&I). This directive presents additional restrictions and challenges to duty holders who desire to extend the operations of their installations. Moreover, the abolition of R22 which is widely used in heat pump, refrigeration systems and air-conditioners since 1990 is supposed to be phased out and replaced by environmentally friendly refrigerants by 2014 (Calm and Domanski, 2004). This means that HVAC (heating, ventilation, and air conditioning) systems on the offshore O&G platforms will be affected during LE period of operation. The evidence above indicates that tighter regulations at both international and national level may impact LE process. According to Russell and Keith (2014) significant changes in the OSPAR convention (Oslo and Paris convention) in 2006, which reduced the oil in produced water overboard discharge limit from 40 to 30mg/l, has been problematic for installations as watercut increase is synonymous with depleted reservoir. This requires installation of new equipment to comply with this regulation and comes with its safety and cost implication.

The proposed EU legislation on the safety of offshore assets will come with some changes to existing regulations in different countries, which will require duty holders to effect changes in their operation (Ashurst, 2013, 2014). There is no doubt that legislative changes comes at a huge cost to duty holders and this could be more challenging during LE period.

2.8.1.7 Economic

Economic consideration is an important part of the LE investment evaluation process (Brandt and Mohd Sarif, 2013). Possible LE scenarios may results in improvement with associated cost. Therefore, the element of cost becomes an important decision-making criterion during LE decision making process. According to Lohrenz (1995) O&G production activities involves various

engineering decisions, with the aim of maximising net economic value. However, these engineering decisions results in expenditure in the form of CAPEX and OPEX. The actual cost of a LE project depends on many variables including: cost of modification and replacement of candidate equipment; the length of refurbishment period and cost of downtime due to refurbishment or replacement activities (Grigorian et al., 2001; Brandt and Mohd Sarif, 2013). Hence, the offshore O&G industry must endeavour to determine the business impact of any LE scenario. Raising a business case for LE is more vital due to the uncertainty in O&G economics.

2.8.1.8 Safety

All technical items (components, subsystems, systems) are designed to perform one or more required functions according to procedure in their prescribed environment of operation (Rausand and Hoyland, 2004). Best practices ensure that the safety and reliability of critical equipment are maintained throughout asset lifecycle. To achieve maximum level of safety during LE period of operation, performance standards should be correctly set for continuous operation (Dhar, 2011). Performance standards are set of criteria used to measure asset function, safety, reliability and availability. However, Dhar (2011), indicated that there are no existing criteria in the offshore O&G industry for establishing performance standards for SCEs management. This has resulted in different companies adopting different approaches in establishing performance standards. Setting universal performance standards for the industry will ensure improved safety and reliability of SCEs. In the absences of performance standards, historical performance data and risk assessment should identify any ageing related failures or indications on critical equipment/components with safety implications. In the event of no available data, a generic data or Bayesian updating methodology could be used to assess the safety levels of critical equipment (Skogdalen and Vinnem, 2012). Safety and cost are the two major conflicting factors during LE decision making process. Hence, decision-making must ensure a balance between the two factors to arrive at suitable solution (Vaidya and Rausand, 2011).

Overview: From the literature review, there are considerable number of publications that have discussed the factors that may influences LE decision making process in the offshore O&G industry. Nonetheless, the lists of factors are fragmented and none of the publications have attempted to classify the list of factors influencing LE decision making process by using appropriate classification framework. Therefore, in order to make LE decision making process less complex, there is the need to categorise LE decision making factors using appropriate classification framework.

2.8.2 Type of Assets

Generally, assets are classified as physical, human, financial and intangible assets (BSI, 2004). However, this research focuses on LE of physical assets operating in the offshore O&G industry. Physical assets operating in the offshore O&G industry can be classified into structures, systems and pipelines. The author investigates the level of attention structures, systems and pipelines have received in the offshore O&G industry in relation to LE. Table 2-1 shows the distribution of publications that have addressed LE of structures, systems and pipelines in the O&G industry. The results from the Table 2-1 indicate that structures have received much attention in the offshore O&G industry as compared to systems and pipelines. In what follows, a brief discussion on each asset is provided below.

2.8.2.1 Structure

Offshore O&G structures include fixed platforms and floaters used for exploration and production of O&G from the seabed for further processing. Examples of fixed platforms used for exploration and production in the O&G industry including, steel jacket, concrete gravity structures, compliant towers, jack-up rigs and tension legs. The fixed platforms are economical for water depth less than 500m (Nallayarasu, 2009). While floaters include semi-submersibles, spars and ship shape vessels such as FPSO, FSO and FSU. The floaters are convenient for deep water operations. Most of these structures in the world are approaching their end of life and the need to qualify these

structures for extended operations is increasingly becoming important in offshore O&G industry.

2.8.2.2 Systems

The offshore O&G structure and the seabed consist of several pieces of equipment including SCEs to support operations. The NORSOK S-001 standard for technical safety identifies a number of safety systems on offshore O&G installations. According to Håbrekke et al. (2011) safety systems operating on offshore O&G platforms can be classified into frequency reducing safety systems and consequences reducing safety systems. They include the following:

1. Containment and Process control (CPC) systems: These safety systems involve alarms and other forms of operator interventions. These safety systems are critical to ensure that the demand on other safety barriers is reduced.
2. Process safety systems: These safety systems includes pressure relief valves (PRV), process shut down (PSD) valves and drain valves.
3. Fire and Gas (F&G) detection systems includes ignition source control, smoke detectors, gas detectors and fire detectors.
4. Active firefighting systems with examples such as water deluge system, firewater monitoring equipment, pumps etc.
5. Passive firefighting equipment such as firewalls, blast walls, and closed drains.
6. Escape and evacuation routes and rescue and safety facilities. These include temporal safe of refuge and life boats for escape.

In order to extend the remaining service life of a platform and subsea facilities, the condition of the SCEs must be assessed and ensure that it complies with relevant rules and regulations. Håbrekke et al. (2011) indicated that addressing issues LE in relation to structures have received much attention in the offshore O&G industry compared to safety systems.

2.8.2.3 Pipelines

Pipelines are the key transportation medium for O&G products in offshore O&G industry. The pipeline systems include flowlines, umbilicals, power cables and trunk lines with diameters ranging from 2 to over 44 inches.

Table 2-1 presents a distribution of publications according the type of assets classification.

Table 2-1 Distribution of papers according to type of asset

Ref	Structures	Systems	Pipelines	Ref	Structure	Systems	Pipelines
Zuccarelli et al. (1991)	x			Pederson et al.(2013)		x	
Grigorian et al. (2001)	x			Ramírez and Utne (2013)		x	
Ersdal and Langen (2002)	x			Zhong and Cai (2013)	x		
Ersdal (2005)	x			Adamou (2014)	x		
Jansen and Van (2005)				Gibbs and Graf (2014)	x		
Rincónand González (2007)			x	Liu et al., (2014)		x	
Franklin et al. (2008)			x	Nezamian and Clarke (2014)	x		
Hudson (2008)		x		Nezamian and Nezamian (2014)	x		
Hudson (2009)		x		Nezamian and Sucharov (2014)	x		
Ersdal and Hörnlund (2008)	x			Wang, Sun and Lee (2014)	x		
Lewis et al. (2009)		x		Carvalho et al.(2015)		x	
Marshall and Copanoglu (2009)	x			Leira et al.(2015)			x
Marshall and Copanoglu (2009)	x			Masson et al. (2015)			x
Windle and Broos (2009)		x		Ramírez and Utne (2015)		x	
Hudson (2010)		x		Zeinoddini et al. (2015)	x		
Saunders and Sullivan (2010)			x	Sahasakkul et al. (2016)	x		
Albertini et al.(2011)		x		Sari et al., (2016)	x		
Ayello et al.(2011)			x	Carpenter and Nomanbhoy (2016)	x		
Henderson et al. (2011)			x	Selman and Hubbard (2016)			x
Martinez (2011)	x			Aeran et al. (2016)	x		
Ray et al. (2011)		x		Kajuputra et al. (2016)	x		
Solland et al. (2011)	x			Nezamian et al. (2016)		x	x
Vaidya and Rausand (2011)		x		Omari et al. (2016)		x	
Husen and Irawan (2012)	x			Muren et al. (2016)			x
Martinez et al. (2012)	x			Shafiee et al. (2016)		x	
Copello and Castelli (2013)	x						

Overview: Out of the 75 classified publications, 50 were reviewed under this attribute. Out of the 50, 24 (48%) of the publications focused attention on structures, followed by systems 16(32) and pipelines 10 (20%). As can be observed from Table 2-1, there is opportunity for more research on LE of systems and pipelines operating on offshore O&G installations. Therefore, this research focuses attention on LE of systems which are critical to safety during LE phase of operation in the offshore O&G industry.

2.8.3 LE Assessment

LE assessment processes plays a crucial role in LE decision making process for both topside and subsea facilities. The results of LE assessment forms the basis for determining whether an asset qualify for LE or whether some remedial actions must be taken before assets qualify for LE or whether the asset must be decommissioned. Moreover, some standards and regulations mandate operators to perform LE assessment as the basis for issuing LE licence. This research classifies the LE assessment processes into technical, economic and integrated assessment processes.

2.8.3.1 Technical Assessment

Technical feasibility assessment of SCEs for LE involves activities such as screening and prioritising critical components, condition assessment and forecasting remaining useful life of components.

2.8.3.1.1 Screening and Prioritisation

The key goal for screening and prioritisation is to identify which system, subsystem or component qualifies to be classified as SCEs (Hokstad et al., 2010). Screening could determine which critical systems/components are particularly sensitive to ageing and whether ageing mechanisms could influence safety during LE period of operation. Screening of installation critical systems have the additional benefit of identifying systems/components with higher risk of failure for further detailed analysis and prioritisation (Palkar and Markeset, 2012). For ease of identification of safety relevant equipment, installation must be divided into major systems, with each system further divided into sub-

systems and components (Khan and Haddara, 2004; Khan et al., 2008; Krishnasamy et al., 2005; Rausand and Hoyland, 2004). The process of screening and prioritising SCEs has become a pre-occupation of many companies in the O&G industry who desire to extend operations beyond the original design lives of their installations.

Some studies which have proposed various means of identifying, screening and prioritising SCEs are highlighted. NORSOK (2001) specified that screening activity should be based on classification of critical failure and the resulted consequences of the failure of critical systems. In most cases qualitative categorisation of consequences is used such as; low, medium and high. If consequences of failure of a particular critical system/component is high after initial screening then, the system is considered critical and further analysis and secondary screening is required to achieve ALARP (as low as reasonably possible). When consequences fall within medium category, then the system is considered critical but it is not compulsory to carry out secondary analysis. It should be enough to follow prescribed ageing management strategy or safety management system. When consequence category falls within the low category, it is normally recommended that the system does not comprise safety and the system/component is not considered critical.

Other studies have relied on already prepared industry list and expert knowledge as the basis for screening and prioritisation of critical systems/components. These lists are often more generic and less helpful in specific cases during LE decision making process. Scientific works published by Hokstad et al. (2010), Horrocks et al. (2010) and Cortina et al. (2014) contains list of SCEs present in the offshore O&G industry. Nezamian and Nezamian (2014) suggested that the use of generic list and experts, including consultant and operators for screening and prioritisation of SCEs often results in confusion. Hence, there is a growing need for a systematic and structured approach for screening and prioritisation of SCEs for extended operations.

2.8.3.1.2 Condition Assessment

Majority of critical systems/components in the offshore O&G industry are characterised by various failure modes, located in deep water and operates under harsh environmental conditions making condition assessment a very important part of LE decision making process. Vaidya and Rausand (2009) defined condition assessment as a means of evaluating the current health status of equipment/components at a given time. Currently, assessing the condition of existing facilities to support LE decision making process in the offshore O&G industry is demonstrated by means of qualitative, quantitative or semi-quantitative methodologies.

Qualitative assessment methods found in a literature are highly dependent on expert knowledge. Among the studies that have used qualitative condition assessment techniques for LE assessment are presented. Vaidya and Rausand (2011) applied qualitative failure mode effect analysis (FMEA) approach to determine current condition of production systems based on RPN values. Ray et al (2011) employed visual examination and chemical wet method based on changes of tube colour for health assessment of 22 years exposed radiant tube found in an oil refinery. Palkar and Markeset (2012) suggested the use of qualitative risk assessment and gap analysis in assessing current health status of offshore O&G assets for LE. Pederson et al. (2013) and Nezamian and Clarke (2014) applied a qualitative risk assessment methodology to assess the condition of mooring lines and other structures for LE. Liu et al. (2014) employed a qualitative risk assessment to assess current condition of existing SCEs for LE on a platform in the China Bohai Bay. Adamou (2014) employed gap analysis to evaluate the condition of cryogenic tanks for recertification and LE by assessing “*To Be and AS Is*” conditions. Carvalho et al. (2015) employed qualitative risk assessment tool to assess the conditions of existing subsea systems for LE. Muren et al. (2016) applied expert knowledge to assess the condition of flexible riser for continuous operation.

Quantitative tools have also been used to assess the condition of offshore O&G facilities to support LE decision making process. Grigorian et al. (2001) applied

reliability technique for condition assessment of offshore structures in the Norwegian sector of the North Sea. Albertini et al (2011) developed analytical condition assessment approach which combines semi-empirical models and experimental techniques. The method was applied to assess the health status of a high pressure gas well by calculating rate of metal loss and general fitness for service assessment.

The API 579-1/ASME FFS-1 standard is developed for fitness-for- service assessment of various systems/components in the refining and petrochemical industries but has been applied successfully in the upstream sector of the O&G industry (Nettikaden et al., 2014). The fitness for service assessment involves the use of engineering quantitative equations to demonstrate that equipment already in service contains flaws or damage i.e. corrosion or fatigue cracks. The procedure follows 8 basic steps and for more on its application readers are referred to Anderson and Osage (2000). However, it is very analytical and may require much time for processing and also may require workforce with competence in reliability studies (Hudson, 2008). It is also highly dependent on high quality data to achieve desired outcome (Anderson and Osage, 2000). Ramírez and Utne (2013) and Ramírez and Utne (2015) proposed an approach to facilitate technical assessment of repairable systems using Dynamic Bayesian Network (DBN) for purposes of LE. The model was based on parametric models considering degradation process, imperfect maintenance, cost, safety and risk as well as expert knowledge in providing probabilities of inputs variables. However, DBN relies on empirical data for decision making but such data for LE assessment of offshore O&G facilities are limited (Hokstad et al., 2010; Ramírez and Utne, 2015). Hutchison et al. (2016) utilised Finite Element Analysis (FEA) to assess the remaining fatigue lives of key components on flash separator vessel constructed in the 1990 as benchmark for LE of similar separator vessels. Sari et al. (2016) carried out nonlinear pushover analysis using FEA to model structural corrosion damage for strength assessment of fixed offshore platforms for LE. Sahasakkul et al. (2016) applied fatigue reliability approaches with Monte Carlo simulation to assess the strength of fixed offshore platform for LE. Selman and Hubbard (2016) assessed the

condition of a flowline for LE by analysing 5years operating data using quantitative tool like Monte Carlo simulation. Omari et al. (2016) performed fitness of service assessment of crude oil storage tanks for LE using Computational Fluid Dynamics (CFD) and FEA simulations. Aeran et al. (2016) applied time dependent corrosion model to assess the suitability of ageing offshore structures for LE.

Semi-quantitative condition assessment techniques are recently gaining popularity because both the qualitative and quantitative techniques have limitations. Therefore, applying semi quantitative condition assessment technique ensures that the strength of one technique compensate the weakness of the other technique. Studies that have applied semi-quantitative condition assessment techniques to support LE feasibility assessment are briefly described. Ingvarson et al. (2009) and Refsdal and Urdahl (2014) developed a semi-quantitative condition assessment technique called Teknisk Tilstand Sikkerhet (TTS) for assessing the current health status of existing topside components. TTS technique has been applied in Norway to determine the current health status of a safety component. TTS is a structured approach of evaluating the technical safety of existing process safety equipment/components and has successfully been implemented on 35 offshore and onshore installations (Ingvarson et al., 2009). However, the approach does not consider age, usage and frequency of failure occurrence which are fundamental input for LE decision-making. Nezamian et al. (2016) applied semi-quantitative condition assessment technique to assess the feasibility of extending the service life of gas distribution facilities and pipe network. Shafiee et al. (2016) developed the condition index matrix tools to support the condition assessment of water deluge system for LE.

2.8.3.2 Economic Assessment

The purpose of economic assessment is to identify the cost drivers and economic assessment tools required for LE decision making process. Economic analysis for LE could assist companies to determining whether; LE is a better

alternative as compared to other EOLMS or which LE strategy would result in greater net benefit to companies during LE phase of operations.

In order to evaluate the economic feasibility of LE project, extended cost calculations should be carried out based on the cost drivers. The project must be evaluated using project economics approach, accounting for all CAPEX, OPEX and production revenue accruing over the remaining life of the field. Baseline and benchmark cost of existing activities prior to LE process must be established, so that economic impact of LE activities could be measured. Typical OPEX cost would include labour cost, shutdown cost, administrative cost, O&M cost and regulatory cost while replacement, repair, retrofitting or anything other modification cost would be classified as CAPEX. However, unlike the development of a Greenfield, LE phase of operation involves huge risk and therefore the risk expenditure (RISKEX) must be taken into account during economic analysis.

According to Joshi et al. (1998) some of the inputs parameters for economic assessment of LE are uncertain and should be treated as random numbers using Monte Carlo simulation or sensitivity analysis. Basic economic analysis tool such as net present value (NPV), cost-benefit ratio (CBR), annualised cost method (AMC) and internal rate of return (IRR) are used for economic analysis in the offshore O&G industry.

2.8.3.2.1 Net Present Value

Net Present Value (NPV) has traditionally been used for evaluating economic potential of offshore O&G projects (Ferreira and Suslick, 2001; Gupta and Grossmann, 2012). NPV have the advantage of bringing "time value of money" into the calculation as compared to other approaches. To measure the NPV of a project, the relevant project cash flows are specified, and the time value of money is taken into account by discounting future cash flows by the appropriate discount rate. The formula used to calculate NPV is expressed as:

$$NPV = \frac{X_t}{(1+r)^t} \quad (2-1)$$

where X_t is equal to the cash flow at year t , T is the time period considered (in years) and r is the discount rate. Even though its application in the offshore O&G industry have been acknowledged, very little is published on using NPV for LE economic analysis. According Aven et al. (2007) NPV could be supplemented with uncertainty assessments to determine which economic parameters when changed are likely to impact decision making. Chitwood et al. (2004) utilised NPV analysis to assess the suitability of marginal fields for LE.

2.8.3.2.2 Cost Benefit Ratio

The purpose of cost benefit ratio (CBR) analysis during LE is to provide a reliable procedure for evaluating decision in terms of consequences and benefits. It requires monetary estimation of both cost and benefit. In practices, if the ratio of benefit to cost exceeds one, it is always advisable for regulators to approve operators request for LE. However, cost and benefit must be fairly balanced. The standard procedure for CBR is to assign monetary values to a list of burdens and benefits. CBR struggles as an approach where a project has cash flows that come in over a number of periods of time, particularly where returns vary from period to period.

2.8.3.3 Integrated Approach

Although technical and economic assessment of LE produced some level of results for companies and regulators, they are with some shortcomings. Decision making tends to skew to one side, sometimes leading to incorrect conclusion and recommendations. Therefore, successfully integrating the two approaches for LE assessment is increasingly becoming crucial in the offshore O&G industry. However, evidence from literature indicates that no study has successfully combined the two assessment methods to support LE decision making process.

Overview: A total of 32 published works were reviewed in this area. Out of the 32 publications reviewed, 4 (12.5%) publications are associated with screening and prioritisation of SCEs. However, three of the publications relied on generic

list from the industry while one study used experts' opinion as means of identifying, screening and prioritising SCEs for LE.

Also, 27 (87.5%) publications out of the 32 publications focused on development and implementation of various methodologies to perform condition assessment for LE. Out of the 27 publications reviewed on condition assessment, 15 publications employed quantitative approaches to assess the suitability of equipment for LE, followed by qualitative approach with eight publications and semi-quantitative approach with four papers. Therefore, there is the need to intensify the use of semi-quantitative approaches for LE assessment of SCEs. This is because both qualitative and quantitative approaches have limitations, thus using the semi-quantitative approach; the strength of one approach will complement the weakness of another approach. On the other hand, one study was identified to have employed the use of NPV to assess the suitability of marginal fields for LE. The use of economic assessment and integrated assessment techniques have received limited attention in literature. Therefore, in order to qualify assets for LE, future research must seek to integrate technical and economic assessment techniques due to the benefits this approach offers.

2.8.4 Remaining Useful Life

Remaining useful life (RUL) estimation is central to LE decision making process. RUL of SCEs is random and in most cases unknown, therefore it must be estimated using available data obtained from condition and health monitoring. The concept is now gaining popularity in many safety critical industries due to the advancement in condition and health monitoring systems. According to Banjevic and Jardine (2006); Si et al. (2011) and Galar et al. (2012) the amount of time left before a system fails to operate within acceptable criteria is referred to as RUL. The objective of RUL is to predict failure before it occurs based on current and past conditions of a system (Jardine et al., 2006). It is one of the important factors to consider when implementing condition monitoring (CM) and prognostic health management (PHM) (Cui et al., 2004; Lee et al., 2006; Si et al., 2011). Wang and Zhang (2008) suggested that

accurate and proper estimation of equipment RUL is essential for cost-effective operations as well as prompt maintenance response. In the last few years, RUL has emerged as a possible technical health assessment decision making tool for equipment in the offshore O&G industry while keeping lifecycle cost low and helping operators meet regulatory requirements.

2.8.4.1 Remaining Useful Life Classification

Literature on RUL estimation to support decision making in the offshore O&G industry covers both deterministic and probabilistic methods. RUL approaches are classified as physics based approach, data driven approach and fusion approach which is a hybrid of the physics and data driven approaches (Varde et al., 2014) while Ahmadzadeh and Lundberg (2014) in a study added the experiment based approach as the fourth classification. Brief discussion and application of each approach in the offshore O&G industry is presented below.

2.8.4.1.1 Physics Based Approach

The fundamental principle behind the physics based approach is the formulation of theoretical mathematical models to describe equipment degradation and damage modelling over time. These models involve typical description of failure modes such as crack propagation, wear and corrosion degradation rate of equipment (Galar, et al., 2012). In situations where accuracy of prediction is important, access to data is limited and taking into consideration environmental conditions, the physics-based models are suitable. These models are often expressed by means of differential equations or partial differential equations and are solved analytically or numerically due to their level of complexity.

In the offshore O&G industry, studies that have employed physics based approach for estimating RUL to support decision making process are highlighted. Dowdy and Graham (1988) developed a methodology for predicting the RUL of an in-service mooring chain. Divine et al. (1993) presented both qualitative and quantitative approaches for determining the RUL of submersible pumps used in the upstream sector of the O&G industry. Ammtatmula and Ohl (1997) investigated the corrosion related life limiting conditions of a double-shell tank and later developed a model to estimate the RUL of the tank for extended

service life. Vaidya (2010) discussed the technical health factors that influence RUL decision making in the offshore O&G industry. The paper suggested the use of Bayesian Belief Network (BBN) for RUL estimation. Vaidya and Rausand (2011) proposed LE decision making model based on RUL prediction, the decision model combined heterogeneous requirements such as degradation modelling, uncertain environmental and operational conditions, uncertain sensor data and expert judgement. The study further concluded that physics based approach is most suitable to support LE decision making in the offshore O&G industry. Yasseri and Mahani (2016) developed a simple spread-sheet probabilistic procedure to support engineers in determining the RUL of offshore O&G pipelines. The approach was based on reliability index methods.

2.8.4.1.2 Data Driven Approach

The data driven approach employs network of sensors to monitor equipment health status. Data is further extracted from sensor signals and RUL prediction models such as Bayesian models, Cox model, regression model etc. are then used to estimate remnant life of equipment. In the offshore O&G industry, studies that have employed data driven approach for estimating RUL to support decision making process are presented. Kallenberg (1998) developed a probabilistic RUL approach to determine the remaining service life of reformer furnace catalyst tubes. The proposed methodology was used to estimate cumulative probability of failure, time-to-crack initiation, and time-to-failure in terms of the furnace operating hours. Kallenberg and Freeway (2002) outlined the information and guidance needed to estimate the RUL of catalytic reformer reactor in a petrochemical refinery using data driven approach. Garvey et al. (2009) introduced the pattern recognition based method to predict the RUL of bottom-hole assembly tool. Gola and Nystad (2011) employed statistical methods to calculate the degradation and RUL of choke valves used in the oil industry. Wilks (2012) demonstrated how corrosion process data could be used in omega simulation to predict the RUL of Coker furnaces in refineries. Nystad et al. (2012) investigated the problems associated with RUL prediction in the offshore O&G industry when using stochastic models. Sharifi et al. (2015) predicted the RUL of pipes using machine learning technique from thickness

measurements in order to alert maintenance engineers when to take appropriate action.

2.8.4.1.3 Fusion Based Approach

The fusion based approach was proposed because both physics based approach and data driven approach have limitations (Cheng and Pecht, 2009; Varde et al., 2014). For the fusion based approach the strength of one approach compensate the weakness of another. The approach combines sensor acquired data and physics based monitored data to form new database in order to predict RUL of a system. The approach has been applied to cases in electronics, railway and the aircraft industries (Cheng and Pecht, 2009; Galar et al., 2013; Sankavaram et al., 2009; Xu et al., 2014). In the offshore O&G industry, studies that have employed fusion based approach for estimating RUL to support decision making process are presented. Nystad et al. (2010) proposed prognostic model as a solution to a practical prognostic problem for Norwegian oil company, Statoil. The model was used to estimate the RUL of choke valves on a platform subjected to erosion due to sand particles in well product. Jaske and Shannon (2007) combined specialised analytical models with a multi-parameter inspection technique to predict the RUL of reformer tubes. Gola and Nystad (2011) proposed a diagnostic-prognostic model for estimating RUL as well as the technical health condition of choke valves on O&G platforms.

2.8.4.1.4 Experimental Based Approach

The experimental based approach collects data for RUL estimation through experiments for better understanding of the life time and behaviour of equipment. Data obtained from accelerated life testing of components in laboratories using test rigs to simulate the real life condition is a typical data collection process for this approach. For example Medjaher et al., (2012) verified the physic based approach and data driven approach utilising experimental data obtained from accelerated life testing of bearings.

In reviewing literature on RUL estimation and its application in the offshore O&G industry, the physics based approach and data driven approach are popular and have been researched by many studies compared to other approaches.

However, Vaidya and Rausand (2011) indicated that the physic based approach is most suitable for LE application for equipment in the offshore O&G industry. Hokstad et al. (2010) also indicated that due to the limited access to good quality data in the offshore O&G industry, physic based approach is suitable for LE analysis, since it require fewer data in comparison to the other approaches. However, to the best of the author knowledge, few studies have attempted to establish a relationship between condition assessment of critical assets, RUL prediction and LE decision making.

2.8.4.2 RUL Prediction Models

Numerous prediction models have been developed to help estimate the RUL of industrial equipment. Some of the prediction models relevant for application in the offshore O&G industry are reviewed below.

2.8.4.2.1 Bayesian Model

The Bayesian technique deals with how a prior estimate should be modified in the light of additional information (e.g. later information or information from another source). A parameter to be estimated must be known on the basis of information available at the time to have a certain value, since that information is incomplete or of a probabilistic character, i.e. there is a “prior probability distribution” of that parameter. Further information with different value and probability distribution for the same parameter may be available. Bayesian technique allows the initial estimate (prior distribution) to be modified based on the additional information, in order to obtain a redefined estimate (posterior distribution). Vaidya (2010) suggested that Bayesian based RUL model presents the opportunity to combine both data from monitoring systems and expert judgement simultaneously for assessment. The selection of prior data is a difficult task during LE decision making process, where availability of good quality data is always a problem. In the absence of prior data, the selection of prior distribution should start with expert elicitation. For a comprehensive literature on Bayesian approach, readers are referred to Gelman et al. (2014).

2.8.4.2.2 Statistical Techniques and Stochastic Models

Statistical techniques are often used in processing event data to assist in identifying possible failures in the case of increasing rate of occurrence of failures (ROCOF). Statistical analysis is commonly used for reliability calculations and maintenance optimisation from available failure records collected over the life time of a system. Some of the techniques used are the counting process, regression analysis and trend test. The MIL-HDBK-189; MIL-HDBK-217F and OREDA (2009) handbooks contains statistical data and models for mechanical and electronic/electrical components respectively. For more comprehensive review on statistical data driven RUL approach, see Si et al. (2011). However, Vaidya and Rausand (2011) in a study indicated that this approach should not be used to estimate RUL of some offshore O&G components due to the scarcity of data. On the other hand, stochastic models are used to model equipment degradation process. This approach has the capacity to incorporate dynamic covariate as well as the environmental conditions. Some of the commonly used stochastic models are regression models, proportional hazard models, Cox regression models and Weibull regression models (Cox, 1972; Kumar and Westberg, 1996; Newby, 1994; Singpurwalla and Wilson, 1995; Vlok et al., 2002; Wang, 2002). A comprehensive review on stochastic models for RUL prediction can be found in Singpurwalla (1995).

2.8.4.2.3 Computational Intelligence Models

Computational intelligence (CI) models involve techniques such as artificial neural network (ANN), genetic algorithms (GA) and fuzzy logic. The CI techniques require inputs data to achieve the required output and are sometimes referred to as *Soft Computing* techniques (Okoh et al., 2014). Data obtain from sensors and other monitoring equipment can be used by intelligent models to predict RUL. A comprehensive review on CI models can be found in Siddique et al., (2003). Nonetheless, Vaidya and Rausand (2011) suggested that it may be impossible to use this approach for predicting RUL of subsea facilities to support LE decision making process due lack of available data,

impossibility of obtaining training data as well as lack of knowledge and trained personnel to use these models.

2.8.4.2.4 Physic of Failure

Physics of failure (PoF) techniques require parametric data and engineering knowledge on topics such as life cycle assessment, environmental stresses, operating conditions, material selection and degradation mechanisms. The purpose of this RUL prediction technique is to identify possible failure causes and how to eliminate the potential operational failures through design. The technique makes use of accurate mathematical principles which in effect provide details of component life and reliability. It is applicable to wide range of systems including mechanical and electrical/electronics. According to Vaidya and Rausand (2011) this approach is suitable for predicting RUL of offshore O&G systems to support LE decision making. This is because offshore operations is remote and require accurate models to support LE decision making. The PoF techniques are considered consistent for LE analysis and require less sensor data for possible RUL prediction. Also, Winning and Belhimer (2006) described data obtained from monitoring sensors in offshore O&G industry as unreliable thereby making PoF technique popular. The technique is suitable for RUL prediction of components that suffer from degradation such as fatigue cracks, corrosion, erosion and wear.

2.8.4.2.5 Expert Judgement

This technique is specific to experience and knowledge gathered by experts over a period of time. In the offshore O&G industry, environmental and operational factors changes over a period of time with respect to the factor considered during design. In this case expert judgement and experience becomes crucial in predicting the RUL of systems and components. This approach has been employed in literature for maintenance optimisation and reliability analysis for various system and components (van Noortwijk et al., 1992). Vaidya and Rausand (2011) discussed the reasons why expert must be engaged for RUL prediction in the offshore O&G industry. Data gather from

experts through elicitation can be very useful in situation where sensor data, observation, experimental and simulated results are unavailable.

Overview: The literature review indicates the application of RUL concept to support decision making is becoming popular in the offshore O&G industry. A total of 17 publications have utilised the RUL concept in the offshore O&G industry, with seven publications using data driven approach, 6 physics of failure approach, 3 fusion-based approaches and zero experimental based approach. However, very limited effort has been directed towards investigating how the concept of RUL can support LE decision making in the offshore O&G industry.

2.8.5 Life Extension Strategies

In order to successfully complete a LE programme, selection of suitable LE strategy depending on the condition of the asset is very crucial in the offshore O&G industry. There are different LE strategies that could be considered for LE of SCEs in the offshore O&G industry. However, each strategy has its potential advantages and disadvantages and failure on the part of LE decision making team to select the most suitable LE strategy could impact equipment operations negatively. The strengths and weaknesses of each LE strategy based on factors such level of improvement, material addition; labour cost and complexity of the strategy are identified. A brief description of each LE strategy is presented below.

2.8.5.1 Replacement

This LE strategy is described as the activities to substitute an existing system or component with a new one or upgrade system at the end of original life irrespective of the functional status of the system. Replacement actions in most cases return a system or component to “*as good as new condition*” (AGAN). However, its application is cost intensive, results in potential outages, presents safety consequences and results in longer downtime, therefore a decision to select replacement as a suitable LE strategy must consider factors such as the risk of unavailability, economic implications of the duration of replacement and implications of lack of good quality data. Due to these factors, the decision to

replace systems versus other LE strategies becomes supreme only when there is difficulty in acquiring obsolete parts, overly increasing maintenance cost, changes in regulations, insurance consideration, warranty consideration, high attrition rate of staff and ageing work force. However, replacement as a LE strategy is famous in some industries, especially the nuclear and electrical utility industries. This is because it is regarded as the most suitable LE strategy for obsolete instrument and communication systems.

2.8.5.2 Reconditioning

Reconditioning involves restoring a system to satisfactory working condition while its outputs may be lesser to that of OEM original performance (Ijomah et al., 2007). Normally, the improved equipment has a warranty that is less than that of a newly manufactured equivalent (Ijomah et al., 2007). As compared to remanufacturing, reconditioning as a LE strategy involves less work and labour. This is because reconditioning requires rebuilding and replacing major components of system to functional condition, which is regarded inferior compared to original model from OEM (King et al., 2006). This strategy has widely been used for household products such as fridges and washing machines, thereby creating “grey goods” market. The strategy is appropriate for systems with low obsolescence, high inherent material failure and easy to assemble and disassemble. It has added value of low production cost and environmental impact, since components with high failure rate are the ones remedied. It also has the social benefit of improving the skill and technical knowledge of workforce. On the other hand, the warranty of reconditioned systems is limited making people raise concerns about the quality of product.

Kin et al. (2014) grouped reconditioning processes into five classes namely; removal of dirty surfaces, exposure of defects, addition of extra materials, restoration of material properties, assembling and fastening and super surface finishing. From the classification, it is clear that knowledge of design principles and requirements, material properties and damage tolerance are required to drive reconditioning process as a suitable LE strategy.

2.8.5.3 Remanufacturing

Remanufacturing is considered as the most environmentally friendly LE strategy alternative for ageing systems. A remanufactured system can easily replace a new system, with the benefit of avoiding resource use and emissions associated with production of new system. Also, remanufactured product is sold for 50-80% of the new product (Gutowski et al., 2011). Hence, remanufacturing is not only considered environmental friendly but also economically favourable LE strategy (Animah et al., 2017). Ijomah et al. (2007) indicated that the condition of a remanufactured product is equivalent to specification with functional state warranty of OEM's newly manufactured product. Its implementation focuses on possible product upgradability through the use of standardised modularisation; in order to accommodate future changes in standards and technology into equipment at the design stages. This means that the decision to use remanufacturing as LE strategy must be made at the design stages of asset lifecycle. The strategy requires significant time and high investment cost to start the remanufacturing process. It is suitable for systems with major components having high inherent material failure and easy to assemble and disassemble.

The strategy has added value of reducing usage of materials, reducing workload and retaining profit by reducing production cost but it has high initial cost. However, SCEs which cannot be dismantled or disassembled cannot undergo remanufacturing process to return equipment to manufacturer's specification. Also, the strategy requires significant time and high investment cost to start the remanufacturing process.

2.8.5.4 Retrofitting

Retrofitting is the process of replacing old components or equipment on an installation with modern equivalent. It is ideally conducive for equipment and components with highest maintenance cost and failure rate. Retrofitting results in increased in functionality, availability, safety and also reduces equipment downtime. Retrofitting represents the best strategy, if the aim for LE is modernisation.

2.8.5.5 Use-up

Use-up is an economic driven strategy which cannot be ignored during LE decision making process. It is the process of operating an equipment or component on an installation until the end of its economic life (i.e. operating cost of equipment in terms of maintenance and service cost become over excessive). Although use-up is mainly an economic driven strategy, it can sometime be selected from safety and reliability point of view. Factors such as old design, increasing rate of ageing and the risk of maintenance induced failures may compel asset managers to run an asset to fail and dispose it. Experiences from use-up strategy may be used as basis to review economic value of investing in other strategies.

2.8.5.6 Refurbishment

Refurbishment refers to actions taking near the end of life in order to return a system to its functional state and achieve a performance higher than OEM functional requirement. This strategy integrates partial replacement, reconditioning and partial redesigning. The process involves high labour cost and addition of extra material while ensuring high level of improvement during LE phase of operation.

2.8.5.7 Repair

Repair as a LE strategy restores a system to functional condition after damage or failure. This strategy is adopted in complex engineering systems LE due to the fact that many sub-system and components have different life expectancy. It is also the simple and less expensive LE strategy compared to other strategies. Repair activity for LE may be carried out using parts of existing system, parts provided by manufacturer or by an outsourced company. Repair as a LE strategy is popular especially in the electrical utility industry. Generally, the quality of a repaired system is low compared to those of reconditioning and remanufacturing alternatives.

2.8.5.8 Repurpose

Repurpose is creating a new “use or purpose” for system that has reached its original design life by making some transformation to key components (Aguirre, 2010; Coughlan et al., 2015). With this strategy the system is used for purpose it was not originally design for during LE phase of operation. Repurpose as a LE strategy has the advantages of providing users with additional functions from systems they might have been discarded, it reduces environmental impact provided transformation avoids production of parts and the flexibility in allowing users to change functionality of the system to maximize the potential of their businesses. The strategy is now gaining popularity in the E-waste sector as a driver for resource efficiency. Also, in the offshore O&G industry, ocean tankers that reaches end of life are converted to FPSO for a new purpose. The strategy is useful in extending the lifetime of assets by avoiding early disposal.

2.8.5.9 Re-use

The objective of this LE strategy is to put back a system into service for the same purpose it was designed for beyond original design life without any manufacturing process. It involves leasing the system or selling the system to new owner or the original owner continues using the system (Linton and Jayaraman, 2005). Systems with low technological and aesthetic obsolescence are suitable for reuse at the end of life and are often sold on second hand markets. Due to the economic prospects of this strategy, it is commonly used in the automotive industry (Ferrer and Whybark, 2001). The cost of this strategy is less than cost of reconditioning, remanufacturing, repair and retrofitting strategies. The cost for testing of the equipment for quality control purposes represent the main expenditure as results of selecting re-use as the suitable LE strategy. The labour cost is also low, since the strategy focuses on removal and placement of equipment. The strategy also results in less environmental impacts compared to other strategies. However, there are concerns of poor quality and less fitness for service products.

2.8.5.10 Reclaiming

Reclaiming is a suitable LE strategy for assets such transformers. This is because the temperature of insulating oil is the main cause of ageing in electric transformers causing change in the mechanical and electrical properties of the dielectric structure (Raymon and Karthik 2015). This strategy enhances the aged insulating oil for reuse, which help asset manager to save money from not investing into oil due to shortages. The strategy is also beneficial in preventing the harmful disposal of used transformer oil into the environment. The process of reclaiming involves refining transformer oil by eliminates all contaminants and insoluble particles to attain oil with features similar to new transformer oil.

2.8.5.11 Retrofilling

This strategy is appropriate for extending the life of transformers by replacing existing transform oil with natural ester dielectric coolant. Retrofilling present similar advantages to reclaiming, however, unlike reclaiming, during retrofilling the old oil is disposed-off. However, implementing retrofilling at the end of original design life does not only extend lifetime of transformer but also increases the fire safety of the transformer. For more on retrofilling procedure, reader can refer to (Mcshane and Rapp 2003; Moore et al., 2012).

2.8.5.12 Process Control and Safety Add on Measures

This strategy involves using the existing systems entirely, however, processes control systems or safety add-on systems or hybrid of process control and safety-add on systems are introduced to reduce the risk posed by extending the life of the system. These strategies are mostly applicable to process system LE.

The strength and weaknesses of some LE strategies considered in this research are shown in Table 2-2.

Table 2-2 Strength and weakness of LE strategies (Shafiee and Animah, 2017)

Strategy	Level of improvement	Material addition	Labour cost	Added value	Complexity
Replacement	Moderate	High	Moderate	High	Moderate
Reconditioning	High	Low	High	High	High
Remanufacturing	High	Low	High	High	High

Retrofitting	High	Moderate	Moderate	Moderate	Moderate
Use-up	Low	Low	Low	Low	Low
Refurbishment	High	Moderate	High	High	High
Repair	Moderate	Moderate	Low	Moderate	Moderate
Re-use	Low	None	Low	None	Low

The list of references that have applied LE strategy to support LE decision making process in the offshore O&G industry are summarised in Table 2-3.

Table 2-3 Summary of studies that have applied LE strategy

Ref	Strategy applied	Component strategy applied	Selection method
Blanksby et al. (2005)	Replacement	Horizontal tree and Electrical submersible pump	Not specified
Hudson (2008)	Replacement	Piping, weather and fire doors and diesel generator	Not specified
Hudson (2009)	Replacement	Pipe works, weather and fire doors and rotating equipment	Not specified
Lewis et al. (2009)	Replacement	Process control system, fire and gas protection system and emergency shut down system	Not specified
Windle & Broos (2009)	Refurbishment	Offshore platform and onshore gas plant	Not specified
Brandt & Mohd Sarif (2013)	Replacement and refurbishment	Tank, control systems and topside pipework	Expected knowledge
Leira et al. (2015)	Replacement and repair	Riser	Not specified
Nezamian et al. (2016)	Replacement	Gas distribution facilities and pipeline network	Expected knowledge
Muren et al. (2016)	Repair	Riser	Expected knowledge

Overview: As can be seen in Table 2-3, 9 publications have applied LE strategies to support LE decision making in the offshore O&G industry. Majority of the publications under this category identified replacement as the most suitable LE, followed by refurbishment and repair. Also, the method used for selecting suitable LE strategy has not specified in most publications and few publications have used experts' knowledge to select suitable LE strategy.

2.8.6 Decision Support Methods for Life Extension

In this section different decision support methods (DSMs) can that enhance decision making by stakeholders during LE phase of operation are discussed.

The DSMs are classified into life cycle costing benefits (LCCB) technique, multi-criteria decision making (MCDM) methods and expert judgement.

2.8.6.1 Life Cycle Costing Benefits Approach

In literature, very few studies have applied LCCB concept to evaluate and select suitable decision alternatives. LCCB philosophy is an extended concept of LCC which takes into account costs (benefits) elements not included in the conventional LCC analysis. Although, it is a relatively new concept, it is gaining some interest in recent years. For example, in the steel and concrete bridges industry, Thoft-christensen (2006) discussed the importance of modelling user costs in LCCB analysis and developed a parametric model for estimating the benefits. The model demonstrated clearly the importance of including user cost in estimating economic consequences of maintenance and replacement work of single bridges in order to reduce potential travel time. Thoft-christensen (2008) highlighted the benefits of LCCB concept and modelled user cost in LCCB analysis for bridges. The paper further demonstrated how to relate and estimate user cost for repairing single bridges. It concluded that the high discount rate set out by politicians is one of the key limitations to the LCCB approach. Padgett et al. (2010) developed a framework for risk-based seismic LCCB analysis. The framework integrated probabilistic seismic hazard models, fragility of as-built and retrofitted bridges for a range of damage states, and associated costs of damage and retrofit. The framework was subsequently applied to evaluate and select the best retrofitting strategies among five different strategies such as steel column jackets, elastomeric isolation bearings, steel restrainer cables, seat extenders, and transverse shear keys. The paper further suggested that the LCCB approach provided an opportunity for a paradigm shift from the current investment cost analysis to evaluation of life-time expected loss through strategies such as retrofit. Thoft-Christensen (2012) discussed the design and maintenance of bridge infrastructure using LCCB approach and subsequently developed an LCCB model for maintenance of bridge infrastructure. The model included key cost components such societal, owner, user and environmental cost, which are not used in the conventional LCC

analysis for maintenance of bridges. The key contribution of this paper was that user cost dominates cost of inspection and repair of infrastructure.

In other applications, Carter and Keeler (2008) in a study quantified data collected from an experimental green roof plot to develop LCCB model for the lifecycle assessment of (thin layer) green roof systems in urban Tanyard Branch watershed. The results of the LCCB analysis compared green roofing (vegetation on roof) to traditional roofing scenario. Li and Madanu (2009) proposed a novel uncertainty based LCCB methodology for evaluating highway projects considering inputs factors capable of handling uncertainties in the calculations. The model was applied to a case study to assess the impacts of risk and uncertainty consideration in estimating overall benefit of a highway project under deterministic, risk and uncertainty scenarios. The case study results revealed that using the proposed uncertainty based LCCB methodology has an added value of higher percentage of matching rate compared to the matching rate when using risk based or deterministic approaches. The paper further concluded that the LCCB methodology provides an opportunity to address the issue of uncertainty characterising project life-cycle benefit/cost analysis to enhance decision making. Shen et al. (2011) employed LCCB analysis to evaluate the roof greening project in urban buildings in China. The study provided the path and method for estimating economic benefit and cost calculations, which is considered as reference for evaluating the value of urban roof greening projects in China. However, the paper failed to validate the model with appropriate case study. The benefit and cost evaluation criteria considered in the study included economic, environmental and social impact of roof greening projects on a whole building's lifecycle. Yang et al. (2016) developed LCCB model for economic evaluation of green roofing projects of urban buildings in China, taking into account social and environmental cost. Here, various risk and opportunity factors such as electricity price and government incentives were considered in the LCCB calculation. The key contribution of this study was the demonstration of in-depth understanding of applying LCCB to Building Integrated Photovoltaics (BIPV) projects by considering comprehensive costs and benefits factors during the life span of the project.

2.8.6.2 Life Cycle Costing Approach

The LCC concept is a traditional decision making method which considers all direct cost incurred over the life-time of an asset ranging from explorations to decommission. The studies using LCC concept to address economic challenges of field development and platforms design and operations have dominated literature in the offshore O&G industry and these studies are highlighted.

Smith and Celant (1995) utilised the LCC approach to compare the cost of alternative materials by estimating present value of future cost related to the selected material. The approach was used to compare the cost of alternative materials for downhole tubing and subsequently selected the most suitable material by calculating the present value associated with each material. The results of the analysis indicated that using expensive corrosion resistance alloys (CRAs) at the start of a project rather than selecting a cheap material such as carbon steel, ensures significant saving in operation, maintenance and repair cost in the future. Winkel (1996) employed LCC for material selection during the conceptual phase of the Ekofisk redevelopment project. The study concluded that the increasing use of LCC as an evaluation tool is good for the offshore O&G industry, since it can profitably be applied to both green and brown field development. However, the authors pointed out that the discount rate and service tubing life are key decision making parameters. Vorarat et al. (2004) explored the possibility of implementing LCC model in the offshore O&G industry. The study proposed a systematic process which provided a structural breakdown of cost. The model was applied to a water injection pump case study using data stored in SAP (System Application and Product in Data Processing) for existing offshore O&G assets. Islam and Powell (2005) employed LCC analysis to select the most suitable material for flowline replacement for a major O&G company in the Middle East. The study was limited to the analysis of four different materials such as carbon steel with inhibitor, in-situ coating, in-situ HDPE linings and corrosion resistance alloys (CRAs), with alternative materials such as GRP and GRP-lined steel. The LCC calculation showed that the use of in-situ HDPE linings was the best option while carbon steel with inhibitors or CRAs were least attractive option from economic perspective. Kayrbekova and

Markeset (2008) applied LCC concept to develop operational, maintenance and support services strategies to help reduce risk. The study further discussed the challenges associated with LCC concept and its application to operations and maintenance support of advance complex and integrated offshore O&G production facilities in harsh environment. Kayrbekova and Markeset (2010) investigated the current practices available for usage of LCC in the NCS and the need for possible improvement. The study methodology focused on interviewing industrial experts and review of literature on LCC. Kayrbekova et al. (2011) discussed the difference between activity based LCC (AB-LCC) and conventional LCC used in engineering design. In order to perform quantitative comparison of the two concepts, the study applied both methods to case study in the Arctic offshore environment. The results from the case study indicated that AB-LCC is capable of handling both cost and cash flow, in contrast to conventional LCC approach which deals with cash flow only. Also, it is easier to establish the cause and effect relationship between activities and cost when using the AB-LCC methodology. Nam et al. (2011) proposed a new LCC methodology taking into account risk expenditure for comparative evaluation of offshore liquefaction process alternatives at conceptual design stage. The study further demonstrated that LCC can play a key role in selecting best liquefaction process alternative for floating LNG production facility. Burlini and Araruna (2013) applied the concept of LCC analysis to waste management during the exploration phase of offshore O&G projects in Brazil. The goal of this study was to help companies involved in exploration of O&G in Brazil to integrate LCC methodology into waste management decision-making in order to comply with current regulatory regime. Marten and Gatzen (2014) developed an integrated bottom-up LCC approach to support objective decision making through transparency of cost by oilfield service providers. The model development involved professionals such as process developers, cost subject matter experts, R&M specialists as well as purchasing and manufacturing engineers. The approach was used in proposing a cost effective solution for a close-loop-rotary steering service for oilfield service provider. The outcome of the validation process indicated that the model can help oilfield service providers to forecast,

monitor and decrease CAPEX and OPEX simultaneously. Gordon and Duncanson (2015) discussed the importance of cost drivers in managing uncertainty to deliver sustainable unmanned operations, develop operational philosophies and design out hazards, in the early stages of projects. The study brought to light the ability of appropriate LCC model to help reduce cumulative risk to individuals and contribute significantly to project certainty. Wardt and Peterson (2015) provided a cost classification framework which is intended to improve decision making by asset managers when investing in wells, planning for selection of suitable well design and drilling technologies and improving the control of cost. The author further suggested that LCC models are appropriate for optimising well development cost. This is because it enables range of costs in an uncertain and risk environment to be expressed in a way that support decision making. Johannknecht et al. (2016) developed a modular and holistic model to analyse and optimise LCC and service availability of drilling systems from conceptual design phase through to deployment. The modular models are connected for exchange of data through standard interfaces and calculate future projection and identify key cost drivers. The model ensured continuous optimisation of cost throughout asset lifecycle. The model was applied to support the development of a drilling tool in order to demonstrate its cost saving potential. The results indicated the approach was fast, easy to use and standardised for high-technology drilling equipment. However, the study failed to incorporate the benefits of the process into the model. Johannknecht et al. (2016) described an approach combining LCC and simulation service availability models to optimise cost of fleet for oilfield service companies. The model considered CAPEX such as material cost in addition to assembly time while the OPEX included labour, consumables, warranty charges, loss of revenue, maintenance and repair and third-party cost. The model enabled fast and easy determination of optimal fleet size (reduction in fleet cost) for different phases of oil field development. Ortiz-Volcan et al.(2016) presented LCC model for cost optimisation of thermal recovery project in a heavy green field in Kuwait. The objective of the model was to help companies understand the total cost breakdown for CAPEX and OPEX for all physical assets during economic

analysis of green field project and subsequently identify the root causes of cost drivers responsible for project cost increase and potential project delay. The cost breakdown included design, construction, installation, O&M, repair, replacement and disposal costs. Adam and Ghosh (2016) applied LCC model to assists Brunei Shell Petroleum (BSP) to compare and select the most suitable material for design of piping systems based on cost-saving. The study considered three materials namely carbon steel (CS), corrosion resistance alloys (CRA) and flexible composite pipe (FCP) system. FCP was selected as the cost-effective material for the piping system design. However, the approach focused on differences in CAPEX, disregarding OPEX. Most of the cost parameters were also based on assumptions.

The rationale for LCC analysis is to consider all direct cost incurred over the life-time of an asset ranging from explorations to decommission. However, during LE decision making process both direct and indirect cost is required for sound and effective decision making. Hence, LCC concept will be insufficient for comparing LE strategies in order to select the most suitable strategy.

2.8.6.3 Multi-Criteria Decision Making Method

Multi criteria decision making (MCDM) approach is one of the popular and commonly used DSM in the energy industry. This approach is increasingly becoming popular for decision making in the upstream petroleum sector because the conventional single criteria approach can no longer deliver appropriate results considering complexity of operations and decision making problems confronts the sector. Also, the MCDM provides a flexible approach in solving complex and multiple attributes (i.e. economic, technical, social, environmental and legal) problems by helping decision makers to make clear and consistent choices. According to Pohekar and Ramachandran (2004) the MCDM approach is appropriate for providing solutions to both conflicting qualitative and quantitative criteria of decision makers.

Several MCDM techniques have been developed for solving conflicting and multi-criteria problems. The most popular and commonly used techniques for energy planning and policy formulation includes Analytic hierarchy process

(AHP), Analytical Network Process (ANP), The Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), Elimination Et Choix Traduisant la REalité (Elimination and Choice Expressing (ELECTRE), Multi-attribute utility theory (MAUT), VIKOR, hybrid MCDM techniques and MCDM technique with fuzzy method.

In reviewing literature concerning MCDM method and application, the approach has been implemented in the O&G industry for decisions making such as selection of suitable maintenance strategy (Ratnayaka and Markeset, 2010), geosteering operations (Kullawan et al., 2014), project portfolio selection (Lev and Murphy, 2007) and reservoir planning (Gerbacia and Al-Shammari, 2001). In what follows, the common and popularly used MCDM methods are described below.

Weighted linear combination (WLC)

This is the best known and most commonly used MCDM technique (Shafiee, 2015). It is also referred to as the simple additive weighting (SAW) or weighted sum method (WSM) in some literature and it is suitable for a single dimensional problem. The fundamental principle behind this approach is to determine weighted sum of rating for each alternative consider in an analysis. For example, when K (e.g. $A_1, A_2, A_3, \dots, A_n$) alternatives and N number of decision making attributes (criteria) are consider during wind farm site selection, then the best alternative is selected using the expression in Eq. (1)

$$A^* = \text{Max} \sum_i^j a_{ij} w_{ij} \text{ for } i = 1, 2, 3, \dots, N \quad (2-2)$$

where, A^* is the alternative with the highest WLC score, representing the best alternative, a_{ij} is the numerical value of i^{th} alternatives in relation to j^{th} attribute and w_j is the weight of importance of j^{th} attribute.

Multi-Attribute Utility Theory (MAUT)

This MCDM methodology takes into account the decision makers preferences as a utility function for a set of possible attributes associated with alternatives and the best alternative which maximizes decision makers expected utility function is then selected. With respect to single attribute utility, the utility function can be either be separated additively or multiplicatively (Pohekar and Ramachandran, 2004).

Analytical hierarchy process (AHP)

AHP was developed by Saaty in the 1970's to address the difficulty in determining the relative importance of a set of activities in an MCDM decision making problem and since then it has become the popular MCDM method. AHP incorporates judgements of intangible qualitative criteria alongside tangible quantitative criteria (Badri, 2001). The method helps decision makers to break down complex decision making problems such wind farm site selection into hierarchical structure with goal at the top, followed by criteria, sub-criteria and alternatives (Saaty, 1990; Zio, 1996). Selection of suitable alternative requires pairwise comparison and further testing the consistency of the pairwise comparison by computing an index called consistency ratio. The weight for pairwise comparison is obtained using Saaty's fundamental scale of 1-9, where 1 indicates equal importance, 3 moderately more, 5 strongly more, 7 very strongly and 9 indicates extremely more importance. The values of 2, 4, 6, and 8 are assigned to indicate compromise values of importance.

Analytical network process (ANP)

Despite the positive attributes of AHP methodology, it has been criticised for structuring decision making problem in hierarchical manner (Meade and Presley, 2002; Shafiee, 2015). This is because not all MCDM problems can be structured hierarchically and may involve interaction and dependence of decision making elements (Saaty, 1996). To address the problem of

dependence involving alternatives and criteria, Saaty suggested the use of ANP, which is considered a generalized form of AHP. The methodology allows decision makers to select suitable alternative in complex decision problem without making the assumption of independence of criterion from criterion and criterion from alternative. Unlike AHP, in ANP pairwise comparison matrices are transformed into a super matrix.

Elimination and choice expressing the reality (ELECTRE)

This method is able to handling complex decision making problems which involves criteria with both quantitative and non-quantitative data with discrete alternatives. The problem must be formulated in a way that the decision maker selects preferred alternatives over a lot of criteria in manner that it does not cause unacceptable dissatisfaction for any of the criteria. The method uses concordance, discordance and threshold values in decision making and is also considered as an outranking method. Finally, it produces a system of binary outranking relation between alternatives. The method has evolved from ELECTRE I to ELECTRE III/ELECTRE TRI. The application of ELECTRE approach is convenient when decision making involves few criteria with large number of alternatives (Goicoechea et al.,1982).

The technique for order preference by similarity to ideal solutions (TOPSIS)

TOPSIS is a useful MCDM tool for ranking and selection of a number of alternatives determined through measurement of distance. The fundamental principle of this technique is that the selected alternative should have a shortest geometric distance from positive ideal solution and farthest distance from the negative ideal solution. The methods ranks alternatives in increasing or decreasing utility, which makes it easier to identify ideal negative solution. Thus, decision makers' preference order of alternatives is obtained through comparing Euclidean distances. The best solution is the alternative with the shortest distance to the positive ideal solution and longest distance to negative ideal solution.

Preference ranking organization method for enrichment evaluation (PROMETHEE)

This MCDM technique was first developed by Brans in 1982 and later expanded in 1985 (Brans and Vincke 1985). The method is based on outranking principles in order to rank and prioritise decision alternatives. Compared to other MCDM techniques, it is easier to use due to decreased in complexity. The basic principle of PROMETHEE is pairwise comparison of all alternatives on each evaluation criterion (Zhaoxu and Min 2010). The performance of one alternative compared to another in the pairwise comparison for each criterion is based on a preference function. The preference function differentiates between two alternatives for each criterion by using real values ranging from 0-1. When the difference between two alternatives is 0, then there is no preference and if the difference is 1, then there is full preference (Mareschal and De Smet 2009). There are six different generalised types of preference functions namely, usual criterion, U-shape criterion, Gaussian criterion, V-shape criterion, V-shape with indifference and level criterion (Behzadian et al., 2010). For this study the usual criterion is chosen as the preference function because evidence in literature indicates that it is the most appropriate preference function for subjective type evaluation criteria (Silva et al., 2010).

VIKOR

This MCDM method can be referred to as the compromising technique because it determines compromise ranking of alternatives and the best alternative is the one whose point is the least distance from an ideal point (Zeleny, 1982). The main objective of using this technique is to select a suitable alternative that is possibly close to ideal solution. It introduces multi-criteria ranking index based on the particular measure of “closeness” to the “ideal” solution (Sayadi et al. 2009). The distance measure used in VIKOR is developed from family of L_p -metrics and is used as an aggregation function in a compromise programming.

Hybrid MCDM method

Majority of MCDM methods have practical limitations. Therefore, in order to minimize the effects of the limitations on decision making many hybrid MCDM techniques have been developed. In the hybrid technique, the strength of one met

2.8.6.4 Expert Judgement

An expert is person with experience and knowledge in a specific area of study (Mayer and Booker, 1991). During LE decision making process in the offshore O&G industry, there are instances where experts judgement and knowledge will be required. Experts' judgement has widely been used in the offshore O&G industry and other industries for reliability analysis and maintenance optimisation (van Noortwijk et al., 1992). According to Vaidya and Rausand (2011) during LE decision making process, experts judgement may be required for the following:

1. To identify failure mechanisms of equipment with their corresponding causes to support root cause analysis.
2. To provide estimate on the allowable maximum limits for parameters which are being measured with sensors.
3. To select the suitable degradation and RUL models for analysis of each failure mechanism.
4. To interpret and integrate the results from different models at component level in order to assess the overall technical health condition of a system.
5. To compliment data collection in situations, where there is lack of experience as well as operational data.
6. To provide inputs data to support the use of semi-quantitative models
7. To help estimate prior probability distribution (Bayesian technique) for condition assessment models.
8. To provide feedback on failure modes which are observed during operations of equipment.

9. To validate the assumptions used in developing decision making models for analysis.

2.8.7 Tools

LE analysis requires commercial tools in order to verify and validate reliability, availability and cost models. An overview of some of the commonly used commercial packages is provided below:

1. Predict (schedule only): Is a decision support tool that aims to enhance the management of risk and uncertainty in predicting cost and schedule.
2. @risk: Is the most widely used risk analysis tool that utilises MS Excel to perform Monte Carlo simulation.
3. Crystal Ball: Is used to predict software and service costs
4. MATLAB: It allows matrix manipulations, plotting of functions and data, implementation of algorithms.

Also, some commercially bespoke software packages are available for use in the offshore O&G industry and these software packages include OLGA, OrcaFlex, ReliaSoft, LedaFlow, ProFES and TACITE.

Overview: The literature survey did not reveal any scientific publication in relation to LE with application of the above mentioned tools.

2.8.8 Regulations

Regulations, codes and standards play important role in the offshore O&G industry, enabling duty holders and regulators to identify technical safety levels during lifecycle of O&G installations. They continue to remain crucial from technical and environmental perspective regarding O&G offshore installations. Understanding regulations that applies to duty holders during LE will enable them put in place measures to ensure minimum compliance. Good and harmonised regulations in the industry would make exploration, development, and production of offshore O&G fields as well as, LE and decommissioning of offshore asset more economical and easier in a growing complex industry.

Currently the offshore O&G industry has different regulations and standards presenting a challenge to duty holders operating in different countries. The global O&G industry makes use of several thousands of standards plus greater number of companies project specifications. A study conducted by CEN (committee for standardization) in 1994 in collaboration with OGP revealed that about two thousand standards are in use by a number of operators in Europe only. Regulators are mainly the pacesetters of regulations in the O&G industry, with some international conventions applying.

Most regulators across the globe use industry developed standards as the basis for regulating activities of companies. This has led to different regulations in the industry across different locations. These regulations are underpinned by work ethic and cultural backgrounds of various countries. According OGP (international oil and gas producer association) report (2010) duty holders prefer to have common technical requirements globally with national adaption, taking into account conditions at the site of operation to that of the diverse regulations on national levels which present a challenge to duty holders. By understanding the existing regulations and the intent behind them, stakeholders could get a clearer picture of how existing and future regulations would impact LE management in the offshore O&G industry. In the absence of any regional, national and local regulations, operators rely on their own internal requirements, standards and good practices to assure adequate safety and compliance during LE.

Overview: Most of the codes and standards in the offshore O&G industry apply to design and operational phases of installation lifecycle and not explicitly to LE. However, some of these codes and standards remain relevant during LE phase of operation due to similarities between design and operational phases to LE phase of operation. The Norwegian authority in recent times has developed specific standards for use during LE period of operation. Table 2-4 shows relevant standards developed purposely for LE activities in the offshore O&G industry.

Table 2-4 Relevant LE standards

Relevant codes & standards	Application	Country
NORSOK-N-006	Load bearing structures	Norway
NORSOK U-009	Subsea systems LE	Norway
NORSOK Y-002	Transportation systems LE	Norway
ISO/TS 12747	Transportation systems LE	International

2.9 Summary of Research Gaps

State of the art publications on LE in the offshore O&G industry has been systematically and critically reviewed. The systematic literature review has provided better understanding of state of the art of LE research in the offshore O&G industry. From what has been discovered throughout this Chapter, it can be concluded that it is important to study LE management of SCEs on offshore O&G installations. For more comprehensive review on LE application and trends in safety critical industries, readers can refer to Shafiee and Animah (2017).

The research on LE is growing especially in the offshore O&G industry. However, majority of scientific publications has focused on addressing the LE challenges in relation to structures and also most of the solutions prescribed for identified challenges are based on accumulated experience of engineers, inspectors and consultant. Although experts' knowledge and experience are vital during LE decision making process, but for safe and continuous operation of offshore O&G installations, LE management framework for SCEs is now required by both scholars and practitioners in the offshore O&G industry. This has provided the basis for the development of a comprehensive LE framework integrated for screening and prioritisation, condition assessment, remaining useful life estimation, risk analysis and cost-benefit analysis for SCEs.

The key research gaps observed as a result of the systematic literature review are summarised below:

1. The outcome of the literature survey indicates that LE management process for structures have received much attention while little attention has been given to SCEs (in the form of systems) as well as pipelines.

2. The list of factors that may influence LE decision making process are not exhaustive and therefore interacting with experts with experience in offshore O&G sector could further provide a more comprehensive list.
3. The list of factors influencing LE decision making in the offshore O&G are fragmented. Therefore, it will be interesting if future work deals with this gap by categorising them using a suitable classification framework.
4. Although, publications in this area of study indicate an increasing trend, there is lack of structured approach to screen and prioritise SCEs for LE feasibility assessment.
5. The review indicates that LE feasibility assessment frameworks are either technical only or economics only. These frameworks tend to provide misleading results during LE decision making process; therefore, a framework which integrates both technical and economic assessment procedures simultaneously for LE assessment is required.
6. Majority of LE case studies in the offshore O&G industry have employed the use of qualitative or quantitative condition assessment methodology. However, both qualitative and quantitative condition assessment tools have limitations, thus introducing semi-quantitative condition assessment tools could overcome the limitations of both qualitative and quantitative condition assessment tools.
7. The concerns of lack of good quality data to support LE assessment continue to be a huge obstacle during LE decision making process in the offshore O&G industry.
8. The decision to select most suitable LE strategy is based on expert experience and judgement, thereby introducing uncertainty into LE decision making. Therefore, it will be interesting to propose a scientific and systematic approach for selecting the most suitable LE strategy for the offshore O&G assets operating beyond original design life.
9. It was discovered during literature review that very few studies have researched on obsolescence management with respect to LE of offshore O&G assets.

3 CURRENT PRACTICES, CHALLENGES AND EXPERIENCES FROM OTHER INDUSTRY

3.1 Introduction

This chapter identifies current practices and challenges in relation to LE of offshore O&G installations. This Chapter serves the purpose of guiding research into LE of SCEs, providing the structure for understanding LE challenges, helping researchers and practitioners to be abreast with current practices and also providing lessons and good practices from other industries.

The rest of the Chapter is organised as follows. In Section 3.2, the research methodology the author followed to collect the needed information required for determination of current practices and challenges associated LE management of SCEs is presented. Section 3.3 describes the current practices captured through interactions with industrial expert. In Section 3.4, the author provides lists of challenges facing asset managers during LE phase of operation. Finally, Section 3.5 presents experiences and practices in other industries and the good lessons the offshore O&G industry can learn from these industries.

3.2 Research Methodology for Determination of Current Practices and Challenges

This section discusses the research methodology used to collect the data needed to identify current practices and challenges during LE phase of operation in the offshore O&G industry. Table 3-1 presents details of the experts interviewed, their job roles, their work experience, the purpose of the interview and the type of data collection technique used.

Table 3-1 Primary data collection

Participant	Role	Years of experience	Purpose of data collection	Type of technique
1	Head of Technical Safety	15	Identification of challenges and determination of current practices	Face-to-face
2	Chief Engineer - Technical Safety	10	Identification of challenges and determination of current practices	E-mail
3	Head of Technical Safety	20	Identification of challenges and determination of current practices	Face-to-face
4	Oil & Gas facility Manager	5	Identification of challenges and determination of current practices	Face-to-face
5	Consultant	32	Identification of challenges and determination of current practices	Telephone
6	Safety Case Consultant	15	Identification of challenges and determination of current practices	E-mail
7	Offshore facility manager	5	Identification of challenges and determination of current practices	Telephone

3.2.1 Semi –Structured Interview

Based on literature review, questions were compiled for semi-structured interview with 23 identified experts with several years of experience in dealing with LE issues in the offshore O&G industry. Out of the 23 experts contacted, a total of 7 responded, representing a response rate of around 30.4%, which is highly successful response rate as far as this research, is concerned.

Due to the exploratory nature of this section of the research, it was suitable to select semi-structured questions for the interview. This is because, it combines open and close questions to gain in-depth understanding of current practices and challenges during LE phase of operation in the offshore O&G industry. The processes involved in collecting the data are shown in Fig.3-1.

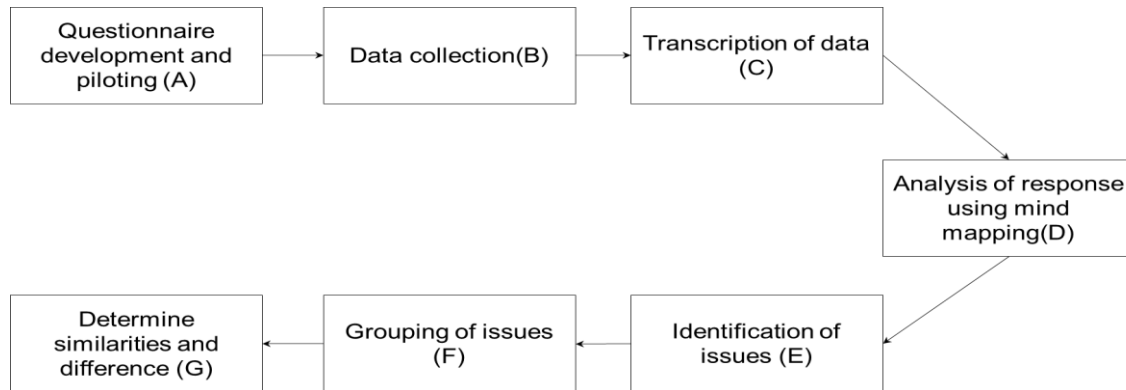


Figure 3-1 Process involved in semi structured interview

Activity A involved development of specific semi-structured questions to elicit expert information. This was achieved through brainstorming activities with two colleague researchers and two supervisors, who have strong background, experience and knowledge in this subject area. The questions were designed to solicit broad coverage of likely issues from each interviewee. The questions were then piloted and validated with colleague researchers. It was further piloted and validated with an expert and this was also to facilitate invitation of other interested experts within the field of LE to participate in the interview process. The interview process was developed to last for an hour using the Delphi technique. APPENDIX A.1.2 shows the questions used for the interview.

Activity B focused on using the semi-structured questions for purpose of data collection. During the face-to-face interviews, the author took notes and recorded the interviews using a tape recorder. The interview questions were supported by literature review in obtaining adequate data. **Activity C** involved transcription of interview response and mind map technique was used to analyse response (**Activity D**). Mind mapping of the response from the interview can be found in APPEDIX B.2. After the analysis, key issues involving LE practices in the offshore O&G industry were identified using **Activity E**. These issues were grouped under different titles, showing current practices and challenges in the offshore O&G industry (**Activity F**). Finally, for each issue, similarities, differences and unique responses were grouped to determine convergence and divergence responses (**Activity G**).

3.2.1.1 Responses from Experts in Table 3.1

The interview process was conducted using face-to-face approach, telephone as well as electronic mailing of the questions for response. The subsequent sections provide approaches used by each expert in responding to interview questions as well as detailed explanation of the outcomes from the interviews with each expert. Experts are grouped according to the approach used in responding to the questions.

3.2.2 Responses from Experts, 1, 3 and 4

Face-to-face approach was used in conducting semi –structured interviews for experts 1, 3 and 4. A total of one hours and 15 minutes were used in collecting data through face-to-face interview. The approach provided the author opportunity to ask fellow up questions to gain deeper understanding and capture current practices. However, follow up questions did not follow any sequential order. Table 3-2 shows the key outcomes from the semi-structured interviews, which were conducted using face to face approach, in order to capture current practices.

Table 3-2 Current practices responses from experts

Respondent	Current Practices
1	Corrosion and fatigue considered as degradation mechanisms. Generic list for identification of SCEs. Risk analysis tools for deciding whether SCEs qualify for LE. Safe and cost effective approach for LE is through the use of appropriate management framework.
3	Corrosion and fatigue. Identification of SCEs based regulators prepared list. Inspection is used to determine if SCEs could qualify for LE. Safe and cost effective approach for LE is a good question but cannot provide answer due the presence of safety.
4	Corrosion, fatigue and other material failure. Industry generic list containing SCEs. Good management with right skill and knowledge. Safe and cost effective approach for LE is through use of good management skills.

3.2.3 Responses from Expert 2 and 6

Four of the experts were sent electronic version of the questions to provide their responses. However, the author received two responses out of the number sent out. It took a total of six months and two weeks to receive all the responses from the experts. Table 3-3 shows the results from the questions sent by electronic mail.

Table 3-3 Current practices responses from experts

Respondent	Current practices
2	Corrosion, fatigue and erosion Safety critical elements are identified based on the function of the system and sometimes use of facility register Risk assessment tools are used to ascertain conditions of safety critical elements Safe and cost effective manner for LE is by updating to match the change of Major Accident Hazards.
6	Unavailable skilled labour and material degradation Companies provides list of SCEs Inspection is mainly used for condition assessment Safe and cost effective manner: difficult in answering the question

3.2.4 Response from Expert 5 and 7

Telephone interview was the last semi-structured interview technique used for collecting data with regards to current practice and challenges. Table 3-4 shows the results from the question answered using telephone interview.

Table 3-4 Current practices response from experts

Respondent	Current practices
5	Material degradation Generic list of SCEs Inspection used for condition assessment Safe and cost effective manner for LE is through continuous inspection.
7	Corrosion, fatigue and wear Use of experts Inspection techniques No response

3.3 Comparative Analysis of Responses between Different Experts

This section presents a comparison of experts' responses by focusing on the current practice. The similarities and differences in experts' responses are briefly discussed. From the analysis of the responses, corrosion and fatigue which are considered as ageing mechanisms were common to all the response received from each expert. Qualitative risk based inspection technique and expert judgement are the common tools used for determining the current health status of SCEs for LE qualification. However, there were variations in the some of the responses. For example, the responses to how screening and prioritisation of SCEs is carried out in the offshore O&G industry during LE decision making process differed. Also, the responses to suitable approach to ensure safe and cost effective continuous operation of SCEs varied.

3.4 Establishing of Current Challenges

This section highlights challenges that were captured while interviewing experts from collaborating institutions. The identified challenges set out the major gaps experienced in the offshore O&G industry during LE of SCEs. Table 3-5 presents the list of challenges that were captured during the interviewing process.

Table 3-5 Challenges of LE process

Respondent	Challenges
1	Rapid changes in safety critical elements performance. Lack of mathematical models to support LE assessment. Difficulty in predicting rate of deterioration at wear-out phase of operation. Methods for verification of expected performance of ageing systems (SCEs in particular) is difficult for those systems that are untestable. Ageing workforce.
2	Lack of understanding of aging mechanism. Lack of facilities for data collection and storage. Lack of historic information regarding aging and LE.
3	Lack of understanding the current condition of non-repairable system. Lack of skilled human resources to undertake LE activities Limitation of current inspection and technical assessment techniques used in the industry
4	Lack of plans to handle obsolescence. Lack of good quality data. Lack of reliability models to support LE activities

	No specific tools for data analysis. Current practices not enough to determine RUL.
5	Difficulty in predicting rate of deterioration at wear-out phase of operation. Management of change Cost of assessment for un-inspectable areas.
6	No established comprehensive management framework.
7	Lack of established process to identify, screen and prioritise critical assets. Supporting LE with RUL prediction

3.4.1 Comparison to the Literature Review Findings

The research identified over 15 challenges in relation to LE management of SCEs in the offshore O&G industry from both literature review and consultation with industrial experts. Findings from literature review and expert's responses were compared. Some of the findings from literature review supported the responses from the experts, which increased the justification and the need for this research. Five key challenges were selected as the focus of this study.

Firstly, the factors that influences LE decision making process in the offshore O&G industry is not adequate and therefore it will be prudent to provide exhaustive lists of factors that influence LE decision making and subsequently categorise the factors using the appropriate classification framework.

Secondly, there is lack of a structured and systematic approach which integrates technical and economic assessment processes to support LE feasibility assessment of SCEs. Finding solutions to this challenge is crucial because both economics and technical health status of assets drives many decisions in the offshore O&G industry including LE decision making process.

Thirdly, screening and prioritisation of SCEs is a challenging task, due to the lack of structured and standardised procedure to perform this activity. This is because the offshore O&G platforms are occupied with hundreds of systems and components which present a genuine difficulty in accurately determining which element is critical to safety. Therefore, a structured and robust process will reduce the confusion involving the use of generic list as the means of screening and prioritising SCEs.

Fourthly, rating the health status of existing systems and components for LE is largely depended on outcomes of inspections, use of qualitative risk assessment tool and the use of accumulated experience of experts. This means that the challenge of applying semi-quantitative tools to perform condition assessment exists. Also, estimation of RUL to support LE decision making has not received the needed attention in the offshore O&G industry.

Fifthly, there is the need to select suitable LE strategy using established methodologies compared to the use of expert experience. This means that a structured approach to select a suitable LE strategy using tools such as multi-criteria decision making methods (MCDM) and life cycle cost benefit (LCCB) approach will improve LE decision making significantly.

3.5 Experiences from other Industries

In order to propose solutions to the identified challenges, the author looked beyond the offshore O&G industry to learn lessons and good practices from nuclear power plant, electrical distribution and transmission, wind energy and transport industries on how they have handled similar LE challenges confronting the offshore O&G industry.

3.5.1 Nuclear Power Plant Industry

The nuclear power plant industry provides key technical procedures and actions to ensure safe continuous operation of structures, system and components (SSCs) in accordance with regulatory requirements during extended period of operation. LE in the nuclear power plant industry has been described as the means of ensuring availability of required safety function throughout the extended service life period of a plant (IAEA, 2008). The Fig.3-2 below shows the age distribution of commercial nuclear reactors operating around the world by January 2014.

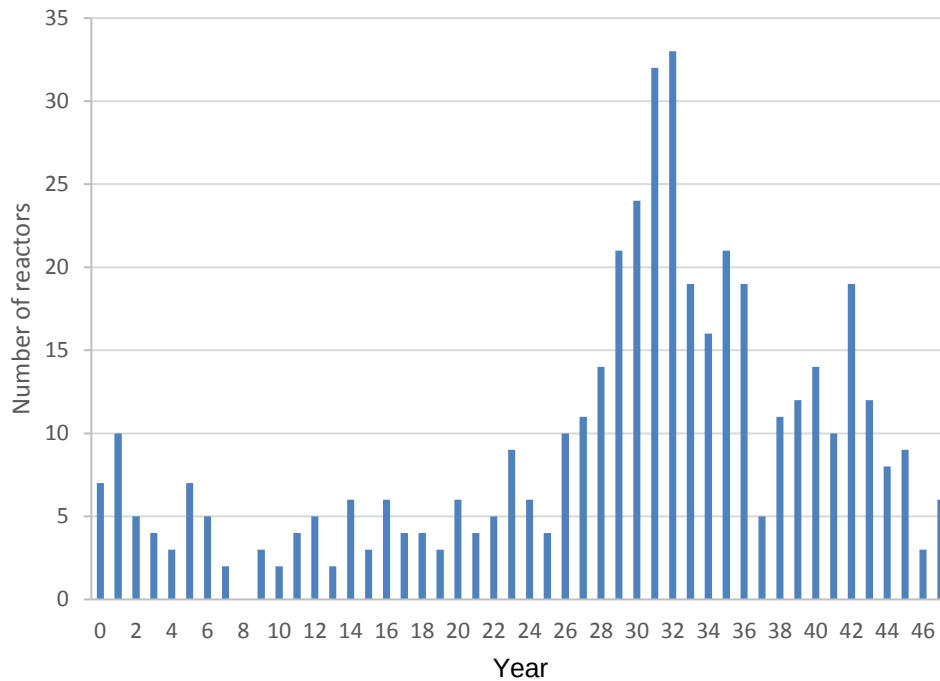


Figure 3-2 Ages of commercially operating nuclear reactors in 2014 (Mohr et al., 2014)

Most nuclear power plants are operating more than their original design life. Nuclear power plants are designed for a period between 30-40 years and may be extended by 10 to 20 more years provided the plant or equipment can demonstrate enough safety through analysis (IAEA, 2004, 2008). The nuclear power plant industry realising the fact that ignoring the impact of ageing to plants systems and components will be costly, have developed a comprehensive framework for LE management of SSCs (IAEA, 2008). Fig.3-3 provides the overview of the processes used for implementing LE programmes for safety related assets in the nuclear power plant industry.

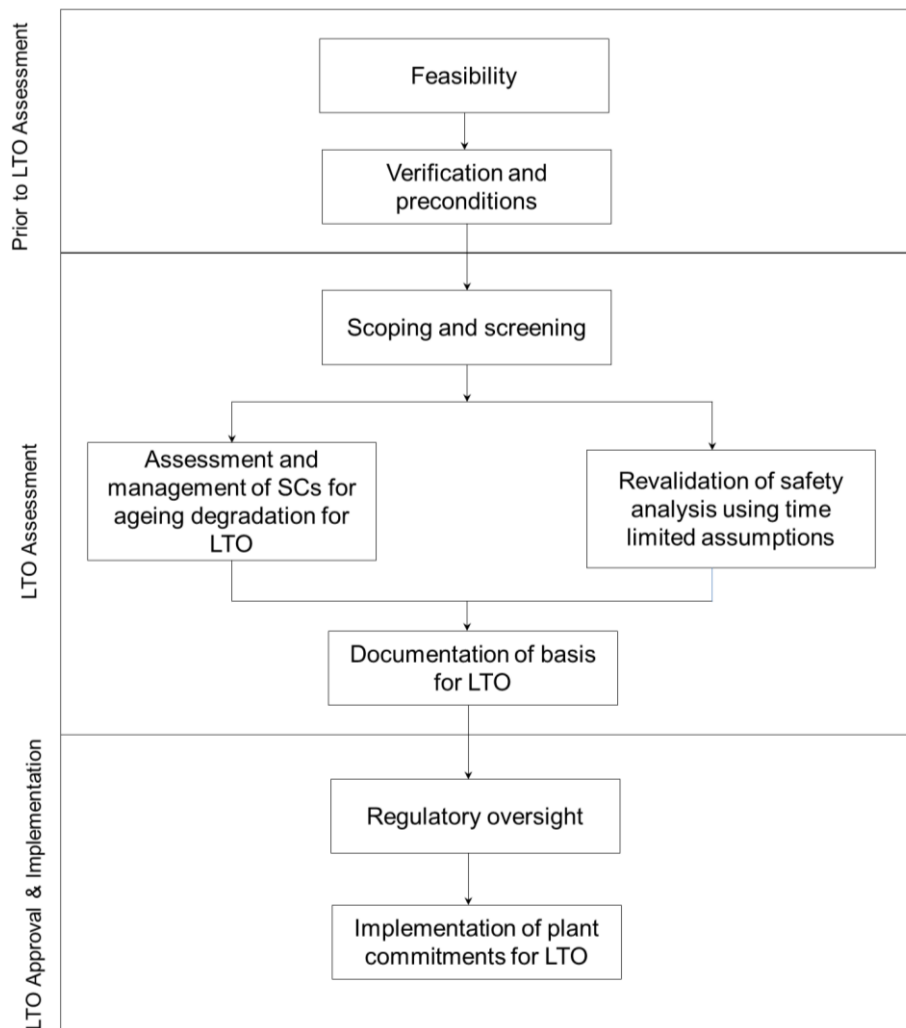


Figure 3-3 LE management processes for SSCs in the nuclear power plant industry (IAEA, 2008).

The framework above is divided into three sections and the first section labelled prior LTO assessment provides an outline and principles associated with LE in the nuclear power plant industry. The second section labelled LTO assessment includes activities to screen for critical SSCs, an approach to demonstrate whether SSCs life could be extended technically for continuous safe operation. The third section labelled LTO approval and implementation describes documentation and regulatory approval processes to secure LE licence. Ramírez and Utne (2011) indicated that based on this comprehensive

framework, the nuclear power plant industry has been able to handle ageing and LE issues more effectively than the offshore O&G industry.

The nuclear power plant industry has handled the challenge of identification, screening and prioritisation of SCEs by allowing operating organisations to identify which systems/components are within the scope of LE assessment based on their functions as opposed to generic list provided by regulators in the offshore O&G industry (IAEA, 2008). Also, screening and prioritisation of safety critical assets in the nuclear power plant industry has been achieved through the use of a developed methodological flow process. Probabilistic safety assessment (PSA) approaches have also been utilised in the nuclear power plant industry to support screening and prioritisation process of safety critical assets. Nitoi and Pavelescu (2009) developed the Ageing Failure Mode and Effect Analysis (AFMEA) for identification, screening and prioritisation of nuclear power plant systems and components for ageing and LE management. AFMEA approach identifies possible failures before they occur. This approach enables each of the elements of a process to be attributed a cumulative numerical value called Risk Priority Number (RPN) which is then used to screen and prioritise critical components for actions to be taken against a particular failure mode. The numerical value rates the severity(S), probability of occurrence (O) and detectability (D) of each failure mode. The potential risk of each failure mode is calculated with the interpretation of three indexes that consider the severity of the event which assesses the implications of the failure, probability of occurrence assesses the likelihood of the failure to appear and probability of detection which assesses the likelihood of detecting a failure. These indexes give rise to the RPN.

The LTO assessment section of Fig.3-3 represents the heart of the LE management framework, which involves applying appropriate engineering techniques to rate the current health status of candidate safety critical assets for LE qualification. This is achieved through review and comparison of existing plant conditions and programmes such as mitigating actions against ageing degradation, monitored parameters and other forms of failure mode to

companies KPIs or established regulatory threshold (for more see IAEA, 2008b; Tipping, 2010). In parallel, revalidation of safety analysis employed at design stage of SSCs using time limiting equations and assumptions is performed. Although the nuclear power plant industry has managed to develop a comprehensive LE management framework, it falls short of capturing issues on economic feasibility and how to deal with uncertainties in relations to cost components of LE. Also, there is an absence of a methodological process to monitor the performance of asset during LE period of operation. The literature search could not reveal any methodological approach for selecting suitable LE strategy in the nuclear power plant industry.

3.5.2 Electrical Distribution and Transmission Industry

Many electrical power systems around the world have operated beyond their original design life and majority of these systems are still in operation. Notable among these systems are transformer, cables, switch gears and transmission systems.

The electrical distribution and transmission industry manages LE at the system level rather than component level. The causes of degradation in electrical distribution and transmission systems are heat, oxygen, moisture, mechanical stresses, acids and sludge's (Kelly and Myers, 1995). Systems abnormalities such as overloading, switching, ambient conditions and poor maintenance also accelerate degradation process (Arshad et al., 2004). Unlike the offshore O&G industry where installations are expected to operate within a period of 20 – 25 year, electric power systems are expected to operate between 25 – 40 years (Storms and Shipp, 1988; Storms and Shipp, 1989; Storms and Shipp, 1991). Technological obsolescence is the most prevalent form of ageing mechanism in the electrical distribution and transmission industry. This form of ageing is more characteristic to the electrical power systems and mostly results in more catastrophic damage.

LE as an EOLMS has enabled the electrical distribution and transmission companies to expand their capacity without building new plants. LE of power

infrastructure and systems has also resulted in modernisation and upgrade of many companies (Valiquette, 2002). According to Picard et al. (2007) LE has demonstrated to be a cost-effective strategy and is likely to remain an attractive end of life alternative for many electrical companies. Electrical distribution and transmission industry like other industries main motivation for LE is financial.

One of the major achievements in the electrical distribution and transmission industry with respect to LE is the condition assessment techniques used to determine current health status of equipment. However, a careful review of literature indicates that the electrical distribution and transmission companies also have some challenges as far as LE is concerned. For example, the electrical distribution and transmission industry does not have a comprehensive framework for managing safety systems during LE period of operation. This is a departure from nuclear power plant industry, which has established frameworks to support LE decision making process. Also, there is no established procedure for identification, screening and prioritisation of SCEs for LE assessment in the electrical distribution and transmission industry.

On the challenge of rating the health condition of systems for LE, the electrical distribution and transmission industry utilises qualitative, semi-quantitative and quantitative analyses tools. According Valiquette (2002) reliance on historical performance data to predict future trends has been proven wrong in the industry. This is not due to deficiencies in data but, rather inherent uncertainties experienced in the life cycle of power systems after these predictions.

Some LE studies conducted in the electrical distribution and transmission industry are presented. Fer (1990) and Ishac et al. (1995) employed qualitative methods which compares existing inspection and testing records to current operational records to support technical health assessment of ageing systems for LE. Semi- quantitative condition assessment tools have also been developed specifically for technical health assessment of transformers for possible LE. These tools are based on collected data and expert knowledge to produce an index as the basis for rating current condition of systems. Dominelli et al. (2006) developed an approach for assessing transformers current health

status for LE. The approach calculates an index representing the health status of a transformer based on weights assigned to the following data; age, test, inspection and operational records. Miletic (2009) introduced another method in determining condition index and benchmarking but the methodology is strictly suited for application in the electrical distribution and transmission industry and is not easily adaptable. Young et al. (2010) also proposed a method for determining condition index by summing rating condition score and applied the approach to a power transformer LE assessment; however, they did not give details of rating method. Amir and Muttalib (2014) determined the condition index of oil-filled ring main unit by assigning higher weight to failure mode with higher RPN and subsequently multiplied with the health index of individual condition indicators to obtain the overall health assessment index. However, the study did not provide the rationale for the using the rating and weighting scores.

Quantitative condition assessment technique such as Prognostic Health Management (PHM) system is currently used in the electrical distribution and transmission industry for technical assessment of components, despite it challenges. PHM as a condition assessment technique is gaining prominence because the methodology is suitable for integrity assessment and capable of estimating RUL of systems and components.

On the challenge of selecting suitable LE strategy, there was no identified research to that respect in the electrical distribution and transmission industry.

However, all the methods identified in the electrical distribution and transmission industry for condition assessment of safety systems ignores some of the key LE decision making factors peculiar to the offshore O&G industry.

3.5.3 Wind Energy Industry

In the wind power industry, Hughes (2012) indicated that onshore dataset containing information on 282 installations in the UK and 823 installations in Denmark have turbines with ages ranging from 0 to 19 years by 2012. Staffell and Green (2014) reported that about 45 wind farms built in the UK in the 1990s were more than 15 years old by the year 2014 and almost 78% of the turbines

in these wind farms are currently approaching the end of their original design lives. The first offshore wind farm installed in Denmark near Ravensborg reached the end of its original design life in 2016 (Beauson and Brøndsted, 2016).

The few LE studies conducted in the wind energy industry includes; Rubert et al. (2016) presented. LE economic scenario for wind turbines as well as complimentary structural health monitoring technique for turbine foundations based on an advanced optical sensor network. Kolios and Martínez-Luengo (2016) discussed the need for the wind energy industry to be proactive about the topic of LE. Ziegler and Muskulus (2016) introduced lifetime extension problems, existing guidelines and proposed an approach to support LE decision making process in the wind energy industry. Loraux and Brühwiler (2016) discussed how long term monitoring data could be used to support extension of service life of existing turbine support structures.

3.5.4 Transportation Industry

In the transportation (rail, aviation and aerospace) industry, Leung et al. (2012) discussed an asset life assurance programme to support LE decision making process and illustrated the programme on ageing M-train in Korea. The result of illustration indicated that the train can be used for additional 25 years after its original design life. Wang et al. (2009) and Wang et al. (2012) presented a service LE programme employed to upgrade and extend the service life of long range surveillance radar in the aviation industry. Kandadai et al. (2014) in a case study on ageing railway LE described the method to determine the current condition of a bridge and further explained additional measures to slow down degradation in the LE phase of operation.

3.5.5 Lessons Learned

Issues of LE have received considerable attention in both nuclear power plant and electrical distribution and transmission industries as compared to offshore O&G industry. While reviewing experiences from the other industries, it was discovered that lessons could be learned by the offshore O&G industry in

overcoming some of the identified challenges during LE phase of operation and these include:

1. A framework integrating technical and economic techniques for LE assessment could be a solution to the lack of decision making model for SCEs LE assessment from both technical and economic perspective simultaneously.
2. Data such as test report, degradation/condition monitoring report, maintenance report and equipment design data are valuable in performing detailed semi-quantitative or quantitative assessment, in order to rate current health status of SCEs on platforms.
3. Beside availability of appropriate data for condition assessment, the author learned that methodological process with support of PSA tool has the potential of providing an effective solution to the challenge of screening and prioritisation of SCEs for LE assessment. In addition, the PSA tools could be used in performing root causes analysis to establish integrity issues before condition assessment.
4. Majority of the methodologies developed for LE application in other industries are specific to those industries, thereby ignoring some of the essential LE factors and considerations specific to the offshore O&G industry. Therefore, adopting an approach from these industries for direct application in the offshore O&G industry could lead to inaccurate conclusions.

3.6 Summary of Chapter

This Chapter presented the main challenges confronting asset managers during LE phase of operation. Moreover, it deepened the author's understanding about the current practices regarding LE management of SCEs on offshore O&G installations. The author also discovered that most LE decision making largely involves expert judgement, which sometime leads to unrealistic conclusions.

In Section 3.2, the research methodology followed to capture the information required for determination of current practices and challenges associated LE

management process for SCEs on offshore O&G installations was presented. Step by step approach which involved the use of semi-structured interview with industrial experts was explained in Section 3.2.1.

In Sections 3.3, the outcomes of the semi-structured interview with industrial experts in relation to current practices were presented. The outcome from each expert was compared to determine similarities and differences in the answers provided. Some of the current practices identified include the use of generic list prepared by the industry for purpose of screening and prioritisation of SCEs while corrosion and fatigue are the main physical ageing mechanisms to deal with during LE phase of operation.

Section 3.4 presented the LE challenges captured from the interview with experts. In all, over 15 challenges were identified from both literature and interaction with experts and after comparing the challenges from expert to those identified in literature, the research focused on solving five key challenges, notable among them is lack of LE management framework which integrates technical and economic assessment processes to support LE assessment of SCEs.

Finally, in Section 3.5, the research learned lesson and good practices from other industries, which are also extending the service life of existing installations. Some of the key industries the author considered included the nuclear power plant, electric distribution and transmission, wind energy and transportation industries.

4 DEVELOPMENT OF TECHNO-ECONOMIC FRAMEWORK

4.1 Introduction

Having reviewed literature in Chapter 2, it was discovered that for the past years significant amount of studies have discussed the factors that may influencing LE decision making process. This is because LE is increasingly becoming an attractive EOLMS in the offshore O&G industry. However, the review of literature indicated that no study has attempted to classify these factors using appropriate classification framework to support LE decision making in the offshore O&G industry. This was identified as a key research gap and in order to fill this gap, the author presents a classification of LE decision making factors in this Chapter.

Also, the review of literature and interaction with experts brought to light the lack of LE feasibility assessment framework which integrates technical and economic assessment procedures simultaneously to resolve the issues of which equipment should qualify for LE. Therefore, this Chapter develops a techno-economic framework capable of qualifying equipment for LE from both technical and economic assessment perspective. The framework serves the purpose of providing the basis for qualifying SCEs for LE. Moreover, the framework provides adequate methodology to integrate the technical and economic processes for feasibility assessment of critical equipment for LE. The framework has additional benefits of supporting asset managers to screen and prioritise SCEs using PSA tools, establishes a relationship between RUL and LE decision making process and provides solution to other related asset management issues during LE phase of operation.

The rest of the Chapter is organised as follows. Section 4.2 provides a description of the research methodology applied to identify and classify the factors influencing LE decision making in the offshore O&G industry. Section 4.3 describes each phase of the techno-economic framework while Section 4.4 provides details of the technical and economic tools used to support the

implementation of the proposed framework. A decision making process capable of establishing a relationship between condition assessment, RUL and LE decision making is proposed in Section 4.5. In section 4.6 a water deluge system in oil installation is used to validate the model. Finally, the results of the case study are presented and discussed in section 4.7

4.2 Methodology for Identification of LE Decision Making Factors

LE decision making process require decision making factors to enable stakeholders make suitable decisions. Although systematic literature review identified eight LE decision making factors, there was still an opportunity to validate the list from literature and also identify other factors that may have not been captured by literature. This was achieved by interviewing industrial experts with experience in handling LE projects in the offshore O&G industry. For the purposes of validation, three experts with vast experience in the offshore O&G industry were interviewed. The research method presented in Fig.4-1 below was used in identifying the lists of factors that may influence LE decision making in the offshore O&G industry.

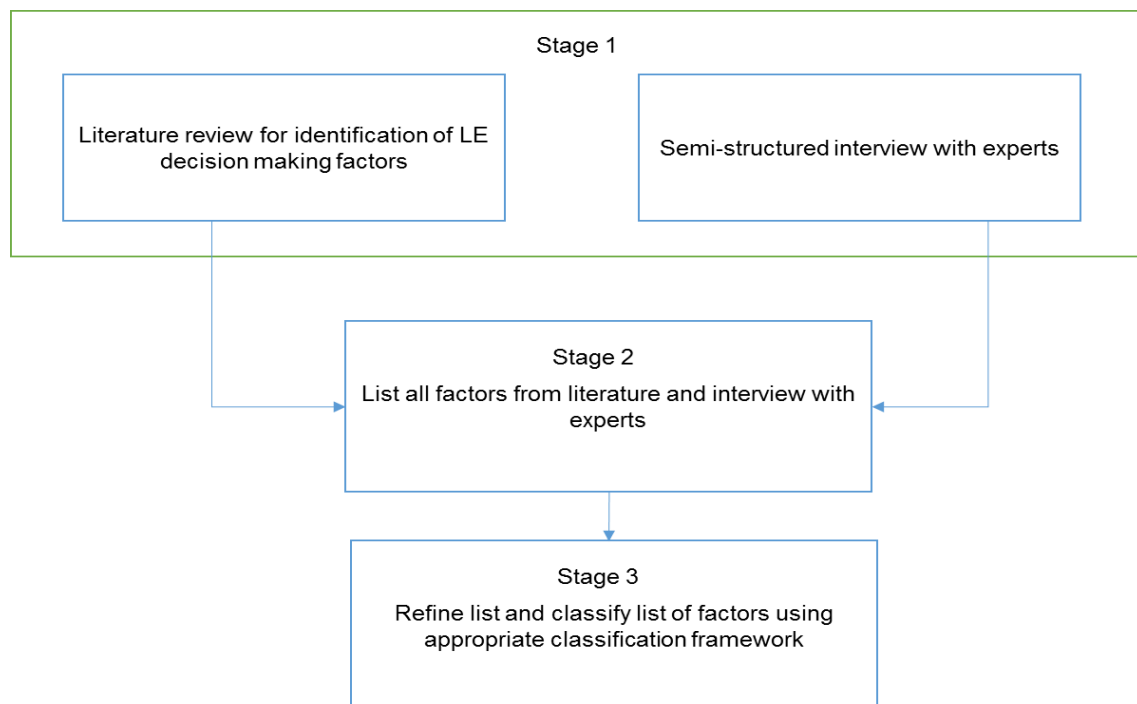


Figure 4-1 Research methodology

4.2.1 The First Stage

The first stage of the methodology combined literature review and semi-structured interview with industrial experts to identify LE decision making factors. Literature review identified list of factors for LE decision making process by reviewing published articles, conference papers and industrial report. Literature review highlighted lists of factors required for LE decision making process; however, the lists were considered as not exhaustive. In order to further validate the list from literature and identify more factors for purposes of triangulation, there was an interaction with experts through semi-structured interview. The researcher took notes during the face to face interview about the suggested list of factors that can influence LE decision making process in the offshore O&G industry. The process involved in organising the semi- structured interview is illustrated Fig.4-2 below.

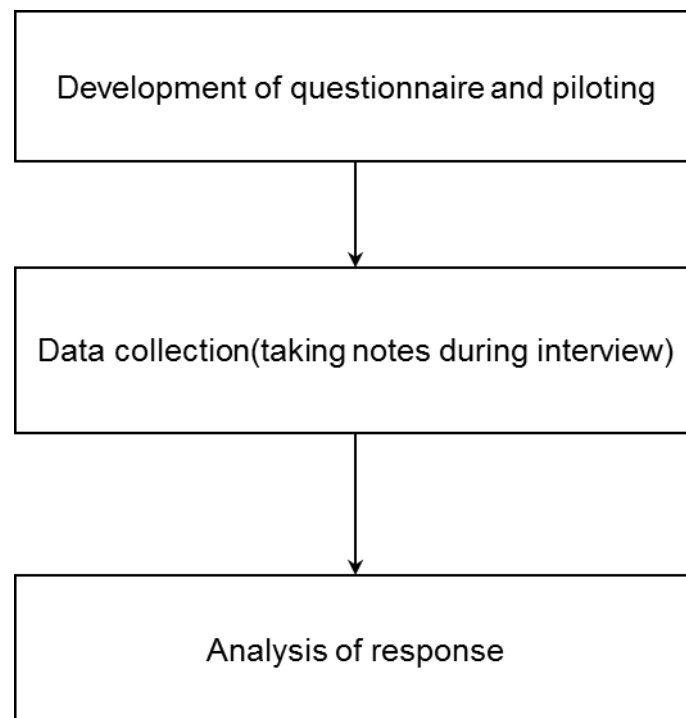


Figure 4-2 Process for performing semi-structured interview

The first activity of the first stage was development of questionnaire to solicit information about factor that may influence LE decision making process. It was

achieved through brainstorming session with author and supervisors based on the outcome of literature review. These questions were piloted and validated with colleague researchers.

4.2.2 The Second Stage

The second stage was data collection process. The process involved organising the list of factors identified from both literature review and interactions with industrial experts. The Table 4-1 below provides the complete list of LE influencing factors identified by the author.

Table 4-1 List of factors influencing LE decision making process

Category	Factors
Life	Physical life, economic life and technological life
Technical health	Physical conditions, expert's knowledge, environmental history, operation and maintenance
Degradation	Corrosion, fatigue, erosion and wear
Age of installation	Time and Usage
Economics	Capex, Opex, CAPManEx, Riskex, revenue etc
Historical data	Maintenance, operational, design, anticipated future operational records and failure records
Safety	Safety culture, safety regulation
Technical obsolescence	Unavailability of suppliers and unavailability of manufacturers
Legislative changes	Code and standards
Nature of production fluid and fluid composition	Increase water cut, increase CO ₂ and H ₂ S
Management of change	Ageing work force, lack of information flow
Materials	Types of material, composition and possible degradation effect

4.2.3 The Third Stage

The third stage involved the refinement of the list of factors identified during the two previous stages and classified them accordingly. Here, the author compared the list of factors obtained from both literature review and interactions with industrial experts in order to delete duplicate from the list. It also helped the author to determine the similarities and differences in the experts' responses and that of literature. The refinement of the list also involved meeting with another expert for further validation. The outcome of the meeting indicated that

the lists provided in Table 4-1 were improvements over the lists identified in literature and deemed sufficient for the research. The influencing factors identified were classified into inputs, constraints and output factors to help stakeholders during LE decision making process. Classification of the identified factors was achieved through the use of SADT diagram as shown in Fig.4-3.

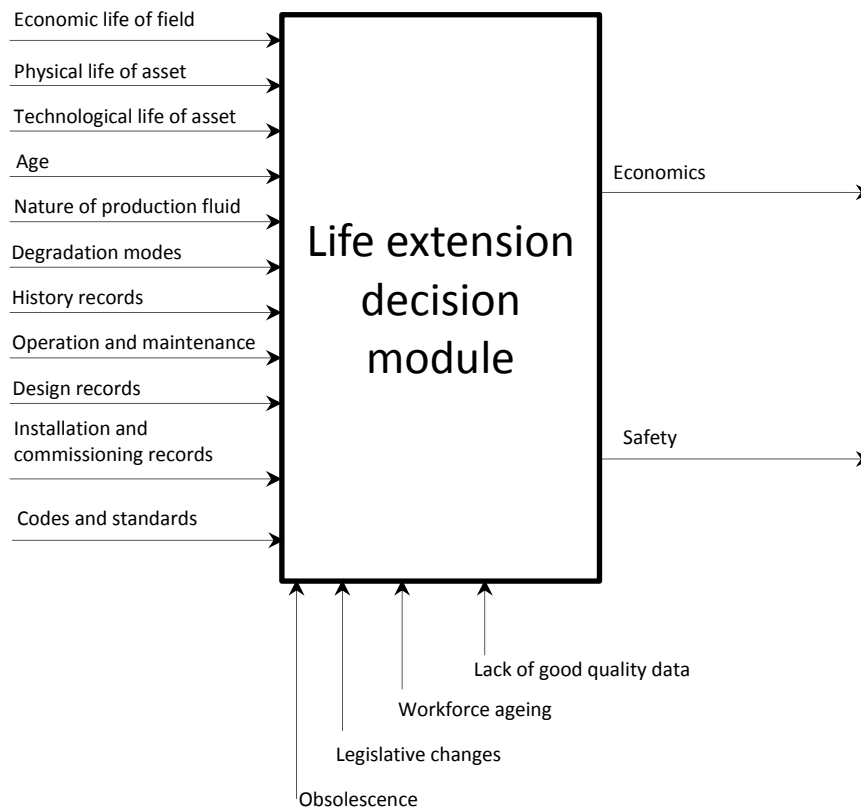


Figure 4-3 Factors influencing LE in the offshore O&G industry

4.3 Description of Proposed Techno-economic Framework

Systematic literature review and interactions with experts resulted in both qualitative and quantitative data which formed the basis for the framework development. The approach for designing the framework involved the use of qualitative data to form the concept that are represented by the processes developed in each phase of the framework while the quantitative data were used to develop tools or models for achieving specific goals of each phase. The framework was developed through an evolving process. Grounded theory application subsequently enabled us to set the initial structure of the framework

based on analysis of data obtained from both literature review and experts' interactions. The initial framework structure was subjected to further rigorous review by the research team which informed the current structure of the framework.

The proposed framework consists of three phases which serves as the basic structure and was derived based on the outcome of systematic literature review in Chapter 2 and the interaction with experts in Chapter 3. A diagrammatic representation of the framework is presented in Fig.4-4.

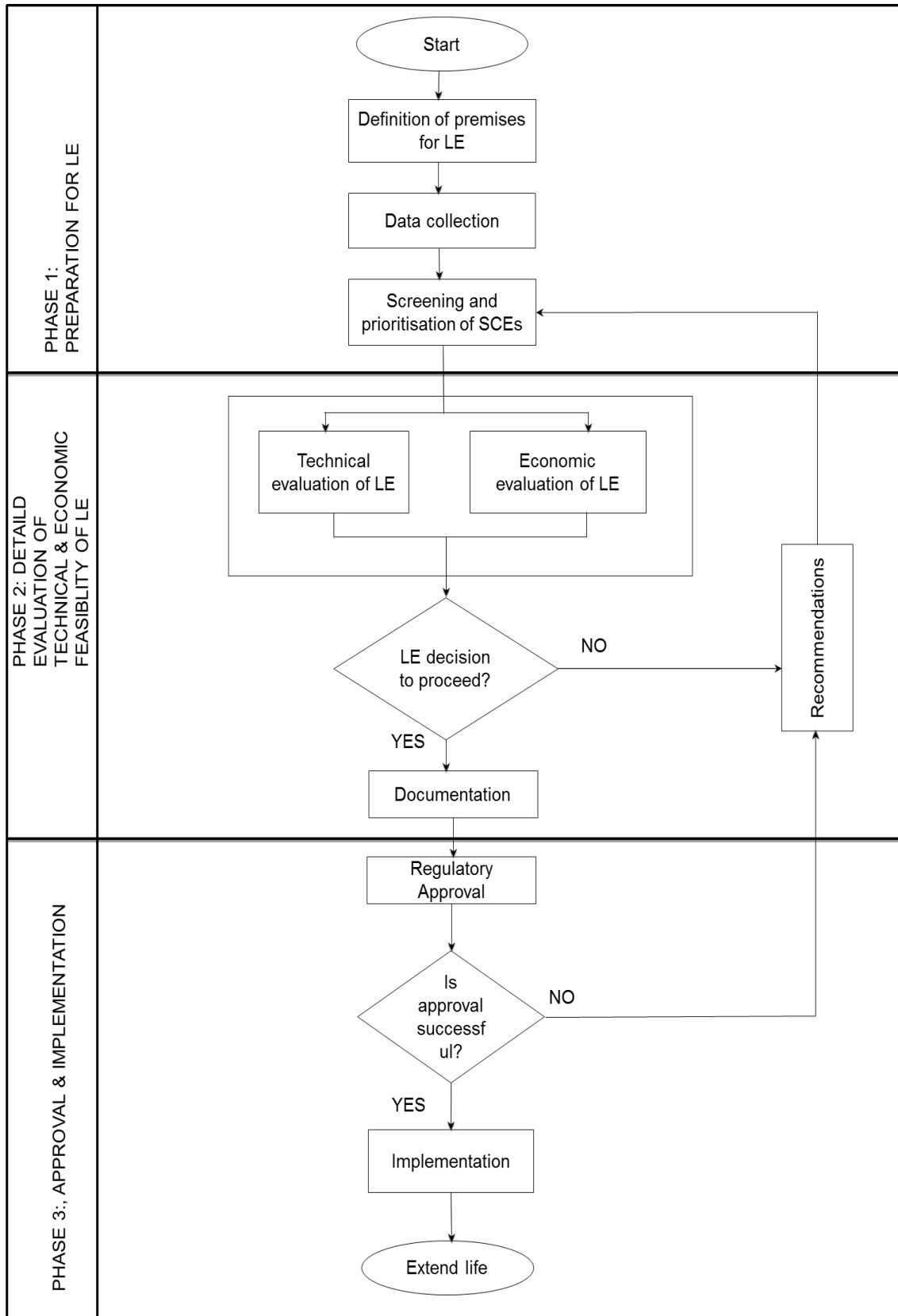


Figure 4-4 The proposed framework for LE management of SCEs

The structure above was adopted as a key component in addressing the challenges and gaps identified during literature review and interaction with experts. The framework comprises preparation, technical and economic and approval and implementation phases. Each phase of the framework is described below.

4.3.1 Phase 1: Preparation Stage

The first phase is for LE preparation, which involves defining the premise for LE, data collection, review of data as well as screening and prioritisation of SCEs.

4.3.1.1 Define Premise for LE

This step of the first phase involves identification of stakeholders, defining their roles and translating stakeholders' requirements into LE objectives.

4.3.1.2 Identification of Stakeholder's Roles and Requirements

The first stage of the first phase involves recognising and assembling all stakeholders' and their requirements which are often incompatible. This helps to determine the objectives that will drive the performance and long-term survival of SCEs during LE period of operation. This study has expanded the stakeholders' base beyond the conventional operator, investor and regulator relationship. This research further viewed LE as mean to sustainable development and therefore the stakeholders identified belonged to the three pillars of sustainability development, namely, social responsibility, environmental management and economic interest groups (see Fig.4-5).

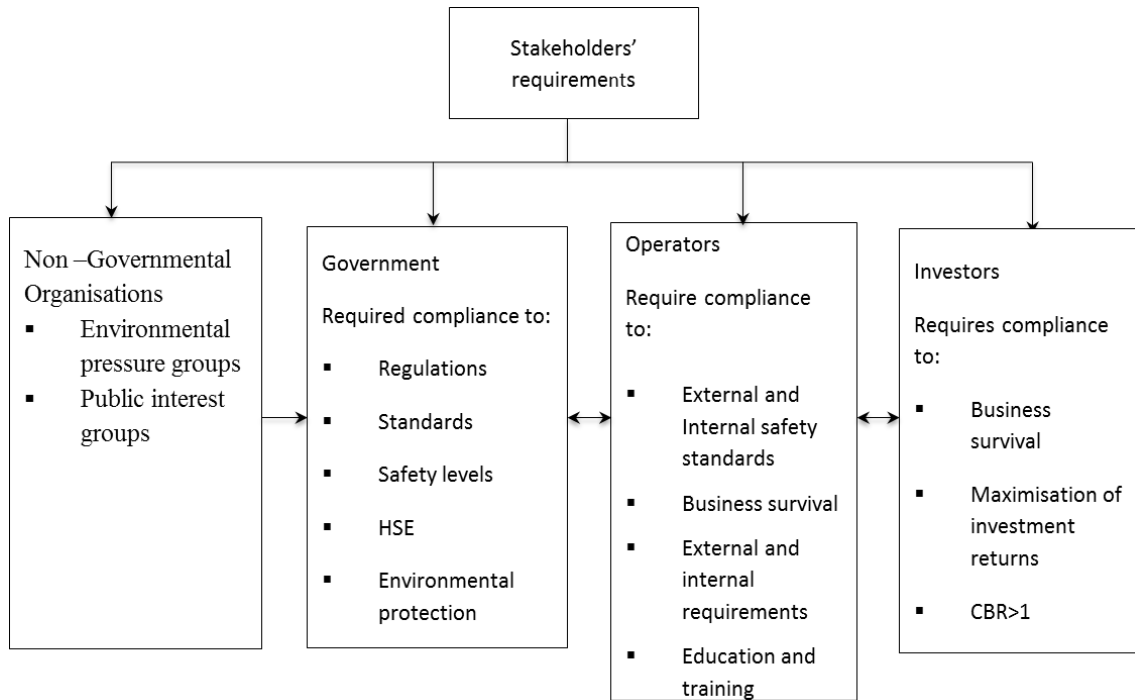


Figure 4-5 LE stakeholders and requirements

Stakeholders are identified as groups whose actions can impact LE project. A simple stakeholder selection approach was adopted. The rationale behind this is to build partnership between various interest groups. The stakeholders identified above are based on literature review and interaction with research team. The stakeholder categories consists of those whose lives may be affected by LE of offshore O&G installations; those who have technical knowledge about LE issue; those who have made financial commitment into LE projects and those who can influence LE project by issuing licence. This study focuses on the activities of operators; however, necessary lesson would be learned from other stakeholders for successful implementation of the framework. The primary roles of each stakeholder category are explained below:

4.3.1.2.1 The Role of Regulators

Regulations for the O&G industry are enacted by national regulators, with a few international exceptions such as ILO and IMO laws (OGP, 2010). This has inadvertently resulted in differences in regulations across many O&G producing countries, as they are written by different people of different background and

culture. Most of the regulators use standards in defining their regulations, guidelines or other regulatory documents. Most governments set up regulatory bodies to oversee the design, construction, operations, LE and decommission of offshore O&G installations. The primary objective of the regulator during LE is to provide confidence and assurance to society, government, companies, environmental pressure groups etc. that health and safety risk have been identified during LE assessment and adequate measures are in place to manage and control risk. Additional responsibilities of regulators are to evaluate the evidence from LE assessment and indicate if operators can secure LE approval licence within the necessary regulatory framework.

In some countries, it is the sole responsibility of the regulator to assess how well an operator is utilising available knowledge during LE period in order to protect lives and the environment. For example, in the UK it is the Health and Safety Executive (HSE), Coast guards in USA and the Petroleum Safety Authority (PSA) in Norway are in charge of LE activities in the offshore O&G industry.

The extent to which LE is explicitly addressed in standards and regulations vary, however, the Norwegian regulations are most explicit with respect to LE.

4.3.1.2.2 The Role of Operators

The decision to extend the life of an installation and its facilities is the sole responsibility of operators. Their primary role of operators during LE is to enhance production in a rapid and cost effective approach. Nonetheless, in situations where the operators are also investors, then there is an additional responsibility to ensure business survival by maintaining optimal production levels. Additional roles of operators during LE period of operation is to assemble LE team, apply for certificate of consent, screen relevant data, demonstrate fitness for purpose and maintain installation and its facilities during LE phase of operation. Training of staff and scheduling for LE activities is also a responsibility of the operator. The implementation of an effective LE management programme is strongly emphasised by the UK HSE and Norwegian PSA as an operator's responsibility. The proposed LE management framework focuses on operators' participation during LE decision making

process, however; other stakeholders' requirements where appropriate is considered.

4.3.1.2.3 The Role of Investors

The role of investors during LE period of operation is to establish business objective in order to ensure business survival by maximising profit through rapid and cost effective approach. Cost effective approaches may include slim organisational structure, use of fitness for purpose technologies and adaptation of lean operational strategies. Most investors rely on outcome of CBA to make LE decisions. Examples of investors include banks, pension funds, operators' governments etc. These investors provide the capital investment for LE project and ensure that operators generate enough revenue to pay interest and retire debt. To persuade banks and other investment firms to participate in LE project, re-evaluation of remaining field reserves is required, since LE is characterised by reduction in production.

4.3.1.2.4 The Role Non-Governmental Organisations

Non-Governmental Organisations (NGO's) main role is to pressure decision-makers to incorporate public interest concerns into LE decision making process. NGO's such as environmental pressure groups and social groups always plays an important role by exerting pressure on operators and regulators to achieve appreciable compliance to environmental regulations and public safety. Therefore, this group is considered as stakeholder during LE, where social licence for operation is concerned.

4.3.1.3 Data Collection

LE assessment of SCEs to assure asset integrity requires availability of good quality data. The continuous operation of existing SCEs is dependent on the manner the systems were designed, constructed, manufactured, operated and maintained over time (Liu et al., 2014). Hence, data collection becomes an important aspect of LE management process in the offshore O&G industry. According to Hokstad et al. (2010) data and information from the design, commissioning and operational life stages of asset lifecycle should be collected

for LE assessment. Liu et al. (2014) suggested the need to introduce requirement to enhance reliable data collection in the offshore O&G industry to ensure asset integrity during LE period of operation. For more on data requirements for LE assessment of critical assets, readers can refer to Appendix C. The types of data and possible sources of such data have further been classified into design data, operational data, and economics analysis data.

4.3.1.4 System Breakdown and Selection of Critical Components

This section screens and prioritises SCEs for LE assessment. It will be costly and time consuming conducting LE assessment for all components of a system. Therefore, resources for LE should focus on systems or components that have direct or indirect impact on safety or whose failure may result in longer downtime. Fig.4-6 illustrates a methodological process developed to screen and prioritised critical components for further detailed analysis.

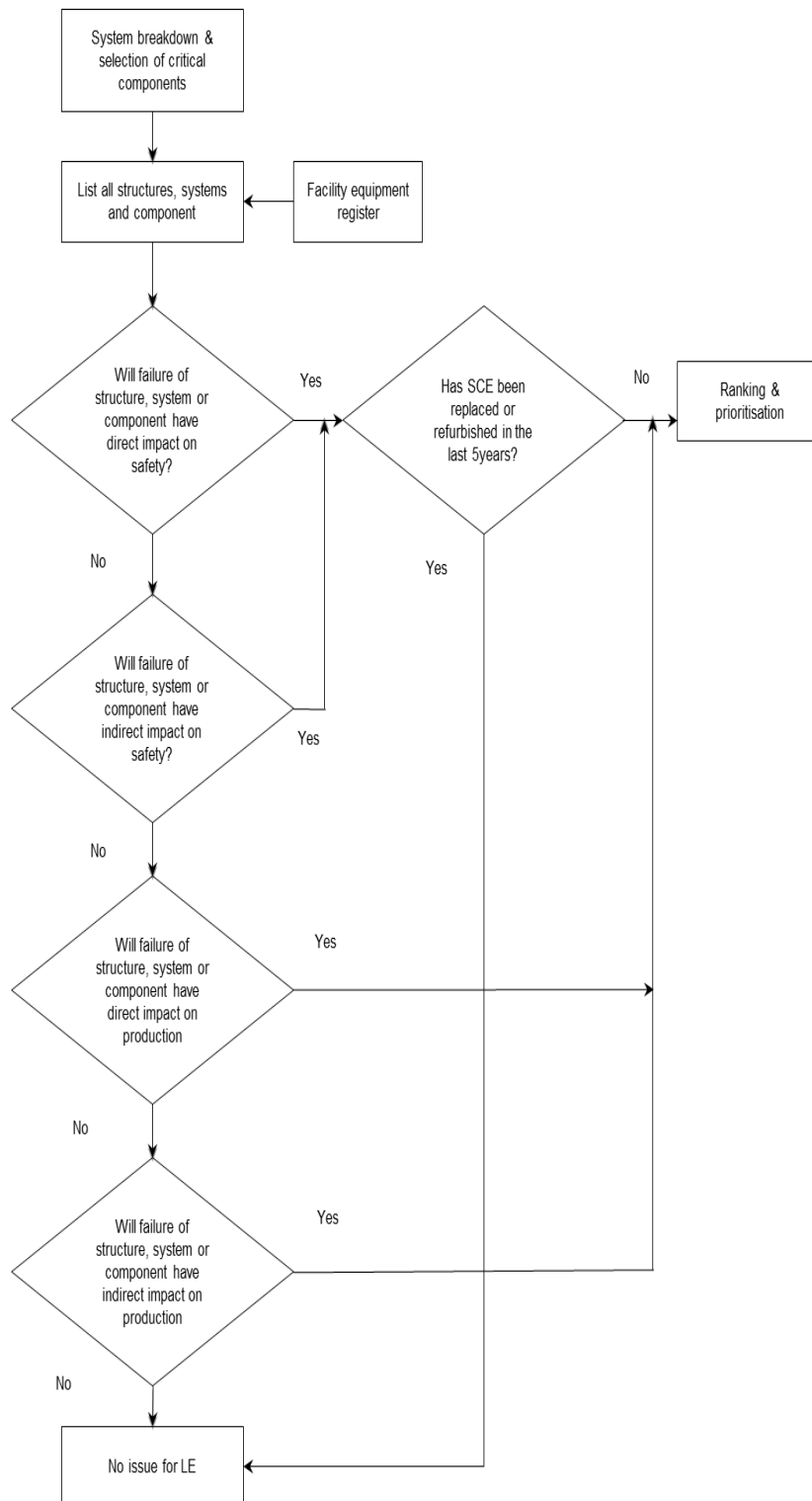


Figure 4-6: A flow diagram for screening and prioritising SCEs critical systems/components

The main objective of screening is to target critical equipment and components relevant to safety. Vaidya and Rausand (2011) suggested that LE decision making requires prioritisation of critical SSCs relevant to safety and sensitive to ageing effects. Screening of systems and its components could also reveal which critical systems/components are particularly sensitive to ageing and whether ageing mechanisms could influence safety. Also, identification of critical components coupled with failure analysis using available data and methods contributes significantly in improving efficient and reliability of SCEs.

4.3.1.5 Prioritisation

Several asset management tools are now available to screen and prioritise critical components of a system. Cause-consequence analysis, checklist, event tree analysis, fault tree analysis, hazard & operability analysis (HAZOP), failure modes and effects analysis (FMEA), failure modes effects and criticality analysis (FMECA), What-if analysis, etc. are examples of some available tools. This study uses a modified FMEA called Ageing Failure Mode Effect Analysis (AFMEA) as a means of ranking and prioritising ageing system or components for detailed analysis. RPN for potential ageing failure modes are evaluated using a 10-point rating scale for Severity(S), Probability of Occurrence (O) and Detection (D) which are tabulated in Tables 4-2 to 4-4.

Table 4-2: Ratings for severity of ageing failure mode

Scale	Description	Criteria
1	None	Be unnoticed and not affect the performance and safety of system
2	Very Minor	Be unnoticed; minor effect on system performance and safety
3	Minor	Cause a minor nuisance; can be overcome with no loss of function to system and compromise safety.
4	Very Low	Cause minor performance loss
5	Low	Cause a loss of performance likely to result in a complaint
6	Moderate	Result in partial malfunction
7	High	Causes extreme process and equipment dissatisfaction
8	Very High	Render the process and equipment unfit for use
9	Hazardous, with warning	Be illegal
10	Hazardous, without warning	Injures are life threaten

Table 4-3: Ratings for probability of occurrence of ageing failure mode

Scale	Description	Criteria I	Criteria II
1	Failure is unlikely. No failures ever associated with almost identical processes	< 2 per million	Once every 6-100 years
2	Only isolated failures associated with almost identical processes	< 3 per 10 million	Once every 3-6 years
3	Isolated failures associated with similar processes	< 6 per million	Once every 1-3 years
4	Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions	< 6 per 100,000	Once per year
5		< 1 per 10,000	Once every 6 months
6		< 0.03 %	Once every 3 months
7	Generally associated with processes similar to previous processes that have often failed	< 1 %	Once per month
8		< 5 %	Once per week
9	Failure is almost inevitable	< 30 %	Once every 3-4 days
10		> 30 %	More than once per day

Table 4-4: Ratings for detection of ageing failure mode

Scale	Description	Criteria
1	Almost Certain	Defect is obvious and can be kept from affecting process
2	Very High	All units are automatically inspected
3	High	Condition monitoring, with 100% inspection surrounding out-of-control units
4	Moderately High	Condition monitoring used, with an immediate reaction to out-of-control conditions
5	Moderate	Degradation monitored via condition monitoring systems and manually inspected
6	Low	Manual inspection with mistake-proofing modifications
7	Very Low	All units are manually inspected
8	Remote	Units are systematically sampled and inspected
9	Very Remote	Occasional units are checked for degradation
10	Almost Impossible	Failure caused by degradation is not detectable

AFMEA as a technique has been applied in the nuclear power plant industry for estimating ageing impact on critical components and identifying components with high degradation rate for ageing and LE management (Nitoi et al., 2011). It has an advantage of analysing performance changes due to failure, estimating component risk and also been structured, sequential and repeatable. AFMEA could be performed using the following step:

1. Breakdown system into subsystem and components.

2. Identify subsystem/components function.
3. For each subsystem/component identify stress factors and determine possible ageing failure modes.
4. Specify detection methods for each possible ageing failure mode.
5. Evaluate each ageing failure mode by assigning indices to Severity(S), Probability of Occurrence (O) and Detection (D) using tables 4-2 to 4-4 above.
6. Estimate RPN by multiplying $S \times O \times D$
7. Rank and prioritise subsystems/components
8. Make recommendation

The RPN is used to prioritise failure mode caused by ageing degradation. This number is a value between 1 and 1000 according to the agreed scale, with 1 being the minimum impact of ageing and 1000 the maximum impact of ageing based on the agreed scale. RPN is estimated by finding the product of $S \times O \times D$. The RPN value represents overall ageing contribution to system/component failure.

The RPN values are then classified as less sensitive to ageing, moderately sensitive to ageing and highly sensitive to ageing. For ease of interpretation, the ageing failure modes with RPN values less than 100 are accepted as less sensitive ageing and therefore less critical. RPN values between 100 and 200 are classified as moderately critical because of moderate impact of ageing on such components. Then RPN values > 200 are classified as highly critical because such components remain highly sensitive ageing with high degradation rate. Components are further prioritised into the following three classes: very sensitive to ageing, moderately sensitive to ageing and minimum impact to ageing.

4.3.2 Phase 2: Technical and Economic Analysis of Life Extension

The second phase of the framework focuses on technical and economic appraisal of LE (Fig.4-7). This section of the framework comprises two main modules: technical module, which produces the equipment health index (EHI) and economic module which produces the economic index (EI). The product of EHI and EI results in a single index to qualify the SCEs for future operations.

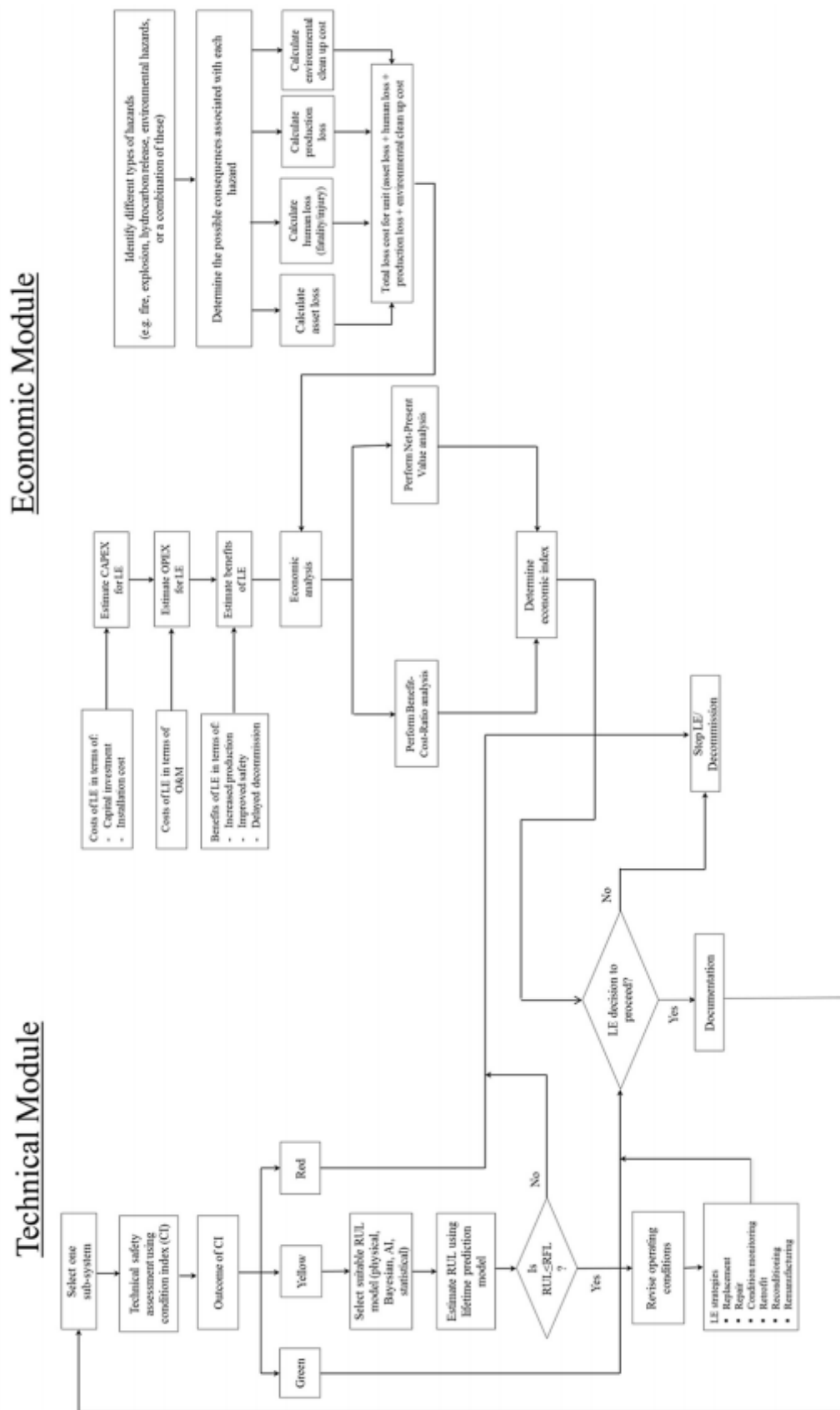


Figure 4-7 A techno-economic LE feasibility analysis framework

4.3.2.1 Technical Evaluation

This involves applying engineering assessment techniques to analyse equipment health status in order to judge SCEs based on current conditions. Techniques such as gap analysis, RCM, condition assessment rating techniques and PSA models can be used to ascertain current condition of system/component for LE.

This research develops a simple semi-quantitative condition assessment rating tool called condition index matrix (CIM) approach. This approach incorporates physics of failure prediction models for estimating remaining useful life of component and also considers other information based on expert's knowledge. It could be considered as a fusion of the qualitative and quantitative tools for integrity assessment. The CIM technique is aimed at assessing the actual technical condition of structures, electrical systems and mechanical components. It offers companies the opportunity to establish sound basis for decision-making or investments into extended life operations of their installations. The first step of the CIM technique is to identify condition assessment factors which contribute to system/component health risk. These factors include operational parameters, usage and age, location of operations, testing, maintenance and failure records. The corresponding records of these factors are then benchmarked against established company and regulatory KPIs. Weights are subsequently assigned based on system/component condition risk factors and index called condition index (CI) is calculated, which reflects the overall health status of an ageing system/component. Detailed description of CIM technique is presented in section 4.4.

4.3.2.2 Economic Evaluation

Although technical assessment and knowledge are key components for safe and reliable operation of SCEs during LE period, economic evaluation of technical requirement and recommendation during LE cannot be under estimated. The economic module accounts for the total investment cost for LE programme. In order to make economic decision using the framework, an economic indexing (EI) system was developed based on cost benefit analysis

(CBA) to measure the economic efficiency of LE programme. According to Mechler and Hochrainer-Stigler (2013) and Tuan et al. (2015) CBA compares the cost of implementing a programme with its benefits and subsequently calculate the net benefit or economic efficiency. Finally, economic index (EI) is determined by using net present value (NPV) and benefit-cost-ratio (BCR) analysis. These techniques are described into details in Section 4.4.

4.3.3 Phase 3: Regulatory Approval and Implementation

Phase three of the framework focuses on regulatory approval as well as implementation of measures to monitor the effectiveness of LE management programme (Fig.4-8).

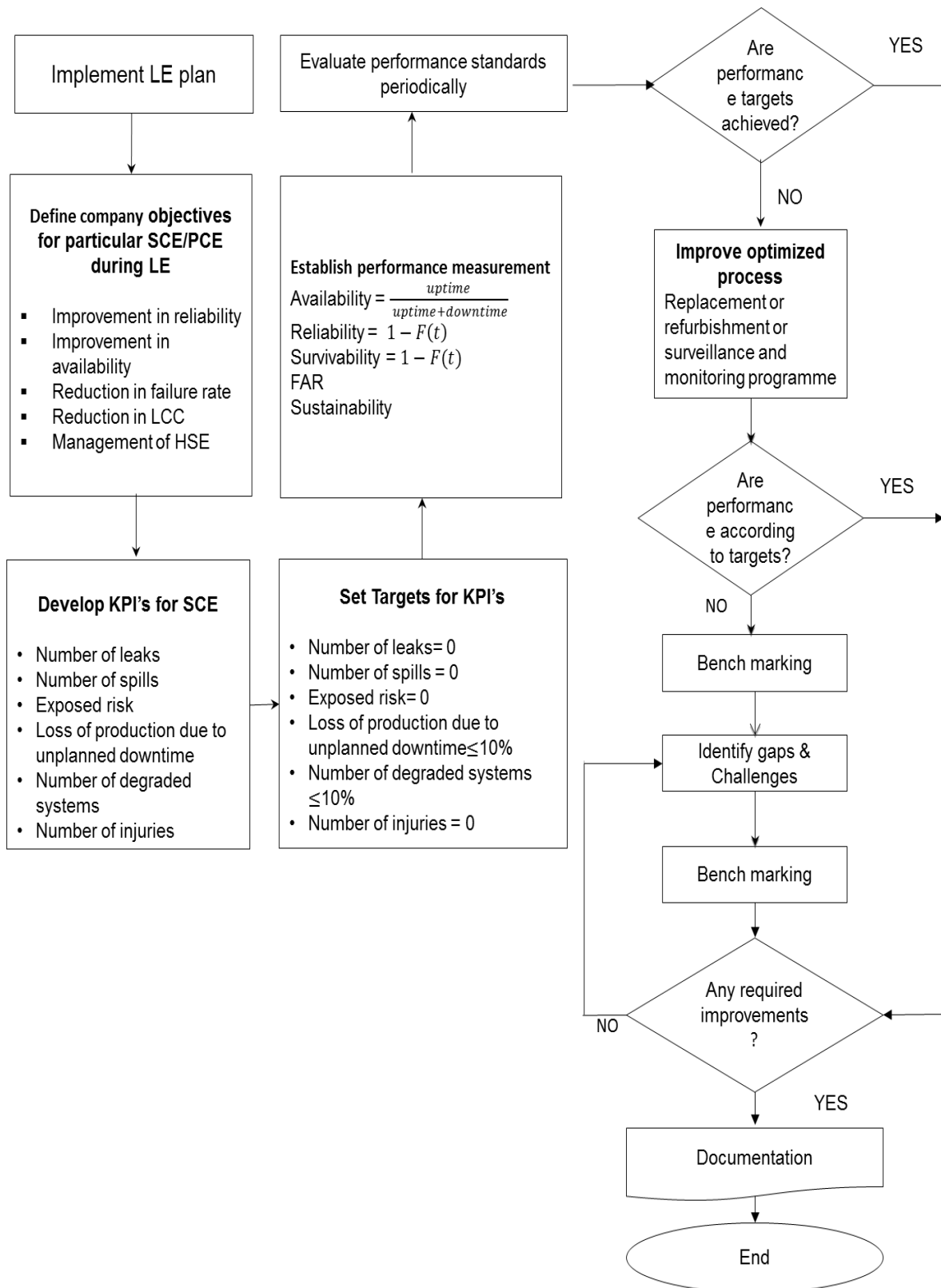


Figure 4-8 A flow diagram for LE implementation

4.3.3.1 Regulatory Approval

LE processes must be supported by engineering and technical documentation for justification of continual operation of SCEs beyond their design life. The main purpose of regulatory consideration and approval is to thoroughly assess documentation submitted by operators and ensure that critical component or system could perform their intended function during LE period of operation in accordance with relevant regulations. Regulators are required to review and verify that LE management programme is consistent with regulations and industry approved standards. In an event that SCE do not qualify for approval at this stage, then a recommendation is made whether to decommission or institute improved ageing management programme.

4.3.3.2 Implementation

This stage of the phase three of the framework involves capturing the outputs from the proposed LE management framework to enable continuous improvement of the testing, inspection and maintenance activities required during the extended life period. The study designs a process to ensure that asset integrity is always known, how it is changing overtime, provide indication of ageing and select the appropriate actions to upgrade or restore asset (see Fig.4-8).

4.4 Description of Proposed Technical and Economic Tools

Through interactions with industrial experts, it was observed that the methodologies for supporting techno-economic analysis are a challenge during LE period of operation in the offshore O&G industry. Thus, this study aimed to present suitable methodologies capable of supporting technical and economic feasibility assessment SCEs. These methodologies are described below.

4.4.1 Technical tools

4.4.1.1 Condition Index Matrix

A condition assessment rating tool for LE assessment is vital for evaluating current health status of existing SCEs to facilitate decision-making. In this study,

a CIM methodology is proposed to justify safe and continuous operation of critical assets during LE phase of operation. The method establishes an index called CI to establish the current health status of SCE for technical justification of LE. The approach combines risk assessment factors and condition indicators to produce a decision matrix. Weights are assigned to these factors through experienced field experts and literature. These weights are determined based on the severity of factors to equipment condition and risk. The weights can be modified based on expert's experience as well as the quality of available data. Overall CI is then calculated based on the weighted sum of the individual condition indicators. The CI is plotted on a matrix to interpret the condition of equipment. The proposed condition assessment methodology can be applied in other industries due to its generic nature. The steps involved in using CIM for condition assessment of SCEs are outlined below:

Step 1: Identify condition assessment factors for LE (See Appendix D for sample of condition factors).

Step 2: Group similar assessment factors into history and health factors according to their risk contribution.

Step 3: Assign scores to history and health factors based available data and experience of field experts or assessment team (See Table 4-5).

Table 4-5 Condition score analysis

Historic Factors	A	B	C	D
1	W	X	Y	Z
2	W	X	Y	Z
3	W	X	Y	Z
4	W	X	Y	Z
6	W	X	Y	Z
7	W	X	Y	Z
$n+1$	W	X	Y	Z
Health factors	A	B	C	D
1	W	X	Y	Z
2	W	X	Y	Z
3	W	X	Y	Z
4	W	X	Y	Z

5	W	X	Y	Z
6	W	X	Y	Z
7	W	X	Y	Z
$n+1$	W	X	Y	Z

Table 4-6 Rating scores for condition assessment factors

Rating	Score	Risk level	Description
A	4	None	Normal
B	3	Low	Quite normal
C	2	Moderate	Not normal
D	1	High	Worse

Step 4: Sum weighted history and health scores using Eq. (4-1)

$$\text{Condition Score} = \sum_{i=1}^n S_i w_i \quad (4-1)$$

where n indicates the number of elements (parameters) taken into account in each factor, S_i represents the rating score of the i th element, and w_i is the relative importance (weight) of element i which is calculated using a pairwise comparison of elements. Eq. (4-1) is based on the Simple Additive Weighting (SAW) or Weighted Sum Method (WSM), which is considered the simplest and most used approach for scoring and prioritising SCEs based on multiple attributes.

Step 5: Determine the CI using Eq. (4-2) as below (Jahromi et al., 2009)

$$\text{CI} = \alpha \times \text{history score} + (1 - \alpha) \times \text{health score}, \quad 0 < \alpha < 1 \quad (4-2)$$

where α and $1 - \alpha$ represent the relative importance of history and health factors in relation to each other.

Step 6: Display sub-system CI on square matrix to rate the condition of system as shown in Fig.4-9 or use Table 4-7.

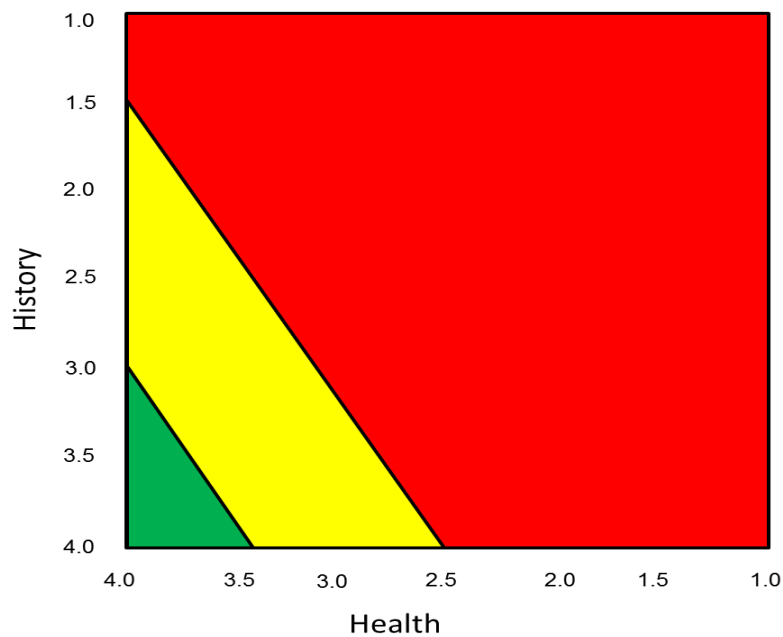


Figure 4-9: Condition index matrix

Table 4-7 Interpretation of asset health based on condition index

CI	Colour
[4.0 -3.5]	Green
[3.4 -3.0]	Yellow
[2.9 – 0.0]	Red

Step 7: Estimate RUL of SCE when CI is between [3.4 – 3.0] or if assets health is displayed in yellow zone.

Step 8: Repeat process for each candidate equipment for LE.

4.4.1.2 Interpretation of Rating Matrix and Table

Technical justification of SCE for LE is represented by binary variables (0 and 1), where 1 indicates a healthy condition and vice versa. After calculating CI, SCEs found in the green zone indicates that the particular SCE technically qualifies for LE and does not require estimation of RUL. This means that the particular SCE is assigned equipment health index (EHI) of one. The red zone is termed the risk zone and SCEs found within this zone do not qualify for LE technically and hence EHI value of zero is assigned. If equipment is found in the

yellow zone, which is a warning zone, it means that some measures (i.e. safety and/or process control measures) must taking before SCE could qualify for LE. In order to assign EHI to equipment found in the warning zone a decision-maker must proceeds to determine the RUL of the SCE. Literature on various methods for estimating the RUL of system/components can be found in Galar et al. (2012) and Jardine et al. (2006). The RUL of SCE is then compared to the principal LE decision-making variable. For example, in the offshore O&G industry the principal LE decision-making variable is the remaining field life (RFL). If the RUL is less than or equal to RFL, then EHI value of one is assigned, which implies that the sub-system can be qualified for LE from technical point of view. This is mathematically expressed by Eq. (4-3) and (4-4).

$$EHI \in [0, RFL - RUL] \quad (4-3)$$

$$EHI = \begin{cases} 1 & \text{if } 0 \leq LE \leq RFL - RUL \\ 0 & \text{Otherwise} \end{cases} \quad (4-4)$$

4.4.2 Economic Tools

4.4.2.1 Net Present Value (NPV)

The basic methods for analysing economic feasibility of LE programme are internal rate of return (IROR), net present value (NPV), annual cost method (ACM) and benefit cost ratio (BCR). However, this research adopts the NPV and BCR methods because it allows for comparison of more alternatives considering the time value of money (Sodha et al., 1991; Kablan, 2004). NPV is the difference between cost and benefit discounted over time in a given year (Tuan et al., 2015). Eq. (4-5) is used in computing the NPV for a system.

$$NPV = \sum_{t=0}^T \frac{1}{(1+r)^t} [B(t) - C(t)] \quad (4-5)$$

where $B(t) = B1 + B2 + \dots + Bn$ and $C(t) = C1 + C2 + \dots + Cn$ are the sum of benefits and costs in a given year t , $r > 0$ is the discount rate and T is the length of LE

programme. Therefore the NPV of a subsystem/component during LE period of operation is estimated as:

$$NPV = \sum_{i=1}^n \sum_{t=0}^T \frac{1}{(1+r)^t} [B_i(t) - C_i(t)] \quad (4-6)$$

So, if the NPV is positive ($NPV > 0$), then EI value of one is assigned and if $NPV < 0$, the EI value of zero is assigned.

4.4.2.2 Benefit-Cost Ratio (BCR)

This approach is at variant to the NPV method. With this method the present value of all benefits is divided by present value of all costs. Therefore,

$$BCR = \frac{\sum_{i=1}^n \sum_{t=0}^T \frac{B_i(t)}{(1+r)^t}}{\sum_{i=1}^n \sum_{t=0}^T \frac{C_i(t)}{(1+r)^t}} \quad (4-7)$$

So, if the ratio of benefit to cost is greater than one ($BCR \geq 1$), then EI value of one is assigned and if $BCR < 1$, then EI value of zero is assigned.

4.4.3 Total Risk Cost Estimation

The economic assessment module in the second phase of the proposed framework uses a risk-cost assessment approach to calculate the risks costs associated with a LE project. The total risk-cost (TRC) includes four types of risks arising due to asset loss, human health loss, environmental damage, and production loss. Therefore,

$$TRC = ALRC + HHLRC + EDRC + PLRC \quad (4-8)$$

In what follow, the four types of risk considered in this study are explained into details

4.4.3.1 Asset Loss Risk Cost (ALRC)

Asset loss risk-cost refers to the costs associated with loss of equipment function or damage to equipment as a result of ageing phenomenon. Ageing

effects on SCEs may also lead to major accidents such as fire and explosion. ALRC can be calculated using Eq. (4-9).

$$ALRC = A_D \times C_A \quad (4-9)$$

where A_D represents the equipment's damage area and C_A is the asset loss cost per unit area.

4.4.3.2 Human Health Loss Risk-Cost (HHLRC)

Human health loss risk-cost (also known as statistical cost of life) is calculated by the product of the number of people that may be affected (N_D) and the health care cost associated with each fatality (C_H). Thus,

$$HHLRC = N_D \times C_H \quad (4-10)$$

There is always a difficulty in assigning monetary values to human fatalities. For this reason, the cost of human fatalities may introduce a degree of uncertainty into the cost calculations. Khan and Amyotte (2005) suggested that some indicators such as cost of rehabilitation, insurance and worker's compensation rate can be used instead.

4.4.3.3 Environmental Damage Risk-Cost (EDRC)

Environmental damage risk-cost includes cost of all kinds of damage to operating environment and surface cleaning charges, if required. Thus,

$$EDRC = (A_{ED} \times C_{ED}) \times C_{SC} \quad (4-11)$$

where A_{ED} represents environment damage area, C_{ED} is the cost of environmental damage per unit area, and C_{SC} represents the surface clean-up cost.

4.4.3.4 Production loss risk-cost (PLRC)

Production loss risk-cost due to asset damage is calculated by the production rate per day (C_p) multiplied by expected downtime (T_d) in days. Thus,

$$PLRC = C_p \times T_d \quad (4-12)$$

4.4.4 Life Extension Measure

Finally, the Life Extension Measure (LEM) is calculated as a product of the equipment health condition and economic add value index, i.e.

$$\text{LEM} = \text{EHI} \times \text{EI} \quad (4-13)$$

If LEM equals one, the sub-system will be qualified for LE from both the technical and economic perspectives and can be included in the LE programme.

4.5 Remaining Useful Life and Life Extension

The techno-economic framework helps asset managers to answer the question whether existing SCEs could qualify for LE. In applying the techno-economic framework the EHI of the candidate equipment for LE is categorised into green, yellow and red zones. However, when the result of the EHI is displayed in the yellow zone, then asset managers still have the opportunity to extend the life of the asset provided some proactive measures can be carried out. However, before determining the necessary actions to be carried out to extend the life of an asset in the yellow zone, asset managers must know the *maximum length of time the asset is required to operate during LE phase of operation*. In order to determine the maximum length of time an asset could operate, Vaidya and Rausand (2011); Animah et al. (2016) and Shafiee et al. (2016) suggested in their respective studies that, it will be vital for LE decision makers in the offshore O&G industry to estimate RUL of their candidate equipment to enable stakeholders to arrive at accurate conclusions during LE decision making process. Also, Liao et al. (2006) suggested that when ageing degradation is detected, it is important to estimate the RUL to facilitate urgent maintenance decision to avert possible failure. This is because the RUL estimated for offshore O&G equipment at design stage is conservative, since in practice the operational and environmental conditions changes with respect to those considered during design. Therefore, during LE decision making process, an improved process is required to determine the actual remaining service life of

critical systems, subsystems and components which may be longer compared to the life estimated during design.

Having reviewed literature on LE application and trend in the offshore O&G industry, no study has developed a process to be used in establishing a relationship between condition assessment, RUL and LE decision making. Therefore, the research at this stage focused on developing a process capable of establishing a relationship between condition assessment technique, RUL estimation and LE decision making process.

4.5.1 Factors Influencing Remaining Useful Life Estimation in the Offshore O&G industry

LE decision making process for SCEs takes into account technical, economic and organisational factors. A study of these factors provides a strong foundation for making correct decisions concerning data collection, condition assessment, RUL estimation and regulatory approval for continuous operation.

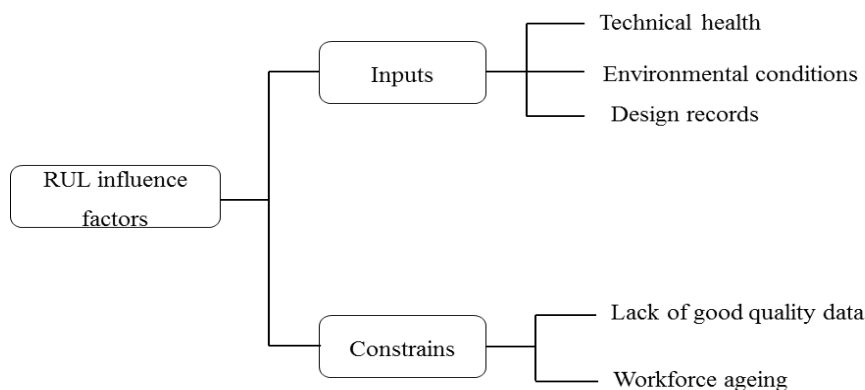


Figure 4-10 RUL influencing factors

In this research, the author classifies the factors influencing RUL estimation into inputs and constraints factors (see Fig.4-10). Brief discussions of these factors are presented in the next sub-sections.

4.5.1.1 Input Factors

Vaidya (2010) and Vaidya and Rausand (2011) categorised the inputs factors influencing RUL prediction into technical health, design records and environmental conditions.

4.5.1.1.1 Technical Health

The technical health of an asset is assessed or judged using indicators such as technical condition, working life history, environmental history, design records and reliability data (Vaidya and Rausand, 2009). Thus, the technical health of an asset at a time t can be described as the accumulated knowledge about an asset at that particular time. The technical health status of equipment is determined based on technical conditions and working life history, which are explained in brief details below.

Technical condition: The technical condition of an asset is the health status measured by indicators such as temperature, pressure, vibration, oil analysis, wear, shock etc. at the time t . According Vaidya and Rausand (2011) some of these technical condition indicators are useful when monitored on continuous scale for example temperature, pressure and noise while some of the indicators are discrete such as leakage. Deterioration models are often employed to determine the health conditions of some industrial assets.

Working life history/Operational conditions: As O&G production field matures, operators gather huge amount of operational data or working life data. Therefore, determining the RUL of critical asset at the time t to support LE decision making process must involve all operational information gathered since installation to the time of LE decision. The working life information includes age of the asset, degradation records, failure records, condition monitoring information, and maintenance and modification information. The sources of this data include the use of experts' judgement, manufacturers manual, operation and maintenance log books, input by workforce working on platforms and electronic databases kept by companies.

4.5.1.1.2 Environmental Conditions

The environmental conditions predicted at the early life stage of an asset lifecycle may change over the life of the asset, thereby subjecting the asset to different environmental conditions. This may introduce new failure mode and also increase the rate of deterioration of existing failure. Hence, the technical health of an asset must take into account the environmental conditions in which the asset has operated until time t . According to Vaidya and Rausand (2011) environmental condition information must include geographical location of operations, geology of the well, well data such temperature, pressure, viscosity level of the well product, gas content, water content and sand particles. Also, depending on the location of the critical asset, environmental factors such wave height, current and wind speed can be considered.

4.5.1.1.3 Design Records

Some offshore O&G assets (i.e. christmas tree, umbilicals, manifold templates, control modules, subsea pumps, subsea separators, pipelines etc.) are designed not to be maintained on regular basis. Therefore, estimating the RUL of such assets to support LE decision making must take into account verification of calculations employed during the design phase of the asset lifecycle. Design phase information that may help estimate RUL includes material selection information, equipment specification, design codes and standards; design drawings, design life calculations and engineering variations post design.

4.5.1.2 Constraints

The two key constraints to LE decision making process in the offshore O&G industry is the lack of access to good quality data and ageing working force. Hokstad et al. (2010) reported that the offshore O&G industry lacks data with high degree of confidence to support LE decision making process. Also, workforce ageing and lack of trained personnel has been an obstacle to successful LE decision making process. This is because by the time LE is due, some critical workforce with vital information may have changed companies or retire from active service. These obstacles are likely to impact the effort of

establishing a relationship between condition assessment, RUL prediction and LE decision making.

4.5.2 The Proposed Process

The process establishing the relation between condition assessment, RUL estimation and LE decision making process is presented. The process consists of three modules, as shown in Fig.4-11.

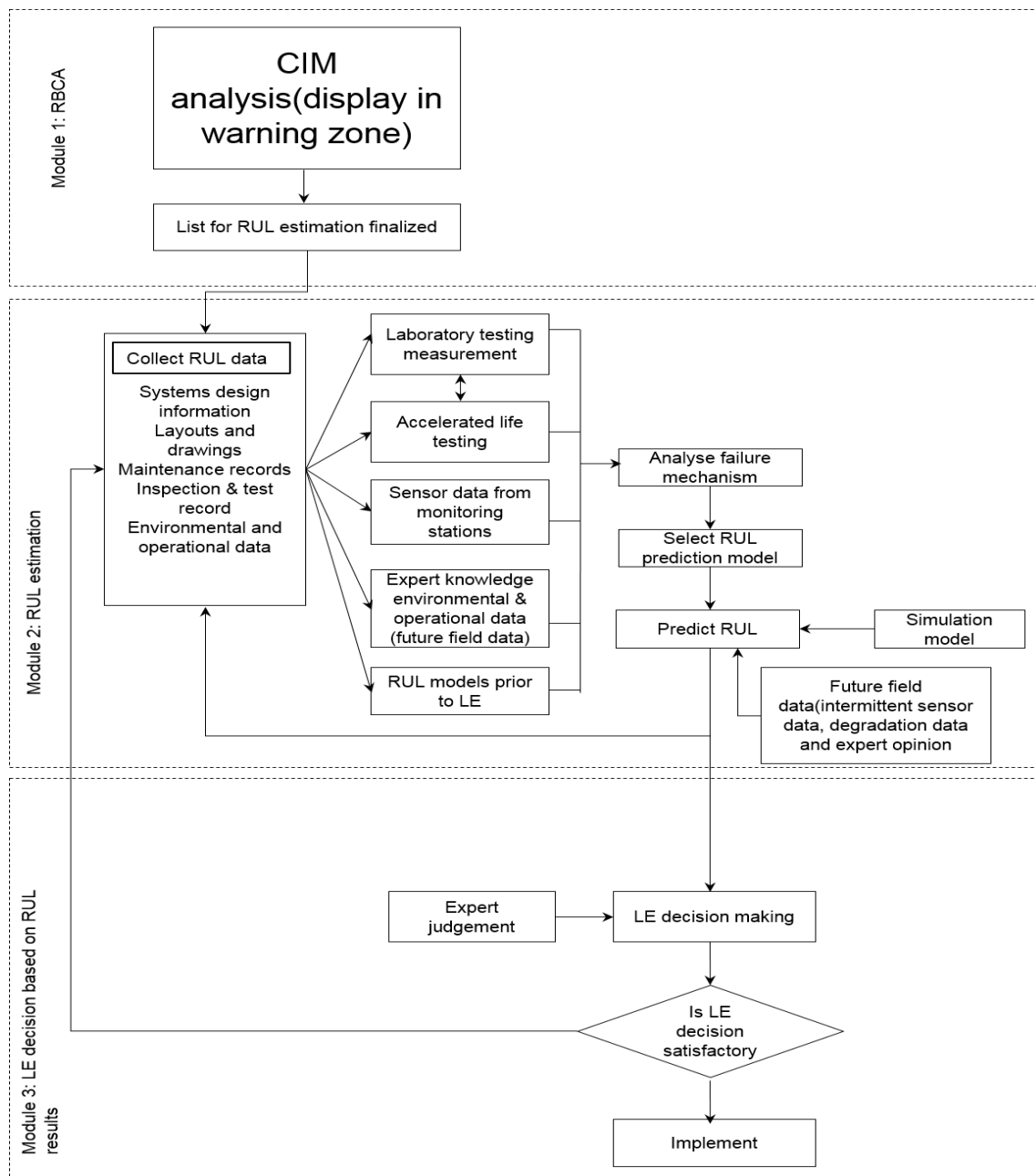


Figure 4-11 Process to estimate RUL for LE decision making

4.5.2.1 Module 1: Condition Assessment Module

This module is responsible for assessing the current health status of critical subsystem or components for extended operations. The techno-economic model explained in the previous section is responsible for performing the task of condition assessment.

4.5.2.2 Module 2: RUL Prediction Techniques for LE

In this module, the concept of RUL is used to predict the maximum length of service time for a subsystem or component displayed in the warning zone as results of condition assessment using the techno-economic framework. The purpose is to optimise operations while minimising catastrophic failure during LE phase of operation. In this case, RUL prediction models can either be probabilistic or deterministic but must take into account degradation mechanisms, material properties, geometry, operational and environmental conditions (Vaidya and Rausand, 2011). The key stages of the second module are presented below.

4.5.2.2.1 Collect RUL data

The first step of the second module is to collect relevant RUL data for candidate subsystem or component. These data includes laboratory testing measurement, accelerated life testing data, sensor data from monitoring systems, expert knowledge, environmental data and operational information.

4.5.2.2.2 Analyse Failure Mechanism

In real life application, there is more than one failure mechanism associated with a particular failure mode for subsystem or component operating in the offshore environment. Therefore, it is very vital for asset managers to analyse various failure mechanisms associated a particular failure mode and identify the dominant failure mechanism that impact the functionality of the subsystem or component. According to Vaidya and Rausand (2011) this dominant failure mechanism play the crucial role in predicting the RUL of candidate subsystems or component for LE.

4.5.2.2.3 Select RUL Prediction Model

Lifetime estimation models applied in the offshore O&G industry to predict RUL of systems and structures includes Bayesian models, statistical and stochastic models, computational intelligence models, physics of failure models and expert judgement. After analyses of the possible failure mechanisms associated with subsystems and components, decision makers are required to select the most suitable prediction model for specific application. One of the possible ways to select the most suitable model is to map techniques against degradation mechanisms or map technique against type of data. Table 4-8 shows the RUL prediction techniques mapped against possible degradation mechanisms available in the offshore O&G industry.

Table 4-8 Technique versus degradation mechanism (adapted from Okoh et al., 2014)

Degradation mechanism	Bayesian model	Statistical techniques and stochastic models	Computational intelligence models	Physic of failure	Expert Judgement
Fatigue	x	x	x	x	-
Wear	x	x	x	x	-
Deformation	-	-	-	x	x
Corrosion	x	x	x	x	-

The selection of suitable lifetime prediction model is based on the dominant failure mechanisms associated with the subsystem or components.

4.5.2.2.4 Prediction of RUL

At this stage, the RUL of the candidate subsystem or components is estimated for further decision making. From literature and interaction with industrial experts in Chapter 3, the most dominant failure mechanisms subsystems or components are likely to experience in the offshore O&G industry during LE phase of operation is corrosion, which is due to metal loss as well as failure due to crack propagation or fatigue.

A PoF technique was selected together with expert judgement to determine the RUL of the subsystems and components. The corrosion model for estimating

the RUL is based on API 570. Hence, the remaining life of a subsystem or component can be calculated using Eq. (4-1) as follows:

$$RUL = \frac{T_A - T_R}{CR} \quad (4-14)$$

where, T_A is the actual thickness measured during inspection, T_R is the design thickness without corrosion allowance and CR is the measured corrosion rate (mm/year). The subsystem/component is considered failed if a section of the component is equal to or below zero. This is expressed mathematically as:

$$Probability\ of\ failure = \Pr(RUL \leq 0) \quad (4-15)$$

The fatigue crack growth rate is estimated using the Paris law:

$$\frac{da}{dN} = C(\Delta K)^m \quad (4-16)$$

where, $\frac{da}{dN}$ represent the crack growth rate, ΔK is the stress intensity, C and m are constants parameter related to subsystem or components material properties and is obtained through experiments. The number of fatigue cycle to failure N_f is expressed as:

$$N_f = \int_0^N dN = \frac{1}{C} \int_{a_1}^{a_{cr}} \frac{da}{(\Delta K)^m} \quad (4-17)$$

where, $\Delta K = \beta \Delta \sigma \sqrt{\pi a}$, where $\Delta \sigma_{\max} - \Delta \sigma_{\min} = \sigma_{\max}$, if $\Delta \sigma_{\min} = 0$, β is the Young's modulus and depends on components geometry.

Thus, expressing the number of cycles to failure N_f in time is defined as:

$$T_f = \frac{2}{(2-m)C(\beta \Delta \sigma \sqrt{\pi})^m} \left(a_{cr}^{\left[1-\left(\frac{m}{2}\right)\right]} - a_1^{\left[1-\left(\frac{m}{2}\right)\right]} \right) \quad (4-18)$$

where, a_1 represent initial crack size, a_{cr} is the critical crack size. A crack beyond a_{cr} will be considered as failure. The above model is deterministic and

convenient for determining the number of cycles; however during LE decision making process probabilistic modelling is essential to handle uncertainties in crack growth. The probabilistic model is expressed as:

$$P[T_f \leq t] = P[a_{cr} - A(t) < 0] = P[T_o + T_G(a_{cr}) - t < 0] \quad (4-19)$$

where T_f is the time to failure, t is a specific time, a_{cr} critical crack depth, $A(t)$ is the crack size at a time t , T_o is the time for crack initiation and T_G is the time for crack growth to critical path.

4.5.2.2.5 Module 3: Life Extension Decision Making

The third module is for making suitable decisions based on the RUL results for future operations. The suitable LE decision could include selection of suitable LE strategy including replacement, remanufacturing and refurbishment of the system for continuous operation. Another important decision during LE phase of operation is determination of the frequency of maintenance for candidate assets.

4.6 Case Study

In this section the techno-economic framework is applied to support LE decision making process for water deluge system in an offshore O&G platform. The offshore O&G platform was commissioned in the year 1990 for producing crude oil and natural gas. The platform is a tanker based floating production and storage (FPSO) facility and its water deluge system is expected to operate for an extended length of time, up to seven years.

The water deluge system on the platform has been designed and constructed according to ISO standards and guidelines as described in the company's engineering documents. The typical sub-systems of a water deluge system are illustrated by the schematic diagram in Fig. 4-12.

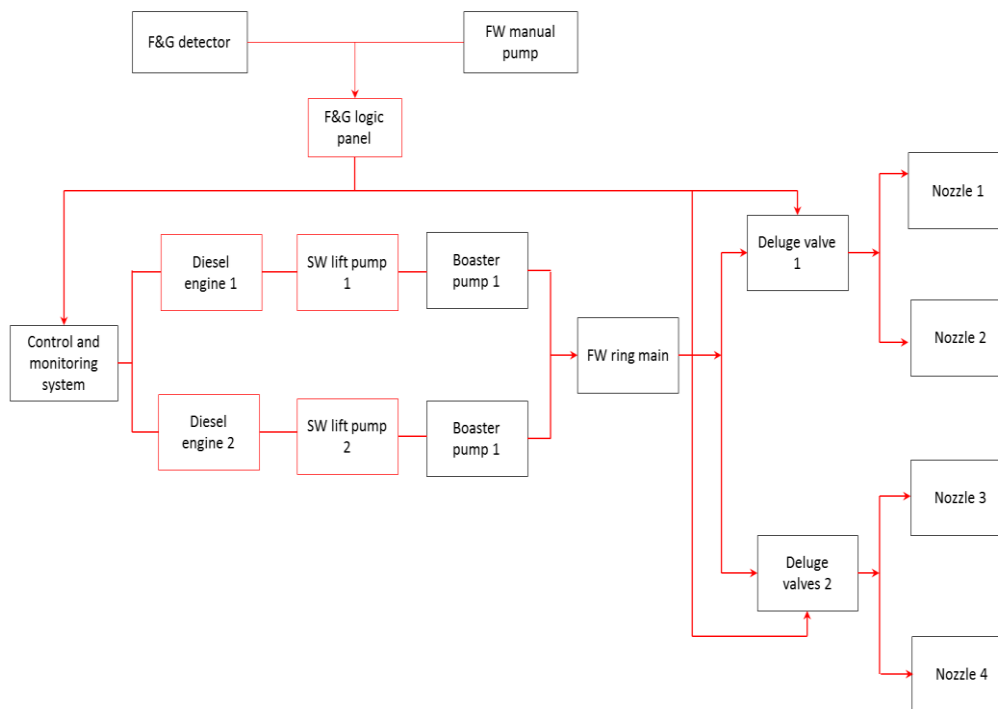


Figure 4-12 A schematic diagram of the water deluge system

As shown in Fig.4-12, they include seawater (SW) lift pump and booster pump packages with diesel power direct-driven system. The diesel engine drive system was replaced by a new one 10 years ago. The water deluge system is independent of SW cooling system and according to the inspection of piping and instrument data (P&ID), it is also independent of all other systems on the platform. Other sub-systems include: fire and gas (F&G) logic, nozzles, detectors, firewater (FW) ring main, pipes, controls, instrumentation and valves used for various purposes. In Fig. 7-1, the arrows illustrate the direction of the water flow. The seawater is pumped at a height of 80m by the lift pump. The water then flows through the booster pump to the FW ring main for distribution. In addition, 55 m³ water per hour is used for diesel engine cooling. The FW ring main is fitted with check valves to avoid back flow to the pumping system. FW ring main piping sections are situated outside of hazardous areas to use for multi-directional flow. There is an F&G logic which is responsible for starting diesel engine and pumps as well as opening of deluge valves at the alarm from detectors. According to the information collected from design manuals, the

water deluge system is constructed from materials such as Cu/Ni (90/10) alloy for pumps and diesel engine cooling system and galvanised carbon steel for the piping network. The required data for this study was collected from databases such as manufacturer's catalogues and if some information were not available, an independent expert elicitation was performed with experts.

4.7 Analysis of Results

In this section, the results of the case study are presented and discussed.

4.7.1 Phase 1

- Premise for LE

The objective of this case study is to determine if water deluge system can qualify for extended operations.

Identification of Stakeholder's Requirement

The key stakeholders identified to play crucial roles in the LE decision making process was operator and regulator. The operator is required to maximize investment returns during LE phase of operation while the regulator is required to ensure that the risk posed to the environment and personnel working on the platform are minimised during LE phase of operation.

Data Collection

The information required for analysis was collected from design, operation and maintenance manuals as well as from experts.

The Table 4-9 below contains the design information and records for the water deluge system. While operational data, RUL data, economic data and technical data for CIM analysis are shown in Table 4-10, Table 4-11, Table 4-12 and Table 4-13 respectively.

Table 4-9 Design phase data (Confidential)

Data	Source	Documents	Means of collection
Design standards	operator	ISO 13702:1999(1-4) API RP 521, HSE/E publication	Retrieval from archival document
Drawings and layout	"	FEED	"

Design calculations	"	FEED, offshore information sheet 9/2008	"
Material specification	Operators and regulators standards documents	Carbon steel and Cu/Ni (90/10)	"
Technical and engineering adjustment during installation	N/A	N/A	
Applicable regulation	Operators, regulators	PFEER, 1995	Review of regulatory document

Table 4-10 Operational and maintenance data sources (Confidential)

	Source	Document	Means of collection
RAMS	Operator	FEED, maintenance log book	Review of FEED, maintenance log & interview of experts
Modifications	N/A	N/A	
Time of water flow from nozzles	Operator	Testing log book	Review of data sheet
Pressure at deluge valve (bar)	"	"	"
Response time for deluge valve to operate	"	"	"
Water pressure at the pump	"	"	"
Sea water supply temperature	"	System manual	
Operating procedure	"	"	
CM information	"		
New standards and recommended practices	N/A	N/A	
Ageing degradation records	Operator	Inspection and testing records	Operator
Ageing management programme (If any?)	Operator	inspection and maintenance manual and software system	

Table 4-11 RUL data for SW pump seals (Confidential)

Data	Parameters
Analysis object	Seal
Yield stress	90MPa
Material	Carbon Steel
Temperature	293
Wall thickness	1.6 mm
C	9.59×10^{-17} m/cycle
m	5.57

a_c	2×10^{-3}
a_f	$5 \times 10^{-3}m$
Fatigue crack growth threshold(ΔK_I)	13.31 MPa $\sqrt{m}$

Table 4-12 Economic data (Confidential)

Cost components	Seawater lift pump	Piping	Diesel engine	F&G logic	Other economic parameters
Capital cost	\$71878.97	\$496249.89	\$399350.93	\$577056.59	
Installation cost	-	\$87573.52	\$120000	-	
Operation and maintenance cost	\$118084.03	-	\$57705.66	-	
Risk expenditure	\$308026.70	\$583823.41	\$583823.41	\$583823.41	
Royalty cost	NA	NA	NA	NA	\$36000
Taxes	NA	NA	NA	NA	-
Product cost	NA	NA	NA	NA	\$50/BBL
Volume of production/year	NA	NA	NA	NA	120 bopd
Production period in a year	NA	NA	NA	NA	200
Period of LE	NA	NA	NA	NA	10
Discount rate	NA	NA	NA	NA	10%

Table 4-13 Condition index matrix assessment factors (Confidential)

Historic Factors	A	B	C	D
Usage (rated capacity %)	<60	60-75	76-95	>95
Inspection (months)	<12	12	>12	>12
Failure history(number of times in a years)	0	1	2	>2
Location	-	Topside close to flammable substance	Subsea	-
Manufacturer	Still operation	Still in operation but longer produces parts	Lack of suppliers	Not in operation
Age (years)	0-3	4-10	11-20	>20

Environmental conditions		harsh	Moderate harsh	Extreme harsh
Health factors	A	B	C	D
NDT /other functional test frequency	>2	2	1	0
Deterioration change/yr.	Constant	1%	≤4%	5%
Design conditions	Conforms to current design requirements	Conforms to original design requirements	Non-conformity to current design requirements but acceptable for safety	Non-conformity both current and original design requirement
Maintenance interval	Within 1 year of allowed time interval	Between 1 and 2 years of time interval	Between 2 and 3years of time interval	>3 years overdue

Screening and Prioritisation of SCEs

With reference to Fig.4-6, the screening and prioritisation analysis is presented. AFMEA study revealed that failure modes of each sub-system were caused by ageing phenomenon.

The Table 4-14 below shows the process followed to identify SCEs that are possible candidates for screen and prioritisation. The Table 4-13 further indicates that subsystems with IDs FP 1, FP 2, FP 3 FP 6, FP 7 and FP 9 did qualified to be classified as SCEs further screening and prioritisation. On the other hand, subsystems with IDs FP 4, FP 5 and FP 9 did not qualify to be classified as SCEs for further screening and prioritisation.

Table 4-14 Sub-systems identification and screening

ID	Components name	Direct impact on safety	Indirect impact on safety	Direct impact on production	Indirect impact on production	Refurbished/Replaced in the last 5years
FP 1	Piping	Yes	N/A	N/A	N/A	No
FP 2	SW pumps	"	N/A	N/A	N/A	No
FP 3	Steel nozzles	"	N/A	N/A	N/A	No
FP 4	Detectors	"	N/A	N/A	N/A	Yes
FP 5	FW ring	"	N/A	N/A	N/A	Yes
FP 6	F&G logic	"	N/A	N/A	N/A	No
FP 7	Diesel engine	"	N/A	N/A	N/A	No
FP 8	Instrumentation	"	N/A	N/A	N/A	-
FP 9	Valves	"	N/A	N/A	N/A	Yes

In order to prioritise each subsystem for techno-economic analysis, the AFMEA technique is used. Table 4-15 shows the failure modes of the piping system which are caused by ageing phenomenon.

Table 4-15 RPN value for Piping

Ageing failure	Corrosion	Fatigue cracks	No flow/plugged	External leakage
Severity	8	8	9	10
Occurrence	5	5	8	9
Detection	5	7	8	9
RPN	200	280	576	810

The Table 14-16, reveals the ageing failure modes for the SW pump operating on the platform.

Table 4-16 RPN value for SW pumps

Ageing failure	Fail to run	Inadequate flow	Fail to start	External leakage
Severity	10	8	10	2
Occurrence	9	7	9	3
Detection	9	8	9	3
RPN	810	448	810	18

The Table 4-17, shows the failure modes of the nozzles caused by ageing phenomenon.

Table 4-17 RPN value for Nozzles

Ageing failure	External leakage	Delayed deluge initiation	Blocked nozzle
Severity	7	8	3
Occurrence	4	9	4
Detection	6	9	5
RPN	168	648	60

The Table 4-18, reveals the ageing failure modes of the F&G logic system.

Table 4-18 RPN value F&G logic

Ageing failure	Plugged	Delayed deluge initiation	External leakage
Severity	5	7	1
Occurrence	2	3	2
Detection	2	7	2
RPN	20	147	4

The Table 4-19, shows the failure modes of the diesel drive engine caused by ageing mechanisms.

Table 4-19 RPN value for Diesel engine

Ageing failure	Leakage	clogged
Severity	4	8
Occurrence	5	4
Detection	3	5
RPN	60	160

Therefore, based on the RPN values obtained from AFMEA for all sub-systems were ranked and prioritised for LE analysis (Table 4-20). However, the assessments focused on sub-systems with RPN values greater than 200.

Table 4-20 Selected SCEs for LE assessment and analysis

Highly critical(RPN> 200)	Moderately critical(100<RPN<200)	Low critical (RPN<100)
Piping	F&G logic	Nozzles
SW pumps & Diesel engine	Diesel engine	

4.7.2 Phase 2

Techno-economic assessment

The current health status of each subsystem and economic implications of the selected LE strategies are assessed. The results of the technical assessment using the CIM analysis are presented in Table 4-21.

Table 4-21 Results of technical analysis

Factors	Weight	Scores			
		SW pumps	Piping	Diesel engine	F&G logic
Failure history	4	A	D	A	A
Location	2	B	B	A	C
Manufacturer	2	A	D	A	A
Age	4	D	D	A	D
Environmental conditions	4	A	D	A	A
Total history score	16	3.10	1.25	4	3.5
Testing	4	A	D	A	A
Degradation checks	4	B	C	A	A
Design standards	4	A	A	A	A
Inspection & Maintenance	4	B	D	B	B
Total health scores	16	3.50	2	3.75	3.75
Total CI		3.30	1.70	3.90	3.70

The results of the techno-economic analysis of each sub-system are presented in Table 4-22.

Table 4-22 LEM results from techno-economic LE assessment

SCEs	CI	RUL(yrs)	NPV(\$)	EHl	EI	LEM
SW pump	3.3	4	7615.50	1	1	1
Piping section	1.7	-	-1406	0	0	0
Diesel engine	3.9	-	3120	1	1	1
F&G logic	3.7	-	4800.39	1	1	1

Results from the first case study indicated that the technical assessment of F&G logic has CI of 3.7 and hence qualifies for LE technically. This means that existing maintenance and ageing management programmes could be used to manage the F&G system degradation during extended period of operation. Economic assessment result indicated that the F&G logic's NPV is greater than zero, hence assigning an EI value of 1. The analysis of the diesel engine drive system assessment produced CI of 3.9 and a positive NPV value. Therefore, it was qualified for extended operations. The CI for SW lift pump was evaluated

as 3.3, implying that the condition of sub-system is in the warning zone (displayed in yellow colour). The value of EHI was assigned to be 1, because the RUL of subsystem from available data was estimated to be four years which is less than the RFL of seven years. This indicates that the oil field still has the potential to be considered for LE interventions, e.g., remanufacturing, reconditioning, etc. On another side, the economic assessment showed an NPV of \$7615.50, meaning that LE for the SW lift pump will result in substantial economic benefits to asset managers. Technical assessment of piping network produced a CI of 1.7, indicating that the sub-system is not technically qualified for extended operations. Moreover, its economic assessment produced a negative NPV. Despite three of the critical sub-systems having LEM of 1, the entire water deluge system life cannot be considered for LE management because one of the sub-system LEM is 0. Hence the entire system is considered unsafe for future operation. However, if asset manager want to proceed with LE of the water deluge system, then asset managers must ensure that corrective and preventive measures are implemented regardless of cost implications.

In order to determine the robustness of the decision and also to identify parameters that can influence the LEM results when changed, sensitivity analysis was performed. Results from the sensitivity analysis indicated that when the capital cost of the sub-systems are increased from 100% to 500% none of the subsystems qualifies for extended operations (See Table 4-23).

Table 4-23 LEM results for increasing capital expenditure

SCEs	LEM@100%	LEM@200%	LEM@300%	LEM@400%	LEM@500%
SW pump	0	0	0	0	0
Piping section	0	0	0	0	0
Diesel engine	0	0	0	0	0
F&G logic	0	0	0	0	0

On another side, the LEM of all the subsystems remained 0, when the O&M cost is also increased from 100% to 500%. Therefore, in this particular case the

capital cost and O&M cost are key economic factor in the LE decision making process. When the cost of product was increased from \$100/BBL to \$500/BBL, the LEM of 1 was obtained for all subsystem, except the piping network. Again, when the cost of product was reduced from \$40/BBL to \$20/BBL each subsystem's LEM was 0.

Table 4-24 LEM results for increasing O&M expenditure

SCES	LEM@100%	LEM@200%	LEM@300%	LEM@400%	LEM@500%
SW pump	0	0	0	0	0
Piping section	0	0	0	0	0
Diesel engine	0	0	0	0	0
F&G logic	0	0	0	0	0

Also, varying the weights of the history and health factors has an impact on the LEM results. As shown in Table 4-25, when the weights for the *age factor* (history factor) in the CIM analysis was changed to 1, the CI of the SW lift pump remained in the warning zone (displayed in yellow colour), piping remained in the risk zone (displayed in the red colour), while diesel engine and F&G logic moved from the good zone (displayed in the green colour) to the warning zone.

Table 4-25 LEM when history factor's weight is varied

History factors weight	SW pump		Piping		Diesel engine		F&G logic	
	CI	LEM	CI	LEM	CI	LEM	CI	LEM
1	3.06	RUL must be determined	1.60	0	3.25	RUL must be determined	3.25	RUL must be determined
2	3.14	"	1.64	0	3.5	1	3.35	"
3	3.22	"	1.68	0	3.75	1	3.45	"
4	3.3	"	1.70	0	3.9	1	3.7	1

This indicated that the LEM for piping remained 0 while the rest of the subsystem required the estimation of RUL for LEM decision making. When the weight was changed from 1 to 2, the SW lift pump and F&G logic remained in the amber zone. The piping continued to be in the risk zone while diesel engine

was in the good zone. The corresponding LEM indicated that SW lift pump and F&G logic requires estimation of RUL while the diesel engine and piping had LEM of 1 and 0 respectively. Now, varying the weight from 2 to 3, condition of each subsystem and corresponding LEM remains the same as when the weight was 2.

On the another side in Table 4-26, when the weight for *inspection and maintenance* (health factor) in the CIM analysis was changed to 1, SW lift pump and F&G logic were displayed in the risk zone with LEM of 0 respectively.

Table 4-26 LEM when health factor's weight is varied

History factors weight	SW pump		Piping		Diesel engine		F&G logic	
	CI	LEM	C1	LEM	CI	LEM	CI	LEM
1	2.89	0	1.58	0	3.4	RUL must be determined	3.2	RUL must be determined
2	3.04	RUL must be determined	1.62	0	3.55	1	3.35	"
3	3.19	"	1.66	0	3.70	1	3.5	1
4	3.30	"	1.70	0	3.90	1	3.7	1

The diesel engine and F&G logic were in the amber zone, meaning their respective RULs must be estimated in order to determine LEM. Varying the weights from 1 to 2 indicated that the CI of SW lift pump moved from risk zone to warning zone, piping continued to be in the risk zone, diesel engine in the good zone and F&G logic in the warning zone. This means that SW lift pump and F&G logic will require RUL estimation for LEM analysis while diesel engine and piping had LEM of 1 and 0 respectively. When the weight was changed from 2 to 3, the diesel engine and F&G logic LEM's changed to 1 with SW lift pump requiring RUL estimation and piping with LEM of 0. From technical assessment perspective, it can be established that the health factors are likely to influence LEM results compared to the history factors. Also, from economic perspective, the capital cost and O&M cost when increased can disqualify an asset for extended service operation. On another side, when cost of product is

increased during the extended period of operation, LE of existing assets becomes highly favourable compared to other EOLMS like replacement and decommissioning. Therefore, it can be concluded that to proceed with LE of ageing assets in the offshore O&G industry the cost of product and the volumes of production are very critical economic decision making factors that must be considered by asset managers during LE decision making process.

4.7.3 Phase 3

Approval and implementation

The third phase is implemented based on the process developed in Fig.4-8 in Chapter 4 of the thesis

4.8 Summary of Chapter

In this Chapter, the factors that can influence LE decision making process in the offshore O&G industry have been identified and subsequently classified. In order to identify and classify these factors, a research methodology was developed and presented in Section 4.2. Although the classification framework is for LE phase of operation, it can also be applied by engineers at the design stages of assets lifecycle to support efficient design of equipment capable of operating at the LE phase with fewer challenges.

Based on the results from literature review and interactions with experts a techno-economic framework to support the LE feasibility assessment of SCEs was developed. The framework consisted of three phases, namely; preparation for LE, technical and economic feasibility and regulatory approval and implementation phases. The framework was presented in Section 4.4.

In Section 4.5 a process to help asset managers select the most suitable RUL models to determine the maximum length of time equipment displayed in the warning zone could be operated during LE period was presented. It is concluded that in the offshore O&G industry, physics of failure method is most suitable for estimating the RUL for equipment being assessed for extended operations.

For the purpose of clarity, the efficacy of the proposed model was shown through an application to a water deluge system in offshore oil installations in section 4.6. The results of the application case study demonstrated the validity of the proposed framework for LE process in the offshore oil and gas industry. This study also overcame the shortcomings of available LE decision making models which are restricted solely to either technical or economic considerations. Our proposed model provides decision makers the ability to incorporate simultaneously all the technical and economic issues when applying LE strategies to SCEs.

5 LIFE EXTENSION STRATEGY SELECTION

5.1 Introduction

In previous Chapter, the techno-economic framework for qualifying SCEs for continuous operation has been presented. However, after this decision, LE requirements demand asset managers to select the most suitable LE strategy for safe and continuous operations of SCEs. This is because selection of inappropriate LE strategy has the potential to increase cost of operation and maintenance as well as the environmental burden associated with LE phase of operation, thus making LE less attractive option compared to other EOLMS. Therefore, in order to meet LE requirements while simultaneously minimising cost and not compromising safety, it is critical for asset managers to select the most suitable LE.

However, from literature review, the decision regarding selection of most suitable LE strategy have often been made in a qualitative way based on the accumulated knowledge and experience of engineers and consultants in the offshore O&G industry. Also, in relation to Section 2.8 of the literature review, no study has employed both quantitative and qualitative scientific approaches to support selection of the most suitable LE strategy in the offshore O&G industry. Therefore, any scientific approach to help determine suitable LE strategy will inure to the benefit of asset managers whose assets are approaching end of life. In this chapter, the author develops both quantitative and qualitative decision making processes to help evaluate and select suitable LE strategy.

The remainder of the Chapter is structured as follows. In Section 5.2, the author develops a quantitative process based on Life Cycle Cost Benefit (LCCB) concept to select suitable LE strategy. In Section 5.5, the author develops an alternative process based on Multi-Criteria Decision Making (MCDM) Methods, which is capable of tackling complex decision making problem where multiple and conflicting decision making criteria (both quantifiable and non-quantifiable) are involved.

5.2 Life Cycle Cost Benefit (LCCB) Model

For many complex systems such as SCEs, the cost and benefits involved in managing the assets lifecycle plays an important role during LE decision making process. Therefore, a methodology which compares the costs and benefits associated with LE strategies could provide the needed framework to assist asset managers make the best decision based on wide range of options.

However, in the offshore O&G industry today, evaluating wide range of decision alternatives quantitatively is based on the cost parameters associated with particular alternative, ignoring the benefits that may be obtained from implementing the alternative. Also, the selection of suitable LE strategy is mostly accomplished through expert knowledge. In order to address these challenges during LE phase of operation, the author aim to develop a process that can be used to evaluate and select suitable LE strategy among various alternatives, which takes into account costs and benefits associated with LE phase of operation. To the best of author's knowledge, no published research about selection of suitable LE strategy using LCCB approach is found in literature.

5.2.1 Identification of Cost and Benefit Drivers for Life Extension

The successful implementation of LCCB models to select suitable LE strategy requires decision makers to identify costs and benefits drivers associated with LE phase of operation. The relevant LE costs and benefits parameters required as inputs for LCCB analysis were identified through literature review and interaction with industrial experts. The possible benefits and costs items that may be associated with LE of SCEs are summarised in Table 5-1.

Table 5-1 Benefit (B) and Cost(C) associated with LE

Main items	Sub-items
B1.Increased production	B1a.Reduced equipment downtime, B1b.Increased revenue
B2.Improved safety	B2a.Reduced injury to personnel, B2b. Reduce death, B2c.Reduced equipment failure rate
B3. Delayed decommission cost	-
C1. Capital cost	C1a. Cost of purchasing new equipment, C1b. Cost of

	upgrading an equipment,C1c. Cost of software upgrade, C1d. Cost of computer hardware
C2.Installation cost	C2a. labour cost,C2b.downtime cost, C2c. logistical support cost
C3.Operating & maintenance expenditure	C3a.Maintenance cost, C3b. logistical support cost
C4 Statutory payment	C4a Royalty, C4b Taxes

5.2.2 Benefits of Life Extension

The benefits of extending the service life of SCEs are identified as increased production, improved safety and delayed decommission cost. Increased production (B1) is interpreted as the ability to reduce equipment downtime (B1a) which may be achieved through improving fault detection or reduction in maintenance lead-time. Another benefits associated with B1 is increased revenue generation; this is because in the offshore O&G industries increased production translate into improved revenue generation (Tveit et al., 2014). Improved safety (B2) involves the benefits derived from the reduction in fatalities (B2a & B2b) as a result of implementing LE programme. However, this benefit can be considered as non-monetary due to the difficulty in quantifying them (Brandt and Mohd Sarif, 2013). It is shown in many studies that existing asset operating at the end of the bathtub curve are characterised with increased failure rate and failure consequences could be catastrophic to lives, environment and eventually loss of asset. So extending the service life with appropriate strategy could potentially reduce equipment failure rate (B2c). It is also an established fact that extending the service life of existing assets delays decommissioning cost (B3), which becomes an added-value to asset managers.

5.2.3 Cost Elements of Life Extension

The associated costs of LE include CAPEX, installation cost, O&M cost, risk expenditure and statutory expenditure. The CAPEX (C1) associated with LE involves the cost of acquiring new equipment and the cost of upgrading existing SCEs to achieve appreciable safety levels which is a requirement for LE licence application. Other CAPEX may include cost of upgrading software and acquiring computer hardware (C1c & C1d). Installation of newly acquired equipment would

require hiring and paying a number of labourers (C2a). In addition, the installation of new equipment may require some facilities to be shut down for a period of time, resulting in production loss penalties (C2b). For example, offshore wind power and offshore O&G industries have to mobilise LE team and hire service boat for purposes of installation and this cost is accounted for by (C2c). C3 is the O&M expenditure which includes maintenance and logistical supply cost. Statutory cost such as royalty, LE licence cost and taxes from jurisdiction of operation is also taking into account as C4. Finally the risk expenditure associated with failure of SCEs during LE phase of operation is considered in analysis.

5.2.4 The Proposed LCCB Decision Making Model

A step-by-step process of the proposed decision making model is presented in Fig.5-1. The features of the proposed decision making model include identifying LE strategies through brainstorming; modelling of SCEs LE LCC and application of Benefit Cost Ratio (BCR) technique to select most suitable LE strategy. The details of each step of the proposed process are explained below.

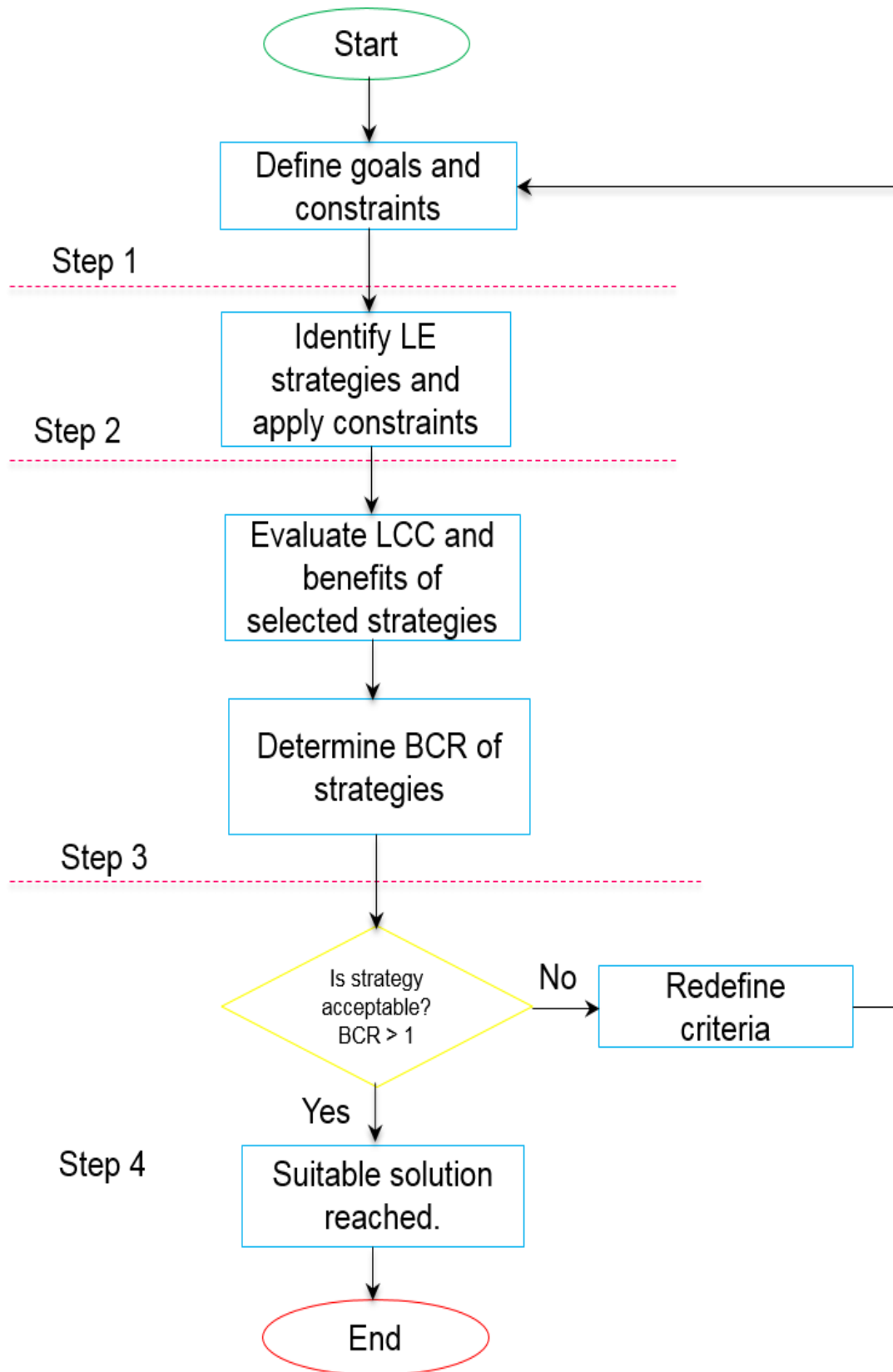


Figure 5-1 Proposed approach for LE strategy selection

5.2.4.1 Define Goals and Constraints

The first step of the process is to set the basic goals and constraints for LE. For example, the goal for LE project may be to maximize production to improve revenue generation. The constraints for LE projects are mainly economic, technical, regulatory and organisational (See Fig.4-3). Economic constraint that can affect LE strategy selection is the maximum available budget. This means that a strategy with cost higher than the available budget for LE period of operation cannot be considered. Maximum LE budget could be expressed as a percentage of capital cost of a system/component actual operation (Tugnoli and Cozzani, 2009). On the other hand, maximum budget could also reflect companies' inability to spend in the direction of risk reduction. Technical constraints such as limited size, weight, space, nature of production fluid and obsolescence (age of technology) can render some LE strategies not feasible. Changes in regulations and standards in the offshore O&G industry may also not permit the use some strategies. For example, HSE requirements under the Atmosphere Explosibles (ATEX) directive by European Union (EU) and UK regulation for Prevention of Fire, Explosion and Emergency Response (PFEER) poses a challenge for duty holders in considering some LE strategies.

5.2.4.2 Identify LE Strategies and Apply Constraints

This step identifies the available LE strategies and then decision making constraints are subsequently applied to reduce the number of strategies considered, if possible. This is achieved through a brainstorming session involving LE stakeholders and experts. For further details on various LE strategies applicable in the offshore O&G industry, readers must refer to Section 2.8.6 of Chapter 2 of the thesis.

5.2.4.3 Evaluate LCC and Benefits of Selected Strategies

Brown and Willis (2006) suggested that LE strategies should be examined based on their economic attractiveness. Operating economically without compromising safety during LE phase of operation requires careful evaluation of factors that drive CAPEX and OPEX of various LE strategies. The conventional

LCC model for economic evaluation of a system life cycle is expressed in Eq. (1) (ISO, 2000);

$$LCC_o = CAP_o + \sum_{t=0}^{l_o} \frac{C_o(t)}{(1+r)^t} \quad (5-1)$$

where, LCC_o represent cost (expenditure), CAP_o represent the CAPEX, r represent the discount rate, $C_o(t)$ represent the OPEX, t represent duration of extended life and l_o indicates the anticipated life expectancy of the asset in years. The traditional LCC model considered in Eq. (5-1) do not take into account maintenance and risk expenditures but treats maintenance expenditure as a component of operational cost. However, during LE phase of operation failure rate of a system increases due to ageing mechanisms like corrosion and fatigue, making the system vulnerable to risk such as fire and explosion. Also, in order to reduce the impact of ageing during LE period, maintenance activities becomes extremely important and therefore cannot be treated as a component of operational cost. Nam et al.(2011) suggest that LCC analysis for offshore O&G application should not treat maintenance cost as part of operational cost, since it may leads to inaccurate conclusions. Therefore, Eq. (5-1) is modified to capture risk and maintenance expenditure specific to LE phase of operation.

$$LCC_e = CAP_e + C_{INST} + \sum_{t=l_o}^{l_o+l_e} \frac{C_o(t) + C_M(t) + C_R(t)}{(1+r)^t} \quad (5-2)$$

where CAP_e represents the capital investment required for the LE program, C_{INST} represent the installation cost of new hardware/software upgrades, and $C_M(t)$ and $C_R(t)$ represent respectively the maintenance cost and the risk expenditure in year t of the extended life, and l_e indicates the allowable duration of LE from the safety point of view.

5.2.4.3.1 Capital Cost

The CAP_e includes cost of acquiring new systems/components. The cost of new systems/components can be obtained through market survey or directly contacting operating companies. If the CAPEX occurs in a single year, then it is annualised as:

$$C_\alpha(t) = \left[\frac{i(1+r)^t}{(1+r)^t - 1} \right] (CAP_e) \quad (5-3)$$

where, C_α represent the annualised CAPEX and i is the annual interest rate.

5.2.4.3.2 Installation Cost

The cost for installing new component consists of labour, downtime and logistics costs and is calculated using Eq. (5-4). However, not all asset installation may result in equipment downtime.

$$C_{INST} = C_{INST}^{lab} + C_{INST}^{dt} + C_{INST}^L \quad (5-4)$$

where, C_{INST}^{lab} denote labour cost during installation, C_{INST}^{dt} is the downtime cost due to installation, and C_{INST}^L is logistics cost incurred due to installation. Logistic cost for component installation in the offshore O&G industry includes hiring a barge, spares order, shipping time and labour mobilisation time. The labour cost is estimated using Eq. (5-5) while downtime cost is estimated by Eq. (5-6).

$$C_{INST}^{lab} = L_{RT/d} \times Mh^{INST} \times N_{INST} \quad (5-5)$$

$$C_{INST}^{dt} = C_{PL} \times N_D \quad (5-6)$$

where, $L_{RT/d}$ is labour rate/day, Mh^{INST} is the total man-hours for installations, N_{INST} is number of installation team. C_{PL} is production loss cost and N_D represent expected number of days required to perform expected action respectively.

The production loss cost is calculated using the formula suggested by ISO (2000) given by

$$C_{PL} = P_{RT/d} \times C_p (1 - PA) \quad (5-7)$$

where, $P_{RT/d}$ is the production rate in barrels per day (BOPD), C_p represent the value of unit production and PA is the production availability. PA is defined as the measure of the production loss. It is expressed as the ratio of actual production rate over estimated production rate over a specific length of time (ISO, 2000).

5.2.4.3.3 Operational Cost

In offshore O&G projects, OPEX is categorised into two, namely; production dependent and production independent. Thus,

$$C_o(t) = C_{o(dependent)} + C_{o(independent)} \quad (5-8)$$

5.2.4.3.3.1 OPEX Production Dependent

OPEX production dependent variables are directly proportional to production. Examples of such variables are glycol cost, corrosion inhibitor cost, oil treatment chemical cost, cost of operational tools and minor equipment, tax, royalty etc. Thus,

$$C_{dependent} = C_{glycol} + C_{inhibitor} + C_{treatment} + C_{tool} + Tax + Royalty \quad (5-9)$$

Alternatively, $C_{dependent}$ can also be estimated as a percentage of revenue. In this study, it is estimated as:

$$C_{dependent} = Revenue \times 10\% \quad (5-10)$$

On the other hand, revenue is estimated as

$$Revenue = P_{RT/d} \times C_p \quad (5-11)$$

5.2.4.3.3.2 OPEX Production Independent

OPEX production independent variables are normally part of the supply chain and the uncertainties related to these variables are relatively small. Examples of such variables include; cost related to logistic e.g. helicopter transport of crew, transport of spare parts and cost related to onshore support such as administrative cost.

5.2.4.3.4 Maintenance Cost Model

Maintenance represents a significant share of expenditure during the LE phase of operation. Maintenance expenditure during LE phase of operation depends on factors such as ageing failure modes, type of maintenance policy, maintenance lead-time, operational conditions and cost of maintenance logistics. In developing the maintenance cost model, the author considered fixed maintenance, corrective maintenance and preventive maintenance policies. The maintenance cost C_M over LE period is estimated by:

$$C_M = [C_{FM} \cdot Mh^{FM}] + [C_{CM} \cdot Mh^{CM} \cdot \lambda(t)] + [C_{PM} \cdot Mh^{PM}] \quad (5-12)$$

$$C_M = [(X_1 \cdot C_{FM}^{insp} + X_2 \cdot C_{FM}^{repair} + X_3 \cdot C_{FM}^L)] + [(C_{CM}^{lab} + C_{CM}^{dt} + C_{CM}^{fab}) Mh^{CM} \cdot \lambda(t)] + [(X_1 \cdot C_{PM}^{insp} + X_2 \cdot C_{PM}^{repair} + X_3 \cdot C_{PM}^L) Mh^{PM}] \quad (5-13)$$

where, C_{FM} , C_{CM} and C_{PM} are fixed maintenance (FM) cost, corrective maintenance (CM) cost and PM cost respectively, $\lambda(t)$ is asset failure rate and is characteristic of breakdown occurrence frequency (Asfarnia et al., 2014) and, X_1 , X_2 and X_3 represent fraction of time assigned to inspection, repair and logistic activities during FM and PM actions. Mh^{FM} , Mh^{CM} and Mh^{PM} represent man-hour time for FM, CM and PM respectively. The constraints for the model are defined for man-hours, PM and CM costs.

$$C_{PM} \geq 0; C_{CM} \geq 0; Mh > 0$$

A two parameter Weibull distribution is convenient for determining $\lambda(t)$ given by:

$$\lambda(t) = \frac{\beta \cdot t^{(\beta-1)}}{\eta^\beta} \quad (5-14)$$

where, β and η represent scale and shape parameters respectively

5.2.4.3.5 Risk Expenditure

The risk expenditure considers major accident such as fire, explosion and drop object etc. However, this study considers economic evaluation of the fire and explosion risk. Fire and explosion can result in significant asset damage and severe fatalities in the offshore O&G industry. Thus, risk cost analysis should take into account the cost of all the damages and losses. Quantitative risk assessment (QRA) is one of the accepted approaches for assessing the risk of offshore O&G facilities. One of the challenges in assess risk expenditure is to accurately quantify the financial consequences of asset damage and fatalities. The risk expenditure can be calculated using Eq. (4-8) – (4-12) in Chapter 4 of the thesis. Alternatively, risk expenditure can be calculated from the result of risk assessment based on frequency and severity of the consequences. Nam et al. (2011) suggested Eq. (5-15) and (5-16) for estimating the cost of fatalities and asset damage.

$$C_{FC} = \sum_{j=0}^k \lambda_{Fj} \times C_{Fj} \quad (5-15)$$

$$C_{AD} = \sum_{j=0}^k \lambda_{AD,j} \times [C_{Asset,j} + t_m (PR \cdot C_p + C_{MH})] \quad (5-16)$$

where, λ_j , C_j , t_m , PR , C_p and C_{MH} denotes frequency, cost related to accident of j -th type, maintenance time in hours associated to the risk type j , production rate, value of product and cost of man hours respectively.

5.2.4.4 Determining Benefit Cost Ratio (BCR)

The final step of the process is to apply BCR to select most suitable LE strategy. LE benefits could be categorised according to stakeholders' interest such as the society whose interest is represented by the state (i.e. employment

creation, revenue generation from taxes and royalties), operators (i.e. revenue from sale of product and delayed deposal cost) and environment (i.e. reduction in CO₂ cost). The benefit of LE is mathematically expressed as:

$$Benefit_{LE} = B_{soc}^k + B_{op}^k + B_{env}^k \quad (5-17)$$

where, k is the number of LE benefits. In this study, LE benefits to the operator are considered. Therefore, the benefit to the operator as result of direct sale of the product is estimated as follows:

$$Revenue = C_p \times \text{Actual production rate} \quad (5-18)$$

At the point, when the system is incapable of operations, we assumed that the components are still valuable through disposal, which is referred to as the salvage value. Generally, it is expressed as 10% of the CAPEX. Therefore, the cost of disposal C_d can be expressed as:

$$C_d = C_{CAP} \times 10\% \quad (5-19)$$

However, in this research, only the benefit through the sale of the product is considered. Thus;

$$Benefit_e = \sum_{t=l_o}^{l_o+l_e} B_{op,t}^k \frac{1}{(1+r)^t} \quad (5-20)$$

Alternatively, the benefit can be evaluated as the difference between the expected present values of losses without the implementation of LE strategy $LCC_{as-built}$ and the expected present values of losses with implementation of LE strategy, LCC_{LE} , as shown below.

$$Benefit_e = E[LCC_{as-built}] - E[LCC_{LE}] \quad (5-21)$$

Then, the BCR for a particular LE strategy is evaluated as the ratio between the net present value of reinvestment by asset managers (*Benefits*) and the LCC during LE period of operation.

$$BCR_{LE} = \frac{Benefit_e}{LCC_e} \quad (5-22)$$

The BCR is the measure of return for each amount of money reinvested into LE project. A BCR greater than one indicates positive rate of return while a BCR less than one indicate less returns on reinvestment. So, the strategy with the largest BCR has the largest savings over the LE period of operation. However, a strategy with less BCR in some special instances may be considered suitable when non-monetary benefit such as social and safety impact of LE is considered.

5.3 Case Study

In this section, the proposed LCCB model is applied to select the most suitable LE strategy for a three phase separation system on offshore oil platform.

The three phase separation system is located on a jack-up rig commissioned in the late 1970s for oil production. When originally commissioned, the field produces product consisting of medium crude oil with low water content and solids. The production from the reservoirs has steadily changed over the maturity period and currently produces heavy and more viscous product with high water content.

The system consists of three phase first stage high pressure vessel, with water lines directed to the produced water treatment tank. The wet crude is then delivered through an intermediate two phase degassing separator to remove solution gas. The crude oil is then exported through the oil export line. Separation is mainly achieved by gravity with the assistance of chemical and heat. Separated gas is routed to the gas dehydration system, which is later transported using pipelines while separated water flows into produced water treatment tank for conditioning. A schematic process layout of the separation system showing the details of the separation system's configuration is shown in Fig.5-2 & 5-3.

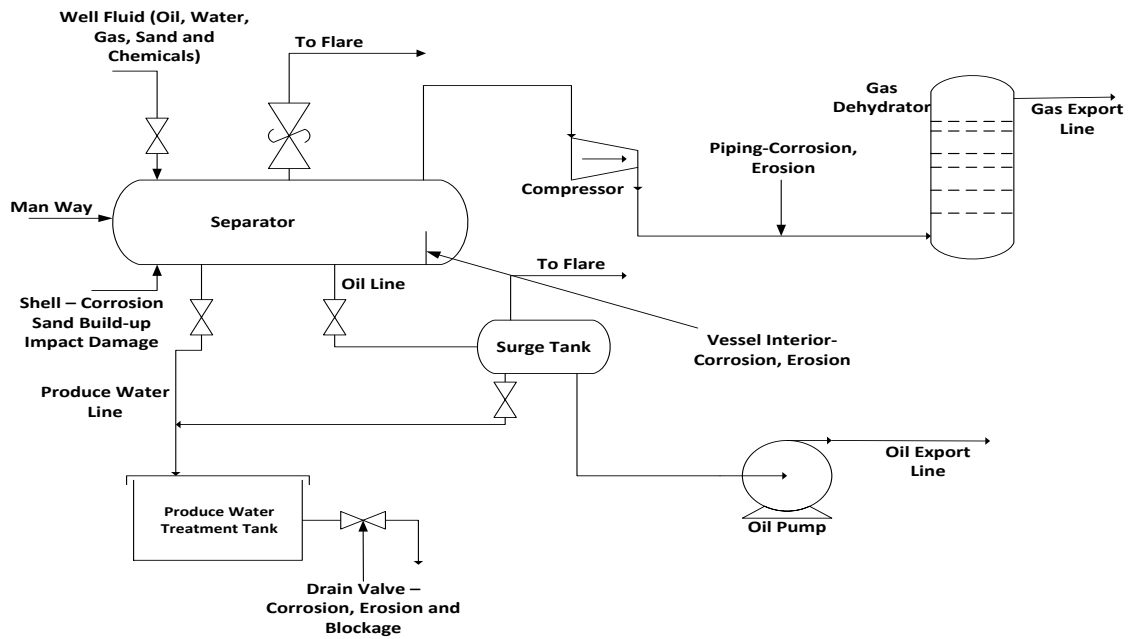


Figure 5-2 A schematic process layout of the separation systems

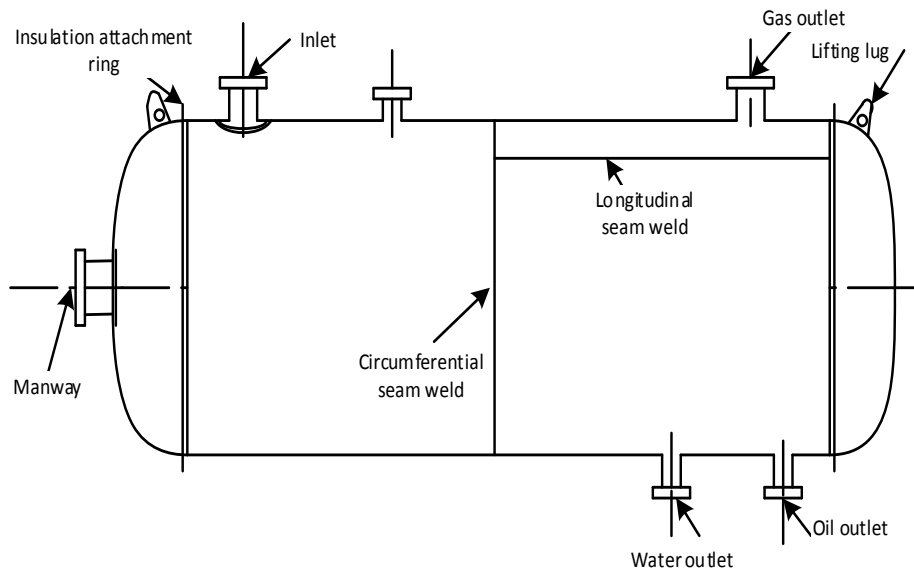


Figure 5-3 Key external features of the separator vessel

The design pressure is 49barg but is now operating at a pressure of 25barg. The first stage high pressure separator vessel was designed to the BS 1515 part 1 specification which was the recommended standards for construction of

hydrocarbon pressure vessels at the time. During inspection of the high pressure separator vessel, corrosion pit of up to 5mm depth was discovered although corrosion management plan is partially implemented by duty holder. Corrosion rates were predicted to have increased from 0.41mm/year to 0.77mm/year in the last 4years of operation. However, the operator has discovered a new well which could economically be explored for the next five years provided the critical subsystems of the separation system would qualify for continuous safe operation.

5.4 Analysis of Results

The following sub section illustrates a step-by-step application of the proposed LCCB model shown in Fig.5-1 to the three phase separation system case study. The analyses were performed using data presented in Table 5-2.

Table 5-2 Data for case study (Confidential)

Non cost parameters		Cost parameters (\$)	
$P_{RT/day}$	480bopd	C_{PM}^{insp}/hr	60
β	4	C_{PM}^{repair}/hr	1800
η	24	C_{PM}^L/hr	60
Mh^{FM}	2	C_{CM}^{lab}/hr	84
Mh^{CM}	9	C_{CM}^{fab}/hr	2400
Mh^{PM}	0.91	C_{EM}^{insp}/hr	60
X_1	0.5	C_{EM}^{repair}/hr	1800
X_2	0.3	C_{PM}^L/hr	60
X_3	0.2	Cost of product/barrel	40
Discount rate	7%	Cost of sub-sea separator	66,000,000
Extended LE period	5years	Cost of pH control	16,000
Interest rate	25%	Pressure control	19900
		Blast wall	33100
		FFE	31900
		Operational cost	10% of annual production

5.4.1 Definition of Goals and Constraints

The goal of the project is to select the most suitable LE strategies in order to maintain the technical integrity of a three phase separation system for safe and continuous operation. The constraints for this project are limited budgetary allocation, congested spaces and lack of good quality data.

5.4.2 Identify LE Strategies and Apply Constraints

The LE strategies discussed in Section 2.8.6 of Chapter 2 were considered. After application of the constraints, safety add-on measures, process control measures, hybrid of safety - add on and process control measures and replacement were considered as the appropriate strategies among which the best one will be selected.

Table 5-3 Identified LE strategy

Identified LE strategies			
Replacement	Safety-add on measures	Process control measures	Hybrid
Subsea separation system	Blastwall + FFE(Firefighting equipment)	pH control + pressure control	pH control + FFE

5.4.3 Evaluate LCC and benefit of Selected Strategies

This stage of the proposed process presents the results of the LCC analysis. In Fig. 5-4 cost fraction of each LCC components for each strategy is shown. It should be noted that the installation cost is included in the CAPEX, since installation of the system is the responsibility of suppliers.

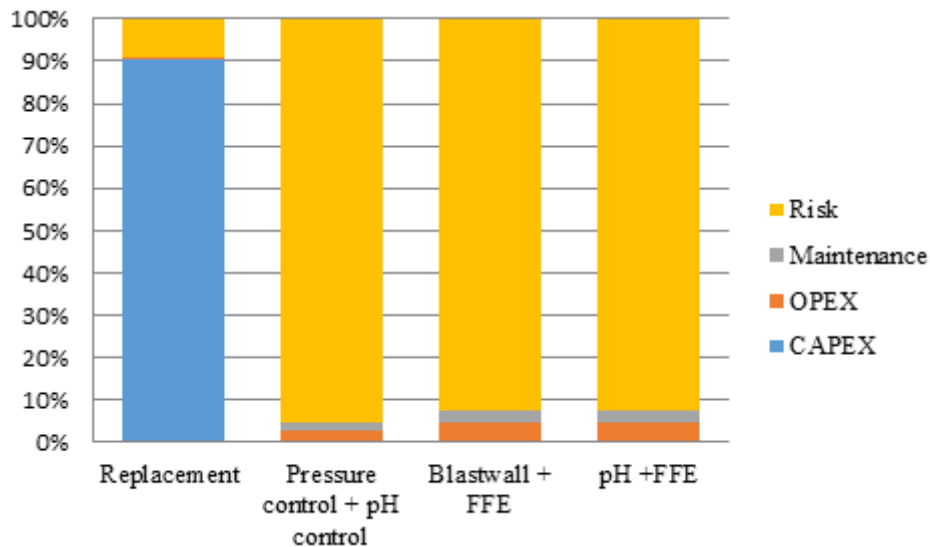


Figure 5-4 Fraction of each LCC component

From Fig 5-4, the CAPEX for replacing existing system with subsea separator constituted the largest portion of the LCC compared to the other strategies,

although replacement strategy contributed the lower maintenance and risk cost during 5 years of LE operations. This makes replacement of existing system with a completely new system expensive. Therefore, the decision to select replacement over other strategies for LE could be justified based on reason such as obsolescence and safety. However, the other strategies resulted in lower CAPEX but with huge associated risk cost. Now, in order to select the most suitable LE strategy, the benefits of LE was also estimated. At a production rate of 480bopd at a price of \$40, none of the strategies recorded a BCR value greater than one, which suggested that implementing any of the strategy above will make no economic sense. This is due to the sharp decline in both oil prices and production levels which is a characteristic of a marginal field during LE phase of operation.

5.4.4 Determining Benefit Cost Ratio (BCR)

Table 5-4 gives BCR values of the four strategies respectively. The calculated BCR values are 0.26, 0.54, 0.88 and 0.88 for replacement, process control measures, safety-add on measures and hybrid respectively.

Table 5-4 BCR values for LE strategies considered

Strategy	System	BCR
Replacement	Subsea separator	0.26
Pressure control measures	Prssure + pH control	0.54
Safety add-on	Blastwall + FFE	0.88
Hybrid	pH control + FFE	0.88

5.4.5 Sensitivity Analysis

In this section, sensitivity analysis is performed to evaluate how key economic variables can impact the selection process when changed. To this aim, sensitivity analysis is carried out for the four key dominant economic variables. These are; value of product, production volumes, discount rate and interest rate. It should be noted that only one parameter is changed with the others remaining unchanged.

5.4.5.1 Value of Product

The price of crude oil is always an important determinant factor during LE decision making process. Fig.5-5 presents relative BCR with the changes in crude oil price. A 20% increase in crude oil prices leads to $BCR > 1$ for safety-add on and hybrid LE strategies.

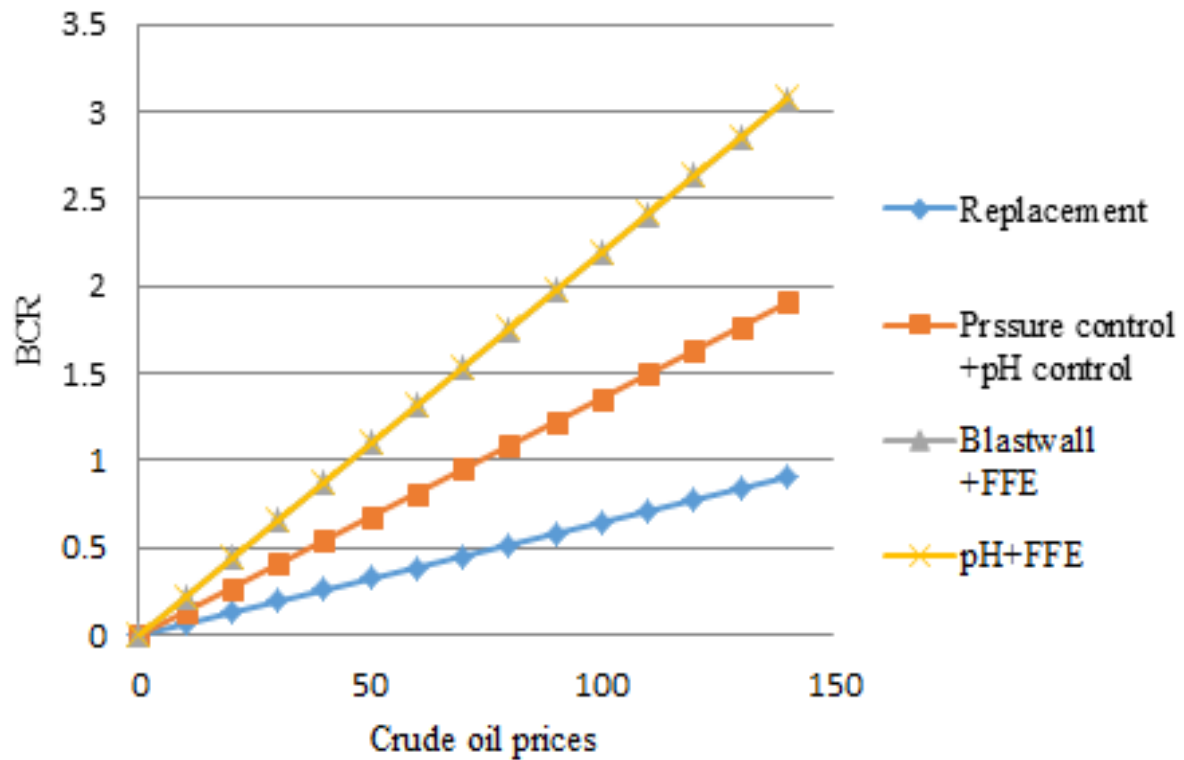


Figure 5-5 Effect of value of product changes on BCR

5.4.5.2 Production Volumes

Enhancing the rate of production of a marginal field is seen as one of the important decision making variables for LE feasibility. Fig.5-6 shows that 400% increase in production volume at current price of \$40 per barrel will make the replacement strategy $BCR > 1$.

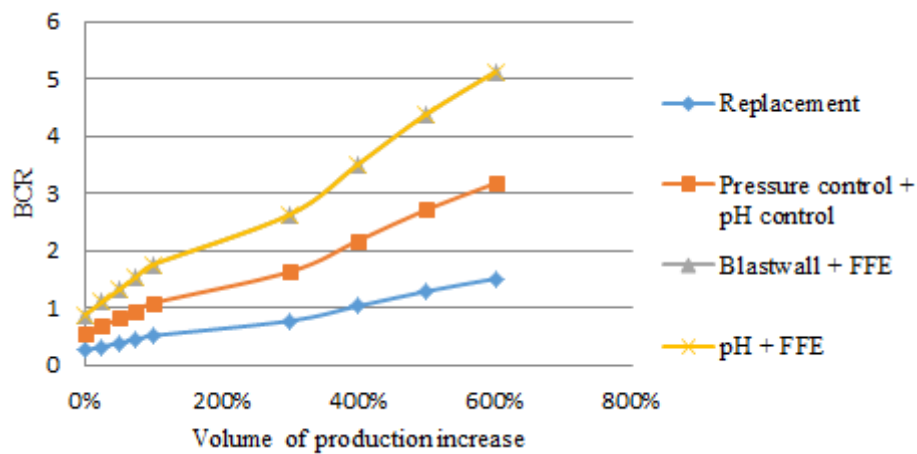


Figure 5-6 Effect of change in production volumes

5.4.5.3 Discount Rate

The increased in discount rate resulted in a considerable decrease in LCC as shown in Fig.5-7 however, this did not change the BCR values.

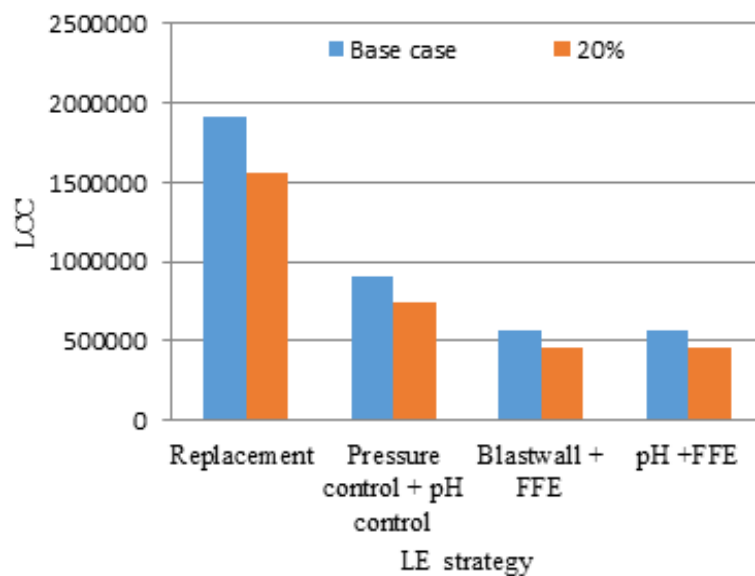


Figure 5-7 Effect of change of discount rate on LCC

When the discount rate was increased to 20% there was a considerable reduction in the LCC as can be seen in Fig. 5-7, however, the BCR values did not change.

5.4.5.4 Interest Rate

Interest rate plays a considerable role in the replacement strategy. A 1% reduction in interest resulted in 3.2% reduction in the LCC of the replacement strategy. It caused a marginal increase in BCR values for other strategies; however the values still remained less than one. Pressure control +pH control, blastwall +FFE and pH control + FFE resulted in 0.07%, 0.11% and 0.05% reduction in LCC respectively.

5.5 Multi-Criteria Decision Making (MCDM) Model

In Section 5.2, a quantitative process based on LCCB concept was developed to assist asset managers select the most suitable LE strategy. This also serves as a solution to a gap identified in literature review and confirmed through interactions with industrial experts. Although the process above is convenient for selection of the most suitable LE strategy, it is with some draw backs. First, the approach requires quantitative inputs data for analysis. However, the relevant data required in order to implement the model is sometimes not readily available during LE decision making process. Second, the selection of suitable LE strategy can be considered as a complex decision making problem. This is because the selection of suitable LE strategy in some instances involves multiple (both quantifiable and non-quantifiable) and conflicting criteria, thereby making the decision making process complex. In tackling such complex decision making problem, the application of MCDM is considered the appropriate solution. This study proposes a decision making model on the basis of PROMETHEE II to select the most suitable LE strategy for SCEs. PROMETHEE II is selected because of its usefulness as outranking method and the realistic nature of its final results (Kazem and Hadinejad 2015). Haralambopoulos and Polatidis (2003) suggested that outranking method such as PROMETHEE is well suited for energy and environmental management decision making problems.

A survey of literature shows that majority of publications using PROMTHEE method have concentrated effort on selecting the suitable energy generation alternative (Behzadian et al., 2010). However, what has not been reported is the use of PROMETHEE method to select the most suitable LE strategy for SCEs.

5.5.1 The Proposed Decision Making Model

The basic layout of the whole decision making model is presented in Fig.5-8. It comprises all the vital steps required for LE decision making process in the offshore O&G industry. The model has been divided into two modules. The first module deals with preparations toward decision making. This involves forming a team of decision makers, identifying all possible evaluation criteria and alternatives and subsequently constructing a decision making chart. The first module leads to the second module which is for decision making. It incorporates PROMETHEE II method to rank alternatives in order to select the best strategy. Finally, sensitivity analysis is conducted by modifying the weights of evaluation criteria to test robustness of final ranking and verify the visual stability intervals for each evaluation criterion.

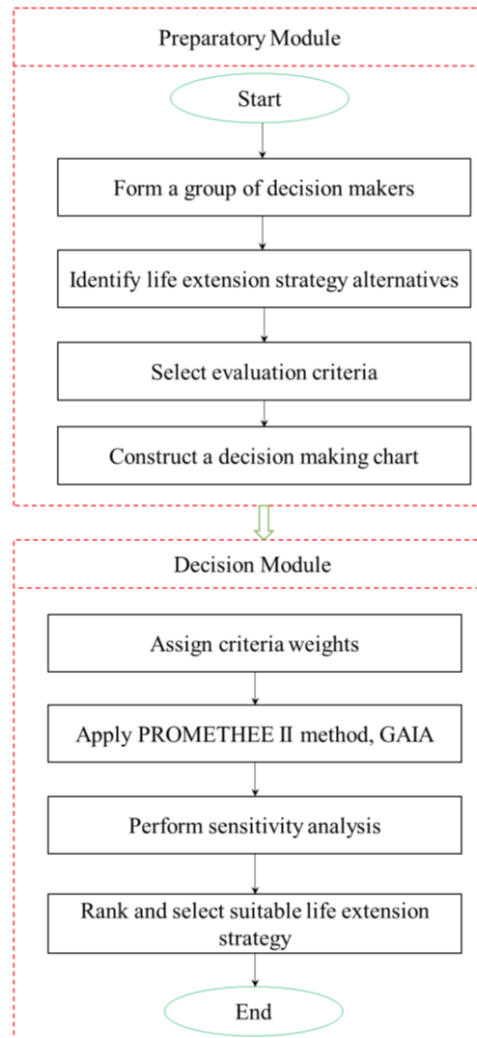


Figure 5-8 Flowchart of the decision making model

5.5.1.1 Form a Group of Decision Makers

The panel of decision makers to select most suitable LE strategy typically includes operators, asset owners, manufacturers, regulators, financial analyst, scholars from relevant institutions and social groups. However, depending on the type of industry, country of operation and the specific asset whose life is being extended, not all stakeholders may be included in the decision making process. Also, internal arrangement of companies for establishing decision making teams can be used.

5.5.1.2 Identify Life Extension Strategy Alternatives

LE strategy alternatives are identified by the decision making team based on their experience as well as reference to literature sources. The LE strategies discussed in Chapter 2 are considered at this stage.

5.5.1.3 Select Evaluation Criteria

The selection of evaluation criteria is one of the important stages when formulating MCDM problem. The number of criteria considered when selecting the most suitable LE strategy depends largely on availability of data. Selection of evaluation criteria is conducted through the use of literature review or other forms of survey techniques to elicit information from experts. In our case, to select evaluation criteria, literature review is conducted to identify evaluation criteria applicable to the study. The identified criteria are then screened using the Delphi technique, in order to select the most relevant evaluation criteria. In the next sub-sections, a total of 9 evaluation criteria relevant to LE strategy selection for ageing SCEs are discussed, out of which four are technical, three economic and one each for environmental and social and legal respectively. A brief description of the main evaluation criteria considered in the study are presented as follows:

5.5.1.3.1 C₁: Economic Criteria

Different LE strategy alternatives have different expenditure implications for hardware, operations, software and workforce training. Each economic criterion considered in this study is evaluated using the scale given in Table 5-5. The relevant factors describing economic criteria are:

Table 5-5 Evaluation scale for criterion C₁₁, C₁₂, C₁₃ and C₁₄

Economic context	Value of C ₁
Very high	1
High	2
Moderate	3
Low	4
No cost	5

C₁₁: Cost of hardware: For implementation of LE strategy, investment expenditure including purchase of asset, purchase of maintenance tools and spare parts, acquisition of monitoring and prognostics management systems and purchase of new computers may be required.

C₁₂: Cost of operations: The operational expenditure incurred for implementing a LE strategy includes wages, material and transportation cost, mobilisation cost and labour cost for some specialised professionals.

C₁₃: Cost of software: In the offshore O&G, nuclear power plant and renewable energy industries more expensive and advanced bespoke software will be needed if the selected LE strategy requires upgrade of monitoring and control systems.

C₁₄: Cost of training: Successful LE strategy implementation in the O&G industry requires sufficient training of workforce.

5.5.1.3.2 C₂: Technical Criteria

High level of safety and technological readiness is required in order to implement LE strategy for SCEs that have reached the end of life. This is because without the support of tested and proven technologies, some LE strategies cannot be implemented. Also, as a requirement for LE licence acquisition by many regulators, stakeholders are expected to demonstrate that both assets and workforce will be safe during LE phase of operation. The relevant factors describing technical criteria are:

C₂₁: Personnel safety: Failure of SCEs such as, gas/air compressors, over pressure protection equipment and high speed rotating equipment during LE phase of operation may result in serious injury or death to the workforce managing an installation. Therefore, in selecting the most suitable LE strategy for SCEs, this criterion cannot be ignored by decision makers. This criterion is evaluated using the scale given in Table 5-6.

Table 5-6 Evaluation scale for criterion C₂₁ and C₂₂

Safety context	Value of C ₂₁ and C ₂₂
Massive effect	1
Major effect	2
Moderate effect	3
Minor effect	4
No effect	5

C₂₂: Asset safety: An offshore O&G installation contains a lot of systems and components; however during LE phase of operation, the failure of one system/component can compromise the safety of an entire installation. For example, Shafiee (2015) indicated that failure of a wind turbine could damage power grid connection, thereby disconnecting the wind farm from the grid. Similarly, the failure of SCEs on offshore O&G platform can result in damage to a plant or an entire installation. To evaluate this criterion, refer to the scale given in Table 5-6.

C₂₃: Maturity of technology: This evaluation criterion refers to reliable and available technologies to support implementation of different LE strategies. For example, implementing reconditioning, remanufacturing and repurpose requires matured and available technologies to support disassembling, assembling, parts production as well as transformation of an existing system for new purpose. This criterion is evaluated using the scale given in Table 5-7.

Table 5-7 Evaluation scale for criterion C₂₃

Technology readiness	Value of C ₂₃
Technologies not available	1
Technologies at the development and research stage	2
Technologies been piloted	3
Technologies available but requires improvements to increase efficiency	4
Technologies matured and commercially available	5

5.5.1.3.3 C₃: Environmental, Legal and Social Criteria

This evaluation criteria deal with the protection and safety of environment and to some extent the principle of sustainable development. The factors considered are:

C₃₁: Legal and social acceptance: Extending the service life of certain type of SCEs is likely to face opposition from residents. Therefore, when selecting the most suitable LE strategy, decision makers must take into consideration factors such as visual effect, noise, disturbances, odour and danger to the immediate communities as result of implementing a LE strategy. This criterion is evaluated using the scale given in Table 5-8.

Table 5-8 Evaluation scale for criterion C₃₁

Community impact	Value of C ₃₁
Community against the use of the strategy	1
Opinion of residents divided	2
Majority of residents accept strategy, since asset is located away from residential area but with very little harmful effect.	3
Majority of residents accept strategy, since asset is located away from residential area and there is no evidence of harmful effect	4
Majority of resident accepts the strategy	5

C₃₂: Environmental impact: This criterion refers to greenhouse gas emissions reduction that can be achieved by implementing a particular LE strategy. This criterion is evaluated using the scale given in Table 5-9.

Table 5-9 Evaluation scale for criterion C₃₂

Environmental context	Value of C ₃₂
Very high impact	1
High impact	2
Moderate impact	3
Low impact	4
No impact	5

5.5.1.4 Construct a Decision Making Chart

Using the evaluation criteria and LE strategy alternatives, a decision making chart is constructed. In this study, the decision making chart for selecting the most suitable LE strategy is illustrated in Fig.5-9. The chart consists of three levels. The first level represents the ultimate goal of the study (i.e. selection of the most suitable LE strategy). The second level comprise the nine evaluation criteria namely, cost of hardware, cost of operations, cost of software, cost of training, personnel safety, asset safety, maturity of technology, legal and social acceptance and environmental impact while the third level consist of the LE strategy alternatives among which decision makers must choose the best strategy.

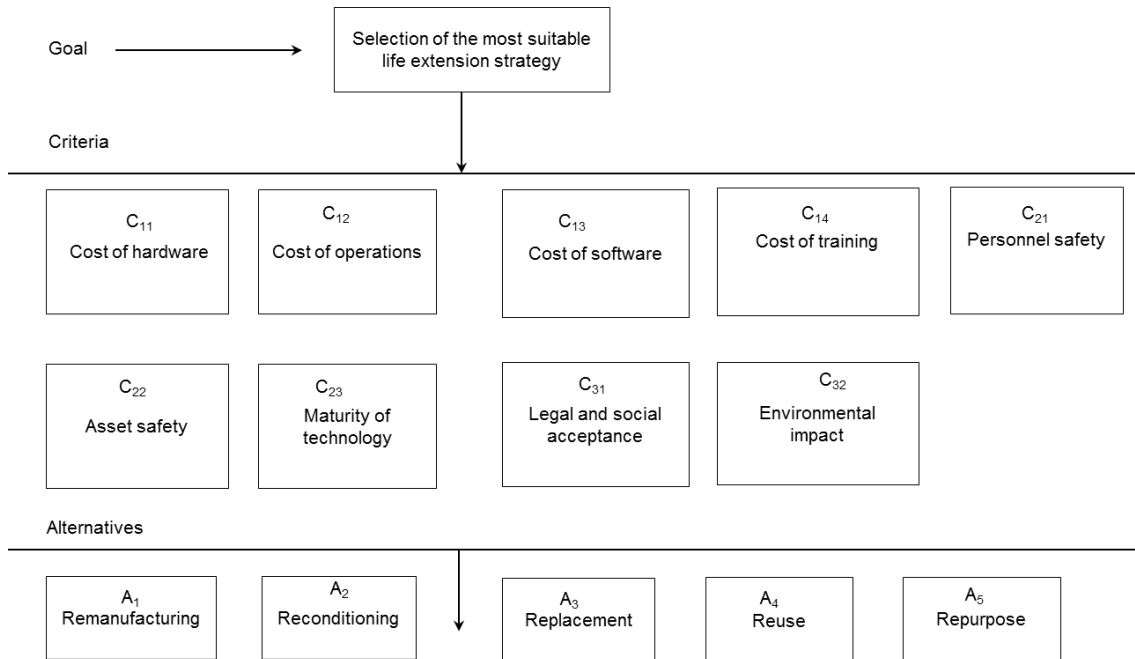


Figure 5-9 A decision making chart for life extension strategy selection for industrial assets

5.5.1.5 Assign criteria weights

Assignment of weights is an important step when using the PROMETHEE method for decision making. This determines the relative importance of each criterion. Macharis et al. (2004) suggested that decision makers are able to weigh evaluation criteria when using PROMETHEE II. If normalisation of weight is required, then;

$$\sum_{j=1}^n w_j = 1 \quad (5-23)$$

where w_j is the weight of each criterion C_j

5.5.1.6 Apply PROMETHEE II

After identifying and defining the evaluation criteria against LE strategy alternatives, the next step is to apply PROMETHEE II to select the most suitable LE strategy. In this study, PROMETHEE II is applied to rank LE strategies because it establishes a complete ranking or pre-order of alternatives (Vinodh and Jeya Girubha, 2011). The main steps required for implementation of PROMETHEE II are described below.

1. Determine deviation based on pairwise comparison

$$d_j(a,b) = C_j(a) - C_j(b) \quad (5-24)$$

where, $d_j(a,b)$ represent the difference between evaluation of alternatives a and b on each criterion.

2. Evaluation of preference function

The preference function is defined as the degree of preference of alternative a over alternative b in the j th criterion (Kabir and Sumi 2014):

$$P_j(a,b) = F_j(d_j(a,b)) \quad (5-25)$$

where, $P_j(a,b)$ represent preference of alternative a with respect to alternative b on each criterion, as a function of $d_j(a,b)$. The preference is calculated by using preference function formulas, for more on preference function formulas refer to Table in Appendix E. The usual criterion which is chosen as the preference function for the study is defined by:

$$p(x) = \begin{cases} 0, & x \leq 0 \\ 1, & x > 0 \end{cases} \quad (5-26)$$

3. Evaluation of global preference index

The aggregated preference index for two alternatives a and b is given by:

$$\pi(a,b) = \sum_{j=1}^n P_j(a,b)w_j, \quad \forall a,b \in A \quad (5-27)$$

where, $\pi(a,b)$ of a over alternative b is the weighted sum of $P(a,b)$ for each criterion C_j , w_j is the weight of j th criterion and A is the set of available alternatives.

4. Evaluation of outranking flows

The net outranking flow which is used to measure the performance of each alternative is calculated. The positive outranking flows indicate the level of preference of one alternative over the other.

$$\varphi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a,x) \quad (5-28)$$

The greater values of $\varphi^+(a)$ shows the strong preference of one alternative in comparison to other alternatives. The negative outranking flow for each alternative is defined as:

$$\varphi^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x,a) \quad (5-29)$$

The net outranking flow $\varphi(a)$ is the difference between the positive flow $\varphi^+(a)$ and the negative flow $\varphi^-(a)$ (Kabir and Sumi 2014), which is calculated as:

$$\varphi(a) = \varphi^+(a) - \varphi^-(a) \quad (5-30)$$

Therefore, if $\varphi(a) > \varphi(b)$, then alternative a is better than alternative b .

5.5.1.7 GAIA Plane

The GAIA (Geometrical Analysis for Interactive Aids) is a visualised tool, which enables graphical representation of criteria used in ranking alternatives (Turcksin et al. 2011; Herva and Roca 2013). The GAIA plane complements the ranking obtained from using PROMETHEE II by helping decision makers to discover the strength and weakness of different alternatives. The GAIA plane is constructed by decomposition of the net outranking flow $\phi(a)$ using principal component analysis (PCA) algorithms (Turcksin et al. 2011; Herva and Roca 2013). PCA is a statistical data analysis technique used to reduce the number of dimensions while minimising the loss of information (Kabir and Sumi 2014). This means that GAIA can transform LE strategy selection problem into two-dimensional plane for geometrical representation. This then provides a new perspective to the selection of most suitable LE strategy decision making problem. The quality of decision is based on the information perceived to be in the GAIA plane. The analysis of GAIA plane is acceptable when the quality level is equal or greater than 70% (Herva and Roca 2013; Kabir and Sumi 2014; Nikouei et al. 2017).

In the GAIA plane, alternatives are represented by points while the criteria are represented by axes. The alternative with the highest score in relation to a particular criterion is represented by points in the direction of the corresponding criterion axis (Visual PROMETHEE, 2013). Alternatives with similar profiles are closer to each other on the GAIA plane and criteria with no conflict have axes that are closer to each other while conflicting criteria have axes pointing in opposition direction.

5.5.1.8 Perform Sensitivity Analysis

PROMETHEE II results are influenced by the criteria weights assigned by decision makers and therefore sensitivity analysis becomes important in order to observe the impact of weight on the final ranking and determine the visual stability range of each criterion. Kabir and Sumi (2014) indicated that sensitivity analysis is valuable when decision maker does not have predetermined weights in mind. The sensitivity analysis is performed by modifying the weights of

evaluation criteria. The walking weight which is a special feature of the Visual PROMETHEE software can be used to modify the weights.

5.5.1.9 Rank and Select Suitable Life Extension Strategy

The LE strategy alternatives are ranked on the basis of the net outranking flow values and the higher the value the better the alternative.

5.6 Case Study

The proposed decision making model is applied to evaluate and select the most suitable LE strategy for an industrial air compressor (see Fig.5-10) which supports operations of energy laboratories in Cranfield University.



Figure 5-10 The air compressor for case study

The air compressor has reached the end of its original design life and assets managers want to extend its service life. However, as a requirement for LE, they are required to select a suitable LE strategy which gives them value for money while at the same time not compromising safety. The failure consequences of this air compressor could lead to revenue loss in excess of £1million annually. The results of the application case are presented and discussed below.

5.7 Analysis of Results

The following sub section shows a step-by-step application of the proposed decision making model to an industrial air compressor case study.

5.7.1 Form a Group of Decision Makers

A panel of five experts were carefully selected to form the team of decision makers. They included representative from Cranfield University asset management team with over 15 years of experience in managing laboratory facilities and two academic with over five years of experience in relation to environmental and social impact of industrial projects. The other two experts included a financial analyst and technical manager both from air compressor manufacturing companies.

5.7.2 Identify Life Extension Strategies

It was concluded by the decision makers that the LE strategy alternatives (i.e. remanufacturing, reconditioning, reuse, repurpose and replacement) explained in Chapter 2 were appropriate for the study.

5.7.3 Select Evaluation Criteria

From detailed literature review conducted on relevant LE strategies for industrial safety asset (See Shafiee and Animah 2017), 15 evaluation criteria were initially identified. These 15 criteria were subjected to two rounds of screening using Delphi iteration process, in order to select the most relevant evaluation criteria for selection of the most suitable LE strategy for an industrial air compressor. The screening process was truncated after the second round of the Delphi iteration process, since there was no significant difference between the first and second round results. The other criteria were not considered because of overlapping function with some other criteria. The nine relevant criteria out of the 15 initially identified for the study have been described in Chapter 5.

Due to the subjective nature of the evaluation criteria the usual criterion preference function was selected for the study. The Table 5-10 shows the preference function selected for each criterion and their respective parameters.

Table 5-10 Preference functions

Criteria	Function	Parameter p
C ₁₁	Usual criterion	NA
C ₁₂	"	"
C ₁₃	"	"
C ₁₄	"	"
C ₂₁	"	"
C ₂₂	"	"
C ₂₃	"	"
C ₃₁	"	"
C ₃₂	Usual criterion	NA

5.7.4 Construct a decision making chart

The decision making chart presented in Fig.5-9 was deemed appropriate for this study.

5.7.5 Assign criteria weights

The criteria weights, which measures the relative importance of each criterion to their preference from each decision maker was aggregated and normalised. The normalised weights are shown in Table 5-11.

Table 5-11 Weights for each criterion

C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₂₁	C ₂₂	C ₂₃	C ₃₁	C ₃₂
0.08	0.17	0.07	0.05	0.13	0.10	0.14	0.09	0.17

5.7.6 Apply PROMETHEE

The PROMETHEE II method was applied to obtain the ranking of LE strategy alternatives. Here the Visual PROMETHEE software (<http://www.promethee-gaia.net/software.html>) was used in evaluating information collected from decision makers in order to rank and prioritise LE strategies. As shown in Table 5-12, the LE strategy alternatives were arranged in descending order according to net outranking flow.

Table 5-12 Positive, negative and net outranking flows for LE strategy alternatives

Rank	Alternatives	$\varphi^+(a)$	$\varphi^-(a)$	$\varphi(a)$
1	A ₃	0.4400	0.1700	0.2700
2	A ₂	0.2725	0.1225	0.1500
3	A ₁	0.1875	0.1650	0.0225
4	A ₄	0.1775	0.2225	-0.0450
5	A ₅	0.0425	0.4400	-0.3975

As shown in Table 5-12, the first ranked life extension strategy alternative is A₃ with net outranking flow value of 0.2700, meaning reuse of the air compressor was the most suitable life extension strategy in relation to the given criteria. The next alternative was A₂, followed by A₁, A₄, and A₅ with net outranking flow values of 0.1500, 0.0225, -0.0450 and -0.3975 respectively. As represented in Fig.5-13, the first two alternatives have less impact in relation to criterion C₃₂. On the other side, the most suitable alternative, A₃ has very high operational cost but there is no cost incurred with respect to criterion C₁₁ and C₁₄ respectively. In addition to the ranking table, the PROMETHEE II complete ranking is illustrated in Fig. 5-11.

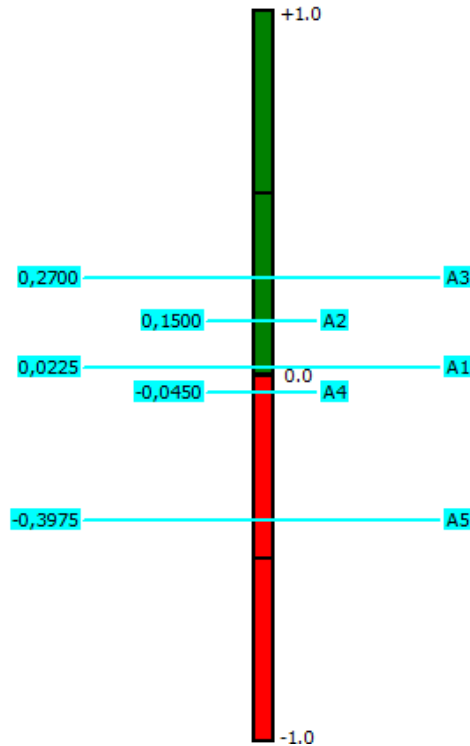


Figure 5-11 The PROMETHEE II complete ranking

The decision problem is visualized in the GAIA plane (Fig.5-12), where six dimensional spaces of criteria are projected on two-dimensional plane via PCA. The quality level for visualization is 94.1%, which means that very few information was lost through the projection and this guarantee's the validity of our results. The GAIA plane showing the six dimensional spaces of criteria are projected using PCA.

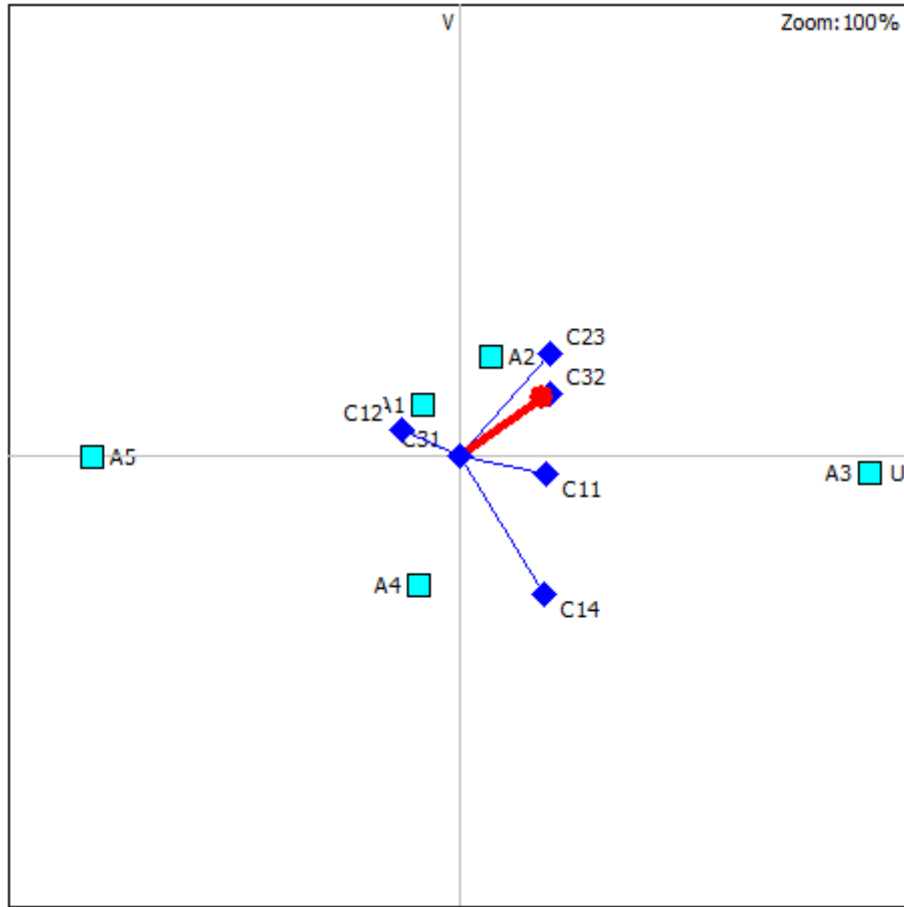


Figure 5-12 GAIA plane

The Fig. 5-12 above indicates that criterion C_{23} and C_{32} are closer to each other. So the most suitable life extension alternative, A_3 performed well with respect to these criteria but did not perform well with respect to criterion C_{12} and C_{31} .

5.7.7 Sensitivity Analysis

After reporting the results of the study, all decision makers agreed with the final ranking illustrated in Fig.5-13. However, asset managers wanted to determine which criteria weights when modified can change the final ranking of the alternatives. This triggered three rounds of consultation with decision makers to modify the criteria weights. The criteria, C_{12} and C_{31} weights were modified, since the most suitable life extension strategy alternative; A_3 did not perform well in relation to these criteria (See Fig. 5-12).

In relation to Fig.5-14, when the weight of criterion C_{31} was increased from 9% to 80%, there was no change in the final ranking. This is attributed to the reason that the air compressor is placed in a confined and isolated space, where its operations do not have legal and social impact such noise on the immediate environment. On the other side, when an increase was provoked in the weight assigned to criterion C_{12} , from 17% to 33%, there was a change in the final ranking. A_3 which is the first ranked alternative in the base case analysis (see Fig.5-13) became the third ranked alternative while A_2 and A_1 became the first and second ranked alternatives respectively (see Fig.5-15). When the weight of criterion C_{12} was further increased from 33% to 41%, the first ranked alternative, A_3 became the fourth ranked alternative while A_2 , A_1 and A_4 , became the first, second and third ranked alternatives respectively (see Fig.5-16). This change in the final ranking, when criterion C_{12} was modified, indicate that the cost of operations is one of the critical and conflicting criterion that can negatively impact life decision making process for industrial air compressors, since the capital cost of air compressors are generally low.

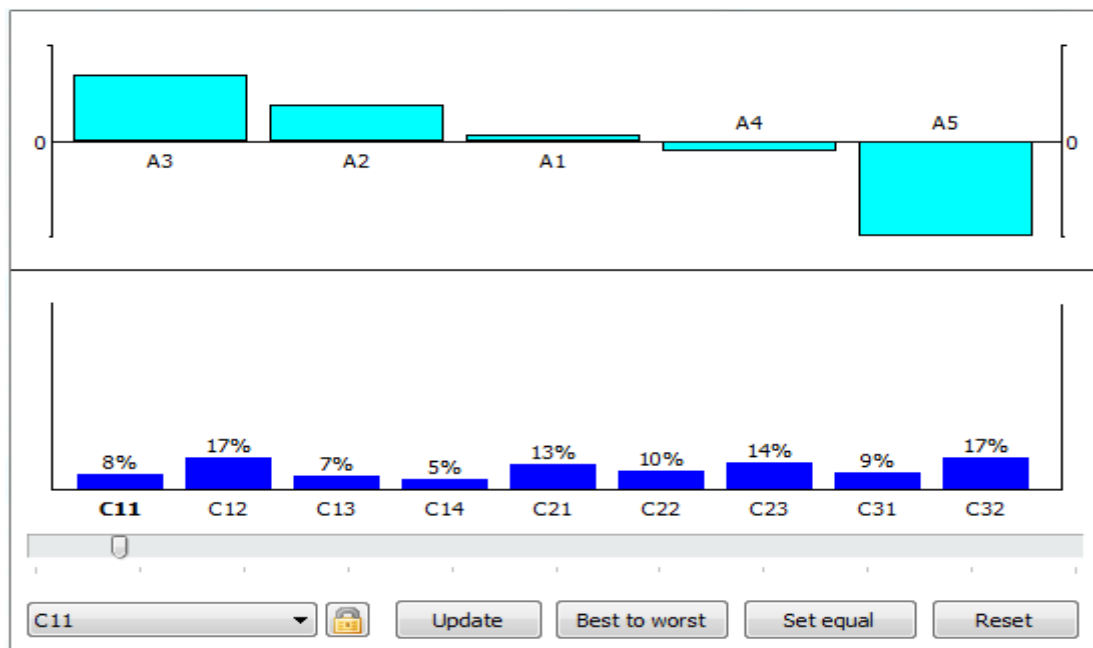


Figure 5-13 Ranking of alternative (Base case analysis)

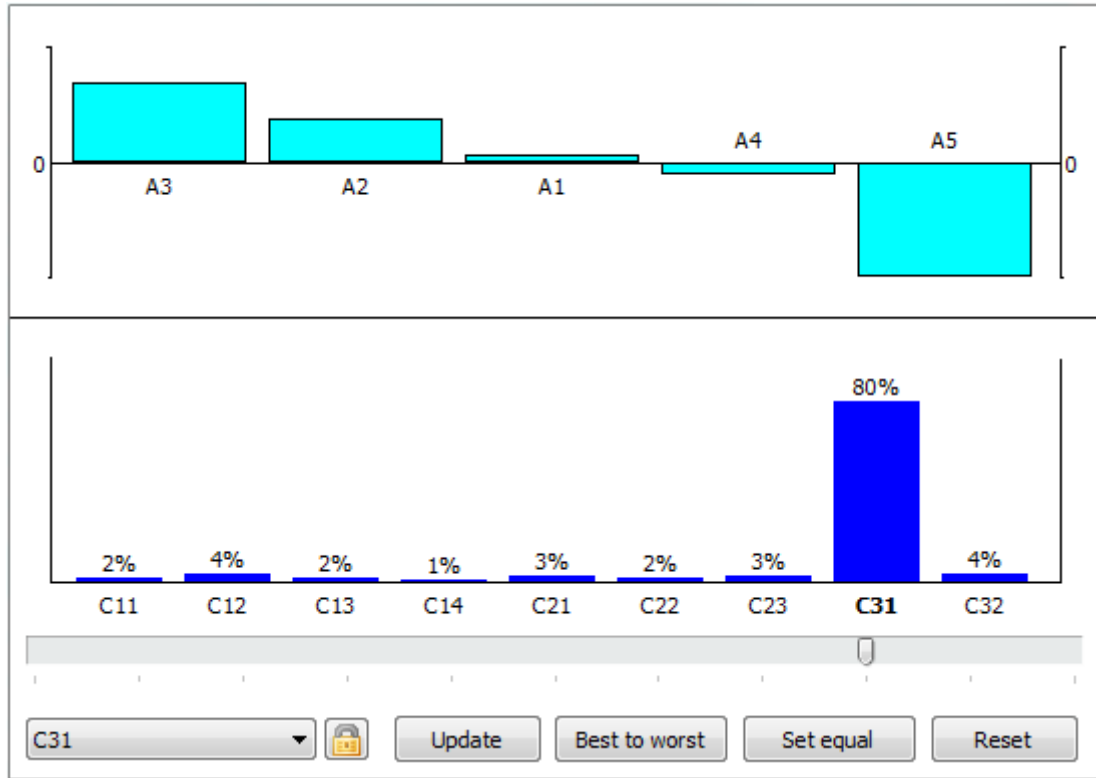


Figure 5-14 Ranking of alternative when weights of criterion C_{31} is changed

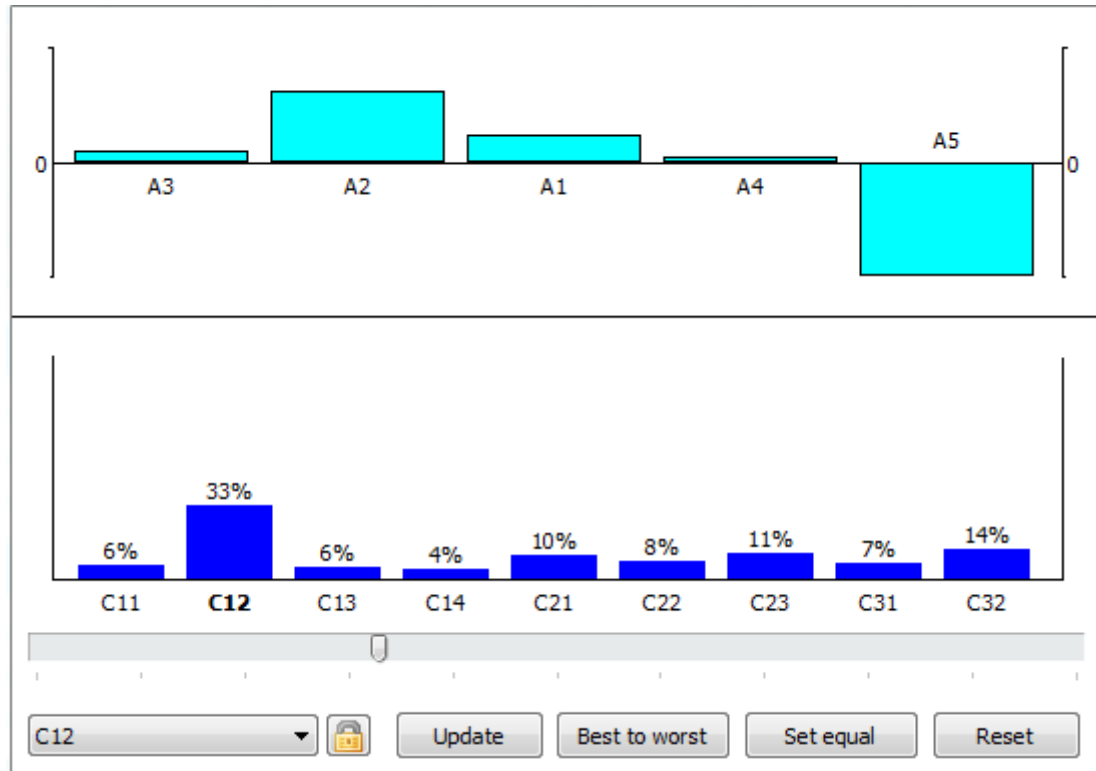


Figure 5-15 Ranking of alternative when weights of criterion C_{12} is changed

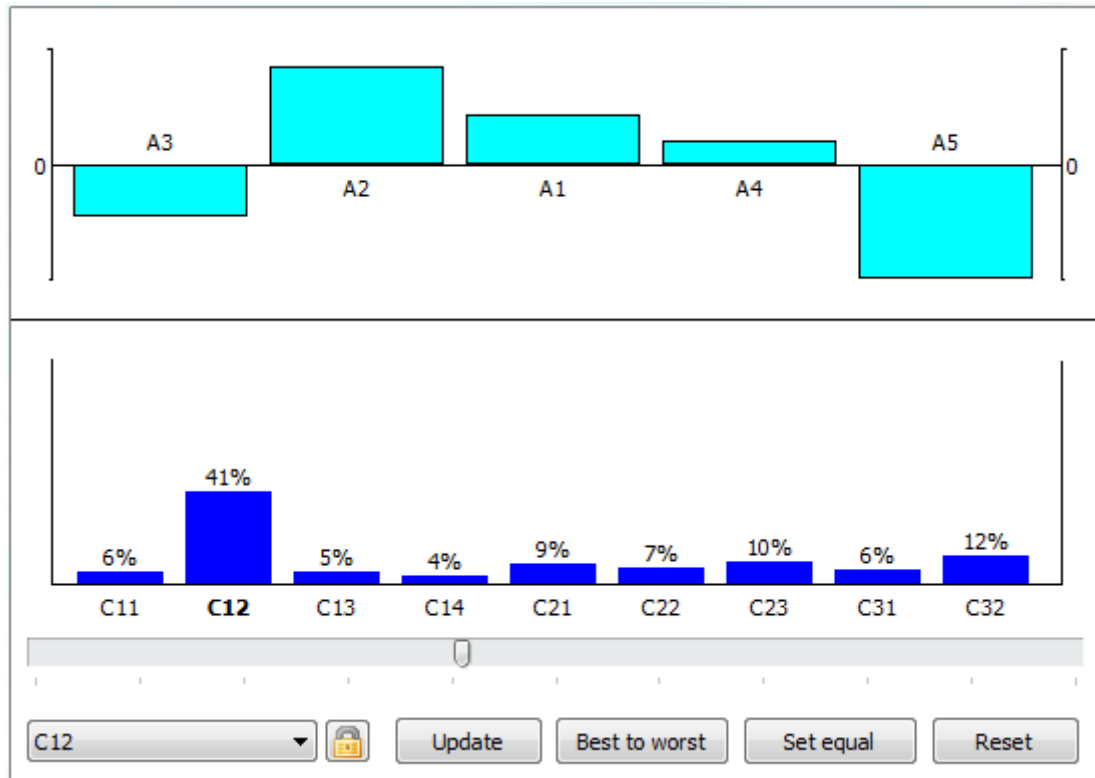


Figure 5-16 Ranking of alternatives when weights of C_{12} is further changed

The result of the stability range for each criterion is presented in Table 5-13 and the criterion C_{32} 's graphical representation of stability range is shown in Fig.5-17 as an example.

Table 5-13 Stability range

Criteria	Visual Stability Intervals %
C11	0% , 100%
C12	0% , 24.27%%
C13	0% , 100%
C14	0% , 12.84%
C21	0% , 100%
C22	0% , 100%
C23	5.49% , 100%
C31	0% , 100%
C32	0% , 100%

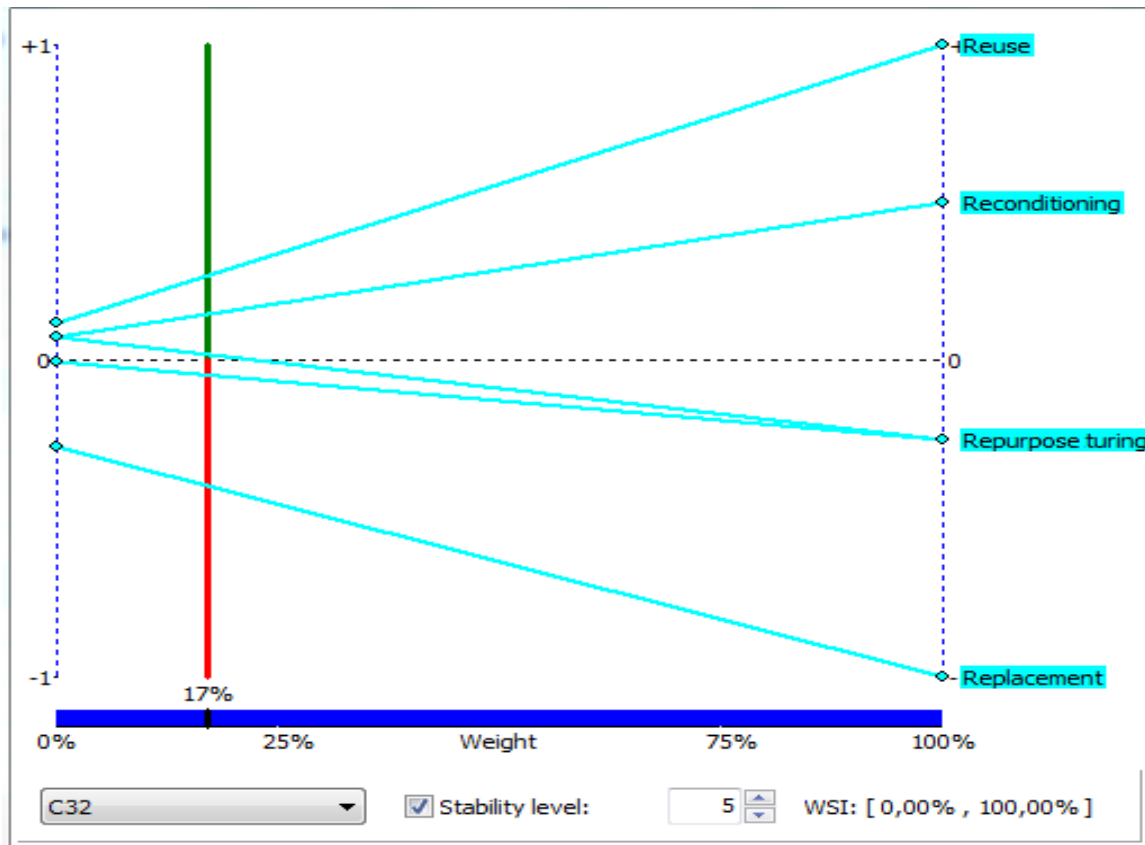


Figure 5-17 Visual stability range for C₃₂ criterion

5.8 Summary of Chapter

In this Chapter, the author has presented details of two methodologies for selecting the most suitable LE strategy. The author presented LCCB approach, which uses quantitative inputs data to evaluate and select the most suitable LE strategy among range of options. Although the LCCB model is appropriate for selecting suitable LE strategy, it is limited in its application as far as multiple criteria decision making problem is concerned. Hence, an approached based on PROMETHEE II methodology, which is an MCDM method was subsequently developed to help asset managers select the most suitable LE strategy when multiple and conflicting criteria are being evaluated during LE decision making process.

6 MULTI-STAGE REMANUFACTURING ARCHITECTURE

6.1 Introduction

LE management process is complex, dynamic and iterative, requiring co-operation of various parts (agents) of an organisation. This means that each agent responsible to ensure smooth operation of SCEs during LE phase of operation must know their responsibilities, when to act and when to interact and communicate with other agents. However, in the past, coordination of LE agents for smooth operation of SCEs have been overly centralised on expert judgement and experience but experts' judgement and experience do not necessarily lead to optimal solutions due to the operational complexities of SCEs as well as their degradation processes. Also, the approach is not flexible and less structured. In order to address the shortcomings of the existing approach, it is required to develop a unified approach to support LE decision making of SCEs as well as economic analysis of corresponding interventions which captures the interactions between various segments within an organisation. Multi agent-based approach has so far been used in various applications including supply chain management (García-Flores and Wang, 2002; Julka et al., 2002), power distribution and transmission (Pipattanasomporn et al., 2009), scheduling (Archimede et al., 2013; Kaplanoğlu, 2014; Kouiss et al.; Zhang et al., 2009), maintenance planning and optimisation (Bouzidi-Hassini and Benbouzid-Sitayeb, 2013; Dahane et al., 2015; Gargiulo et al., 2013; Wang et al., 2014) to ensure pro-activeness, autonomy, interaction, communication, distributed decision making and collaboration among segments of a complex system for efficient decision-making. The rationale behind proposing this approach is to break down the LE decision making problem into several smaller and simpler problems handled by multiple entities responsible for LE organisation.

6.2 The Proposed Approach

Extending the service life of SCEs is a complex task because it is often subjected to several constraints such as lack of appropriate procedures,

unavailability of qualified personnel, shortage of spare parts and poor logistics support such as inaccessibility to specialised equipment. Due to the uncertainties involved in the LE decision making, decomposition of the system into several interacting components and considering each component separately may be an effective way of modelling the degradation of SCEs. Multi-agent architecture, where the system is decomposed into several interconnecting parts can be a useful approach for estimating the impact of remanufacturing on industrial operations during LE. We propose a multi agent architecture in which each part of the system consists of one or more autonomous agents as shown in Fig.6-1.

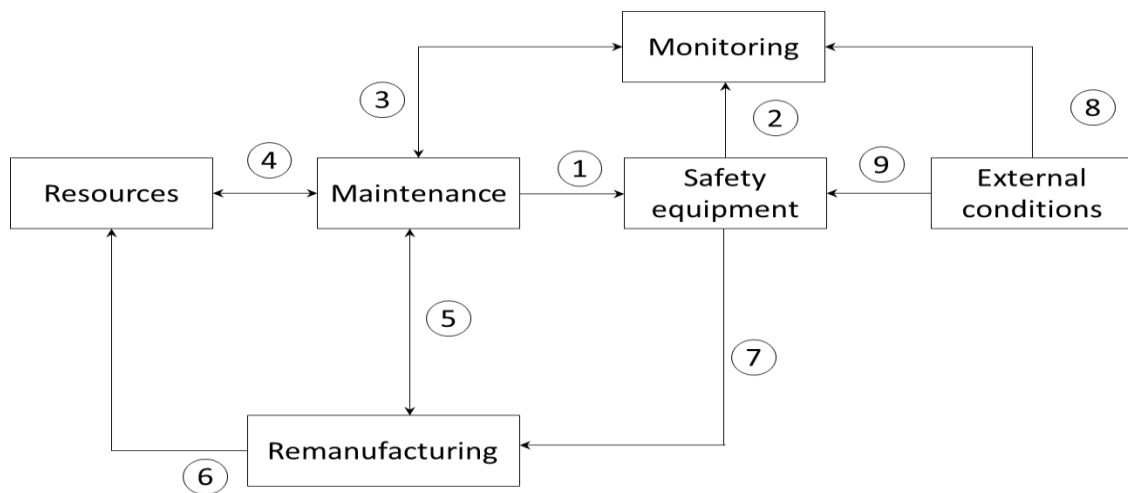


Figure 6-1 Multi-agent architecture: agents and their interconnections

As shown in Fig. 6-1, the agents included in the LE decision making problem are: safety equipment, monitoring, maintenance policies, resources (human or technical), external conditions, and remanufacturing. The following subsections explain the role, behaviour, composition and the interaction of various agents.

6.2.1 Safety Equipment

Safety equipment is described by a number of factors representing the condition of the components through Equipment Health Index (*EHI*), and the production commodity (e.g. energy, compressed air, oil and gas). Each system is considered autonomous in order to allow each element to interact with other

agents such as maintenance, monitoring and external conditions as illustrated in Fig.6-2.

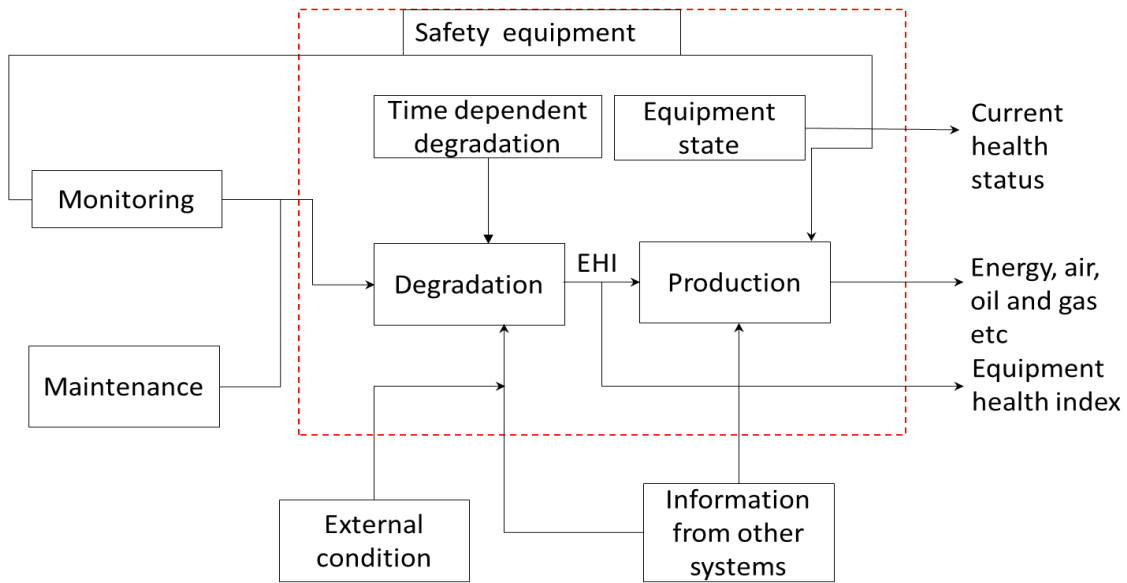


Figure 6-2 The composition of the safety equipment and its interactions with other agents.

In Fig.6-2, the composition of the safety equipment and its interactions with other agents are presented. The equipment conditions are based on degradation condition and production level that are influenced by internal variables (e.g. failures that cause downtime and affect production levels, PM interventions that decrease the degradation rate of the safety equipment) and external variables that are associated with other agents. For example, the weather condition is considered as an external variable affecting the degradation of the safety equipment and resulting in larger failure rate. The maintenance actions improve the degradation condition and production level of the safety equipment. It is assumed that the safety equipment shutdowns during maintenance and remanufacturing processes. However, since the safety equipment is considered to be beyond the ‘wear-out’ stage of the so called ‘bathtub curve’ with an increasing failure rate, the maintenance action will bring back the safety equipment to an operating state between as-good-as-new (AGAN) and as-bad-as-old (ABAO), implying *imperfect* maintenance.

EHI considers time-dependent degradation varying from 10 (the safety equipment is remanufactured to like-new condition with equivalent warranty to OEM) to 0 (the safety equipment has failed). The *EHI* of a safety equipment decreases with time due to ageing mechanisms such as wear and corrosion due to weather and operational conditions. Therefore, the *EHI* of the safety equipment i at the instant $j+1$ is expressed as:

$$EHI_i(j+1) = \begin{cases} 0 & \text{if } f_i(j+1) = 1 \\ EHI_{max} & \text{if } R_i(j+1) = 1 \\ \gamma_i(j) \cdot (EHI_i(j) - deg_{se}(j+1)) & \text{if otherwise} \end{cases} \quad (6-1)$$

where $f_i(j+1)$ represents the probability that a failure occurring at the instant $j+1$ stops the safety equipment i from functioning. It is assumed to follow the Weibull distribution function. EHI_{max} is the value of *EHI* when the safety equipment condition after remanufacturing action becomes like-new. In this case, EHI_{max} is assigned a value of 10. $R_i(j+1)$ is a variable equalling to one if the safety equipment i is remanufactured; otherwise, it will be zero. $deg(j+1)$ represents the status of degradation of the safety equipment in time and is assumed to be proportional to the health condition of the safety equipment, i.e., $EHI_{max} - EHI(j)$. Then, the degradation model is expressed as:

$$deg(j+1) = \psi \times (EHI_{max} - EHI(j)) \quad (6-2)$$

where ψ represents an empirical value ensuring that *EHI* will equal to zero at the end of life expectancy, e.g. fifty years. The coefficient $0 \leq \gamma_i(j) \leq 1$ represents the effect of external conditions on the safety equipment degradation and is calculated using the following equation:

$$\gamma_i(j) = \gamma_i^1(j) \times \gamma_i^2(j) \times \dots \times \gamma_i^k(j) \quad (6-3)$$

where k represents the number of different external conditions to be taken into account, including temperature, wind speed, lightning, etc. The values $\gamma_i^k(j)$ are

between zero and one (inclusively) and are predicted empirically based on factors such as geographical location, season of the year, etc.

6.2.2 External Events

The external events may impact degradation status of safety equipment as well as performance of monitoring system. These events represent weather conditions or natural events such as lightning, vandalism, etc. The external event considered in this paper includes the weather effects which depend on variations in meteorological conditions, geographical location of operation, and seasonal changes. The behaviour of the external event is defined by a function which predicts weather conditions and determines the impact of weather variations on the functionality of safety equipment.

6.2.3 Resources

Dahane et al. (2015) classified the resources required for LE of SCEs into human and material resources. The human resources required for maintenance and remanufacturing actions includes engineers, technicians and administrative staff. Material resources involve logistics support such as service boat, supply vessel, cranes and spare parts. The use of material resources could result in cost and carbon footprint while human resources only incur cost.

6.2.4 Maintenance Policies

The choice of maintenance policy during the extended life period depends on the efficiency of maintenance actions, cost, available resources and operating conditions. These maintenance policies can be categorised into two groups (Shafiee, 2015):

- Preventive maintenance (PM): This maintenance policy is largely dependent on the data gathered on performance of the safety equipment via monitoring systems. It is mainly effective where the failure rate of equipment is increasing. Even though PMs can detect most of the sources of faults before they affect the service, there may still be the

need for reactive maintenance tasks to take place in response to emergency situations.

- Corrective maintenance (CM): This maintenance action is carried out when a failure stops the safety equipment from functioning. This is often an expensive maintenance policy, since it requires hiring service vessels, equipment and a number of sub-contractors and may result in longer downtimes.

6.2.5 Monitoring System

The monitoring system is responsible for data gathering, analysis, planning and scheduling of maintenance activities. Maintenance of the safety equipment is dependent on factors such as degradation level, operational mode, current health status and external conditions. The monitoring system provides information about the safety equipment health status as well as the production levels to ensure that the assets receive timely and reliable maintenance services.

6.2.6 Remanufacturing

Remanufacturing restores the degradation condition of a safety equipment to like-new condition (i.e. $EHI = 10$). Costs of remanufacturing and the associated carbon footprint are taken into account in this study.

6.3 Cost Modelling and Carbon Footprint Assessment

6.3.1 Cost Model

Due to limited resources available for the LE operation, maintenance cost is considered as a key criterion for decision making. These costs depend on the failure mode, type of maintenance policy, duration for maintenance, weather conditions and the availability of human and material resources. The proposed maintenance cost model interacts with other modules to estimate the total cost of maintenance and associated downtime while safety equipment undergoes scheduled maintenances or remanufacturing. In this cost model, we assumed CM actions are more expensive than PMs and they result in longer downtimes.

It is assumed that monitoring system has been already installed and therefore the capital cost of monitoring system is not included. The total of cost maintenance at the instant j over the LE period $C_m(j)$ is expressed as:

$$C_m(j) = \sum_{i=1}^n [C_{PM_i}(j) \times X_{PM_i}(j) + C_{CM_i}(j) \times X_{CM_i}(j) + C_{D_i}(j) \times X_{D_i}(j)], \quad (6-4)$$

where n represents the number of safety equipment, $C_{PM_i}(j)$ and $C_{CM_i}(j)$ are the cost of PM and CM actions respectively, for the safety equipment i at an instant j , and are binary variables defined as below:

$$X_{PM(CM)_i}(j) = \begin{cases} 1 & \text{If PM (CM) is conducted on safety equipment } i \text{ at the instant } j \\ 0 & \text{Otherwise} \end{cases} \quad (6-5)$$

$C_{D_i}(j)$ is the cost of downtime for the safety equipment i at the instant j , and $X_{D_i}(j)$ represents a binary variable that is defined by:

$$X_{D_i}(j) = \begin{cases} 1 & \text{If the safety equipment stops during maintenance action} \\ & \text{occurring at the instant } j \\ 0 & \text{Otherwise} \end{cases} \quad (6-6)$$

On the other side, the total cost of remanufacturing depends on the processes involved in performing the remanufacturing action. The total cost of remanufacturing at the instant j , $C_{REM_i}(j)$ can be expressed as:

$$C_{REM}(j) = \sum_{i=1}^n [C_{REM_i}(j) + C_{D_i}(j) \times Y_{D_i}(j)], \quad (6-7)$$

where, $C_{REM_i}(j)$ represents the cost of remanufacturing at the instant j and is assumed to be proportionally linear to cost of manufacturing a new safety equipment (C_M) (Julka et al., 2002):

$$C_{REM_i}(j) = RCR \times C_{M_i} \quad (6-8)$$

where, $0 < RCR < 1$ is the remanufacturing cost rate, $Y_{D_i}(j)$ represent a binary variable that is defined by:

$$Y_{D_i}(j) = \begin{cases} 1 & \text{If the safety equipment stops during remanufacturing action} \\ & \text{occurring at the instant } j \\ 0 & \text{Otherwise} \end{cases} \quad (6-9)$$

The total cost of maintenance and remanufacturing actions over the LE period T is calculated as:

$$TC = \sum_{j=1}^T [C_m(j) + C_{REM}(j)], \quad (6-10)$$

where, $C_m(j)$ and $C_{REM_i}(j)$ are given by Eq. (6-4) and (6-17) respectively.

6.3.2 Carbon Footprint Assessment

The carbon footprint is determined by calculating the greenhouse gas (GHG) emissions of the safety equipment during maintenance and remanufacturing processes. It includes direct and indirect emissions. In this study, we consider direct emission sources of GHG during the phases of maintenance and remanufacturing. Thus, the total carbon footprint at the instant j , $CF(j)$ is expressed as:

$$CF(j) = \sum_{i=1}^n [CF_{PM_i}(j) \times X_{PM_i}(j) + CF_{CM_i}(j) \times X_{CM_i}(j) + CF_{REM_i}(j)], \quad (6-11)$$

where, $CF_{PM_i}(j)$, $CF_{CM_i}(j)$ and $CF_{REM_i}(j)$ represent the carbon footprint due to PM, CM and remanufacturing of the safety equipment i at the instant j . The carbon footprint due to remanufacturing action can be calculated using the below equation (Rathore et al., 2011);

$$CF_{REM_i}(j) = RCFR \times CF_{M_i} \quad (6-12)$$

where, $RCFR$ is the remanufacturing carbon footprint rate and CF_{M_i} is the carbon footprint due to manufacturing a safety equipment. Therefore, the total carbon footprint over the LE period T is expressed as:

$$TCF = \sum_{j=1}^T CF(j) \quad (6-13)$$

where $CF(j)$ is given by Eq. (6-11).

6.3.3 Model Interactions

In SCEs there may exist interactions, communication and exchange of information between different elements. The safety equipment can be affected by external events which impact degradation status and production levels. The monitoring system performs assessment to determine the condition of safety equipment and suggests whether any of the components requires maintenance service. In the case of maintenance, an appropriate maintenance policy is identified and the maintenance resources to undertake the actions are dispatched as needed. The degradation level of the SCE is monitored on a regular basis to avoid catastrophic failures. Fig.6-3 shows the relationship diagram of the safety equipment incorporating the decisions to be made for LE.

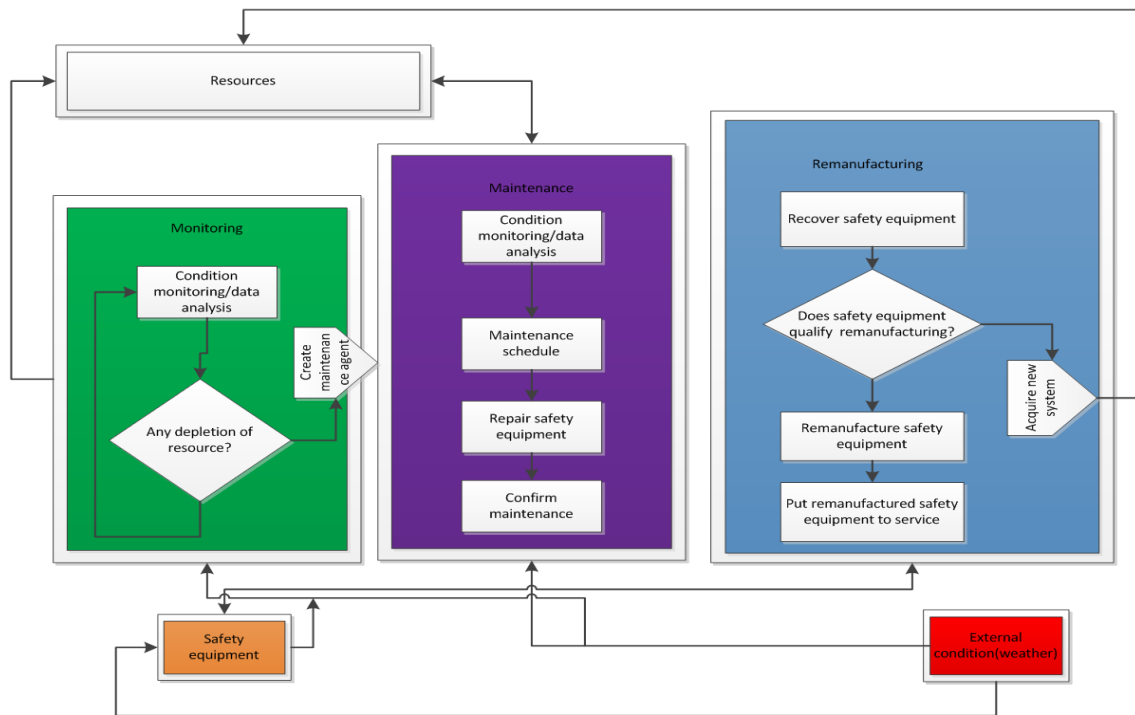


Figure 6-3 Decision making diagram

When maintenance or remanufacturing task is conformed, the data is recorded and asset returns back to service. Also, the safety equipment cannot be maintained or remanufactured for an infinite time, so there is a threshold of designated life span. At the end of lifetime, the safety equipment is considered for disposal. Table 6-1 gives the tasks to be carried out and the decisions to be made by each module for LE of a safety SCEs.

Table 6-1 Decision and agent task analysis

Decision	Agent	Condition	Actions to achieve decision
Condition data	Monitoring	Data analysis	Extract data and provide results of monitoring
Maintenance scheduling	Monitoring	Duration for maintenance	Determine the next available date for maintenance.
Reliable maintenance action	Maintenance	Degradation level, and availability of resource agent	Arrange maintenance personnel and repair safety equipment
Remanufacturing	Remanufacturing	Availability of resource agent and remanufacturing threshold	Reconditioning of safety equipment and reset of safety equipment degradation level
Degradation	Safety equipment	Weather, degradation level and failure rate	Estimation of safety equipment degradation

6.4 Case Study

In order to test the applicability of the proposed approach, a case study of 7.5KW industrial air compressor system is provided. The air compressor considered in this study is used to support experiments at the Agrifood laboratories in Cranfield University. The vast majority of air from the compressor is used for produce storage trials and also for manipulation of biogas constituent to burn well in order to reduce CO₂ content. The compressed air is also used on instrumentation such as Atomic Absorption Spec and Liquid Chromatography-Mass Spectrometry. Plans are also far advanced to install a nitrogen generator, which will also use significant amount of compressed air for produce storage trials.

However, any unexpected loss of air (of more than 1 hour) will have a potential impact on experiments. For example, the produce storage trials go on for months using produce from a particular harvest and once there is an interruption of air supply it may take 6 months to work out the impact. When there is loss of air for 24hours or longer, the University is likely to lose about £1million in business. For this reason the air compressor is considered critical to the sustainability of the Agrifood laboratories. The air compressor was installed in 2007 and has an original design life of 7years. The reading indicates a maximum usage of 0.3 to 0.4 m³/min (11.0 to 14.0 cfm) over 4,425 hours annually from its output of 41.0 cfm. For effective LE operations of the air compressor for the next ten years, the proposed model is used to integrate all elements involved in LE decision making, including maintenance management, condition monitoring, remanufacturing and external factors that may impact LE period of operation. The analysis of the re-manufacturing architecture model was conducted using the data obtained from users and manufacturers of industrial air compressors.

Table 6-2 shows the operational data collected from the users of the industrial air compressor.

Table 6-2 Operating data for air compressor (Confidential)

Criteria	Source	Parameters	Means of collection
Age of equipment	Facility manager	8 years	Retrieval from operators manual
Type of maintenance	"	Used based	"
Type of inspection	"	Visual inspection	"
Operating pressure	"	10 barg	"
Maintenance interval in a year	"	4.38 times annually	"
Inspection interval in a year	"	Annually	"
Availability	"	90%	"
Maintenance requirement	"	Every 2000 running hours	"
Electricity/KWh	"	52.8	"
Operation time in a year	"	4,425 hours	Interview
Failure rate	"	2.9×10^{-6}	"
Annual electricity cost	2	£0.14 p/kWh including VAT	"

The environmental data concerning the manufacturing and operations of industrial air compressors collected from users and manufacturers are shown in Table 6-3.

Table 6-3 Carbon footprint data (Confidential)

Parameter	Electricity consumption(kWh)	kg CO ₂ -e/kWh
New equipment(without usage)	1208.7	640
Assembling	7.96	4.19
Disassembling	5.07	2.67
Cleaning and surface grinding	2.91	1.53
Testing	4	2.10
Usage	462528	241902.1

The cost data required for economic analysis using the remanufacturing architecture is shown in Table 6-4.

Table 6-4 Economic data for air compressor (Confidential)

Data	Source	Parameter
Cost of new machine	Manufacturer	£4200.00 + VAT
Cost of installation(with same machine)	"	£ £4500.00

Cost of installing piping, valve and fittings	"	£300
Cost of reconditioning	"	£3,439.20
Annual electricity usage cost for original compressor	Operator	£9198
Annual electricity cost for new compressor less than 5 years	"	£5223
Annual electricity cost for reconditioned/remanufactured compressor	"	£7358.4
Annual energy saving from new compressor	Manufacturer	£ 530
Cost of PM	Operator	£203.61- £392.42 per 2000 running hours
Cost of CM	"	£210 - £430
Man hours for PM	"	5hrs
Man hours for CM	"	4hrs
Duration of project(T)	"	10yrs
Interest rate	Government	0.5%
Discount rate	Operator	7%
CO ₂ tax cost	Government	£18.08 per tonne of CO ₂ -e
Benefit	University	£1million

6.5 Analysis of Results

A Monte-Carlo simulation (MCS) model is applied to predict the long term impact of maintenance and carbon footprint during the extended lifespan of the air compressor for ten years. The air compressor failures caused a total of 240 hours downtime during the operation cycle of twenty years with a total replacement cost of £25,200. The system degrades with time until the equipment health index (EHI) reaches zero at the end of design life. The results of the analysis are represented in Table 6-5.

Table 6-5 Remanufacturing cost and carbon footprint of safety equipment with and without PM

	Without PM	With PM once per year
Number of failures	3	2
Downtime	240 hours	19 hours
PM cost	0	£392.42
CM cost (replacement)	£25200	£210
Remanufacturing cost	-	£6878.4
Carbon footprint	640 kg CO ₂ -e	10.49 kg CO ₂ -e

The lack of PM actions increases LE cost and possibly will affect the economic benefits that may be achieved. A greater discount rate will result in lower remanufacturing cost than the £6878.4. After remanufacturing, the economic health index is assigned the value of 10. This is because there is no considerable difference between remanufacturing action and replacement in terms of improvement of the condition of the air compressor. In the remanufacturing process, 97% of the parts were reprocessed and used while the rest were replaced with new parts. Conducting no PM action during LE period increases the degradation levels of safety equipment and also increases equipment replacement frequency. On the other hand, implementing PM actions during extended life operations results in decreased safety equipment degradation, thereby reduction of downtime (in hours) and remanufacturing cost. With an effective PM plan, the air compressor will need to be remanufactured twice in ten years of design lifetime compared to three times being replaced in the case of no PM action. This makes remanufactured safety equipment economically viable for industrial operations. From Table 6-5, the replacement strategy results in higher carbon footprint compared to remanufacturing policy. If the penalty of CO₂ emissions is assumed to be £18 per tonne ([Http://uk.reuters.com/article/uk-britain-budget-carbonidUKLNEA2I02620140319](http://uk.reuters.com/article/uk-britain-budget-carbonidUKLNEA2I02620140319)), then the cost of carbon footprint of a new industrial air compressor will equal to £115 while remanufacturing will only cost £0.18. Thus, remanufacturing is not only considered as an economic end of-life strategy but also as a carbon footprint reduction solution for long term operations.

6.6 Summary of Chapter

In this Chapter, the author proposed a multi-stage remanufacturing architecture to integrate all LE decision making elements in order to ensure safe and cost-effective operations during LE period. The proposed architecture integrates all the components involved in LE decision making process, including maintenance, condition monitoring, remanufacturing and external event which affects the cost and benefits of LE process.

The Chapter suggests that remanufacturing is one of the environmentally friendly and economic viable LE strategies for SCEs in terms of carbon foot print and total cost. Furthermore, implementation of remanufacturing as a LE strategy can delay the both replacement and decommissioning of SCEs, resulting in significant savings for asset managers and focus on other investments.

In Section 6.2 the proposed architecture or framework involving all LE decision making elements was presented and explained. Section 6.3 presented the mathematical models for total cost calculation including maintenance and remanufacturing. The carbon footprint model for maintenance and remanufacturing actions were subsequently presented in this section.

7 DISCUSSION OF KEY RESEARCH FINDINGS

7.1 Introduction

The aim of this Chapter is to present a synopsis of research findings discovered throughout the thesis and subsequently discuss their implications to this area of study. Furthermore, the discussions are structured according to the key themes covered in thesis. The sequence of discussion is as follows: current practices, challenges and experiences from other industries, techno-economic framework to support LE feasibility assessment, processes for selecting suitable LE strategy and the multi-stage remanufacturing architecture for LE decision making.

7.2 Current Practices, Challenges and Experiences from other Industries

7.2.1 Current Practices

The author conducted a survey employing face-to-face interviews, telephone interviews, and other electronic means with experts who have several years of experience in managing LE projects and triangulation with industrial documents, current practices associated with LE phase of operation were captured. The current practices included: dominant degradation mechanisms during LE phase of operation, means of screening and prioritising SCEs, means of qualifying SCEs for LE and the safe and cost effective LE practices in the offshore O&G industry.

It was identified that currently in the offshore O&G industry, many degradation mechanisms are experienced but corrosion and fatigue were identified as the dominant degradation mechanisms at the end of original design life of SCEs and this was confirmed by literature review. This implies that any decision making model to support LE assessment of SCEs must consider these key degradation mechanisms. Although a lot of researchers have developed various degradation models and demonstrated how they can be used to estimate RUL, this research has brought to light the lack of understanding of how to establish a

relationship between RUL models and LE decision making process in the offshore O&G industry.

On the means of screening and prioritising SCEs, it was discovered that the current screening and prioritisation process of SCEs is through the use of generic industrial list or expert knowledge and experience. However, using these approaches often results in confusion between regulators and operators because the regulators always sticks to these list while from operator's standpoint, some of the systems on the list may not qualify to be classified as SCEs due to nature of operations. It is worthwhile mentioning that these lists are often conservative, since they are developed at the commissioning stage of the installation but in practice the operational and environmental conditions changes with respect to those considered during commissioning stage of the installation.

The current efforts in assessing whether SCEs qualifies for LE is mainly based on qualitative approaches such as expert knowledge and the use of qualitative risk assessment tools while semi-quantitative approaches with their added value is disregarded. This may partly be due to lack of awareness as well as staff without the requisite capabilities to apply the semi-quantitative tools. Apart from the lack of awareness and staff without the requisite capabilities, the number of semi-quantitative tools to help asset managers perform LE assessment is also limited in the offshore O&G industry.

Through the interactions with industrial experts, responses to the question of safe and cost effective LE practices varied and some experts could not provide appropriate response to this question. However, they acknowledge that this is a vital question and suggested that implementation of good LE management model could help answer this question in future.

7.2.2 Challenges

From the interaction with industrial experts, the author identified several challenges asset managers are facing during LE phase of operation in the offshore O&G industry. The results from the expert's interactions were

triangulated with literature review, and after triangulation the research focused on addressing five key challenges. Key among these challenges were lacks of classification framework for factors influencing LE decision making process, lack of structured approach to screen and prioritise SCEs, lack of integrated technical and economic processes to support LE assessment and lack of appropriate scientific process to help select suitable LE strategy.

7.2.3 Experiences from other Industry

Although the offshore O&G industry is considered unique in its operations, the author looked beyond the offshore O&G industry to learn from proven solutions applied in other industries to address the challenges of LE. This research concludes that in order to effectively address the challenges of LE in the offshore O&G industry, the industry have to look beyond their borders and find solutions from other industries that can successfully be adapted. This will help the industry replace out-of-date problem solving approaches with new and novel approaches. The author considered the nuclear power plant, electrical distribution and transmission, wind energy and the transportation industries as key industries to learn lessons and good practices because their assets have some commonality with assets being used on offshore O&G installations. Installations in these industries, suffer from similar degradation mechanisms at the end of life and the service lives of many assets within these industries have also been extended. Some of the key lessons learned from these industries were that PSA tools has the potential to overcome the challenge of screening and prioritisation of SCEs and also establishment of a proper data and knowledge management platforms in the offshore O&G industry was essential for successful implementation of LE projects. However, it was discovered that some of the tools developed to support LE management process were industry specific and cannot directly be adopted for use in the offshore O&G industry. This means that research is needed to further explore this situation.

7.3 Techno-Economic Framework

As a result of literature review, a research gap was identified in relation to classification of list of factors that influence LE decision making process in the

offshore O&G industry. In order to fill this gap, the author conducted a survey involving industrial experts with several years of experience in managing LE projects in the offshore O&G industry with the aim of obtaining exhaustive list of factors that may influence LE decision making process. After obtaining the list of decision making factors from experts and triangulating with lists from literature, the final list of factors that may influence LE decision making process were captured. The author realised that the list can be classified into inputs, constraints and output decision making factors using the structured analysis and design technique (SADT) concept. Based on this classification, LE decision makers can easily determine what factors they are likely to consider as input variables, the constraints to their decision as well as the expected output of their decision. Validation of the classification framework with case studies revealed that it has the potential to reduce the complexities involved in LE decision making process and also reduce the time involved in decision making process.

Based on the classification of list of factors that may influence LE decision and research gap identified in Chapter 2 as well as the outcome of expert interactions in Chapter 3, the author then investigated how to integrate technical and economic assessment processes to assist in LE assessment of SCEs. The investigation revealed that very few frameworks have been developed for managing LE process in the offshore O&G industry. At this point, it is worthwhile referring to some of the studies that developed and discussed LE assessment frameworks in the offshore O&G industry.

Galbraith et al (2005) in collaboration with Cranfield University and UK HSE developed the Capability Maturing Model (CMM) for assessing offshore O&G installations design safety for LE. The purpose of CMM was to determine how well duty holders have applied the knowledge of materials, requirements, and experiences into LE management of structures. Hokstad et al. (2010) proposed a framework for LE decision making integrating material degradation, obsolescence and organisational issues to ensure acceptable technical integrity of offshore assets throughout LE phase of operation. Vaidya and Rausand (2011) proposed a LE assessment framework involving computational models

for analysing degradation mechanisms and estimating RUL of components. The study failed to incorporate economic assessment and regulatory approval requirements into the framework. The Structure Integrity Management (SIM) framework originally developed for offshore O&G structures integrity assessment has been used to support LE assessment (Ersdal et al., 2014; Galbraith et al., 2005; Wang et al., 2014). However, offshore O&G installations are populated with a lot of equipment and components and therefore adopting the SIM framework for LE assessment for other systems which are not structures is inappropriate. Liu et al. (2014) proposed LE management framework and implemented it to support LE feasibility assessment of SCEs on platforms in the China Bohai Bay. The framework considered technical and regulatory approval issues, ignoring economic factors.

While these frameworks may be convenient for managing LE process of SCEs, they are with draw backs. First, decision making tends to skew to one side, sometimes leading to incorrect conclusion and recommendations. Second, these frameworks are industry specific and may lack applicability outside the industry from which they were originated.

Unlike the other LE management frameworks discussed above, the proposed framework considers technical, economic and regulatory approval factors for LE feasibility assessment. The proposed framework has provided a structured process that addresses the fundamental challenges associated with LE management process. The proposed framework incorporated engineering knowledge and principles, qualitative knowledge contained in guidelines and standards, expert judgement, field experience as well as economic assessment knowledge. The overall basis of the proposed framework is to qualify critical equipment for LE from both technical and economic assessment perspective.

The techno-economic framework was divided into three phases. The first phase of the framework involved defining the premise for LE, data collection and screening and prioritisation of SCEs. Based on the activities to be carried out in the first phase of the framework, there was the need to develop a sub-process to help screen and prioritise SCEs for subsequent LE assessment. In light of

this, the author applied AFMEA, which is a PSA tool to support screening and prioritisation of existing SCEs for LE assessment.

The second phase of the framework integrated technical and economic assessment processes for LE assessment. The aim of the technical assessment process was to establish the current health status of assets by developing techniques to assess the condition of critical systems which takes into account design issues, O&M and environmental conditions. According to Animah et al. (2016) during LE phase of operation, there is the likelihood of experiencing new failure modes which can affect the failure rate of a system due to changes in operational and environmental conditions. Hence, the need for condition assessment methodologies to support LE feasibility assessment of SCEs is increasingly becoming important in the offshore O&G industry. However, existing methodologies for condition assessment of ageing facilities have been either qualitative or quantitative. In place of these qualitative and quantitative methodologies, this research developed a semi-quantitative methodology for rating the health conditions of existing SCEs for purpose of LE. The methodology produced a Condition Index (CI) which is the basis for judging whether equipment is technically fit for extended operations. The approach combined risk assessment factors and condition indicators to produce a decision matrix. Weights were assigned to these factors through experienced field experts and literature. These weights were determined based on the severity of factors to equipment condition and risk. The weights can be modified based on particular experience of experts as well as available data. The overall CI is then calculated based on the weighted sum of the individual condition indicators. The approach has proven to be flexible, less time consuming in its application and compliant to regulatory requirements compared to other methodologies such as ageing models used for the same purpose (Animah and Shafiee, 2016). The CIM outcome can be expressed in the form of colour plots (See Chapter 4). For example when the condition of asset is displayed in the yellow zone, an asset manager is required to estimate the RUL of the system for further analysis. In light of this, the proposed framework has incorporated life time prediction process for RUL estimation. The RUL estimation focused on

dominant degradation mechanisms that are likely to contribute to non-compliance or failure. Incorporating RUL estimation into the proposed framework enabled the author to determine the maximum length of LE period for candidate equipment.

Traditionally, economic assessment has not been integrated into LE assessment models. The common practice has been to consider technical feasibility and economic feasibility separately. However, this framework integrated technical and economic analysis, in order to balance conflicting decision making criteria such as safety and cost during LE phase of operation. The costs and benefits associated with LE process were accounted for fully. The integration of economic feasibility assessment into the proposed framework highlighted the added value of LE. Economic uncertainties encounter during LE decision making process was accounted for by performing sensitivity analysis.

Another important component considered by this framework was regulatory approval, as this is not the case in other frameworks. Evidence available indicates that LE licence has been refused some companies due to non-compliance with regulation provisions in Norway (<http://www.psa.no/>). Finally, the third phase introduced a process to assist asset managers implement LE programme and subsequently monitor and measure the performance of their assets during LE phase of operation.

In summary, this framework has balanced conflicting decision making criteria such as safety and cost during LE decision making process, screened and prioritised SCEs, provided a methodology for techno-economic assessment and proposed a process for implementation of LE programme. In conclusion the framework has addressed some of the challenges and gaps identified from literature review and interaction with experts by providing a structured and standardised approach involving engineering principles, expert judgement and knowledge of economics. The overall contribution of the framework to this research area is summarised as:

1. Provision of a classification framework involving list of factors influencing LE decision making process in the offshore O&G industry.

2. Introduction of modified FMEA approach called AFMEA to support screening and prioritisation of SCEs for LE in the offshore O&G industry.
3. Incorporation of lifetime estimation models into LE management framework to establish a relation between RUL and extended life operation of SCEs, which hitherto was not the case in the offshore O&G industry.
4. Development of a semi-quantitative condition assessment rating technique to support technical feasibility assessment of SCEs.
5. Developments of LE implementation process to assist asset managers monitor the performance of their SCEs during LE phase of operation.

7.4 Selection of Suitable Life Extension Strategy

As mentioned in Chapter 2, it was revealed that existing studies have employed the use of expert judgement and experience to select suitable LE strategies. Therefore, there was the need for scientific approaches to help select suitable LE strategy. This research identified LCCB and MCDM concepts as the appropriate means of handling the challenge of selecting suitable LE strategy in the offshore O&G industry. This finding provided the basis for developing two different processes involving each concept to overcome the challenge of selecting suitable LE strategy.

The first model developed was based on the LCCB concept. This is an effective quantitative tool for comparing alternative strategies and investments. The LCCB model considers issues of cost and benefits associated with LE management process. In recent years, the approach has seen increased application in the bridge and other infrastructure investment industry (Padgett et al., 2010; Thoft-christensen, 2006, 2008; Thoft-Christensen, 2012). To the best of the author knowledge, no study has applied the LCCB concept to select suitable LE strategy in the offshore O&G industry. Thus, this research implemented the LCCB concept which is novel to the offshore O&G industry, to evaluate and select the most suitable LE strategy among a wide range of alternatives taking into account all cost and benefits throughout the LE phase of

an asset lifecycle. However, the approach is limited when both quantitative and qualitative data are considered in selecting suitable LE strategy.

Besides the LCCB concept, MCDM approach which is based on the use of both quantitative and qualitative data and expert judgement can contribute to the selection of most suitable LE strategy decision making. Therefore, a PROMETHEE based decision making model was developed as the second model to support LE strategy selection in situations where the LCCB model is limited. Although PROMETHEE has widely been used to solve decision making problems in many industries, to the best of author knowledge no study has reported the application of the method to select the most suitable LE strategy in the offshore O&G industry.

In comparison with the existing approaches used in selecting suitable LE strategy identified in literature (Brandt and Mohd Sarif, 2013; Leira et al., 2015; Muren et al., 2016; Nezamian et al., 2016), the proposed models are inherently superior because it is scientific with sound technical considerations in their application.

7.5 Multi-Stage Remanufacturing Architecture for Life Extension

After qualifying assets for LE and selecting the suitable LE strategy, each agent responsible for LE management process must work together to ensure safe and continuous operation of the safety asset. This means that each agent must be aware of its responsibility and the right time to act and communicate to other agents. However, currently the coordination among different agents are overly centred on accumulated experiences and judgment of experts, which has very limited added value during LE phase of operation (Animah et al., 2017). The author employed a multi-stage modelling approach, which is a unified approach capable of coordinating and capturing interactions between various agents responsible for ensuring LE management process of SCEs. In comparisons with the traditional approach, the multi-stage approach is more flexible, proactive and ensures autonomous interaction, communication and collaboration among various LE agents. The author used this approach because it is capable of

decomposing complex and overly centred decision making problem into smaller and simple problem.

7.6 Summary of Chapter

This Chapter has presented a synopsis of the thesis and further discussed various key areas of this research. The discussion has highlighted the strengths of various decision making models developed in this research compared to those in literature. In the next Chapter, synthesis, concluding remarks and recommendations for future research intended to help extend the work conducted in this thesis is presented.

8 CONCLUSIONS, RESEARCH LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.1 Introduction

In this Chapter, the author revisits the aim and objectives of this thesis and provides synthesis on how the aim and objectives were met in order to make the necessary conclusions. The concluding remarks alongside future research opportunities are subsequently provided.

8.2 Synthesis and Conclusion

This research was embarked upon based on the realisation that the world's energy demand was growing exponentially on annual basis but many existing infrastructure responsible for energy production are approaching the end of original design life or have exceeded their original design. It was discovered that installations approaching the end of life in the offshore O&G industry are facing the challenge of ageing; however production fields still have the capacity to continue operations. Thus, operators are now encouraged to ensure that their existing ageing infrastructure continue to operate in a safe and economically viable manner beyond the original design life. However, in the offshore O&G industry LE management process has focused much attention on structural parts of ageing installation with ageing safety systems being disregarded. Hence, the development of systematic LE management processes which focus on systems considered as safety critical will contribute to better understanding of how the concept of LE can be applied to manage SCEs.

The purpose of this thesis is to address the challenges and gaps in knowledge associated with LE management process for SCEs by considering the following aim:

To develop LE management framework which is integrated for screening and prioritisation, condition assessment, remaining useful life estimation, risk analysis and cost-benefit analysis for SCEs.

For the rest of this Section, a summary of how the objectives outlined in Chapter 1 of this thesis were achieved with corresponding conclusions drawn is provided for readers.

The first objective was to review state-of-the-art of LE in the offshore O&G industry in order to gain in-depth understanding of existing works and identify gaps in this research area. To achieve this objective a systematic review of literature was conducted in Chapter 2 to provide better understanding of the state-of-the-art in this research area and subsequently identify current research gaps as well as highlighting trends. Based on the literature review, the following conclusions were made:

1. Research on LE management of offshore O&G installations is growing. Based on the trend analysis in Fig.2-2, more publications on offshore O&G LE management are expected in the coming years.
2. It was observed that majority of publications on LE management in the offshore O&G industry over the past years have focused attention on structural parts; with safety critical system as well as pipelines receiving very limited attention.
3. Currently the list of factors influencing LE decision making process provided by literature is not exhaustive and also fragmented.
4. Lack of good quality data is identified as one of the key obstacles to successful implementation of LE programme in the offshore O&G industry.
5. None of the existing studies have developed a bespoke software tool to support LE decision making process in the offshore O&G industry.
6. Semi-quantitative condition assessment techniques have rarely been used to assess the current health status of ageing SCEs for LE.
7. There is lack of comprehensive and integrated techno-economic framework for supporting LE decision making process in the offshore O&G industry.
8. The selection of suitable LE strategy is largely based on expert knowledge and experience.

The second objective was to understand current practices, identify key LE decision making challenges and learn good practices from other industries. This objective was approached in Chapters 2 and 3. After analysing the outcome of a survey with industrial experts on current practices of LE in the offshore O&G industry, the following conclusions were drawn in terms of current practices:

1. Currently, corrosion and fatigue are the most dominant degradation (ageing) mechanisms experienced by SCEs at the end of original design life
2. The screening and prioritisation of SCEs are based on generic industrial list or the use of expert judgement and experience of engineers.
3. Qualitative risk assessment tools or expert knowledge is mostly employed to assess the current health conditions of ageing SCEs for LE in the offshore O&G industry.
4. Both economics and technical health status of assets drives many decisions in the offshore O&G industry including LE decision making process.

Triangulating information from literature review in Chapter 2 with that from industrial experts in Chapter 3, the following conclusions were drawn in terms of challenges:

1. There was lack of structured approach to guide decision makers to screen and prioritise SCEs for LE assessment.
2. Lack of systematic approach to integrate technical and economic assessment processes to support LE feasibility assessment of SCEs.
3. Lack of scientific and structured process to help decision makers select the most suitable LE strategy.

These conclusions were drawn from lessons and good practices learned from other industries:

1. Issues of LE have received a considerable attention in both nuclear power plant and electrical distribution and transmission industries compared to offshore O&G industry.

2. Data such as test report, degradation/condition monitoring report, maintenance report and equipment design data are valuable in performing detailed semi-quantitative assessment, in order to rate current health status of SCEs on platforms for LE.
3. Methodological process incorporating PSA techniques could help stakeholders overcome the challenge of lack of structured process to screen and prioritise SCEs for LE assessment.
4. Due to the difference in design and operation of some equipment in other industries, some of the solutions identified are specific to applications in the industry they originate. Therefore, adopting a solution directly from these industries for application in the offshore O&G industry may lead to inaccurate conclusions.

The third objective was to develop a qualification framework which integrates technical and economic assessment processes to support LE feasibility assessment of SCEs. This objective was approached in Chapter 4 by first identifying and classifying list of factors that influence LE decision making process and subsequently developed a techno-economic framework for LE assessment. The following conclusions were drawn:

1. Over 17 lists of factors that influence LE decision making process has been identified through literature review and consultation with industrial experts of several years of experience in relation to LE of offshore O&G installations.
2. The lists of factors influencing LE decision making process are classified into inputs, constraints and output decision-making factors using SADT concepts.
3. A techno-economic framework has been presented which is capable of assisting stakeholders and decision makers to assess the current health conditions of SCEs for LE.
4. The techno-economic framework incorporates a novel semi-quantitative condition assessment rating technique to assist stakeholders conduct technical assessment of their SCEs for LE.

5. Through verification and validation, it has been observed that the framework is applicable to both offshore O&G and non-offshore O&G case studies.
6. From literature review point of view, the proposed framework fills the gap of lack of comprehensive qualification framework which integrates technical and economic assessment processes to support LE decision making process in the offshore O&G industry.

The fourth objective was to develop processes based on LCCB approach and MCDM method to select the most suitable LE strategy. This objective was approached in the Chapter 5 of thesis. A process was developed based on the LCCB concept and another process developed based on PROMETHEE II methodology which is an MCDM method for selection of suitable LE strategy. The following conclusions were drawn:

1. There are three key benefits driving LE decision making in the offshore O&G industry: remaining field reserves, improved safety and delayed decommission cost.
2. There are five key cost elements that impact LE decision making process in the offshore O&G industry: capital cost, installation cost, O&M cost, risk cost and statutory cost.
3. A quantitative process based on LCCB concept has been proposed for selection of suitable LE strategy, which is inherently superior to the existing approaches used for selecting suitable LE strategy.
4. Through application of the proposed LCCB approach with a case study, sensitivity analysis illustrated that the most important factors to make LE investment economically viable in the offshore O&G industry is the cost of product and the volume of production.
5. The proposed LCCB approach do not only assist stakeholders in selecting most suitable LE strategy but also help them to reduce the cost involved in LE projection.
6. In the absence of quantitative data, the MCDM decision making model can be used as a suitable alternative tool to help select suitable LE strategy.

7. The PROMETHEE II enriched decision making by decomposing complex decision problem into smaller parts and provided a structure that directs preference function to each criterion.

The fifth objective was to propose a multi-stage remanufacturing architecture that integrates all LE decision making elements for effective management of SCEs. This objective was approached in Chapter 6 of the thesis. An agent based remanufacturing architecture which is capable of breaking down complex LE decision making problem into simpler parts and subsequently integrating them for useful decision making was proposed. The following conclusions were drawn:

1. An architecture which integrates all elements involved in LE decision making including maintenance management, condition monitoring, remanufacturing and external events has been proposed.
2. Remanufacturing has been suggested as one of the appropriate LE strategies for ageing industrial air compressors.
3. Remanufacturing is not only considered as economically viable LE strategy but also environmentally beneficial in terms of reduction in carbon footprint.
4. The use of remanufacturing as LE strategy delays the replacement of industrial safety equipment, allowing asset managers to save their budget and focus on other investment opportunities.

The sixth objective was to verify and validate proposed decision making models with real life case studies. To achieve this objective, the author:

1. Implemented the framework classifying list of factors influencing LE decision making process and techno-economic framework with three case studies.
2. Validated the LCCB model for LE strategy selection with a case study involving the three phase separation system.
3. Validated PROMETHEE II based approach for LE strategy selection with industrial air compressor case study.

4. Validated the multi-stage remanufacturing architecture with industrial air compressor case study.

Although the models have been developed for application in the offshore O&G industry but the results from the verification and validation chapter indicates that they can be applied in other industries. Hence, this thesis achieved all the six objectives that have been outlined in Chapter 1.

8.3 Answering of Research Questions

This part of the thesis revisits the research questions proposed in Section 1.5.2 of Chapter 1 and the findings from the thesis are used to decide whether these questions have been answered.

8.3.1 Question 1

How can factors that influence LE decision making process be identified and classified within the scope of the offshore O&G industry?

From literature review perspective, a number of studies have shown to have considered or discussed the factors that influence LE decision making. However, these factors are fragmented and not properly classified in any study. This indicated that this question has not been answered in literature, therefore in order to answer this question; the thesis approached it in Chapter 3 where author interacted with industrial experts with several years of experience in handling LE projects in the offshore O&G industry. The outcome of the survey was triangulated with the list identified from literature review. After triangulation, the list of factors influencing LE decision making process was captured. The SADT concept was used to classify factors into inputs, constraints and output decision making factors.

The thesis findings indicate that this question has been answered. However, more research is required into gathering more information on factors that influence LE decision making process in other industries with similar design and operations to the offshore O&G industry, so that the classification framework can further be improved.

8.3.2 Question 2

How can asset managers trust that their existing SCEs can operate satisfactorily beyond the end of original design life through the use of an integrated technical and economic assessment framework?

In Chapter 2 of the thesis, it was observed that majority of research employed the use of either quantitative or qualitative condition assessment techniques, with semi-quantitative approach barely used. Again, existing models focused on answering technical or economic questions only. This was also confirmed during interactions with industrial experts in Chapter 3. Therefore, a semi-quantitative technique integrating technical and economic assessment process to assess the suitability of an asset for LE was lacking. This provided the author an opportunity to contribute to knowledge by proposing a framework which integrates technical and economic assessment process to support LE feasibility study. The framework also incorporates semi-quantitative condition assessment tool used to evaluate the technical feasibility of SCEs for LE. The framework was validated with three case studies from both offshore O&G and non-offshore O&G industries in Chapter 7 of the thesis.

Therefore, the question presented above can be accepted to have been answered with novelty. However, readers should note that organisational and human issues were barely considered in developing the framework; hence future research may seek to further improve the framework by incorporating human and organisational issues into the framework for LE decision making.

8.3.3 Question 3

How can asset managers ensure that suitable LE strategy selection is not based on entire experience and judgement of experts and engineers?

From Table 2-3 in Chapter 2, the selection of suitable LE strategy has largely be depended on expert opinion and experience of engineers. This was further confirmed by the outcome of the interaction with industrial experts in Chapter 3. This question was approached in Chapter 5 by developing quantitative decision

making process based on LCCB concept and a qualitative decision making process using MCDM method to help answer this question.

It can be concluded that this thesis has answered all the three key questions outlined in Chapter 1.

8.3.4 Question 4

How can asset manager integrate all LE decision making elements for effective operation of SCEs during LE phase in the offshore O&G industry? This question was approached in Chapter 6 by developing a multi-stage remanufacturing architecture using the agent based modelling to integrate all LE decision making elements such as maintenance management, condition monitoring, remanufacturing and external factors agents for smooth operations of SCEs during LE phase of operation. The multi-stage remanufacturing architecture showed that LE has significant benefits when the results were compared to the conventional strategy of replacement.

8.4 Research Limitations

A summary of the key limitations to this research are outlined below in the following points:

1. Unavailability of experts is the main limitation identified during interactions with industrial experts. However, this research received about 30% of response rate out of 23 experts which were contacted. This was a very successful response rate as far this research area is concerned.
2. From the sensitivity analysis performed with respect to the techno-economic framework, it was observed that CIM approach is highly sensitivity to changes in weight. Therefore, the framework must be implemented by experts with good understanding about SCEs, to prevent misjudgement in the inputs weights.
3. The LCCB model for selecting suitable LE strategy is dependent on quantitative input data, therefore, instances where the selection of suitable LE strategy involve multiple (both quantifiable and non-

quantifiable) and conflicting criteria, the approach will be limited in its application.

8.5 Summary of Key Contributions to Knowledge

This research has presented the development of methodologies to support LE decision making process and to improve the effectiveness in LE management of SCEs found on offshore O&G platforms. Application of these methods results in improvement of reliability and availability of SCEs during LE phase of operation while at the same time helping asset managers comply with highly restrictive regulations in the offshore O&G industry. The outcome of this research has been disseminated through journal and conference proceedings as indicated in the publication section of the thesis. The research contributions specific to addressing the gaps in this research area are summarised below.

1. Development of techno-economic framework to support LE feasibility assessment of SCEs. The innovation of this framework is in the integration of technical and economic assessment processes such as CIM and NPV to simultaneously assess the condition of SCEs for LE qualification. This framework addresses the limitations of assessing the condition of SCEs for LE. Although experts' judgement and other frameworks have been applied to assess the condition of SCEs for LE, they are with some drawbacks. The experts' judgements in many cases are imprecise, thereby leading to inaccurate conclusions during decision making process. On another side, the existing frameworks are technically or economically inclined, therefore decision making tends to skew to one side. Therefore, integrating both technical and economic assessment made the framework unique, since it allows for the use of both technical and economic tools simultaneously for decision making. An additional important feature of the framework is the introduction of CIM approach which is unique for allowing the use of both imprecise and precise ratings provided by experts during technical assessment. The CIM framework is flexible in its application compared to existing ageing model.

2. Developments of a process to select the most suitable LE strategy using LCCB approach. Unlike the existing studies that uses only LCC model to support decision making in the offshore O&G industry, this model combines LCC model and benefit model to select the most suitable LE strategy. The novelty of this approach lies in the combination of costs and benefits models to determine the most suitable LE strategy among several alternatives. The additional feature of this model is that it incorporates maintenance cost and risk expenditure which are key to successful implementation of LE programmes.
3. Developments of a process to select the most suitable LE strategy using MCDM method. The novelty of this approach lies in decomposing complex decision problem into smaller parts and provides a structure that directs preference function to each criterion. Additional feature of the approach is the flexibility in capturing both subjective and objective criteria to help model a condition of uncertainty.
4. Propose a multi-stage remanufacturing architecture that integrates all LE decision making elements for effective management of SCEs. The innovation of this architecture is based on the integration of all LE decision making elements for effective management of LE process for SCEs. The approach encourages autonomous interactions among various agents in an organisation responsible for LE. Another important novelty with this approach is the decomposition of complex LE decision making problem into several smaller and simpler ones, handled by various agents for effective LE decision making. The architecture ensures coordination among various LE agents. To the best of author knowledge this approach has never been used to support LE decision making in the past.

8.6 Future Research

This Section is intended to highlight potential areas identified as opportunities for future research work and also serves as means of building upon the findings

of this research. The future suggestions are classified according to the key themes covered in this thesis.

8.6.1 Literature Review

From the literature review perspective the author identified four key areas that will require further research. The suggestions are summarised below.

1. The manner, in which data gathered from all stages of the assets life cycle is handled, can have a significant impact on the overall LE decision making process. However, lack of good quality data has been identified as one of the key obstacles during LE decision making process. Therefore, asset managers in the offshore O&G industry must invest resources in developing platforms, policies and procedures to manage the data acquired at various lifecycle stages of safety critical assets, in order to improve LE decision making process significantly.
2. Obsolescence management has been a challenge in most energy industries as far as SCEs LE is concerned. This is because the control and automation systems supporting the operations of SCEs beyond their original design life must be state-of –the-art due to the rapid changes in safety regulations, and technologies. However, companies are unable to provide this kind of technical support for SCEs during LE phase of operation because most of the SCEs designed two or three decades ago are not compatible with current technology. Therefore, investigating how SCEs designed 20 years ago can be compatible with state-of-the-art automation and control systems during LE phase of operation will be an interesting research topic.
3. There is the need to develop bespoke software tool which is quick and flexible to support LE decision making in the offshore O&G industry.

8.6.2 Techno-Economic Framework

The possible future improvements that could enhance the implementation of the techno-economic framework are summarised below:

1. One of the key challenges that hamper LE decision making process is workforce ageing. Efforts have been made by many practitioners and scholars to address the challenges of physical plant ageing and their impact during LE phase of operation, however very limited effort has been directed toward human and organisational challenges such as workforce ageing. Future research must endeavour to incorporate human and organisational issues into the framework. This will help address the challenge of workforce ageing and its impact during LE phase of operation.
2. The framework currently focuses on assessing the impact of degradation mechanisms such as corrosion and fatigue on the condition of the SCEs at the end of original design life; however the framework could further be improved if the impact of other degradation mechanisms such as obsolescence is considered.
3. It is suggested that future research work must consider the use of group decision making approach in assigning weights when applying the CIM approach for technical assessment.
4. Currently the framework has been tested with one case study outside the offshore O&G industry. Therefore, further research must endeavour to test the framework with case studies from the nuclear power plant, renewable energy, defence and transportation industries which also have many assets approaching the end of original design life. This will enhance the robustness and rigour in feasibility assessment process.
5. In future work, the framework could be applied to assess LE feasibility for structural members and compare results with the SIM framework.

8.6.3 Selection of Suitable LE Strategy

The areas identified as avenues for future work when selecting suitable LE strategy are highlighted below.

1. Future research should consider extending the LCCB model to other strategies such as reuse, reconditioning and remanufacturing when available data is obtained.

2. Selection of suitable LE strategy in some instances may be influenced by uncertainty due to lack of good quality. This research applied sensitivity analyses to address uncertainty in the LCCB decision making. Future research must focus on using more complex methods such as Bayesian models to assess the robustness of the LCCB decision.
3. The MCDM decision making model must incorporate fuzziness into selection of suitable LE strategy decision making, since LE decision making problem is influenced by uncertainty in real life situation.
4. System dynamics method can be combined with the PROMETHEE method to select suitable LE strategy for complex energy systems.
5. The results of this study can be compared to other MCDM methods such as ELECTRE and VIKOR.

8.6.4 Multi-Stage Remanufacturing Architecture

This model focused on analysing the impact of remanufacturing on a single industrial safety asset. Future work must focus on analysing the impact of remanufacturing on a group of industrial safety asset.

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APPENDICES

The following subsections present the supporting materials with the goal of further enhancing readers understanding of various aspects of the thesis.

Appendix A . QUESTIONNAIRE

A.1 Current practices and challenges

A.1.1 Identification of experts: Brainstorming

- Which individuals should be contacted concerning current practices and challenges of LE in the offshore O&G industry?
- What should be the number of years of experience that should be considered?
- What types of questions are required to capture current practices and challenges holistically?

A.1.2 Survey questions

- As per your experience, publications and works in the area of life extension, can you please highlight the challenges and gaps' existing in the offshore O & G industry as far as life extension is concerned?
- What are the life limiting factors in the O&G industry that must be tackled to ensure that installations operate beyond their original design life?
- Please current practices are not adequate to achieve optimal safety during life extension period. Why? And how can we improve on that?
- How are SCEs identified, screened and prioritised for LE assessment?
- Please, what are the current technical issues considered during LE decision making process in the offshore O&G industry?
- Please as you know, It would be more prudent to consider issues of life extension at the early stages of installations life; however this comes with huge uncertainties after sometime of operation during the asset life cycle. How can we deal with these uncertainties in order to reduce risk during life extension?
- Could you please suggest other experts to contact?
- Follow up on Q5. Please, can you also help with companies that may be interested in this research area?

A.1.3 Factors influencing LE decision making

- What kinds of technical and economic factors influence LE decision making process in the offshore O&G industry?
- Which of the factors stated above do you considered as constraints impacting LE decision making process in the offshore O&G industry?
- What factors do decision makers considered as key to successfully LE programme.
- Please, have these factors been classified in the industry?

Appendix B TRANSCRIPTS OF INTERVIEW AND MINDJETS

B.1 Example of a Transcript from interviews

A sample of responses (sanitized to preserve confidentiality) from one of the interviews with experts is presented below.

- Please as per your experience, publications and works in the area of life extension, can you please highlight the challenges and gaps existing in the offshore O & G industry as far as life extension are concerned?

ANS: Most difficult areas are the structure because it is difficult to replace. One obvious challenge is the difficult in knowing and understanding the current condition of non-repairable system. Most especially with structures located both topside and subsea.

Limitation of current inspection techniques used in the industry. For examples for fatigue most widely used technique is flooded member detection, which is only possible for long cracks.

- What are the life limiting factors in the O & G industry that must be tackled to ensure that installations operate beyond their original design life?

ANS: Fatigue and corrosion. Fatigue in particular, because it is difficult to detect and with considerable amount of effort and cost. Ability to detect small cracks and link to extended life of the installation.

- How can duty holders extend the life of an installation in more safe and cost-effective manner?

ANS: Difficult question to answer because of safety which is major interest. Cost is an issue considering current inspection techniques.

- How do we effectively identify SCE in these days of practices?

ANS: There are number of guidance documents by oil and gas UK. Typical list of SCEs are now published but in any case difficult members to inspect becomes safety critical because it is difficult to demonstrate life extension.

- Please current practices are not adequate to achieve optimal safety during life extension period. Why? And how can we improve on that?

ANS: Inspection technique in current practices is not enough to ensure optimal safety. The use of computer models to identify defects or parts which vulnerable to defects are very essential. Computer models should enable estimation of remaining life of member during life extension.

- Please as you know, It would be more prudent to consider issues of life extension at the early stages of installations life; however this comes with huge uncertainties after sometime of operation during the asset life cycle. How can we deal with these uncertainties in order to reduce risk during life extension?

ANS: In the early stages of installations life, more especially during the design stage there is the opportunity to minimise or handling life extension uncertainties, However this may come at very cost. At the design stage of installation we are interested in saving cost, so it will be to handling uncertainties entirely. If there is a possibility of introducing some methods or techniques determining state of non-inspectable areas from the design stage could help during life extension.

- Could you please suggest other experts to contact?

ANS: I will send you a list of colleagues I have worked with in this area.

- Follow up on Q7. Please, can you also help with companies that may be interested in this research area?

ANS: Not really sure because they are busy companies but I will give it a try.

Answers to follow-up questions

- It is important to conduct research into understanding the gaps and challenges in ageing and life extension.
- Check PSA website, there is only piece of work on concrete structure ageing and life extension with few on metals. Many papers are on fixed

structure but will be good to consider mobile structures since very little done on mobile structures.

- I do not know how useful the corrosion and fatigue model will be during life extension of SCEs but trying that I will be very excellent.

B.2 Mindmapping Analysis of Interview



Mindmap results from the analysis of information gather during the interview

Appendix C TYPE OF DATA REQUIRED FOR TECHNO-ECONOMIC ANALYSIS

The types of data required for effective and efficient LE analysis of SCEs are presented.

Description of design phase data required for life extension assessment

Type of data	Source of data
System/component design criteria	Operator
Design specifications of various components	Operator
Design codes and standards	Operators and government
Drawings and layouts	Operators
Design life calculations	Operators
As built documents	Operators
Material specification	ASTME, API, NORSOK etc standard document
Technical and engineering adjustment during installation	Operators
Regulations	Government
HSE Standards	Government
Guidelines	Government

Description of operational phase data required for life extension assessment

Types of data	Source
RAMS	Operator
Modification	"
Operational parameters (e.g. Pressure, temperature, flowrate etc.)	"
Conditioning monitoring information	"
New standards and recommended practices	"
Experience since design and installation	"
New tools since design and installation	"
Systems, subsystems and sub assembly	"
Ageing degradation records	"
Production levels	"

Description of cost data required for life extension assessment

Types of data	Source
Cost of modification	Operator
Cost of operation & maintenance	Operator
Regulatory cost	Government

Taxes	Government
Royalty cost	Government
Revenue	Operator
Market price of oil and gas	Market sources

Description of outputs or deliverables

Type of data	Source
Future planned maintenance or modifications or ageing management programme	Life extension assessment
Length of life extension period	"
Future operational cost	"
Health status of assets	"
Remaining service life	"

Appendix D SAMPLE OF CONDITION INDEX MATRTIX ASSESSMENT FACTORS

D.1 Historical Factors

Historical data is an important input for LE decision making, assisting in describing equipment performance and forecasting equipment failure. Historical factors considered are;

1. Age: Normally, offshore safety and production equipment have reliable life of about 10 -15 years (Tveit et al., 2014) while the structure is designed for 20-25 years. Based on the life cycle bathtub curve, the failure rate of critical components increases at the latter stage of the asset life. Therefore, age becomes one of the risk factors for condition assessment. Also, without proper maintenance, levels of degradation increases with age of components (Gunderson et al., 1992;Kumar et al., 2008).
2. Failure history: This is the accumulated number of times that failures occur on equipment in a specified period. Failure resulting from degradation of equipment performance shortens lifetime of safety critical elements. This factor is ranked 1, when the same failure occurs twice in a calendar year. According to Picard et al. (2007) end of service life is characterised by increased physical aging effects such as cracks, oil leaks and wear, which usually means there is risk of failure. This factor is also applicable to

unplanned number of downtime due to aging failure modes and total alarm recorded in year in case of process systems.

3. Location: Equipment installed in different locations in the offshore oil and gas industry may contribute different failure rates. For example, equipment installed sub-sea are of high risk as compared to topside equipment.
4. Manufacturer: Availability of manufacturers is an important risk factor to equipment condition due to the possibility of obsolescence which is a constraint during LE. Existence of manufacturers assures engineering team of continual supply of spare parts during LE phase of operation. Managing asset for LE requires that the necessary spare parts or critical maintenance supports are available. Hence, this is considered as a risk factor.
5. Environmental conditions: Technical condition of safety critical elements depends on environmental conditions in which the equipment operates. According to Vaidya and Rausand (2011) environmental conditions about region of operation and well geographical depth have an impact on LE assessment. Nonetheless, wave heights could also be viewed as an environmental condition, which contributes to the risk of equipment technical condition.

D.2 Health Factors

Health factors considered include:

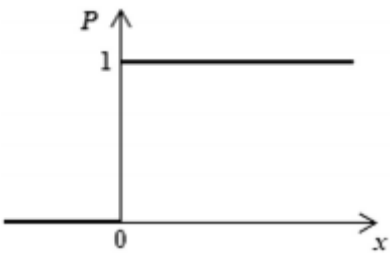
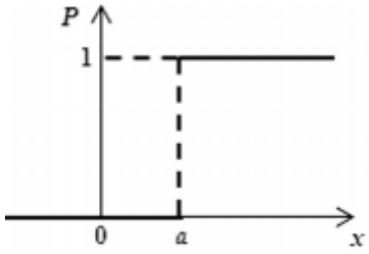
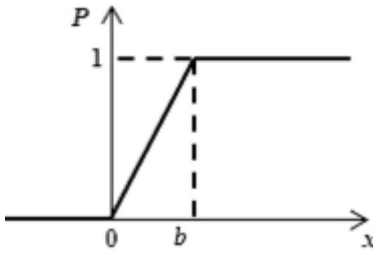
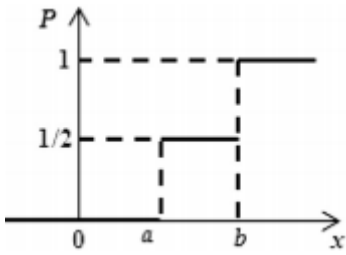
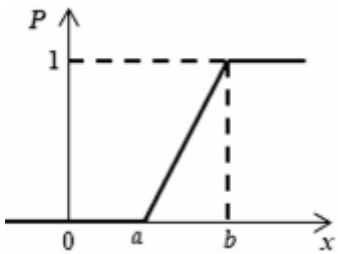
1. Test frequency: Consistent testing of critical equipment is vital in determining the current status of process equipment found on installations. The requirement to pass a test depends on the type of standards adopted by various operators. Components such as vessels and piping require pressure, temperature, hydro and Non-Destructive Testing (NDT) with frequency of testing and type of testing clearly stated.
2. Degradation checks: This health factor reflects the visual state and functional performance of equipment. The purpose of these checks is to identify physical ageing mechanisms and their effects on safety. It requires techniques such as visual inspection, electromagnetic inspection, fatigue inspection, ultrasonic testing and interpretations of sensor reading. Degradation check outcomes may include identification of damage

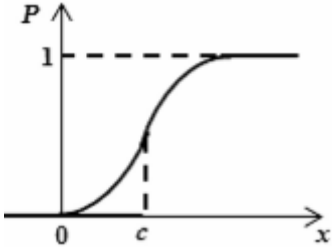
mechanisms, determination of rate of deterioration and assessing tolerance to types of degradation as a direct means of assessing the health status of safety critical asset. Wright (2011) suggested that physical degradation mechanism such as corrosion accounts for 50% of failures in onshore process equipment, thus considered as a risk factor to equipment condition.

3. Design standards: This health factor evaluates the design principles of critical equipment and compares them to current design standards and original design requirements and how they change overtime. This is to ensure that design principle meets minimum safety requirements. This activity is conducted by reviewing documents such as manufacturers' manuals, design handbooks and company internal papers. Interviewing of design professional, suppliers, installers, inspectors and project managers is also an alternative means of assessing suitability of design principles for safety reasons.
4. Maintenance: Equipment maintenance deferrals are common in the offshore oil and gas industry. Failure to inspect and maintain equipment within its scheduled time may cause failures and increase degradation rate. This health factor includes percentage compliance to corrective and preventive maintenance. Scoring this condition factor requires high level of competence and knowledge about the particular equipment.

Appendix E GENERALISED FUNCTIONS FOR PROMETHEE

Table. Types of generalised functions (Kabir and Sumi, 2014 and Nikouei et al. 2017)

Type	Generalised criterion	Definition	Parameter to fix
Type I-usual criterion		$p(x) = \begin{cases} 0, & x \leq 0 \\ 1, & x > 0 \end{cases}$	-
Type II-quasi criterion(U shape)		$p(x) = \begin{cases} 0, & x \leq a \\ 1, & x > a \end{cases}$	a
Type III-criterion with linear preference (V-shape)		$p(x) = \begin{cases} 0, & x \leq 0 \\ x/b, & 0 < x \leq b \\ 1, & x > b \end{cases}$	b
Type IV-level criterion		$p(x) = \begin{cases} 0, & x \leq a \\ 1/2, & a < x \leq b \\ 1, & x > b \end{cases}$	a, b
Type V-criterion with linear preference and indifference area (linear shape)		$p(x) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a < x \leq b \\ 1, & x > b \end{cases}$	a, b

Type VI- Gaussian criterion		$p(x) = \begin{cases} 0, & x \leq 0 \\ 1 - e^{\{(-x^2)/2C^2\}}, & x > 0 \end{cases}$	c
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