

**Sustainable Design for Offshore Oil and Gas Platforms: A
Conceptual Framework for Topside Facilities Projects**

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**This thesis is submitted in fulfilment of the degree of Doctor of
Philosophy**

School of Energy, Geoscience, Infrastructure & Society

28 February 2018

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ABSTRACT

Offshore oil and gas operations are growing rapidly with the high demand for energy and oil being the most important source of energy. Many studies indicate that discovery of future oil will be based more in offshore than onshore areas. However, vast offshore facilities and activities create negative environmental and social impacts, as well as consequences ranging from air and water pollution to health and safety issues. Therefore, sustainability in offshore operation and design is a major challenge in the offshore industry. A framework for stakeholders in the offshore industry which can be used as an effective tool to evaluate and assess the design and materials selection, considering sustainability, at the conceptual stage of a project has been developed.

The literature shows that a limited number of researches have focused on the sustainability of topside facilities for offshore platforms. Moreover, it was difficult to find a complete sustainable framework that considers the three main aspects of sustainability (environmental, social and economic) in offshore engineering design. Therefore, this research fills the gap in the existing knowledge of the offshore industry by contributing to the following area: developing a decision framework for topside projects in terms of materials selection and sustainable design.

In order to achieve this aim, a qualitative approach was adopted to develop and identify the factors affecting sustainable design and materials selection for topside offshore fixed platforms. The methodology has been conducted in two parts, comprising: (1) an exhaustive literature review to determine the sustainability criteria, as well as technical and engineering aspects; and (2) semi-structured face-to-face interviews, which included both open ended and closed ended questions.

The findings from the semi-structured interviews highlighted a consensus among all the interviewees that there is a need for a sustainable framework for engineering design and materials selection for topside facilities. Moreover, most of the interviewees have not experienced such a framework. This supports the research gap: there is no complete sustainable framework available for engineering design. The framework developed here was validated and evaluated by industry professionals through case application and scoring model approaches. The results indicated that the framework and its components are applicable and effective for offshore topside facility projects.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my first supervisor Professor Stephen Ogunlana for his invaluable support, guidance and direction in completing this work. I appreciate his patience and efforts with his students. My appreciation also goes to my second supervisor, Dr Adekunle Oyegoke for his supportive guidance. Thanks also to all the team members in the School of Energy, Geoscience, Infrastructure and Society at Heriot Watt University.

I'm grateful to the Maersk Oil Qatar Company for their support and sponsorship; special thanks goes to Sheikh Faisal Bin Fahd Al-Thani, the deputy managing director at Maersk Oil Qatar. I would also like to thank Qatar Petroleum for their support and supervision over the period of my PhD programme.

I would like to extend my appreciation to all my colleagues and friends in Maersk Oil Qatar and Worley Parsons Qatar for their contributions and support; special thanks to Matthew Tunstall and James Wilson. I also owe a very special thanks to Professor Sadi Assaf from the Department of Construction Engineering and Management at King Fahd University of Petroleum and Minerals.

Finally, and especially, I offer my loving thanks and eternal gratitude to my family members for their understanding and support of my educational dream and aspiration. Without their unconditional love and sacrifice, I could not achieve my goals in life.

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Chapter 1: Introduction

1.1 Introduction

This chapter presents the subject matter and focus of the research. It provides the background of the research, the rationale and significance of the study and the research gaps. Thereafter, the statement of the problem in the offshore oil and gas industry and the aim and objectives of this study are presented. Finally, the research design, process and structure of the thesis are described.

1.2 Background of the Study

The oil and gas industry comprises two main categories: upstream, which includes exploration and all production systems with all facilities, and downstream, which includes the refining and processing of crude oil. Offshore platforms, the first example of which was constructed and installed on the gulf coast of Louisiana in 1947, consist of two main types: fixed and floating platforms. The API Recommended Practice 2A-WSD (2014) defined the fixed platform as a platform that is extended above sea level and supported on the seabed by piles or other means. API also classified fixed platforms into the following types: jacket platforms, tower platforms, gravity structures and compliant towers. Floating platforms, on the other hand, are used as production systems or for drilling purposes; tension-leg, spar and semisubmersible platforms are examples of this type. The most common offshore structures are fixed jacket platforms, and this study will focus on the topside facilities of the fixed jacket platform.

1.3 Rationale and Significance of the Study

Offshore oil and gas operation is growing rapidly with the high demand for energy and oil remains the most important source of energy. Accenture (2012) stated that the majority of the energy supply for society comes from the oil and gas industry and due to the population growth, the demand for energy is expected to continue to rise; the highest

level of energy consumption growth since 1973 was recorded in 2010 at 5.6%. Alba (2010) cited IEA that the world oil demand will increase from 84 million barrels per day in 2007 to 106 million barrels per day in 2030. Many studies have indicated that the discovery of future oil will be more in offshore than onshore areas. It was estimated by Barclay's Capital, cited by Johan Westwood (2012), that 600 billion dollars would be spent in 2012 on oil and gas exploration and production companies. Moreover, it was estimated that 200 and 150 billion dollars would be spent in the deep water and subsea hardware sectors respectively.

However, vast offshore facilities and activities create negative environmental and social impacts as well as consequences ranging from air and water pollution to health and safety issues (Al-Yafei and Ogunlana, 2016). Ruta (2010), citing OECD outlook, noted that the global economy is expected to grow by 3 to 4%; as a consequence the resource extraction and fuel consumption will increase. Therefore, OECD, cited in Ruta (2010), predicted that resource extraction will increase from 58 billion tonnes in 2005 to 80 billion tonnes by 2020; the corresponding green house gas (GHG) emission will increase globally by about 37% from now to 2030, and by 52% between now and 2050. Emam (2016) and Svensson (2011), citing the World Bank, that over 150 billion cubic metres of natural gas related to oil production is being flared annually worldwide and this contributes by adding 400 million tonnes of carbon dioxide (CO₂) into the atmosphere annually. Arabian Gulf states contribute significantly in gas flaring; the World Bank Group (2014) listed four of the Arabian Gulf states among the top 20 flaring countries (Saudi Arabia, Iraq, Oman and Qatar). Qatar is continually ranked first in CO₂ emission per capita; Qatar recorded 70.98 metric tonnes per capita in 1997 and remained the first in the world in 2013 with 40.64 metric tonnes per capita. The average world emission in 2013 was 5 tonnes per capita. Other Gulf States (Kuwait, Bahrain, United Arab Emirates, and Saudi Arabia) were recorded among the top 10 globally in CO₂ emissions per capita. Gas emissions from topside facilities such as carbon dioxide (CO₂), methane (CH₄), sulfur dioxide (SO₂), nitrogen dioxide (NO₂) and others, which are known as greenhouse gases contribute significantly to climate change, global warming, acid rain and ozone depletion.

In terms of marine pollution, there are many sources of topside systems discharging their pollutants into the sea; systems such as produced water, sanitary and domestic water, produced sand, drainage systems and others. Produced water is considered the main

source of water pollution from offshore platforms because it contains harmful substances in its components. According to Emam, Moawad, and Aboul-Gheit (2014), in 1999, it was estimated that 210 million barrels of water were produced worldwide daily, which represents about 77 billion barrels of produced water for the entire year. Hirst (2004, p.29) stated that in 2003, 266 million tonnes of water were discharged in the UK offshore alone containing 5,190 tonnes of oil. Webster (2012), citing OGP, suggested that for every tonne of hydrocarbon produced in 2010, 0.60 tonnes of produced water was discharged into the sea, and 1.0 tonne of produced water was re-injected into the reservoir.

Social issues are another concern in the offshore oil and gas industry, oil companies clearly have a social responsibility towards the communities surrounding their activities. Although there is environmental pollution impacting the surroundings of all such sites, the impact of this pollution is less on the people living in the area near hydrocarbon extraction compared to offshore workers living on the platform itself. Offshore workers are surrounded by huge equipment and facilities containing hazardous and combustible materials. Numerous ignition sources are located on offshore platforms, and various small human errors can lead to major asset losses and death of offshore workers. Therefore, this study focuses on the people who are working offshore and who feel a direct impact on their health and safety.

In terms of economic issues, one of the greatest challenges in offshore industry is operational expenditure cost (OPEX). Corrosion is the first enemy for offshore topside facilities in terms of materials selection due to the harsh environment offshore, especially in humid climates such as the Arabian Gulf states. Koch et al. (2016) estimated that the global cost of corrosion in 2013 was USD 2.5 trillion, which is equivalent to 3.4% of the global GDP. Hays (2010) stated that the direct cost of corrosion is between 3.1 and 3.5% of the world's yearly GDP; this does not include the loss of production, environmental damage and personal injury resulting from corrosion. Hays further mentioned that the estimated saving from applying corrosion control technologies could be 20 to 25% of the annual corrosion cost, about 360 billion euros. There is no clear figure of the global cost of corrosion in the oil and gas sector; however, Papavinasam (2014, p.17) mentioned that the cost of corrosion in all the oil and gas sectors in the USA is about 27.77 billion dollars; we can therefore imagine how much is being lost globally from oil and gas sector.

There is global awareness and, in particular, governmental pressure regarding social and environmental concerns as a result of offshore activities. Exploring and extracting oil in the safest way without consequences is one way to ensure that our needs do not compromise the needs of future generations; this is the concept of sustainability. Governments worldwide believe that cooperation between them and oil operators will play a significant role in mitigating the negative impacts felt by the environment and communities near oil operations. In terms of environmental concerns, at the governmental level most countries impose and encourage oil operators to follow the international standards, as well as legislating to mitigate ocean and air pollution.

The negative effects on the environments and people can be avoided if the principles and concept of sustainability are implemented in the design at an early stage of the project, as we propose in this study. The proper selection of materials, systems and equipment, considering the aspects of environmental, social, economic and engineering are very important in sustainable development. By considering various techniques and tools, sustainable design can achieve optimal cost, prevention of pollution and reduction of health and safety impacts on people and society. Therefore, it is important to develop a comprehensive framework that can include all these aspects at the conceptual stage of the design where the implementation cost remains low.

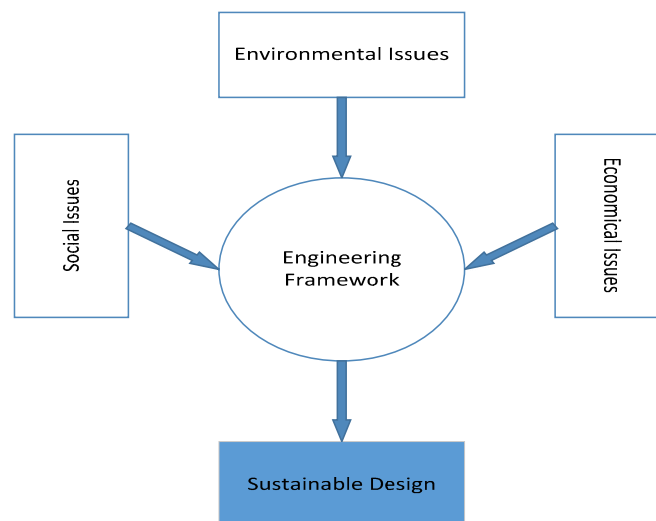


Figure 1 Aspects of a comprehensive framework for topside projects towards sustainability

1.4 Statement of the Problem

Many researches have indicated that the facilities of offshore fixed platforms have a significant negative environmental and social impact (Hirst, 2004; Khan and Islam, 2007). According to Alba (2010), the producers of oil and gas will be forced to expand exploration activity a larger scale in the future; however, this activity will have significant environmental and social impacts if not managed properly. He pointed out the important role of the oil producer's government in protecting the environment and ensuring that sustainable benefits of oil and gas development can be achieved for their citizens now and in the future.

According to Alba (2010), the Petroleum Governance Initiative (PGI), which is the joint effort between the World Bank and Norway, attempts to provide assistance to oil producing countries in terms of the environmental and social management of oil and gas development. PGI conducted a survey included 29 countries to outline the important and essential elements of good governance in managing the environmental and social impacts of oil and gas development. One of the findings showed that "most governments surveyed lack a mechanism requiring oil and gas companies to adhere to regulatory framework for managing environmental and social impacts in their country". Another finding from the study was "there is accelerated pace of oil and gas development in many developing countries; also there is significant pressure to develop their oil and gas resources in the quickest way possible without a complete assessment and mitigation of associated social and environmental impacts". These findings support my view that the best economic position in the oil and gas business is to achieve production as early as possible, and this is one of the reasons why sustainability is not considered in the design. Moreover, from my own 15 years' experience as a topside project engineer in the offshore industry, in most, if not all, topside facilities projects, fabrication is started before detailed engineering is completed. Gibson (2009) also highlighted the same problem and noted that engineering takes longer time and construction in UK start before the design and engineering is fully completed.

All these factors will certainly contribute to cost overrun and negative environmental and social impacts in the future. Gupta and Grossmann (2012) highlighted that the development planning of offshore oil and gas fields has received major attention in recent

years and there is now a strong focus on exploration and development, especially in offshore locations. They also indicated that the installation and operation of offshore projects involves many billion dollars of investment and profit, however, if investment decisions are not made carefully, this can lead to large losses. To ensure a reasonable return on the investment, there is a need to optimise the investment and operations decisions.

It can be concluded therefore that there are various environmental, social and economic challenges facing oil and gas development. An offshore platform contains many kinds of materials and equipment, which have a direct impact on the environment. Many offshore pollutants, like oil, chemicals and emitted gases go into the marine environment. In terms of design, offshore platforms are subject to hostile ocean environment conditions. These conditions make the design of the platform very complicated, with associated risks related to safety, people, the environment and economic expenditures (maintenance and operating cost). Moreover, due to the rapid growth of offshore oil and gas exploration, most oil companies ignore the future cost, environmental aspects and sustainability in the early design. Hancocks (2007) mentioned that although companies are aware of life cycle costing, it has not been used in the upstream sector for asset business planning. This problem is verified in this research in chapter 6, where it is found that 70.7% of the participants in the semi-structured interviewees mentioned that they have heard about the life cycle costing concept, but they don't know how to perform the analysis.

Here the importance of conceptual phase at the early stage of the project in identifying the assessment criteria is coming. After the exploration phase is conducted and completed, the engineering and construction phase is initiated with the conceptual phase, this usually consists of concept study, selection alternatives and FEED (pre-engineering). In this phase, due to the lack of information, there are various uncertainties; one of the major concerns relates to OPEX (operating expenditure) due to materials and equipment selection. The current practice, especially in the Arabian Gulf countries, is focused on the technical and engineering feasibility and this ignores any consideration of the life cycle costing of the alternatives or sustainability. The decision criteria are based only on the engineering criteria; the current approach thus still lacks a strong basis for life cycle costing and aspects of sustainability. These limitations, and the improper selection of alternatives during this phase, comprise some of the major causes of the vast operating

expenditures for topside facilities on offshore platforms. Therefore, a modified approach to capture these gaps in the conceptual phase is required so that, at this phase, the decision maker can select the right alternative to escalate to the next phase. Therefore, selecting the proper materials in terms of sustainability will lead to significant positive impacts on the environment, social and safety issues, with lower life cycle cost.

1.5 Research Gap

This research includes a critical review of the literature on the offshore oil and gas industry in general, with a focus on the topside of fixed platform. The literature demonstrates that many researches have been conducted on sustainability, either as an assessment tool for buildings and or as a ranking tool and technique similar to the Building Research Establishment Environmental Assessment Method (BREEAM) and leadership in Energy and Environmental Design (LEED), for more details refer to section 2.10. Most of these researches and studies concern buildings and have focused on environmental impacts rather than on aspects like economic and social impacts.

However, there are fewer studies, which focus on the oil and gas sector. Ekins and Vanner (2006, p.96) discussed the methodologies that have been utilised in relation to sustainable development in the UK offshore oil and gas industry. Three methods were mentioned: (1) the *Sustainability Assessment Model* (SAM), which was developed by the University of Aberdeen and Genesis Oil on behalf of British Petroleum; (2) the *PSI Assessment Methodology*, which was developed to help the oil and gas sector with environmental challenges; and (3) the *Arthur D. Little Sustainable Assessment Tool*, which was developed by the consulting firm Arthur D. Little with British Petroleum. Ekins and Vanner (2006, p.105) provided a comparison of the three mentioned assessment tools and found that SAM and the PSI are designed for larger projects and to involve the stakeholders at a strategic level, whereas the Arthur D. Little Assessment Tool is more a systematic approach allowing companies to make certain that their values can be applied to practice at the project level. Moreover, the Arthur D. Little Assessment Tool does not engage the stakeholders in impact assessment.

In their *Petroleum Engineering Handbook, Sustainable Operation* Khan and Islam (2007) mentioned several sustainable models such as: (1) the GRI (*Global Reporting Initiative*),

which has been developed by the United Nations Environment Program together with the United States NGO and the Coalition for Environmentally Responsible Economics (CERRES); (2) the *United Nations Commissions on Sustainability Development framework* (UNCSD), which evaluates governmental progress in achieving the sustainability targets; and (3) the (ICChemE) *Institution of Chemical Engineers*, which has published a set of sustainability indicators to measure the sustainability of operations in the process industry. Khan and Islam (2007, p.17) stated that there is a lack of consistency in the explanation of the concept of sustainability. They pointed out that the above mentioned models measure sustainability, but *there are no guidelines on how to achieve sustainability*. They have proposed a generic sustainable methodology to evaluate technology development in the energy sector.

Therefore, it can be concluded that a limited number of studies have focused on sustainability in the offshore industry and even **fewer on the topside facilities** of the offshore fixed platforms. Moreover, these studies have focused on the environmental aspects and ignored the other aspects of sustainability. This research tries to fill this gap in the existing knowledge of the offshore industry.

1.6 Aim and Objectives of the Study

The aim of this research is to produce a sustainable design framework for the offshore industry, which can be used at the early stage of any project in the topside platform. Moreover this framework will be an effective tool for the decision maker to evaluate and assess the design at the conceptual phase of the project from sustainability perspective. In order to achieve this target the objectives of this research are defined as follows:

1. To identify the environmental and social impacts of topside facilities for offshore platforms.
2. To identify the influential factors/criteria that affect materials selection and sustainable design of topside projects for offshore fixed platforms from the sustainability perspective (environmental, social, economic and engineering).
3. To prove and validate the identified criteria by consulting offshore experts through semi-structured interviews; and rate the identified criteria based on their importance.

4. To develop a value-based framework for sustainable design and materials selection in the offshore industry from a sustainability point of view.
5. To validate the framework in terms of applicability through a case application (face validity).
6. To evaluate the framework by conducting semi-structured interviews (scoring model approach).

1.7 Research Methodology and Associated Objectives

The research methodology and the selection approach have been described in details in (chapter 4). Here the research approach and process are shown below in figure 2.

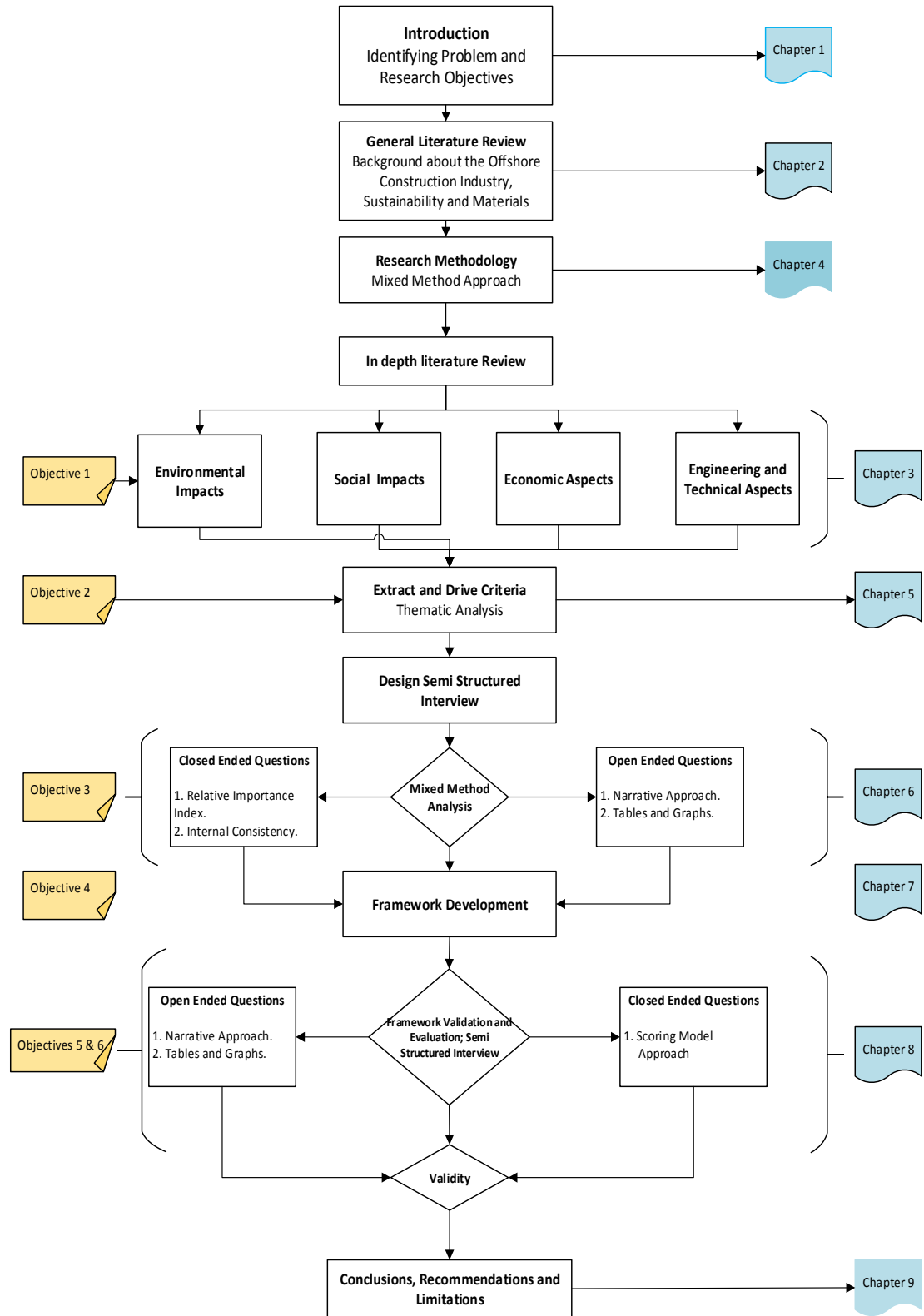


Figure 2 Research process

1.8 Thesis Organization

This thesis will be divided into eleven chapters and an appendix. The eleven chapters will be structured as follows:

Chapter 1: Introduction

The introduction provides an overview of the thesis topic, alongside a brief background of the general subject and the rationale and significance of the study, a problem statement and the research aims and objectives. It also outlines the research design, methodology and the thesis structure.

Chapter 2: Literature Review – Offshore Construction Industry and Materials Selection

This chapter presents a literature review of offshore platforms and the background to the topic, outlining the different types of offshore platforms. It also provides a detailed description of the construction stages of offshore fixed platforms, from the design stage to the installation and commissioning stage. After that, this chapter presents aspects of sustainability such as green design and eco materials. It provides a critique of the existing assessment sustainability tools for the building and construction industry. Finally, it outlines the requirements for offshore materials and corrosion control and monitoring methods in the offshore industry.

Chapter 3: Literature Review – Sustainability and Offshore Industry

This chapter presents an extensive literature review of the sustainability dimensions and its related impacts from offshore topside facilities project. Starting by the economic aspects of sustainability, the importance of the conceptual stage in determining field development cost is highlighted. Project evaluation techniques and concepts are presented, such as value engineering, life cycle costing and time value of money. Moreover, how to conduct value engineering and life cycle costing techniques are also discussed. After that, environmental and social aspects are introduced. It begins by exploring environmental impacts and their effect on eco systems and offshore workers. Then, topside impacts on health, safety and security (social aspects) are discussed.

Finally, recommendations on how to prevent or mitigate the environmental and social impacts are presented as well.

Chapter 4: Research Methodology

This chapter provides detailed information about the research design and it describes the methodology that has been used in this research. It begins by describing the general research philosophy and approaches, then research strategies in construction research in particular. Following this, the selected research strategy for this thesis is explained. Finally, the research design adopted for this study is presented in detail, including the method of collecting and analysing these data; research design processes and procedures are provided to explain the main steps adopted in this study.

Chapter 5: Extracting and Deriving the Sustainable Criteria

Based on the discussion about the literature in chapters 2 and 3 this chapter explores and extracts the main important factors and criteria that affect the sustainable design of offshore topside facilities. It demonstrates how these factors are distributed among themes and groups that represent the three main pillars of sustainability in addition to the engineering and design requirements.

Chapter 6: Interview Design and Analysis – Proving the Criteria Through the Stakeholders

Based on the findings from chapter 5, the derived criteria need to be proved and validated by experts and practitioners from the offshore industry. Semi-structured interviews were designed taking into account two components: closed and open ended questions. Analysis of the interviews are provided in this chapter.

Chapter 7: Developing A Sustainable Engineering Design and Materials Selection Framework for Offshore Topside Facilities

In this chapter, the findings from chapter 6 (semi-structured interviews), the literature reviews and personal offshore experience are considered to create and develop the proposed framework. The framework contains three stages and each of the stages, along with their relevant components, are presented and explained.

Chapter 8: Framework Validation and Evaluation

This chapter presents the validation and evaluation methods adopted for the proposed framework. The validation process was conducted by using the face validity approach, involving end users in determining the framework validity through applying a case application with real data to check framework applicability and workability. Semi-structured interviews comprising open ended and closed ended questions were conducted as well. The open ended part relates to the second part of the validation process. The evaluation process was conducted via the closed ended questions in the semi-structured interview by applying a scoring model approach. The analysis and results of the validation and evaluation process are presented in this chapter.

Chapter 9: Conclusions, Recommendations and Limitations

This chapter draws the general conclusions and output of the research, including how the main aims and objectives were achieved. The research limitations, recommendations for practice and future research are presented. This chapter also highlights the originality of this research and its contribution to the body of knowledge.

Chapter 2

Offshore Construction Industry and Materials Selection

2.1 Introduction

This chapter provides an overview of the field development stages in the offshore industry, in particular focusing on the engineering and construction stage. Fixed offshore platform is described in related to the engineering and construction stage, which includes design requirements, steel fabrication, load-out, transportation and piling and installation. After that, this chapter focuses on sustainability in the construction industry and its importance for the environment. Aspects of green design and requirements thereof are presented, as well as consideration of eco materials. Critiques on the existing sustainability assessment tools in the construction industry are discussed. Moreover, this chapter addresses the requirements of offshore materials and corrosion as major problems for offshore materials due to the harsh offshore environment. Finally, methods of corrosion protection, control and monitoring are presented.

2.2 Offshore Industry and Fixed Platform

The oil and gas industry comprises two main categories: upstream, which includes exploration and all production systems with all facilities, and downstream, which includes the refining and processing of crude oil. Offshore platforms, the first of which was constructed and installed on the gulf coast of Louisiana in 1947, consist of two main types: fixed and floating platforms. The API Recommended Practice 2A-WSD (2014) defined the fixed platform as a platform extended above sea level and supported on the seabed by piles or other means. API also classified fixed platforms into the following types: jacket platforms, tower platforms, gravity structures and compliant towers. Floating platforms, on the other hand, are used as production systems or for drilling purposes; tension-leg, spar and semisubmersible platforms are examples of this type. The most common offshore structures are fixed jacket platforms, and this study will focus on the topside facilities of the fixed jacket platform.

The offshore fixed platform is the most common offshore structure when long-term production is the target. This type of platform is designed and installed in shallow water of up to 450 metres. The main disadvantage of this type is the maintenance cost over the design life of the platform due to the harsh environmental conditions offshore.

Fixed and floating structures are different in their structure, transport and function; however, they have common characteristics in that they both have deck space and payload capacity to support equipment and production operations. In the fixed platform, deck loads are moved by the foundation material under the seabed through steel piles, whereas in the floating platform, loads are moved by the buoyancy force of the hull supporting the deck (Chkrabarti, 2005, p.18).

A fixed offshore platform consists of an upper part and a lower part. The upper part is above the sea level and contains a number of decks, while the lower part is under the sea level and consists of jacket structures. The jacket (subsea structure) is made of tubular leg chords and horizontal and diagonal bracing. The jacket supports and carries the topside module through the piles, which are driven and passed through tubular leg members. Since the first offshore well was constructed in the Gulf of Mexico, more than 10,000 offshore platforms of various types and sizes have been constructed (Chkrabarti, 2005, p.12; Dean, 2010, p.3).

The upper part of the fixed platform, which is above the sea level, is called the topside module. This part is designed for multiple purposes based on the function of the platform itself, for example: an accommodation module, production facility module or as a flare platform used for burning unrequired gases. The accommodation platform contains the bedrooms, recreational facilities, canteen, laundry, communication system, water system, sewage treatment system, power generation system, fire and smoke detection system, and the helideck space where the helicopter lands. The production platform, on the other hand, includes all of the wellheads, control equipment and control systems, separation and treatment systems for oil, gas and water, the water injection system, gas compression system, fire and gas detection system, and pipeline and risers system. Generally, each system listed above has its own components and equipment. All of these systems are integrated from an engineering point of view to represent the final topside facility (see figure 3 for the components of the fixed platform).

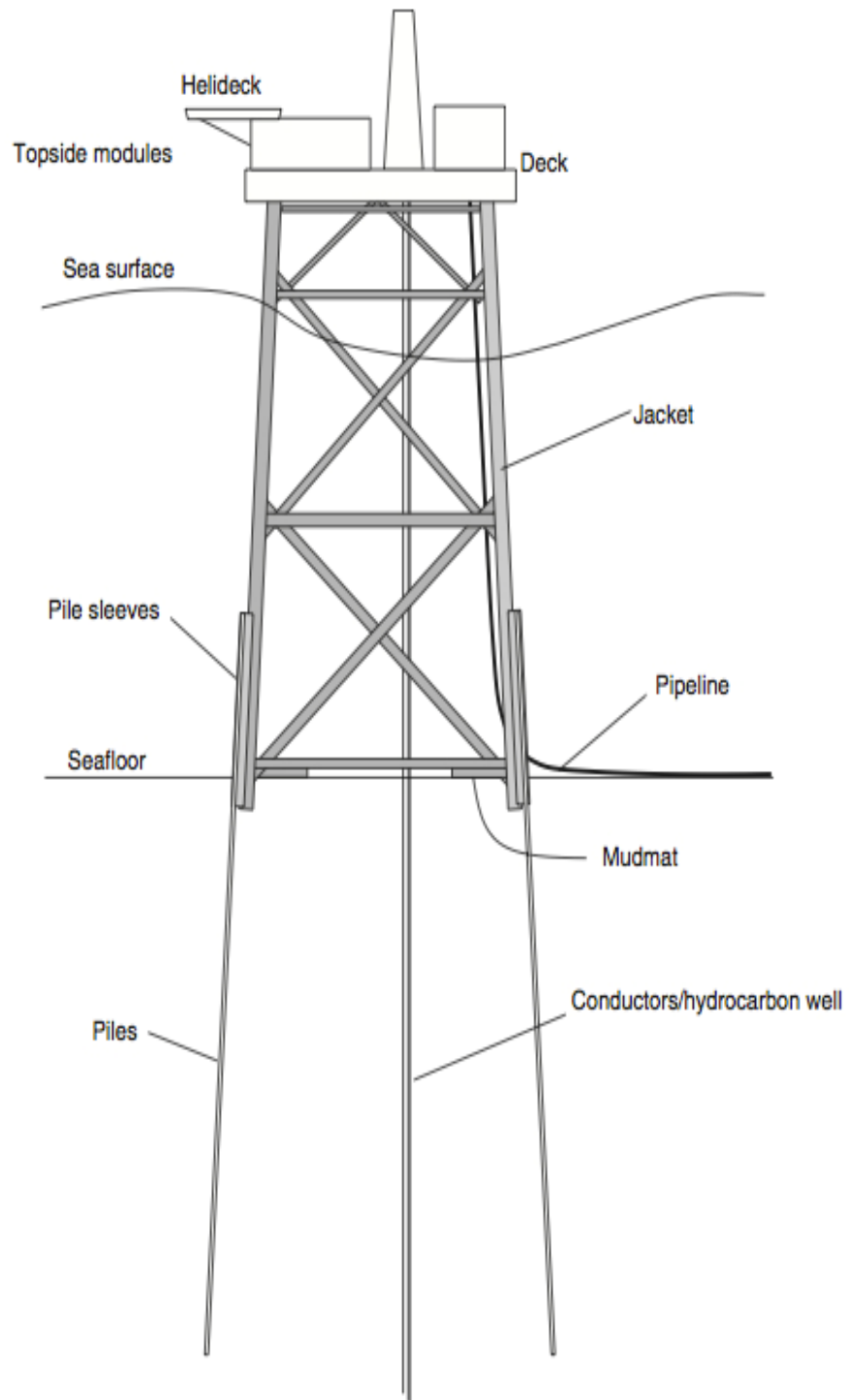


Figure 3 Components of offshore fixed platform (Dean, 2010).

2.3 Construction Stages of Offshore Projects

The author experience of many offshore development plans for greenfield projects, as well as many brownfield projects. From over 15 years' personal experience in the offshore industry, and aligning with the facts and findings of the literature review, the field development plan comprises the following main stages: (1) exploration and feasibility; (2) **engineering and construction**; (3) operation and production; and finally (4) decommissioning. However, in this research, we are focusing on the **engineering and construction** stage, which comprises the following phases: (1) feasibility study; (2) conceptual or pre-design phase; (3) detailed design; (4) materials procurement; (5) fabrication of steel and weighing the structure; (6) loadout and transportation; (7) installation; (8) commissioning; and (9) starting up. Field development stages of offshore projects are shown in figure 4.

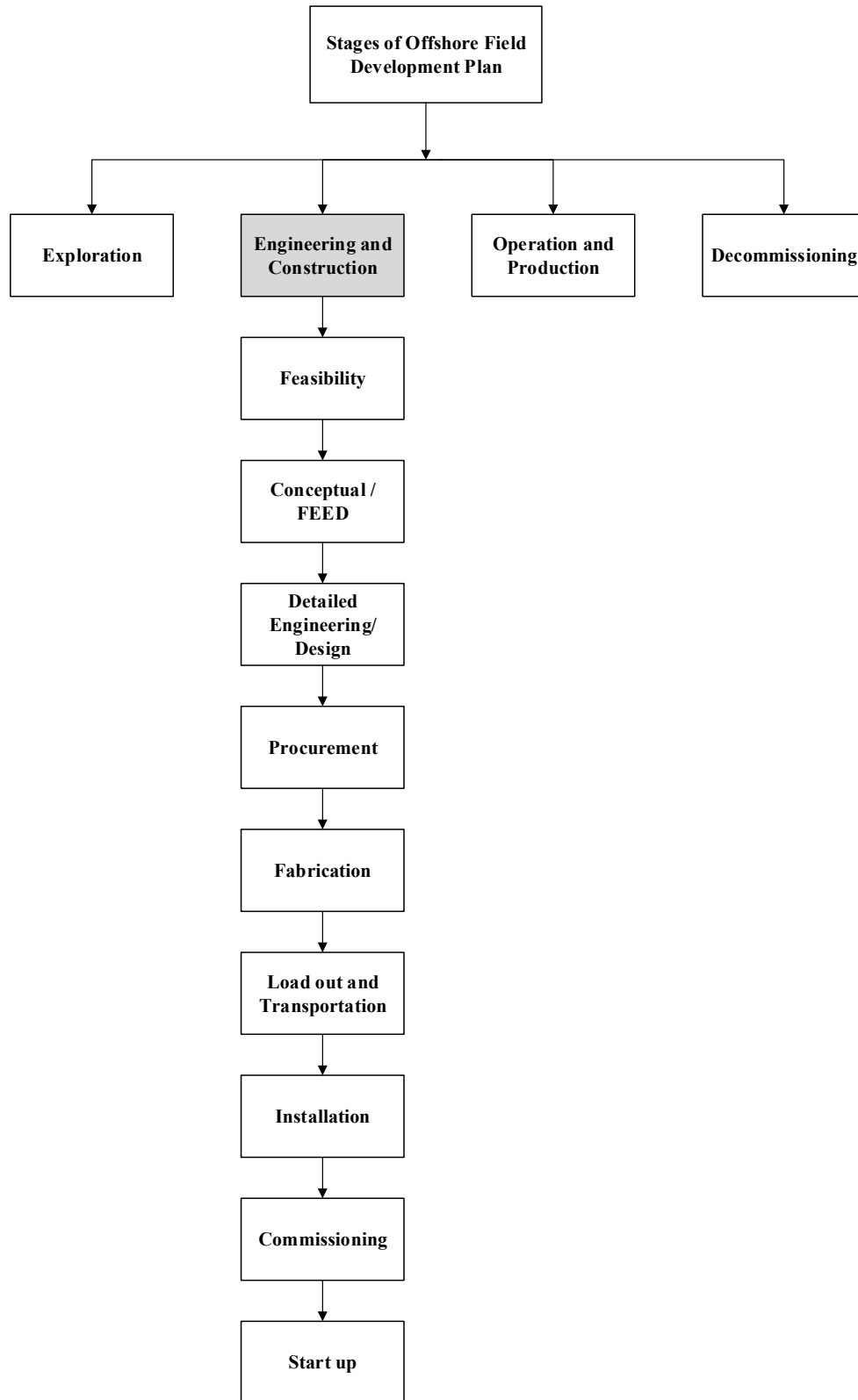


Figure 4 Stages of Offshore Field Development

2.4 Design and Fabrication of Offshore fixed Platform

In the sections below, the following stages will be addressed: design requirements, fabrication of jacket and topside module, loadout, transportation and installation.

2.4.1 Design requirement

The first part of the fixed platform includes the jacket structure, which represents the underwater structure. The steel jacket structures must be designed in accordance with international codes and standards. The design requirements take into consideration the type of structure, loads and load combinations, environmental conditions and construction and installation methods. The most applied international standards are the ISO-19900 (2010) and the API Recommended Practice (planning, designing and constructing fixed offshore platforms) (2014).

The second part of the fixed platform includes the topside, which represents the upper part of the fixed jacket structures, and the structures above sea level. This part consists of the following structure modules: the production (processing) module, which contains the oil and gas separation and treatment systems; the accommodation module; the wellhead module, which contains the well test and drilling activities equipment; and the utility module containing the power generation and production control systems. Sometimes a gas compression module is also required as part of the processing module based on the operation requirement.

Topside structure modules are designed and fabricated based on the requirement of the API Recommended Practice 2A (Planning, designing and constructing fixed offshore platform) and the ISO (International Standards Organization) such as ISO-19901-3 (2010) and ISO-19902 (2007). Each jacket and topside structure will be designed against the following loads: dead loads, live loads, equipment and piping and future loads, in addition to environmental loads such as wind, waves, currents, marine growth, ice and snow and earthquakes. Accidental loads will also be considered, such as dropped objects, ship impact and fire and explosion. The aforementioned loads will be combined to perform the

analysis, either for the jacket or the topside based on the requirements as specified in the international standards and codes.

2.4.2 Fabrication of steel structure

Offshore platforms, both jacket and topside, are built onshore in fabrication yard equipped with construction facilities such as steel and piping prefabrication halls, welding machines, non-destructive testing labs, painting and blasting workshops and mobiles cranes. The fabrication yard is located next to the coast in order to facilitate the loadout and transportation process (see figure 5). The quality of the welding and its procedure is the most important element during the fabrication of both topside and jacket structures. To check the quality of the welding, (NDT) methods, which include X-ray and ultrasonic testing, must be performed after the welding is complete (El-Reedy, 2012, p.296). All fabrication and welding requirements considered and inspections undertaken must be performed based on ISO.



Figure 5 Fabrication yard (Alyafei and Maerskoil Qatar, 2009)

Det Norske Veritas (DNV.GL) standards such as DNV.GL-OS-C201 (2016) and Standards Norway (NORSOK) such as NORSOK-N-001 (2012) and N-004 (2013), which are all compatible with international standards ISO-19900, and ISO-19901-3 have identified two main phases for designing the fixed platform. The first is the non-operational phase and the second phase comprises the operational phase.

2.4.3 Non operational phase

Both Jacket and topside structures for none operational phase shall be designed and fabricated to withstand all type of loads during the fabrication until it takes place in the final position. During the non-operational phase, the structures are exposed to different loads and forces from those in the in-place phase or the operational phase. The non-operational phase includes the following phases:

2.4.3.1 Loadout phase

Weighing and determining the centre of gravity for the offshore structure is an important stage before the loadout stage is begun as this will help to lift or move the structures to the deck of the barge, as well as for installation purposes in the later stage. In the loadout stage, the completed structure is moved from the fabrication yard to the deck of the barge using specific techniques and methods. The most famous methods include using multiwheel hydraulic trailers where the wheels are placed underneath the structures in order to move them to the barge's deck (see figure 6). An alternative method consists of using skid units where the structure is supported and guided over skid rails or beams and then the structure is pushed by jacks or pulled by winches onto the barge's deck. The lifting of the structure involving a land or barge crane comprises another method. This method is governed by the crane availability and capacity. During the loadout phase, the whole structure must be checked and analysed against the new forces resulting from the movement of the structure from the fabrication yard to the deck of the barge (El-Reedy, 2012, p.355; Chakrabarti, 2005, p.1082).



Figure 6 Loadout process (Alyafei and Maerskoil Qatar, 2009)

2.4.3.2 *Transportation phase*

After the loadout is completed, fixing the jacket structure on the barge's deck is the main focus. A seafastening design is considered early in the design, where temporary supports are used to fix the jacket structures to the barge's deck in order to counter the movement due to the barge's motion. These temporary supports are welded to the hardest points of the barge. The structural analysis for the seafastening will be carried out based on international standards and it will consider both static and dynamic conditions. In the event that structural analysis reveals damage to any of the jacket's members, a redesign of the damaged members is considered. The transportation operation to the final position offshore involves consideration of the environmental and motion conditions in the design and calculation (El-Reedy, 2012, p.366).

In addition to the sea-fastening design Chakrabarti (2005, p.1091) mentioned that several engineering studies should be considered for the transportation operation phase. These are: (1) route study to evaluate the environmental criteria and select the most economical and safest route; (2) stability study; (3) motion and acceleration study; and (4) strength assessment of the barge or the vessel study (see figure 7).



Figure 7 Jacket and topside sailing (Alyafei and Maerskoil Qatar, 2009)

2.4.3.3 Installation phase

Installing the jacket can be done by using one of two main methods. The first method comprises lifting by crane and the second consists of launching and upending. All jacket structural members are checked and designed to withstand all stresses caused during the installation process (lifting, or launching and upending).

The lifting method (as shown in figure 8) involves the jacket being lifted off the barge by the crane vessel and then lowered down to its final position on the seabed. In this operation or method, the jacket is designed with lifting lugs on it. Designed slings are then used to connect the crane hook to the jacket lifting lugs. Once all of these stages have taken place and it is ready for the lift operation, the sea-fastening members are cut off and all the weight from the jacket will be transferred to the crane.

Another method includes installation by launching. The launching operation is the most complex operation in jacket installation due to the different forces that will affect the jacket structure during the launching process. The jacket structure is designed with sufficient buoyancy so that it can float as intended. The first step involves removing the sea-fastening members and then pulling the jacket onto the rail skid by winching it toward the stern of the barge. The stern of the barge is then tilted in order to increase the skidding acceleration and once the centre of gravity of the jacket reaches the rocker arm hinges at the stern, the rocker will start to rotate and the jacket will move with the rocker arm and

enter the water (El-Reedy, 2012, p.375). The jacket is then upended by using a crane vessel with new slings connected between the crane hook and the jacket lifting lugs, and then the jacket is lowered to the seabed (see figure 9). There is a difference in the installation method for topside structures modules. The installation can be performed either by direct lifting or by floatover method.



Figure 8 Lifting the jacket and then lower it into the sea (Alyafei and Maerskoil Qatar, 2009)

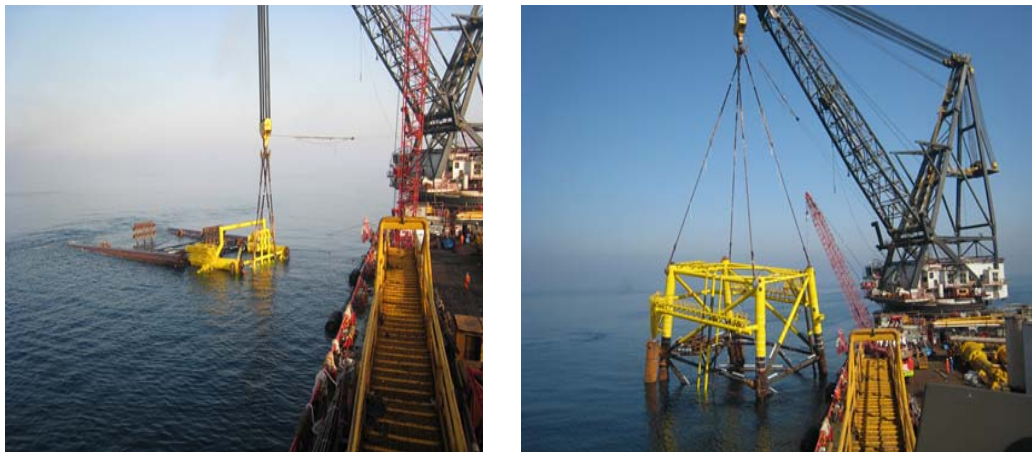


Figure 9 Upending process (Alyafei and Maerskoil Qatar, 2009)

2.4.3.4 *Pile foundation*

There is a risk during installation of the jacket structure and before the jacket is piled that the jacket could be overturned or could slide onto the seabed due to the force of the waves. Therefore, the jacket structures must be designed to be self-standing and supported during pile installation. Therefore, the soil conditions must be checked and investigated before the design of the jacket commences at the proposed location. Soil investigation and a survey will be performed for the seabed. After all geotechnical data are analysed and identified, and based on the bearing capacity of the seafloor, the geotechnical engineer can specify whether or not mud-mats need to be designed and fixed on the jacket. A mud-mat, which is a flat stiffened plate installed on the lower part of the jacket legs, is added in order to transfer the loading to the seabed surface and provide stability and support to the jacket structures during the piling process, fortifying against sliding and overturning (Dean, 2010, p.229).

The piles, which consist of segments, are lifted off the barge's deck by the crane and then driven through the jacket legs into the seabed by using a hydraulic hammer (see figure 10). The first segment must be long enough to go out a few metres to allow for in-place welding with other sections (add-on); a hydraulic hammer is then used to drive the piles into the seabed until the required depth is reached (see figure 11). Finally, the top of the pile of the last section (transition section) will be welded to the jacket and prepared for the topside module installation as shown in figure 12 (Dean, 2010, p.237).



Figure 10 Picking up the pile from the barge's deck (Alyafei and Maerskoil Qatar, 2009)



Figure 11 Driving the pile by using hydraulic hammer (Alyafei and Maerskoil Qatar, 2009)

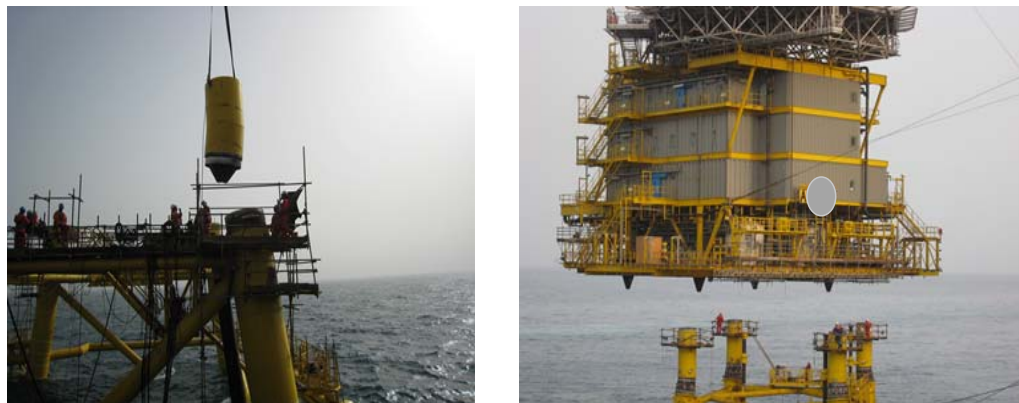


Figure 12 Installing transition section and then topside module (Alyafei and Maerskoil Qatar, 2009)

2.4.4 Operational Phase

The jacket or platform for operational phase will be designed to withstand all types of loads during the platform's service life.

2.4.5 Analysis and Computer Modelling

Each topside and jacket structure must be designed and analysed with regard to non-operational and operational phases considering the loads (discussed above in section 2.4.1) and based on international codes and standards.

In the pre-service or non-operational phase, the following analyses will be performed: (1) loadout analysis; (2) transportation and sea-fastening analysis; (3) lifting analysis; (4) upending analysis; (5) launching analysis in case the launching method is used; (6) on-bottom stability analysis; and (7) pile drivability analysis.

For the operational phase, the following analyses will be performed: (1) in-place analysis; (2) dynamic analysis; (3) vibrational analysis; (4) fatigue analysis; and (5) earthquake analysis.

2.5 Sustainability in Construction

Sustainable development is defined in the Our Common Future report on the environment and development by the United Nations World Commission as “meeting the needs of the present without compromising the ability of the future generations to meet their own needs” (Kates, Parris and Leiserowitz, 2005, p.9). Khalfan (2002, p.3) noted that sustainable development is defined by the Forum of the Future (a sustainable development charity in the UK) as “a process, which enables all people to realise their potential and improve their quality of life in ways that simultaneously protect and enhance the earth’s life support system”. Khalfan (2002, p.4) further mentioned that sustainable development involves ensuring a better quality of life for everyone today, as well as for the next generation, suggesting that it can be achieved through: (1) social development; (2) effective protection of the environment; (3) practical use of natural resources; and (4) maintaining economic growth at a high level.

There is an acceptance among all works of literature in this area that the three themes or pillars of sustainable development are: social, environmental and economic accountability (Dodds and Venables, 2005, p.10; Kates, Parris and Leiserowitz, 2005, p.12). The Building Efficiency Energy Research Project (Hui, 2002) mentioned that sustainable construction can be described as a subset of sustainable development, involving matters such as tendering, site planning, material selection, recycling and waste minimisation. Hui (2002) mentioned that sustainable construction is defined as “the creation and responsible management of a healthily built environment based on resource efficient and ecological principles”.

Zainul-Abidin and Pasquire (2005) mentioned that sustainability is an objective and it can be achieved through the process of sustainable construction. According to Plank (2008), the construction industry is a major consumer of raw materials; consequently, its negative environmental impacts are significant. Jaillon and Poon (2008) highlighted the significant impacts of construction on the environment, such as the use of non-renewable resources; pollution of air and water; noise pollution from construction activities; over consumption of energy and water; and waste generation. Nachawit (2012) also indicated the negative impacts of buildings on environments: the buildings consume energy and materials and generate various types of pollution throughout their life cycles (construction, use and demolition). Therefore, Plank (2008) stated that sustainable construction is considered a subset of sustainable development as construction has major implications for energy consumption and resource use. Similarly, offshore construction is vast (as described above): the weight of a single platform can reach up to 15,000 tonnes, so we can imagine how much raw materials and energy are consumed in the construction of offshore platforms. Offshore platforms are some of the worst for generating pollution in their life cycle. Plank (2008) outlined the importance of considering a long life span for a building, instead of replacement, in order to minimise the consumption of resources, and designing for re-use and recycling at the end of life. Marzouk, Abdelhamid and Elsheikh (2013) suggested that selecting building material is an important factor in sustainable design because of the efforts of extraction, processing and transportation procedures that are required to process them. Moreover, they pointed out that building construction activities contribute to the depletion of natural resources, as well as causing air and water pollution, and there are a wide variety of material choices that can be selected during the design phase, which influence the construction and operation of buildings.

In order to achieve greater sustainability, sustainable construction emphasises the importance of design and materials selection. A significant environmental impact might result depending on the type and features of the selected materials (Khalfan, 2002, p.19). If a sustainable facility is to be created then all materials involved in the composition of the facility should be considered in the pre-design phase when the materials specification takes place. It can therefore be concluded that the most important action toward sustainable development is the consideration of all sustainability dimensions (social, environmental and economical impacts) in the pre-design phase. **Sustainable design** implementation in the pre-design and design phases can thus be defined as a necessary

part of the complete design integration of all the engineering disciplines, along with considering the materials and equipment selection from the perspective of sustainability dimensions. The following hierarchy (figure 13) can be extracted from the above literature. In the following sections, green design requirements, eco materials and offshore materials requirements will be highlighted.

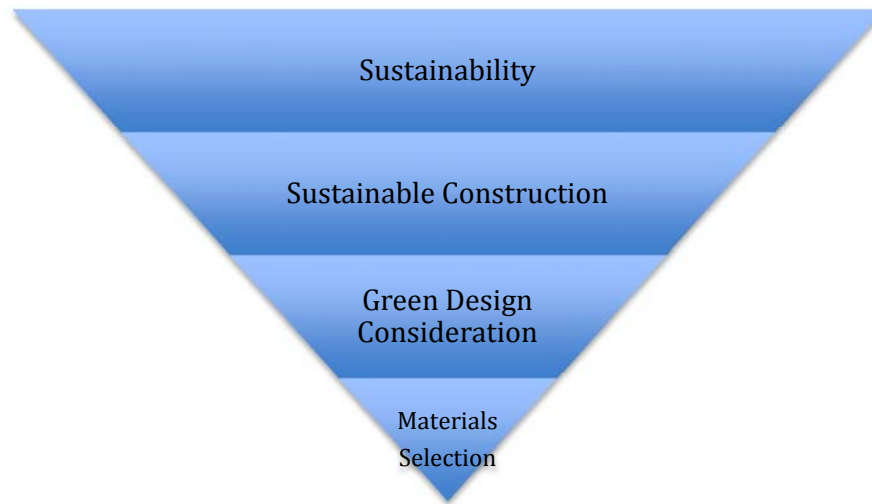


Figure 13 Hierarchy towards sustainable design

2.6 Green Design and Sustainability

Wang and Adeli (2014) noted that sustainable design is also known as green design. Eco design suggests taking into account all the environmental impacts of a product or material from the earliest stage of the design (Prendeville, O’Conner, and Palmer, 2014). However, Wang and Adeli (2014) argued that most researches have focused on saving energy and water and making buildings more environmentally friendly. In my opinion, in order to achieve correctly sustainable or green design, the other aspects of the sustainability should be considered. Zuo, Jin and Flynn (2012) pointed out that most of the studies and researches have focused on the environmental aspects of sustainability such as waste management, gas emission and energy saving etc. However, they argued that although social sustainability is considered in the literature as the weakest aspect of

sustainable development due to the lack of an analytical foundation, there is also a lack of guidelines for considering and measuring social sustainability criteria in the construction industry. From the social impacts of the offshore industry, as described in chapter 3, it can be seen that the offshore industry is still behind the building construction industry and it requires more effort to consider and implement the aspects of social sustainability in the design.

Wang and Adeli (2014) mentioned that leadership in energy and environmental design (LEED) rating system considers six categories of green building: sustainable site, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation and design process. They argued that the materials and resources and innovation and design process categories should be given more weight than they have been allocated thus far. Alwi et al. (2014) mentioned that engineers will have the responsibility to consider the entire field of sustainability aspects in their design and they have to be more innovative and creative in order to ensure that their designs achieve sustainability. Moreover, sustainable engineering should consider the aspects of technology, planning, environment, economic assessment and social dimensions to helping decision making.

Green design encourages the use of eco materials and several aspects and considerations in the design phase; in the following sections will focus on the aspects of green design and eco materials.

2.7 Aspects and Considerations of Green Design

Ljungberg (2005) suggested that the strategies for eco-design are to avoid toxic and hazardous materials, use materials with fewer environmental impacts, maximise the efficiency of the energy in the production and use phases, and design with a view to recycling and waste management. Therefore, he provided the following strategies from the literature to achieve green or sustainable design: modular design for easy repair; designing for disassembly in order to reuse or recycle; designing for recycling by maximising the content of recycled materials; designing for reusability; designing for life extension; designing for energy recovery; and designing for reduction of waste sources. Kubba (2016, p.271) also mentioned that disassembly and flexible design should be considered, as this will help in recycling and reusing the materials with less solid waste

and operating cost. In offshore topside projects, it is very important to consider such factors in order to install and construct the project safely and economically. Mechanical handling studies (installation and removal studies) are very important for topside projects, in order to avoid any accidents that could happen as a result of an object being dropped on critical equipment or pipes. Removal and installation studies require the consideration of easy assembly, disassembly and prefabrication of the project onshore for safety purposes, as well as for economical reasons.

Jaillon and Poon (2008) assessed the economic, social and environmental aspects of using prefabrication in high-rise buildings to achieve sustainable construction. The findings from the study in terms of environmental benefits showed that the use of prefabrication will contribute to materials conservation and waste reduction; air pollution also showed reduction when prefabrication was adopted. Noise can be controlled in the factory more than on site, where it is a nuisance to the surroundings. In terms of economic benefits, although some studies indicated that the initial cost for the prefabrication is higher than conventional construction, the construction time is reduced significantly, which results in a considerable saving. Moreover, quality and quality control will be improved in the factory to a greater degree. In terms of social benefits, the use of the prefabrication technique will provide a safe environment for the workers, and the impact of noise and dust on workers will be reduced. What Jaillon and Poon provided is in line with Pasquire, Gibb and Blismas (2005), who recommended six factors of measurement when comparing prefabrication and traditional construction: cost, time, quality, health and safety, and sustainability and site issues.

In the offshore industry, the above benefits from prefabrication are applicable to offshore projects; furthermore, in offshore projects, the benefits are greater, and the initial cost will be much lower if the prefabrication is used in the design. Offshore installation is very expensive due to the high rate for offshore workers, the requirements for safety such as providing an isolation pressure tent (isolation chamber) for welding purposes, requirements for scaffolding, and need for skilled laborers. Moreover, some projects require shutdown for welding for safety purposes, so this is necessarily costly. I have experienced some brown field projects where the prefabrication and engineering costs were 10,000 USD; but, the installation reached 100,000 USD. Therefore, prefabrication for offshore brown field projects is an important factor to be considered in the design to

minimise the installation cost. The engineer should minimise the number of offshore welding joints as much as possible. Bolted solutions are a good option and these can be an optimal; the offshore installation cost will be reduced significantly, improving safety as welding will not be used, as well as avoiding the impact of welding flame being used by offshore workers.

Zhou, Yin and Hu (2009) provided the following principle for sustainable design and products: use materials with low environmental pollution; consider materials with low energy consumption; avoid hazardous and toxic materials; and consider recycling and easy to reuse and degrade options. From the above, most researchers are focusing on the environmental impacts of the materials when they consider the eco design, and few researchers have extended the concept of eco design further. Marzouk, Abdelhamid and Elsheikh (2013), for example, outlined the social and economic aspects of green design. They noted that green buildings are high quality, operation and maintenance costs are less over their life cycle, and they provide a healthy environment for living and working. Zuo, Jin and Flynn (2012) pointed out that there is a lack of guidelines for considering and measuring social sustainability criteria in the construction industry. They highlighted the importance of considering social sustainability during the design, planning and production; they argue that this effort is environmentally oriented. The most common social criteria identified in the literature are health and safety, safety design, training and education for employees and others such as better quality of life, and equity.

In my opinion, focusing on the environmental impacts to achieve green/ eco design is insufficient; social, economic and engineering aspects should be integrated in the design under the eco or sustainable design, and this is one of the motivations for this research. It is noted that eco materials comprise the main aspect of eco design, as these materials contribute to mitigating the environmental effects, they provide safe and healthy environments (social) and require less maintenance and replacement costs (economic). Therefore, eco materials will be discussed further in the next section.

2.8 Eco Materials Selection and Considerations

According to Ashby (2013, p.8), all human activity has an impact on the environment; impacts derived from the manufacture, use and disposal of materials are an example that

threaten the wellbeing of the environment for future generations. Further, Ashby mentioned that the world consumes 10 billion (10^{10}) metric tonnes of engineering materials per year. Materials consumption in the United States exceeds 10 metric tonnes per person; the average level of global consumption per person is 1.5 metric tonnes.

In order to select materials for eco-design, Zarandi et al. (2011) suggested avoiding materials and additives that emit toxic or harmful substances during pre-production, usage and disposal stages; use renewable and recycled materials; and use materials with low energy consumption during the extraction and transportation phases. Nachawit (2012) stated that the selection of environmentally friendly materials in the design is significant; specific materials impact the degree of effects on the environment. Ogunseitan and Schoenung (2012) noted that the traditional method of materials selection focuses on cost and performance characteristics; however, they emphasised that it is important to integrate toxicity metrics into materials selection in the early design in order to mitigate the effects on human health and environment. Florez and Lacouture (2013) summarised sustainable materials from the existing literature as materials with a high reuse and recycle content; low in emitting contaminants; free of harmful contaminants; low repair and consumption; safe to use; and easy to use and build. Similarly, Kubba (2016, p.221) mentioned that green materials include those are good for environments and made from recycled materials and renewable sources; durable and reusable materials; involve less energy used in extraction, processing and transport; and energy efficient in the usage. Other criteria include whether the materials are suitable for the application, whether they have health impacts on the users etc.

In terms of how to determine the environmental impacts of the materials, the life cycle assessment (LCA) method is the most common technique used for assessing the environmental impacts of materials (Bribian, Uson and Scarpellini, 2009). According to Buyle, Braet and Audenaert (2013) life cycle assessment tool is used widely for evaluating the environmental impacts of products and processes from “cradle to grave”, and LCA is still a powerful tool to assess the environmental impacts of materials and products. Ljungberg (2005) noted that LCA is useful tool, where the product is assessed step by step, and the cost and impacts is evaluated. Oliverira, Melhado and Vittorino (2014) also mentioned that most countries who have reliable environmental indicators

have developed an assessment method based on the life cycle assessment method. However, if the LCA database does not exist for a country, then it will be difficult for them to conduct building sustainability assessment. Some researchers have argued that LCA is a complicated tool. Russell-Smith et al. (2015) mentioned that LCA is avoided because of the difficulty and the level of detailed data required. Nachawit (2012) discussed the limitations of the LCA as a tool for obtaining the environmental impact data of building materials as follows: implementation of the LCA in practice is difficult and not an easy task; LCA is applied to different case studies, and the results of each study are applicable to that specific study, so the generalisation of results is difficult. According to Ashby (2013, p.60), LCA is expensive and time consuming activity. It also involves going into great detail, details that are not in fact available until the product has been produced and used. Ashby suggested that in order to guide the design decisions and materials selection, the designer needs non-complex and fast tools so they can explore alternative options. Therefore, Ashby's method will be adopted for this study.

2.9 Ashby Strategy

Ashby (2013, p.66) suggested a new strategy for environmental impact assessment, which involves three main components: (1) adopt simple metrics for environmental stress, such as energy consumption and CO₂ emissions; (2) distinguish the phases of life for the product or materials, for example, energy consumption and CO₂ emissions can be identified during the materials extraction (creation) phase, manufacturing phase, or transportation and product use phase; (3) choose the materials based on the energy or breakdown for each phase. Therefore, from the above, consumption of energy and CO₂ emissions will be key factors for materials selection. These two factors are discussed further.

2.9.1 Energy consumption through materials life cycle

The energy required to create and shape materials can be extracted from natural sources, such as fossil hydrocarbons, ore bodies and minerals; however, the earth's resources are not infinite (Ashby, 2013, p.8). Therefore, energy consumption must be minimised to save sources of energy. As mentioned above, in order to choose between different materials, energy consumption will be considered during the materials' life phases, which

include the following: (1) during materials creation and extraction, **embodied energy** is the energy required to create 1kg of usable materials in (MJ_{oe})/kg (megajoules, oil equivalent per kilogram); (2) energy consumption through materials processing and manufacturing is the energy required to shape or manufacture 1kg of materials in MJ/kg; (3) energy consumption through transport and use phase, in same principle, is the energy required to transport the products from the factory to where they are used, as well as the energy consumed during the use of materials (Ashby, 2013, p.121).

2.9.2 CO₂ emission during materials life cycle

The CO₂ footprint of a material is the mass of CO₂ released into the air per unit mass of materials, in Kg/kg. During the materials' life cycle, there are other emissions, such as CO and CH₄, therefore, a carbon-equivalent (CO₂eq) is used for reporting, and the unit is still Kg/kg. The CO₂ equivalent should be identified through the main phases, as described above: materials extraction, materials processing and manufacturing, and through the transportation and use phases (Ashby, 2013, p.122).

2.9.3 Determining energy consumption and CO₂ emissions

The energy consumption, such as embodied energy and CO₂eq emissions through the materials' life cycle can be determined from the manufacturer or materials suppliers. However, there are some software that can also determine this information. Ashby (2013) mentioned that CES software as a powerful audit and selection tool that can be used.

2.10 Critique of the Sustainability Assessment Tools for Buildings and Construction

The method of identifying and assessing the impact of alternatives can be referred to as sustainability assessment. There are several methods that have been developed to assess the building and construction industry from a sustainability point of view, but thus far none of them have been considered as a potential worldwide measure (Berardi, 2015, p.506). According to Hastings and Wall (2007), the existing methods can be classified into the following types: (1) cumulative energy demand systems (CED); (2) life cycle analysis systems (LCA); and (3) total quality assessment (TQA). Berardi (2015, p.507)

described the three groups as follows: CED systems are monodimensional systems measuring the sustainability of buildings through their energy consumption; LCA systems evaluate impact on the environment by dividing buildings into small activities and raw materials in order to evaluate their environmental impact over a life cycle, from manufacture and transportation to recycling; and TQA are multidimensional systems considering several parameters.

From the above it can be concluded that the CED cannot be considered a sustainable method as it only covers energy consumption (monodimensional). The limitations of the LCA method in turn were described in section 2.8. Further, the LCA method does not consider the economic and social aspects. The evaluation of the TQA system is based on criteria measured by several parameters: these systems are easy to understand and implement in the design for the final construction (Berardi, 2015, p.511). The following table 1 outlines the most famous multi-criteria systems and methods.

Table 1 Sustainable multi-criteria system around the world

	Assessment Method	Description	Country
1	BREEAM	Building Research Establishment Environmental Assessment Method	UK
2	Green Star	Green Building Council of Australia	Australia
3	HEQ	The High Environmental Quality	France
4	CASBEE	Comprehensive Assessment System for Building Environmental Efficiency	Japan
5	LEED	Leadership in Energy and Environmental Design	USA and Canada
6	GSAS	Global Sustainability Assessment System	Qatar and Arabian Gulf Countries
7	GeSBC	The German Sustainable Building Certification	Germany
8	ABGR	Australian Building Greenhouse Rating	Australia
9	GHEM	Green House Evaluation Manual	China
10	STARS	The US Assessment and Rating System	USA

11	SBAT	Sustainable Building Assessment Tool	South Africa
12	SBTool	Developed by International Initiative for Sustainable Built Environment	Canada and Europe
13	Green Globes	Developed by Green Building Initiative (GBI)	USA
14	BEPAC	Building Environmental Performance Assessment Criteria	Canada
15	CPA	Comprehensive Project Evaluation	UK
16	DQI	Design Quality Indicator	UK
17	GBTool	Green Building Challenge	International: over 20 Countries
18	HKBEAM	Hong Kong Building Environmental Assessment Method	Hong Kong

Sources (Berardi, 2015; Ding, 2008; Wang and Adeli, 2014)

Although the above assessment methods have been widely used, many of them have a number of limitations. Berardi (2015, p.511) argued that most of the multi-criteria systems do not consider some aspects of sustainability, such as social and economic aspects. According to Ding (2008), BREEAM, LEED, BEPAC and HKBEAM don't include financial aspects in their assessment. Crookes and de Wit (2002) and Ding (2008) pointed out the importance of using environmental assessment methods in the identification stages; they claimed that most methods are designed to assess the project at a later design stage, to identify the environmental performance of the project. Another constraint is that most of these methods were created for local use: GreenStar, HKBEAM, BEPAC and others were developed based on the BREEAM system and adapted to their countries' requirements (Ding, 2008). Some systems tend to be more comprehensive, however, this has guided to create complicated system requires large amount of detailed information such as GBtool system (Ding, 2008; Berardi, 2015). One of the most important restrictions is that most of the systems are designed for environmental assessment. These systems assign a higher percentage of the assessment to the energy efficiency indicator; for example, Green Globes assigns 36% of its weight to energy efficiency and the average weight in other systems, such as BREEAM and LEED, is still high at about 25%. Wang and Adeli (2014) argued that the materials and resources and

innovation and design process categories in the LEED system should be given more weight than they have been allocated thus far; most of the assessment weight is in the energy category in the LEED system. The main limitation is the measurement scale: most methods adopt a rating or points system. Although most of the points are reserved for the environmental criteria, however, Ding (2008) argued that there is no clear basis upon which each criterion is given a maximum number of points. In my opinion, a rating system lacks guidance in the design; assigning points based on the existence or absence of certain performance criteria is not a solution.

2.11 Materials and Offshore Environments

Offshore platforms and their components are subject to harsh environments as well as many different complicated loads. These factors therefore, create difficulties for the selection of appropriate materials in the offshore industry. According to Reddy and Swamidas (2016, p.249), offshore platforms are exposed to a number of deteriorating impacts during their lifetime, such as corrosion degradation and fatigue load. Specifically, the authors pointed out that temperature, humidity in the wind, windborne salt content from the sea, and the amount of airborne pollutants such as CO₂ and SO₂ will contribute significantly to the corrosive aspects of the topside structure.

Materials selection plays a vital role in the design, construction and operational phases of marine structures. The materials engineer has a significant role to play in ensuring that the correct materials are selected for the correct systems or components, also assisting the designer in this task. However, in current practice, this role is often entirely delegated to the designer who becomes solely responsible for materials selection based on the engineering judgment and performance requirements for the design (Reddy and Swamidas, 2016, p.251).

Salama (2005, p.1127) classified offshore materials based on several considerations such as strength, corrosion resistance, chemistry, etc. The classification comprises the following groups: (1) structural steel used for pipelines and structure members; (2) production equipment steel; (3) corrosion resistance alloys, which are used for corrosive environments, such as stainless steel, cobalt base alloys, nickel base alloys and titanium alloys; and (4) non metals such as elastomers and the plastic and composite materials.

Reddy and Swamidas (2016, p.296) mentioned a similar categorisation of the offshore materials; They classified the offshore materials according to the following: (1) alloys of iron and steel with low-strength steel, medium-strength steel or high-strength steel; (2) aluminum alloys; (3) titanium alloys; (4) non metallic materials such as fiber reinforced plastic, bakelite and polymers.

2.12 Requirements of Materials Selection in Offshore Industry

Materials qualification is a very important aspect in materials selection. Norsok discussed and described materials selection requirements for offshore industry, with the Norsok M-001 standard (2014) stating that the materials should be listed by relevant design code and standardised by recognized national and international standards and codes. The following points should be considered: corrosivity considering operating conditions; inspection and corrosion monitoring; operating and design temperature; philosophy of the maintenance and repairing; failure probability and failure consequences for human health, environment and safety (reliability and durability); design life and system availability requirements; market and spare parts availability; and weldability.

Salama (2005, p.1127) mentioned similar factors that affect materials selections such as electrochemical properties, corrosion control strategy, operating loads and environment, corrosivity of production fluids, service life, maintenance flexibility, weldability, environmental constraints and regulation. Salama also indicated the importance of the mechanical properties of the materials, such as strength level, fracture toughness, yield strength, elastic modules, elongation to failure and fatigue.

In terms of the polymeric materials selection, ISO 21457 (2010) and Norsok M-001 (2014) mentioned the following additional properties that should be considered when selecting polymeric materials: physical properties, mechanical properties, thermal resistance, thermal stability, thermal expansion, swelling and shrinking due to gas and liquid, chemical and fire resistance.

Salama (2005, p.1127) pointed out that despite progression in materials selection associated with oil and gas platforms, the procedure for materials selection remains unchanged in that the corrosion assessment is carried out for all processes and equipment where the CO₂ and H₂S is presented. ISO 21457 (2010) emphasised the importance of

erosion and corrosion evaluation, as well as the wear and abrasion resistance in process system materials. It is clear that the main concern with materials selection in the offshore environment is corrosion and corrosion control and monitoring. For this reason, in the following sections, corrosion and corrosion control will be discussed.

2.13 Corrosion in The Oil and Gas Industry

Schmitt (2009) defined corrosion as the “deterioration of the material and its properties due to its reaction with the environment”. In other words, corrosion is a deterioration of the mechanical properties of the metal when it reacts with the environment. Schmitt (2009) pointed out that the impact of corrosion on the economy and environment is vast and affects all fields and industries worldwide. Koch et al. (2016) estimated that the global cost of corrosion in 2013 was USD 2.5 trillion, which is equivalent to 3.4% of the global GDP. Koch et al. (2016) also indicated that the cost of corrosion has a major impact on the operational cost (OPEX) of the oil and gas facilities.

Speight (2015) mentioned several atmospheric variables that influence the rate of the corrosive attack, such as climate conditions, temperature, relative humidity, surface shape and condition, and the presence of sulfur dioxide. Corrosion has dangerous consequences on offshore operations; the decline of the metal thickness of any equipment or materials on offshore platforms could lead to structural failure, resulting in serious injuries or fluid spillage from any equipment. Fluid or oil spillage from piping or any system could cause an explosion.

2.14 Types of Corrosion in The Offshore Industry

Bahadori (2014) stated that the greatest cause of plant and equipment breakdown in the oil and gas industry is the corrosion. He emphasised that the engineer and designer should work together in the design process and consider corrosion in the design from the beginning in order to avoid any hazards that could occur due to corrosion. Considering corrosion in the design will ensure the longer life of the selected materials and equipment.

The general classifications and themes of corrosion differ from author to author in the literature. However, most of the corrosion types and forms are in fact the same. In order to aid the designer’s analysis of the project with respect to corrosion, Bahadori (2014)

provided a classification of corrosion as follows: (1) uniform or general corrosion; and (2) localised corrosion.

2.14.1 Uniform or general corrosion

This type of corrosion occurs uniformly over the entire surface of the corroding material. This corrosion can be avoided or stopped by applying coating to the metal surface, applying cathodic protection, selecting proper materials and using inhibitors (Bahadori, 2014; Roberge, 2008).

2.14.2 Localised corrosion

In this type, the corrosion occurs intensely in a small area of the metal's surface due to environmental effects, while the remaining surface area of the metal corrodes at a slower rate. Bahadori (2014) and Roberge (2008) outlined several types of localised corrosion, as shown in table 2.

Table 2 Types of corrosion

Localised Corrosion	
Type of Corrosion	Description
Galvanic Corrosion	Occurs when dissimilar metallics are placed in contact with each other in the presence of an electrolyte.
Pitting Corrosion	Corrosion cavities or holes that are produced in the material's surface in the place where the coating has been removed.
Stray Current Corrosion	Corrosion resulting from a direct current flowing through an intended path or circuit.
Crevice Corrosion	Corrosion in the crevice or shielded area on the metal exposed to corrosives and associated with stagnant solution caused by holes, lap joint and crevices under bolts etc.
Selective Leaching	Refers to the selective removal of one element from an alloy by the corrosion process.
Microbial Corrosion	Refers to the corrosion caused by bacteria, molds and fungi.
Intergranular Corrosion	Corrosion occurs on the grain boundaries of the crystals that form the metal.

Thermogalvanic corrosion	Temperature changes can change the corrosion rate of the materials; local attack occur in a zone between the maximum and minimum
Fretting Corrosion	This occurs in the interface between two metal surfaces in contact due to corrosion and surface motion (slip).
Stress Corrosion	The combined effects of the corrosion and the tensile stress will form cracks and consequently failure of the component.
Fatigue Corrosion	The combined effects of cyclic stress and corrosion will reduce the life of the materials.

2.14.3 Erosion corrosion

Roberge (2008, p.185) highlighted this type of corrosion; related to the mechanical removal of protective surface layer resulting in a subsequent corrosion rate increase by chemical process.

2.14.4 Corrosion in oil, gas and petrochemical industries

Bahadori (2014) mentioned two classifications of corrosion in oil and chemical industries: low temperature corrosion below 260 °C, and high temperature corrosion above 260 °C. The following sections will focus on these two types of corrosion.

2.14.5 Low temperature corrosion

Another source of corrosion is inorganic compounds such as water, hydrogen sulfide, hydrochloric acid, sulfuric acid, etc. There are two sources of these compounds: feed stock contaminants and process chemicals (Bahadori, 2014, p.6).

2.14.5.1 Corrosion by feed stock contaminants

In petrochemical plants, specific corrosives are introduced from the process operation, which causes corrosion to certain products. These contaminants include: (1) air; (2) water; (3) hydrogen sulfide; (4) hydrogen chloride; (5) nitrogen compounds; (6) sour water; and (7) polythionic acids (Bahadori, 2014, p.6).

2.14.5.2 Corrosion by process chemicals

A serious corrosion problem is caused by process chemicals, which are used in certain petrochemical and operation processes. Corrosion can occur due to the following chemicals: (1) acetic acid; (2) aluminum chloride; (3) organic chloride; (4) hydrogen fluoride; (5) sulfuric acid; (6) caustic; (7) amine; and (8) phenol (Bahadori, 2014, p.8).

2.14.6 High temperature corrosion

Petrochemical equipment being left in the presence of high temperature, high pressure and sulfur compounds can result in significant corrosion problems. Different types of high temperature corrosion include the following: (1) sulfidic corrosion; (2) sulfidic corrosion without hydrogen present; (3) sulfidic corrosion with hydrogen present; (4) naphthenic acids; (5) fuel ash; and (6) oxidation (Bahadori, 2014, p.12).

2.15 Corrosion Evaluation in International Standards

International standards such as NORSOK-M001 and the ISO-21457 specify the main parameters to be considered as a minimum in the corrosion evaluation for any hydrocarbon system. The factors include the following: CO₂ content, H₂S content, oxygen content, water content, elemental sulfur, mercury Hg, organic acids, pH, production chemicals, velocity and flow regime, operating temperature and pressure.

2.16 Corrosion Control for Topside Facilities

Corrosion control methods are very important aspects to be considered at the early stage of projects in order to prevent the materials from deteriorating. The main methods for corrosion control for topside facilities are: applying protective coating, applying chemical inhibitors, considering corrosion allowance and finally selection of corrosion resistant materials.

2.16.1 Protective coating

Coating is a barrier that works to protect the material surface from the corrosive environment. Koch and Ruschau (2001) claimed that there are two main types of coating: (1) organic coatings, which are classified by a curing mechanism into two basic types of

cured coatings, including convertible and non-convertible; and (2) metallic (inorganic) coating.

2.16.1.1 Organic coating

Koch and Ruschau (2001) mentioned that the convertible coatings are cured by the polymerisation process when two or more resin molecules combine to form one complex molecule. There are four basic types of polymerisation used in coating technology; these are used to form the protective film based on several reaction chemicals which comprise the following: (1) oxygen induced polymerised coatings such as alkyds and drying oils; (2) chemically induced polymerised coatings like epoxies and polyurethanes; (3) heat induced polymerised coating such as polyester, vinylester, phenolics and silicones; and (4) hydrolysis induced polymerised coatings like moisture cured polyurethanes.

On the other hand, non-convertible coatings are cured by evaporating the solvent with no chemical change into the resins as they transform from liquid to solid state. The most well-known types of non-convertible coatings include chlorinated rubber, vinyls, acrylic, bitumen and flame spray polymer.

2.16.1.2 Inorganic (metallic) coating

Roberge (2008, p.588) stated that metallic coatings provide a barrier layer to the metal surfaces to protect them against the corrosion. The methods by which to apply this coating include electroplating, spraying, hot dipping, chemical vapor deposition and ion vapor deposition. The most common types in this category are galvanising and metallising. Galvanising is the process of coating the steel with layers of zinc by submerging the steel or iron in a bath of molten zinc at a high temperature to form layers of zinc-iron alloy via the reaction between the iron and the zinc. This layer will work as a barrier to protect the component from the external environment that causes the corrosion. Metallisation is a thermal spray of thin metallic film, such as zinc, aluminum and silver, to the base materials in order to provide protective layers. This method can be applied on site where the galvanising process cannot be applied or used.

2.16.2 Chemical inhibitors

Chemical inhibitors are substances which can be added to an environment to reduce the corrosion rate when it reacts with the metal surface. Salama (2005, p.1137) highlighted the importance of chemical inhibitors against production fluids in topside equipment for the oil industry. ISO21457 mentioned that among the methods for chemical inhibitors and treatment are oxygen scavengers, biocides, anodic inhibitors, pH stabilisers and the use of film forming inhibitors. Bahadori (2014, p.128) identified several factors that should be considered during the selection of the inhibitors, which include: type of corrosion, operation pressure, temperature, velocity, type and condition of system, production composition, efficiency of inhibitors and economy.

2.16.3 Corrosion allowance

The corrosion rate, which is the yearly decrease in the thickness of a material, should first be calculated and predicted with a view to adding extra thickness to the selected material in order to meet its design life; this should be done during the design phase of the project. ISO21457 stated that the corrosion allowance should be added with regards to expected internal corrosion based on the corrosion evaluation criteria. ISO further emphasised that the corrosion allowance should consider the possible corrosion during all the project stages, including construction, installation and starting up, in addition to the corrosion expected through normal operation.

2.16.4 Corrosion resistance materials

Selection of corrosion resistant materials is implemented where the protective coatings do not work as intended. Alloys and composite materials can be used and selected for this purpose. Alloys such as stainless steel, titanium, nickel-based alloys and cobalt-based alloys can be used for production equipment on topside facilities where a corrosive environment is present (Bahadori, 2014, p.89).

Composite materials such as FRP (fiber reinforced polymer) provide good corrosion resistance. FRP consists of two materials: the fiber (reinforcing agent) and the polymer resin (matrix). There are many types of fibers used in the composite such as glass fiber, carbon fiber, aramid, and so forth. Similarly, there are also different types of polymer resin or matrix used in the composite materials. The most common type of fiber is glass

fiber, whilst, the thermosetting resins such as epoxy, phenolic and vinyl ester are the most famous among the polymers. Therefore, composite materials such as fiber glass reinforced epoxy and fiber glass reinforced phenolic are commonly used in many applications on topside facilities for example in piping systems.

2.17 Corrosion Monitoring and Inspection

According to Roberge (2000, p.372), corrosion control and inspection are both very important in order to determine the system or the material's condition against the corrosion, and also to determine whether the corrosion control and maintenance programs are performing as intended. Roberge defined inspection as the evaluation of the quality of some features or attributes associated with standards and specification. Monitoring, on the other hand, involves measuring corrosion damage under operating conditions over a longer period of time, as well as attempts to reveal how and why the corrosion rate changes over time. Roberge emphasised the importance of monitoring and inspection, as these are cost effective when integrated together. The importance of corrosion control can be seen as reducing the operating and maintenance cost, reducing downtime, improving safety, reducing the pollution risk and providing an early warning before serious damage takes place.

Several methods are available for performing periodic monitoring and assessment, such as corrosion coupons (mass loss), ER (electrical resistance), LPR polarisation resistance, zero resistance ammetry (also known as galvanic monitoring) and others. Authors have classified and categorised these methods in different ways. Papavinasam (2014, p.493) mentioned the following categorisations: (1) monitoring vs. inspection; (2) intrusive vs. non-intrusive; (3) online vs. offline; (4) leading indicators (real time) vs. lagging indicators; (5) probe monitoring vs. structural monitoring; (6) direct vs. indirect; (7) general vs. localized corrosion; and (8) destructive vs. non-destructive. Papavinaasam summarized different categories and the associated methods in table 3 below.

Table 3 Categories of monitoring and inspection techniques (Papavinaasam, 2014, p.493)

Technique	Type of Corrosion Monitored	Nature of the Technique						
		Destructive or Non-Destructive	Monitoring or Inspection	Intrusive or Non-Intrusive	Online or Offline	Leading or Lagging Indicator	External or Inline Inspection	Probe or Structure Monitoring
Mass loss	General corrosion, erosion-corrosion, and localized corrosion	Destructive	Monitoring	Intrusive	Offline	Lagging	NA	Probe
Electrical probe	General corrosion and erosion-corrosion	Non-destructive	Monitoring	Intrusive	Online	Lagging	NA	Probe
LPR	General	Non-destructive	Monitoring	Intrusive	Online	Leading	NA	Probe
Noise	General and pitting	Non-destructive	Monitoring	Intrusive	Online	Leading	NA	Probe
EIS*	General	Non-destructive	Monitoring	Intrusive	Online	Leading	NA	Probe
Potentiodynamic polarization	General and localized	Destructive	Monitoring	Intrusive	Online	Leading	NA	Probe
Galvanic couple (ZRA)	Galvanic and MIC	Non-destructive	Monitoring	Intrusive	Online	Leading	NA	Probe
Multielectrode	General, galvanic, and localized	Non-destructive	Monitoring	Intrusive	Online	Leading	NA	Probe
Ultrasonic	General, erosion, and localized	Non-destructive	Inspection	Non-intrusive**	Online	Lagging	External***	Structure
Magnetic flux leakage (MFL)	General, erosion, and localized	Non-destructive	Inspection	Non-intrusive**	Online	Lagging	External***	Structure
Electromagnetic – Eddy current	General, erosion, and localized	Non-destructive	Inspection	Non-intrusive	Online	Lagging	External	Structure
Electromagnetic – Remote field technique (RFT)	General, erosion, and localized	Non-destructive	Inspection	Non-intrusive	Online	Lagging	External	Structure
Radiography****	General, erosion, and localized	Non-destructive	Inspection	Non-intrusive	Online	Lagging	External	Structure
Electrical field mapping (EFM)	General, erosion, and localized	Non-destructive	Monitoring	Non-intrusive	Online	Lagging	NA	Structure
Hydrogen probe monitoring	General and hydrogen effects (HIC, SSC, HE, and HB)	Non-destructive	Monitoring	Non-intrusive	Online	Leading	NA	Structure
Corrosion potential	General and localized corrosion tendency	Non-destructive	Monitoring	Non-intrusive	Online	Leading	NA	Structure

NA – Not applicable
 *Not proven in the field
 **May also be used as intrusive probe (see inline inspection)
 ***May also be used as inline inspection tool
 ****Another type of radiography, known as surface activation and gamma radiometry, technique is in the early stages of development. In this technique the internal surface of the infrastructure or a coupon is irradiated with a low level of radioactive material. The corrosion is monitored from measuring the radiation from the irradiated material and comparing that with a reference material

2.18 Summary and literature Gap

In this chapter, the background of the offshore industry and the construction of offshore platforms were presented. This research focuses on fixed offshore platform in particular. The main phases of field development plans are: exploration, engineering and construction, operation and production and decommissioning. The engineering and construction phase was considered in detail in this chapter and the design and fabrication process for offshore fixed platforms was discussed in order to highlight the significance of this phase. It has been discussed that sustainable construction is considered part of sustainable development due to the significant impact of the construction industry on environments; it is impossible to deny the negative impacts of offshore construction in terms of consuming raw materials and energy, using non-renewable resources and

polluting air and water. Some authors have highlighted the importance of materials selection in the design phase as it influences construction activities and building operation. Green design implies the consideration of the environmental aspects of the materials and products. The life cycle assessment method is used to evaluate the environmental impacts of products or materials; however, due to the difficulties and limitations of this method, we suggest using the Ashby method in this study, as described above.

Green design focuses only on the environmental aspects and ignores the economic and social aspects. Most researchers in green design focused on the environmental aspects, such as saving energy and water or gas emissions and waste management. However, few researchers have also pointed out the economic aspects such as maintenance and operation costs, and fewer still have highlighted social sustainability. Many researchers argue that social sustainability remains the weakest aspect of sustainable development due to a lack of guidelines on how to conduct and measure it. It can be concluded therefore that green design is not a sustainable design. A sustainable design in my view should consider the main pillars of sustainability (environmental, social and economic) in addition to engineering and design aspects. A critique of the existing sustainability assessment tools was presented in section 2.10, where the systems were classified into three main categories: oriented for energy saving; based on life cycle assessment and ultimately focused on the environmental aspects of materials; and finally total quality system or multi criteria systems. However, even the multi criteria system still doesn't provide a design guideline that can help the designer; in fact most of these systems, such as the LEED and BREEAM methods, are ratings methods. In these systems most of the weight goes to environmental impact and energy saving indicators.

Zainul-Abidin and Pasquire (2005) emphasised that value management/value engineering should be applied at the early stage of the project as the value engineering process has the potential to heighten focus on sustainability concerns, while maintaining the quality of the outcome at the best cost. One of the objectives of this study is to develop a sustainable framework, not a green framework. The framework in addition to the environmental aspects should address the economic and social aspects in order to fill the gap in the literature. Therefore, the next chapter will focus on the three pillars of sustainability from offshore industry point of view and, in particular, will focus on topside of the fixed offshore platform.

Chapter 3

Sustainability and Offshore Industry

3.1 Introduction

The aim of this chapter is to highlight the challenges that are facing operation of offshore platform from the aspects of sustainability (figure 14). Starting with the economic aspects, the importance of the conceptual stage in offshore construction projects in terms of the effects of cost estimation on the project timeline is highlighted. The first part of this chapter explores the importance of Front End Engineering Design (FEED) as part of the conceptual stage in offshore construction projects in specifying and selecting proper materials with lower life cycle cost. Engineering tools and techniques such as value management, life cycle costing techniques and time value of money will definitely help to achieve sustainability in the design; these techniques are discussed in details in addition to the economic appraisal methods. In the second part, in order to understand the environmental and social impacts of topside facilities, the topside facility components and systems in offshore fixed platforms are explored first. Following consideration of the environmental and social impact of topside facilities on the environment, marine life and offshore workers are presented. Recommendations on how to mitigate the potential impacts are also discussed in this chapter.

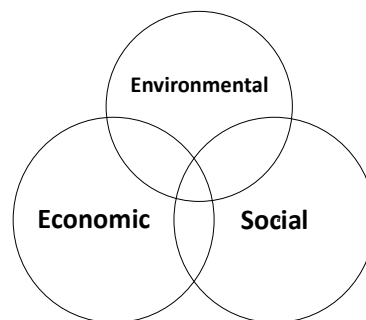


Figure 14 Aspects of sustainability

3.2 The First Pillar - Economic Aspects

3.2.1 *Conceptual stage and field development cost*

Here, we will focus on the field development costs, which occur in the conceptual stage under construction and engineering phase. In this phase, due to the lack of information, there are various uncertainties; one of the major concerns relates to OPEX (operating expenditure) due to materials and equipment selection. The current practice, for oil and gas operators, especially in the Arabian Gulf countries, is focused on the technical and engineering feasibility and this ignores any consideration of the life cycle costing of the alternatives or sustainability. The decision criteria are based only on the engineering criteria; the current approach thus still lacks a strong basis for life cycle costing and aspects of sustainability. These limitations, and the improper selection of alternatives during this phase, comprise some of the major causes of the vast OPEX for topside facilities on offshore platforms. Referring to figure 4 in section 2.3. El-Reedy (2012, p.4) stated that front end engineering design (FEED), which is part of the conceptual stage is considered the most important stage of the field development timeline, where all project activities, components of each system, design requirement, transportation and installation methods are well defined, as well as the cost and schedule are prepared. Further, viable concepts, options, and conceptual design are evaluated and identified at this stage. Papavinasam (2014, 872) noted the importance of the FEED stage in designing and selecting the equipment, stating that the equipment will function properly during the service life if it is designed properly at the beginning of the project. He also mentioned that the selection of vendors, fabricators, materials, shipping and logistics for materials are all identified and included in the FEED process.

El-Reedy (2012, p.9) highlighted the need for the FEED stage, in which the following deliverables are provided:

- Basic design drawings for all components of the platform. These drawings should contain enough details to enable preparation of a cost estimation.
- Detailed design requirement, and environmental parameters (such as wave, ice, seismic, etc).
- Site information such as geotechnical report and water depth.

- Definition of all types of loads (dead load, live load, operating load, etc).
- Definition of the accidental loads such as dropped object and fire and explosions.
- Provide the classification of the materials.
- Provide design codes, regulation and recommended practice.
- Corrosion protection methods.
- Construction, transportation and installation methods.
- Any other requirement that will affect the detailed engineering design in the later stage. Or any other information for the purpose of cost estimation at this stage.

From the above, we can note the importance of the conceptual stage in the field development cost. El-reedy mentioned that 2-3% of the total installed cost (TIC) is consumed in FEED stage; this stage has the highest impact on the cost, schedule and quality. El-Reedy (2012, p.5) emphasises the importance of FEED stage on total installation cost (TIC), pointing out that efficient project management in the execution stage has an effect on the (TIC), but not as much as the FEED stage. Moreover, he mentioned that there are many economic factors affecting the selection of the platform concept, such as discount rate, inflation and time value of money. El-Reedy (2012, p.8) emphasised that these economic analyses should be undertaken and considered. According to Papavinasam (2014, p.872), the feasibility of the project from both the economic and technical point of view is determined in FEED and the life cycle costing can be executed at this stage. He highlighted the importance of specifying the materials during the FEED process mentioning that if due diligence is not applied to materials selection during the FEED process, then premature failure may occur. Thus, in the following, value engineering and life cycle costing methods will be discussed in detail.

3.2.2 Value engineering

The history of value engineering goes back to the Second World War when the General Electric Company (GEC) assigned a task to one engineer called L.D. Miles, to find a more effective way to improve product value. In 1947, Miles initiated the concept of value analysis (VA). This concept was starting as value analysis until 1954 when the Bureau of Ships within the Department of Defense approved this technique to improve

their cost in manufacturing ships and they changed the name from value analysis to value engineering. Since then, the term “value analysis” has been used when the technique is applied on an existing product, and the term “value engineering” is used when it is applied at the design stage. In 1960 Miles was the first president of Society of American Value Engineers (SAVE). In 1961 he wrote his first book titled “*Techniques of Value Analysis and Engineering*”. In 1970 the US Congress then recommended the use of value engineering in federal highway projects and General Service Administration (Mukhopadhyaya, 2009, p.2).

3.2.3 Concept of value engineering

L.D. Miles defined the VA, as cited in Mukhopadhyaya (2009) as “An organized creative approach that has for its purpose the efficient identification of unnecessary cost, that is, cost that provides neither quality nor use nor life nor appearance nor customer features”.

SAVE Internationals (2007) states that value methodology is commonly applied under the terms of value analysis (VA), value engineering (VE), and value management (VM). This is defined as a “systematic process used by a multidisciplinary team to improve the value of project through the analysis of its function”. Here, SAVE used three different terms these are: *Value Analysis, Value Engineering and Value Management*. The difference between the three different terms refers to who the value methodology should be applied by, and when it should be applied. Value analysis is defined as “ the application of the value management on existing product or service to achieve value improvement”, while value engineering is defined as “ the application of the value methodology to a planned or conceptual project or service to achieve value improvement”, and value management is defined as “ the application of the value methodology by an organisation to achieve strategic value improvement”.

Al-Yousefi (2007) defined value engineering as “an organized team effort aimed at analyzing the function and quality of projects in order to generate practical cost effective alternatives that meet customer requirements”. He mentioned that the VE concentrates on effectiveness through stating goals, requirements and objectives of projects, and then it defines the quality feature that makes the product more acceptable. After that the VE proposal with the lowest possible life cycle cost will be generated. Al-Yousefi also presented the three main pillars of value engineering: function analysis, cost, and quality

(refer to figure 15 below). Therefore the balance between function, cost and quality is very important in achieving value engineering. In other words, the aim of value engineering is not cost cutting, but achieving quality with lowest possible cost. As we are focusing on the conceptual stage of the projects in this research, the term Value Engineering will be used.



Figure 15 Pillar of Value Engineering (Al-Yousefi, 2007)

Austin and Thomson (1999) also illustrated that value management and value engineering are indeed two different terms; the value management process can be applied at the beginning of projects, whilst value engineering occurs in the later stages of projects. They indicated that there is a concern about satisfying the requirements of the client and as such they proposed integral value engineering (IVE) as a continuation of value engineering to address the value within the ongoing design activities and especially in the later stages of the project delivery process. In 2001, Thomson and Austin mentioned that this practice was developed by Integrated Collaborated Design, a collaboration by Loughborough University, AMEC Capital Projects Construction and eleven supply organisations. To support this approach (IVE), two mechanisms were suggested – value adding tools and value adding toolbox – however, it was also mentioned that these mechanisms are useful for commercial organisations which is not the case here in this research.

Austin et al. (2002) further mentioned that value engineering is distinguished from VM; value engineering is linked to the client criteria, which is defined during the VM process, and value engineering is focused on the design stage and how the engineering teams can develop the best possible value solution considering cost and quality. They highlighted the importance of the conceptual phase as the most vibrant and creative stage of the overall design process. However, collaborative working between the disciplines may create misunderstandings of the conceptual design process. They also discussed several research projects with a view to improving the planning, control and management of building design, such as the Managing Design Process (MDP) and Integrated Collaborative Design (ICD). The findings from these researches were that designers must improve their understanding of the process and the contractors must be guided by the design process and how it interfaces with the construction.

Thomson et al. (2003) highlighted the role of stakeholders in defining project values, which influences the quality of the work and the designer's expectations. Quality and values may be misunderstood if not defined properly from the beginning. Therefore, they proposed a Design Quality Indicator (DQI) assessment in the project management system to ensure the delivery of stakeholder values during the design stage. Mills et al. (2009) noted that there is a need for tools to facilitate a dialogue of value and human values and integrate them into construction. In oil and gas, and especially in the upstream sector, as is mentioned above in section 3.2.1, the conceptual phase is lacking such frameworks to integrate the value with the best economic and quality option; oil and gas is still behind this and it needs to consider these aspects taking into consideration the stakeholder opinions at early stage of project in order to mitigate the environmental consequences as well as the vast OPEX cost.

3.2.4 Timing of implementation of value engineering

Value engineering shall be applied in the early stages of the project in order to achieve the required functionality with lowest possible cost and highest quality. According to Atabay and Galipogullari (2013), VE should be performed as early as possible to maximise the results. Moreover, they mentioned that if the VE is applied in later stage, two things will increase: the investment required to implement, and resistance to change. Kelly, Male and Graham (2015, p.55) mentioned that value studies within VM or VE can be conducted at

any point during such project phases, strategic briefing, concept design and detailed design. SAVE International (2007) noted that VE can be applied during any stage of a project's design cycle, and it can be applied more than once in the life of the project. However, the greatest benefit can be achieved by applying VE at the conceptual design phase before major development and design are completed (refer to figure 16). Zainul-Abidin and Pasquire (2005) highlighted the importance of integrating sustainability within the value management process at the early stage of the project; this integration will give the VM experts the opportunity to minimise environmental and social damage through selecting sustainable materials and to determine themes of the design and construction.

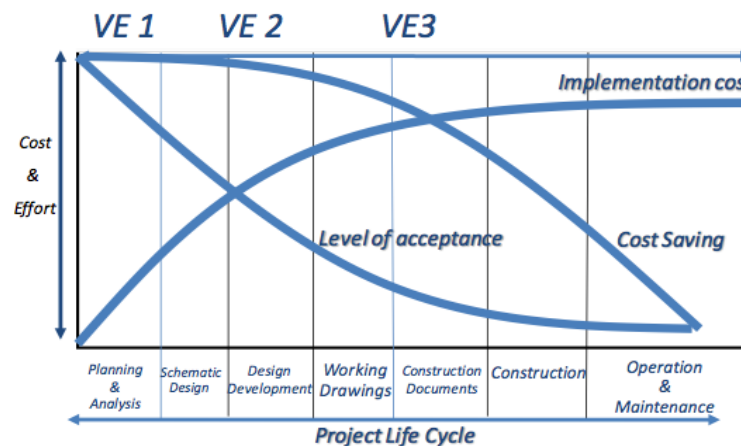


Figure 16 Time of implementation of the value engineering (Al-Yousefi , 2007)

In terms of applicability, SAVE International (2007) mentioned several places where the value methodology can be applied: (1) construction projects phases (concept development, preliminary design, final design, procurement and construction phases); (2) manufacturing products (in the design stage or manufacturing process); (3) in the business systems and process; and (4) in the service organisation. In the next section the value methodology will be presented.

3.2.5 Value engineering phases and methodology

Value studies can be one of two types: proactive development of alternatives or review existing projects. Value study comprises of three main stages: (1) pre-workshop (preparation or orientation stage); (2) workshop stage (execution of the job plan); and (3) the post-workshop stage (documentation and implementation) (SAVE, 2007; Kelly, Male and Graham, 2015, p.55).

The pre-workshop or preparation stage seeks to obtain the document required and all information related to the project, identifying value members and determine the scope and objectives of the value study. The workshop stage is the most important part of the value study, where the analysis and solutions are developed. According to SAVE (2007) this stage comprises six job plan phases: (1) information phase; (2) function analysis phase; (3) creative phase; (4) evaluation phase; (5) development phase; and (6) presentation phase (refer to figure 17). The implementation stage is the last of the three main stages of the value methodology, where the accepted solutions from the previous stage are implemented; action and implementation plans are also created and managed during this stage to make sure that all solutions are taken forward.

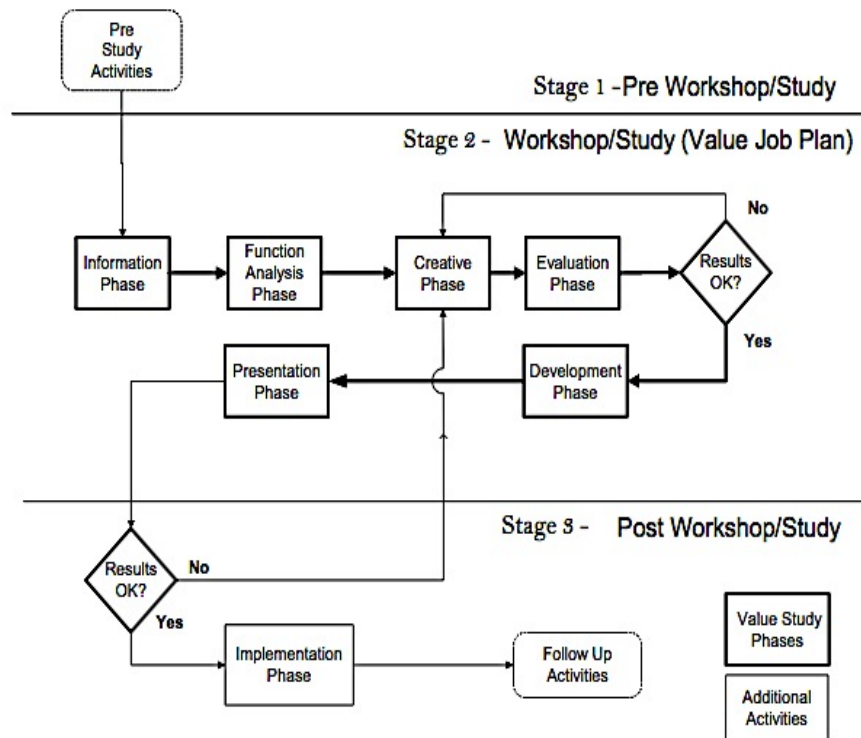


Figure 17 Value methodology (SAVE International, 2007)

As the workshop stage is the core of the VE methodology, this research is focusing on the *function phase*, *creative phase* and *the evaluation phase* of the workshop stage.

3.2.5.1 Function analysis phase

In this phase, the function of the project, product or service is identified and analysed. Function is defined in SAVE International (2007), as “The original intent or purpose that a product, service or process is expected to perform”. Kelly, Male and Graham, (2015, p.97) defined the function as “a characteristic activity or action for which a thing is specifically fitted or used, or for which something exists”. They emphasise that there is a link between function, specification and performance, and this means that when something is designed in accordance with the requirement of use, then it can be termed functional. This phase comprises of two main activities: (1) function identification and classification; and (2) function analysis. In the following sections, the tools and methods of the function identification and function analysis will be described.

3.2.5.1.1 *Function identification and classification*

Function identification is a significant feature of the value methodology, as value study cannot be performed and managed without understanding the functions. The description of the function does not require a measure of efficiency or cost as these are specification matters that follow the determination of function (Kelly, Male and Graham, 2015, p.98).

Random function identification technique is used to determine the functions of the project or product. In this technique the value team determine the functions randomly and generate a simple list of all functions. SAVE (2007) stated that with this technique the value team can use a two-word “active verb”, and “measurable noun” to determine the list of functions. According to Kelly, Male and Graham (2015, p.98), the most precise description of function is achieved when it can be expressed in groups of two words, an active verb and a descriptive noun. An active verb is more important than passive verb, where the active verb implies strong action and the passive verb implies weak action. A descriptive noun is generally limited and conducive to specification. Rich and Holweg (2000) stated that the question to be answered is “ what functions does this product undertake?” Mandelbaum et al. (2012, p.14) mentioned that the verb should answer the question “what does it do”, such as protect, emit, detect or launch. The noun should answer the question “what does it do this to” as the noun tells what is acted upon; a measurable noun combined with an active verb provides a descriptive of a work function such as generate electricity, detect movement and so forth. Moreover, they mentioned that there are several advantages to defining a function in two words: (1) the problem is broken down into simple elements when using two words, hence avoiding a combining function; (2) the possibility of faulty communication or misunderstanding will be minimised when using two words; (3) this focuses on the function rather than on the item; (4) encourages creativity; and (5) facilitates the comparison.

The function is classified in all researches into basic and secondary function. SAVE (1998) stated that basic function is the “primary purpose for which the item or service was designed when it is operating in its normally prescribed manner”, while the secondary function is “the one that support the basic function”. Kelly, Male and Graham (2015, p.99) provided a similar meaning, defining the basic function as “the performance characteristics that must be obtained by the chosen technical solution”, whilst describing

the secondary function as “the function that assist the performance of the basic function”. Mandelbaum et al. (2012, p.16) further extended the definition so that basic function answers the question “what must it do?”, and so the secondary function answers the question “what else does it do?”. In the value study we could have more than basic function. SAVE (1998) emphasised that the most common method to classify the function is to list all the physical parts of the project or product and then attempt to define the function related to each part. It further stated that the function definition will differ from one value team to another, but the most important is the understanding of functions by the value team.

3.2.5.1.2 *Function analysis techniques and tools*

In function analysis phase the method of analysing the function is identified based on the client requirements. There are many techniques and approaches for analysing the functions and linked between them. The famous methods are: (1) function hierarchy logic model; (2) function analysis system techniques (FAST); and (3) multiple criteria decision analysis (MCDA).

The function hierarchy logic model is a tree style model where the functions are broken down into sub functions. This technique requires understanding the hierarchy of importance when dealing with the strategic project level. In addition, in some situations the value team will not be able to organise the functions into a hierarchy, for instance, when functions are of equal importance (Kelly, Male and Graham, 2015, p.101). Moreover, this technique is more applicable when cost function relationship is required.

Mandelbaum et al. (2012, p.20) mentioned that the FAST technique is applicable for a complete project, programme or process requiring interrelated steps or a series of actions. Further, this can be a difficult and time-consuming effort and should not be used in the following cases: (1) if the scope is narrow and constrained; (2) if the team value has no previous experience in how to use FAST; (3) if there are multiple secondary functions; and (4) if the situation is not well understood. Kelly, Male and Graham (2015, p.477) supported Mandelbaum’s view, mentioning that FAST is used with some reservation and it is a very difficult technique to use in workshops. They suggested to use different approaches, and emphasized that the use of the verb-noun statement provides the clarity of function requirement.

Both techniques – FAST and the function hierarchy logic model – are cost function relationships; cost function relationship is not always the one required, many projects need functions related to time, weight or quality and so forth. Thus these methods cannot be adopted for selecting materials or equipment for offshore topside platforms as these methods are unable to weight and score the required functions and criteria.

According to Arroyo, Tommelein and Ballard (2012), stakeholders need to engage the proper decision making process when deciding which alternative or materials are more sustainable than others. Multiple Criteria Decision Analysis (MCDA) methods are used by stakeholders for evaluating alternatives. Belton and Stewart (2002) mentioned that MCDA is “a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups to explore decisions that matter”. The Analytic Hierarchy Process (AHP) for decision-making was developed by Saaty in 1990; this makes use of pair-wise comparisons of criteria. Thurston (1990) explained that it is necessary to assign preference to multiple attributes via weighted averages. In 1999, Suhr developed Choosing by Advantages (CBA), a system that develops the comparison based on the advantages of the alternatives by assigning numerical weight to the advantages (Parrish, 2009). Arroyo, Tommelein and Ballard (2012) argued that although it may appear that all MCDA methods are equal and it is up to the end user to select any one, some methods, such as CBA, are superior to others. Arroyo, Tommelein and Ballard (2012) noted that the process of weighting factors is subjective and this lead to conflicting questions. Suhr (1999) and Arroyo, Tommelein and Ballard (2013) also indicated that decisions in the CBA method are made based on the advantages rather than advantages and disadvantages, in order to avoid double counting. CBA, however, is not without disadvantages and weaknesses. Abraham, Lepech and Haymaker (2013) stated that for complex decision problems, the CBA method is inefficient and it inadequately clarifies the decision rationale. They emphasised the need for future research to implement effective tools for pre-constructing decision making on lean projects. Some studies further show that there is a feeling among some team members that the important scores can be manipulated, especially when the project is related to sustainability and innovation, which are not well defined. Similarly, Arroyo, Tommelein and Ballard (2015) indicated that CBA is inappropriate when decision making is required in conceptual building design,

and it is also invalid when there is uncertainty in the process of identifying the attributes of alternatives. Karakhan, Gambatese and Rajendran (2016) noted the difficulty of using the CBA method as it can be complex and time consuming. Schottle, Arroyo and Georgiev (2017) argued that the CBA method is not widely used in the architectural engineering and construction (AEC) sector, instead only being used in the design process. In the same context, Kpamma et al. (2017) agreed that the CBA method is an emergent tool and underdeveloped in terms of practice and research.

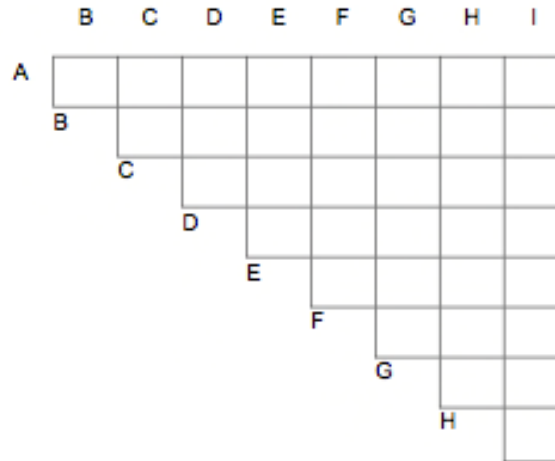
As CBA method is still new method as well as one of the objectives of this research is to develop a simple and practical framework to encourage engineers to use it without any complexity. The numerical method (paired wise comparison) was adopted for this study. However, CBA can be used in future research and compare the results with this research. Paired wise comparison method will be discussed in the following section.

3.2.5.1.3 Paired wise comparison method

The paired wise comparison method is a weighting and scoring technique. Kelly, Male and Graham (2015, p.535) stated that this technique is relevant, particularly in value engineering analysis in situations where a decision needs to be made in selecting an alternative among competing options and where the best option is still not identifiable. The first step in the paired wise comparison method is to determine the criteria by which the options are to be judged. The value matrix is used in weighting the criteria (functions) see figure 18. We have to remember that this activity is a group and team effort. The process is as follows:

1. All criteria are listed and an identification letter will be assigned to each criterion (A, B, C, etc.).
2. Each criterion is compared for importance and preference with each other criterion based on the following measures: 4 = major importance and preference; 3 = medium preference; 2 = minor preference and importance; 1 = slightly preference. So, for example, this will reflect how much criterion A is more important than B on a score of 1 to 4.
3. The procedure will be repeated until all pairs have been compared with one another.

4. Lastly, the score for each criterion will be found by adding all numbers for that particular criterion.



Criteria	A	B	C	D	E	F	G	H	I
Total Score									

Figure 18 Value matrix

So, the weighted criteria as output of this phase will be used later in the evaluation phase. SAVE (1999) stated that the numerical methods, such as paired wise techniques or function analysis method provide an opportunity to identify the best opportunities for value improvement in the following phases of the value methodology job plan. It will be shown later how these weighted criteria used in the evaluation phase, refer to section 3.2.5.3.

3.2.5.2 Creative Phase

The creative phase generates and develops a list of alternative technical solutions to achieve the identified functions from the previous phase. The value team tries to provide as many ideas as possible, which will be screened and evaluated in the next phase. All generated solutions during this phase are applicable, however, there is only one optimum

solution among the alternatives. Usually this phase starts with establishing *ground rules* followed by *brainstorming* technique.

According to Mandelbaum et al. (2012, p.25) citing Parker, E. that ground rules for idea creation can be summarised as follows:

- Do not judge all the new ideas at the same time; however, hold the judgment until the evaluation phase.
- Generate as many solutions as possible, and focus on quantity not quality.
- The greater the number of ideas considered, the greater the likelihood of an option that leads to better value.
- Expand the ideas as they are generated, and include them as new ideas.
- Do not discard or criticise any ideas even if they appear to be impractical.

Brainstorming is a free-association technique that groups use to solve specific problems by recording unstructured ideas generated by the group; it is primarily based on the premise that one idea will suggest others, which suggest even more (Mandelbaum et al. 2012, p.25). The advantage of holding a brainstorming exercise as part of the value study is that by the time brainstorming is reached in the value workshop agenda, the team has coalesced under the guidance of the value team leader. Moreover, the team is familiar with the subject matter by this point, since the team has created the functions that are to be the subject of brainstorming (Kelly, Male and Graham; 2015, p.175).

Kelly, Male and Graham (2015, p.175) provided the following rules and considerations for conducting a structured brainstorming exercise as part of a value study:

- The brainstorming is a group activity facilitated by the value team leader.
- The size of the brainstorming team should not exceed 12, otherwise it is advisable to break it down into smaller cross discipline teams facilitated by a member of the team.
- The problem to be resolved is expressed clearly and briefly.
- Motivation and engagement between the team members are very important.
- Each function or component is examined in turn.

- No judgment of any ideas is allowed until the creative phase is completed.
- No criticism by body language or voice is permitted during the exercise.
- The most important element is the quantity of the idea created: the greater the number of ideas, the more opportunities to develop an optimum idea.
- To keep the problem manageable, take one function or criteria at a time.
- Document and record all ideas during the brainstorming exercise.

There are different techniques that are a variation on the brainstorming theme: ***reverse brainstorming, gordon technique, and checklist***. *Reverse brainstorming* involves finding the opposite of what you are going to achieve, or generating a reverse solution. For instance, instead of asking, “How do I solve the problem”, ask, “How can I cause the problem”. After all negative statements are created; the value team leader will ask the team members to create positive statement to counter the negative statement. *Gordon technique* is a brainstorming session in which no one except the team leader knows the exact nature of the problem. The purpose of this is to remove the group certainty of one right answer within a specific context. The team members will be given a similar scenario of the main function to divert their attention. The *checklist technique* generates ideas by comparing items on a prepared list against the problem under consideration (Kelly, Male and Graham, 2015, p.177).

3.2.5.3 *Evaluation phase*

The objective of this phase is to evaluate and analyse the generated idea or alternatives to the creative phase. Kelly, Male and Graham (2015, p.132) stated that during this phase the large numbers of alternatives from the previous phase are reduced through a logical process of option reduction. A weighting and scoring matrix is useful in some situations, where the technical solution with the highest score is taken for further technical development. SAVE (2007) mentioned several techniques could be used in the evaluation phase among them are ***advantages versus disadvantages*** and ***value metrics***. Al-Yousefi (2007) mentioned that this phase is designed so that the most important alternatives are isolated and prioritised. Moreover, he emphasised the importance of the weighted and numerical evaluation techniques in this phase. Therefore, evaluation matrices methods are adopted for this research.

3.2.5.3.1 Evaluation matrices

The evaluation matrix, which is part of the scoring and weighting technique, is used to evaluate and rank several options and alternatives based on weighted criteria. As mentioned earlier, this technique is easy to use and very useful and practical as well as not requiring more time to perform the analysis. The following procedures could be adopted to perform the analysis:

1. Since the evaluation of the alternatives will be against weighted criteria (function requirement), the weighted and prioritised criteria from the function phase will be used here (Refer to section 3.2.5.1.3).
2. Listing the advantages versus the disadvantages for each alternative can help the value team to judge between the alternatives.
3. Each alternative will be assigned a score (on a range 1 to 5, where 5 is excellent and 1 is poor) reflecting how well the alternative satisfies each criterion.
4. Once all alternatives have been scored against all criteria, these scores are then multiplied by the criterion weighting which has been developed in the functional phase.
5. The total score is then calculated for each alternative; ranking will be performed based on the total score, the greater the score, the higher the ranking.

Table 4 shows how the evaluation matrix works, X represents the weighted factor from the function analysis.

Table 4 Evaluation matrix

	Weighted criterion with assigned weight from function phase (x)				Total
	Criterion (1)	Criterion (2)	Criterion (3)	Criterion (4)	
Alternatives list	X1	X2	X3	X4	
Alternative one	Y = Score (1 to 5)				Summation of Y times (X1, X2, X3..)

Alternative two					
Alternative three					
Alternative four					
Alternative five					

3.2.6 Life cycle costing background

According to Bird (1986), the term “cost in use” was first applied in buildings in UK in the late 1950s by Stone. This concept considered the running cost instead of the capital cost only. Then, in the 1960s, officials from the US Department of Defense (DoD) noted that the total cost of the weapons system could increase by 75% or more over its lifetime due to operation and support costs. Hence, military procurement policies encouraged the development of life cycle engineering and costing concepts, where more consideration was given to total cost of manufacture, operation, use and maintenance (Gupta and Chow, cited in Christensen et al , 2005, p.251).

In 1971, the building maintenance cost information service (BMCIS) was developed by the Royal Institution of Chartered Surveyors as a method of collecting operational and running cost data. This was followed by the publishing of “Life Cycle Costing in the Management of Assets” by the UK Department of Industry in 1977 (Boussabaine and Kirkham, 2004, p.5).

AL-Busaad (1997) reported that in 1972, the term LCC was also used in the construction industry, as reported by Alphonse J. Dell’Isola and used by the American Institute of Architects in 1977 when it published a set of guidelines intended to present the basis of the LCC technique as well as an indication of where LCC fits best into the process of planning and design.

The term was further used in the field of energy conservation in 1978 when a guide for selecting energy conservation projects based on life cycle costs for public buildings was presented by the Department of Commerce, USA, followed by a life cycle costing manual for the Federal Energy Management Program in 1980 (Ruegg, 1980). The term was

formalised further when the American Standard for Testing Material (ASTM) developed a method for life cycle costing in 1983. In 1992, LCC was a concept understood by building economists throughout the world, and a standard was developed in the UK under the British Standard BS3843. In 2000, LCC was then incorporated into ISO 156868-1 (Boussabaine and Kirkham, 2004, p.5&6).

In short, from the 1970s to the beginning of the 1980s, the LCC analysis was applied in the military field. Then spread to other industries such as electrical power plants, oil and chemical industries, and aircrafts manufacture (Kawauchi & Rausand, 1999, p.5).

3.2.6.1 Definition of life cycle costing

According to Boussabaine and Kirkham (2004, p.5) one of the earliest definitions of the LCC was the one provided by the UK Department of Industry in 1977 as:

“A concept which brings together a number of techniques – engineering, accounting, mathematical and statistical – to take account of all significant net expenditures arising during the ownership of an asset. Life cycle costing is concerned with quantifying options to ascertain the optimum choice of asset configuration. It enables the total life-cycle cost and the trade-off between cost elements, during the asset life phases to be studied and for their optimum selection use and replacement”.

In 1992, LCC was then defined in the UK British Standard BS 3843 as:

“The costs associated with acquiring, using, caring for and disposing of physical assets, including feasibility studies, research and development, design, production, maintenance, replacement and disposal; as well as all the support, training and operations costs generated by the acquisition, use, maintenance and replacement of permanent physical assets”.

In 2000, the definition was revised and merged into ISO 156868-1 (2000), highlighting the business dimension in LCC and its purpose by stating its definition as:

“A technique which enables comparative cost assessment to be made over a specified period of time taking into account all relevant economic factors both on terms of initial cost and future operational costs”.

This is a broader definition since it includes all of the relevant economic factors that contribute to LCC.

3.2.6.2 Life cycle costing and whole life cycle costing

ISO 15686-5 (2008) has distinguished between life cycle costing and whole life cycle costing, providing the following definitions: **life cycle costing** as: “a methodology for systematic economic evaluation of life-cycle costs over a period of analysis, as defined in the agreed scope”, **whole life cycle costing** as: “a methodology for systematic economic consideration of all whole life costs and benefits over a period of analysis, as defined in the agreed scope”.

The chart below in figure 19 shows the difference between the LCC and WLCC. Life cycle costing is considered a part of the entire whole life cycle costing. LCC includes mainly the construction and operating cost, while WLCC includes other costs such as income, taxes and lands in addition to LCC. Kelly, Male and Graham (2015, p.355) noted a similar meaning: the LCC costing is focused only on the construction, operating and the maintenance of the asset whereas the WLCC includes user and client costs such as project financing.

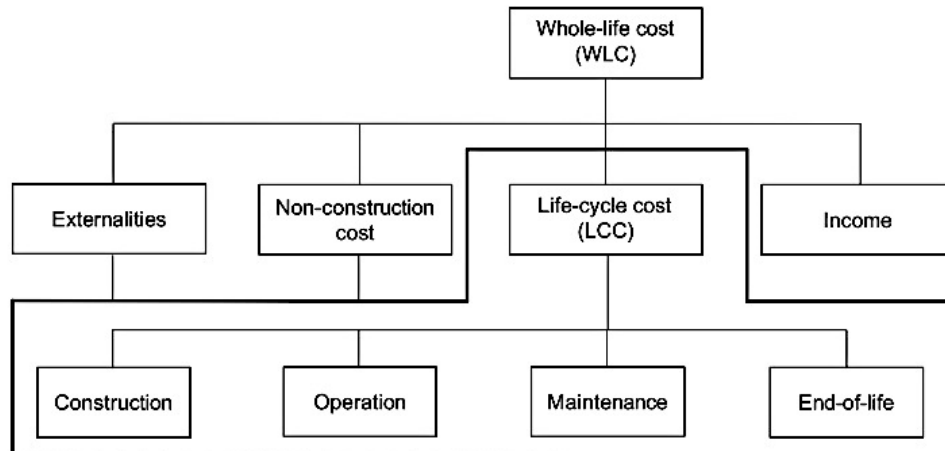


Figure 19 Differences between LCC and WLCC, Source ISO15686-5 (2008)

3.2.6.3 Importance and time of implementation of life cycle costing

Life cycle cost analysis is very important for any project as it assists the decision maker in selecting the best alternatives among certain number of alternatives. The need for the life cycle cost analysis has increased due to the increase in ownership, operating, maintenance, and replacement costs. Moreover, new products are being introduced to the market which make the competition high. The rise in inflation is another reason for considering the life cycle cost analysis.

According to Kawauchi and Rausand (1999, p.8) that life cycle cost analysis is an important part of any feasibility or conceptual study in any project. Moreover, LCC analysis can be carried out in any and all phases of the project's life cycle, helping the decision maker by providing an economic input. However, the earlier the analysis is performed, the better the decision attained; they have pointed out that 80% of the LCC is based on decisions that are made within the first 20% of the life of the project.

Kishk et al (2003, p.6) agreed with Kawauchi and Rausand and stated that whole life cycle costing can be done in any stage of the project, as shown in figure 20, but it is more effective if it is done in the early stages when options are open for investigation and there is still a chance to make the right decision and influence cost. According to Kirk and Dell'Isola (1995) and Mackay (1999), cited in Kishk et al. (2003, p.6) 80-90% percent of the running, maintaining and repairing cost is determined at the design stage of any project.

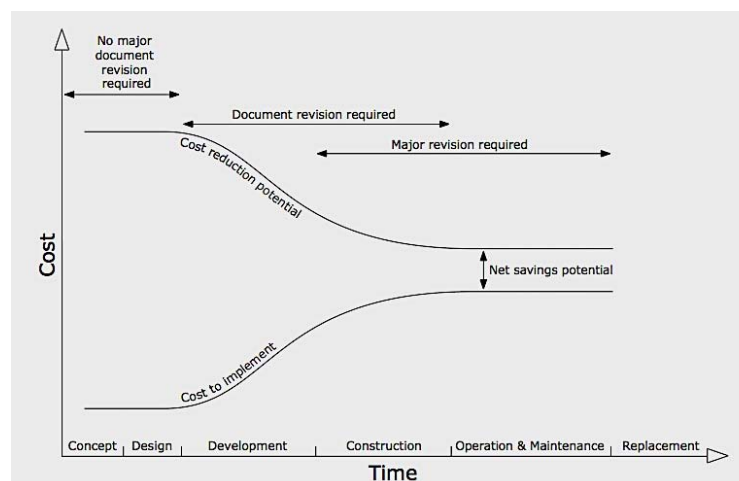


Figure 20 Time of implementation of LCC (Kishk et al., 2003, p.6)

Boussabaine and Kirkham (2004) emphasised the importance of considering the LCC analysis at the conceptual stage, as it will help the owner and cost planner in making a strategic decision based on the output of the results. Moreover, they suggested that all types of costs should be considered during this stage as any bad decision could lead to lower quality and a large maintenance and operation cost. ISO 15686-5 (2008) highlighted the influence of applying LCC analysis during the planning phase, stating that 80% of the operation, maintenance and replacement costs can be influenced in the first 20% of the design process, as shown in the figure 21. Koch et al. (2016) highlighted the importance of applying life cycle costing in determining the actual cost of corrosion; life cycle costing provides a long term view in the expenditures by determining the capital cost (CAPEX), operating cost (OPEX), indirect cost and materials residual cost.

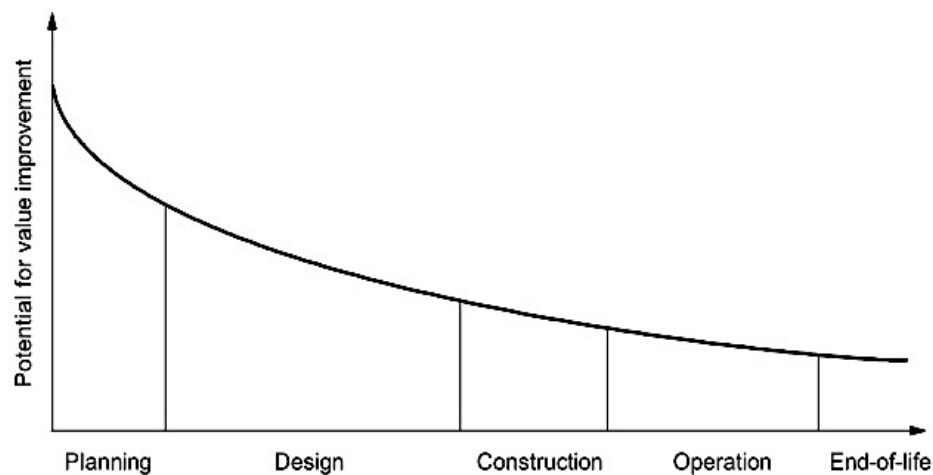


Figure 21 Scope to influence LCC savings over time (ISO 15686-5, 2008)

3.2.6.4 *Cost component of life cycle costing*

The main cost components include **capital** cost, **operating** cost and **residual** cost. The **capital** or **acquisition costs** refer to all expenses required to get a project in place and ready for start-up. This includes, but is not limited to land acquisition, design and engineering, material procurement, construction, installation and commissioning. **Operating costs** are incurred due to operating the facility during its lifetime. This includes : (1) administration costs such as facility cleaning, financing, security and logistics; (2) energy costs such as fuel and labor costs associated with energy and required

to operate the facility; (3) maintenance costs associated with maintaining the systems and keep it in its original state such as spare parts, preventive maintenance and unscheduled maintenance; and (4) replacement costs for any of the facility elements that have a life estimation shorter than the major components. Finally, the **residual cost** is the sales value of the assets at the end of the project life (ISO 15686-5, 2008; Ostwald, 2001; Assaf, 2008).

There are several economic evaluation methods and techniques that can be used in the life cycle cost analysis. The basic concept and methods will be reviewed in this section. The concept of time value of money and then the economic evaluation methods will be presented.

3.2.7 Concept of time value of money

Flanagan et al. (1989) explained the concept of time value of money as “a given sum of money has a different value depending upon when it occurs in time”. Another definition is provided by Boussabaine and Kirkham (2004) as ‘present capital is more valuable than a similar amount of money received in future’.

Based on the above, in order to account for the time value of money, all expenditures and revenues must be converted into a common denominator. The common point in time may be present, future, or even annual, and this is achieved by discounting the cash flow streams (Assaf, 2008; Al-Khalil, 2008). Here, we will highlight the components of the time value of money concept, which include interest rate and the cash flow diagram.

3.2.7.1 Simple and compound interest

Interest can be defined as the rental amount charged for the use of money, very simply it is the increase over the original cost over a specific period of time. Ardalan (2000, p.6) mentioned that “the rate of interest is the percentage of the money you pay for its use over a time period”, also outlining different names for the interest, such as cost of money and value of money.

The interest charged is considered as a cost to the borrower and revenue for the lender. The amount of loaned or borrowed funds is referred to as “**the principal**”, and the interest

rates in the market are linked to the “**prime-lending rate**”, which stems from the **discount rate**, which is fixed by the country’s central banks (Mian, 2011, p.39).

Mian (2011) stated that simple interest is calculated by using the principal only over a fixed period, while the compound interest is the interest accrued on both the principal and the accumulated interest from previous periods.

$$\text{Simple Interest (I)} = (P) \times (n) \times (i), \quad \text{Eq (1)}$$

$$\text{Compound Interest (I)} = (P) \times (1+i)^n \quad \text{Eq(2)}$$

Where:

I = interest earned; P = principal amount; n = number of periods; i = interest rate.

3.2.7.2 *Cash flow diagram*

A cash flow diagram is a graphical description of a cash transaction over time. A cash transaction occurs at the end of each year and is either a cash receipt or cash disbursement. If receipts and disbursements occur in the same period, we can find a net cash flow, which is equal to the differences between the receipts and disbursement. Mian (2011) stated that the drawing of the cash flow diagram is very important because it helps to simplify complicated description problems. The following components are used in the creating of the cash flow diagram:

- The horizontal axis represents the period or t time.
- The vertical axis represents costs and benefits, where the downward arrows show cost and the upward arrows show benefits.

3.2.8 *Project economics and appraisal methods*

There are several analysis techniques used to select from the alternatives in terms of economic viability. Here, economic equivalence will be discussed first, followed by the economic appraisal methods.

3.2.9 Economic equivalence

According to Ardalan (2000, p.9), costs and benefits emerge at different points in time, so in order to make a decision on multiple alternatives, a common measure of performance is required. Mian (2011, 47), mentioned that in order to account for time value of money, all future expenditures and revenues need to be converted to a common point in time or a common denominator; this denominator can be present, future or annual. The discounting rate will be used to convert a present sum of money into its equivalent future sum or vice versa. Therefore, to perform the calculation for the time value of money and convert the sum of money from one denominator to another, we need a cash flow diagram, interest rate (discount rate), and mathematical equation or techniques. In the following section, economics appraisal techniques will be discussed (Ardalan, 2000; Mian, 2011; and Assaf, 2008).

3.2.9.1 Present worth value method

In this method all future costs and expenditures are discounted to present value. Net present value can be calculated by using the following formula:

$$Pv = F_n [1/ (1+i)^N] \dots\dots\dots Eq (3)$$

The above equation can be represented as:

$$P = F(P/F, i, N) , \text{ (find P given F)}$$

Where Pv = present value; F_n = future sum received at time n; i = discount rate; N = number of periods or years.

3.2.9.2 Future worth value method

In this method all present costs are converted to future value. Net future value can be calculated by using the following formula:

$$Fv = Pn (1+i)^N \dots\dots\dots Eq (4)$$

The above equation can be represented as:

$$F = P(F/P, i, N) , \text{ (find F given P)}$$

Where P_n = present value at time n ; F = future sum received at time n ; i = discount rate; N = number of periods or years.

3.2.9.3 *Equivalent uniform annual worth method (EUAW)*

In this method all costs (cash flows), which occur during the lifetime of an investment are discounted to a uniform series of cash flows over the lifetime of the investment. The formulae are used to calculate the EUAW :

1. When A is required and F is given:

$$A = F [i / ((1+i)^N - 1)]; \dots\dots\dots\text{Eq (5)}$$

$$\text{Or } A = F(A/F, i, N)$$

2. When A is required and P is given:

$$A = P [i (1+i)^N / ((1+i)^N - 1)]; \dots\dots\dots\text{Eq (6)}$$

$$\text{Or } A = P(A/P, i, N)$$

In addition, equivalent uniform annual series can be converted to present or future value by using the following formulae:

1. When F is required and A is given:

$$Fv = A [((1+i)^N - 1) / i]; \dots\dots\dots\text{Eq (7)}$$

$$\text{Or } F = A(F/A; i, N)$$

2. When P is required and A is given:

$$Pv = A [(1+i)^N - 1 / i (1+i)^N]; \dots\dots\dots\text{Eq (8)}$$

$$\text{Or } P = A(P/A, i, N)$$

Where Pv = present value; Fv = future value; i = discount rate; N = number of periods or years; A = EUAW

3.2.9.4 Internal rate of return

The rate of return is the break-even interest rate (*i*) at which the present worth of a project is zero (Park, 2004, p.221). Thus, the interest rate makes the equivalent receipts of an investment equal to the equivalent of disbursements; or, alternatively, the interest rate makes the net present value or the equivalent uniform series for any cash flow equal to zero. Refer to equation (9) below.

Park (2004, p.234), noted several names are used to refer to rate of return, such as yield to maturity, marginal efficiency of capital, and internal rate of return. However, internal rate of return (IRR) is used as a measure of profitability. Ardalan (2000) stated that the IRR should be greater than the minimum acceptable rate of return (MARR), which is specified by the investor as a minimum rate for the investment.

$$0 = P_v(i) = \sum^n F_t [1 / (1 + i)^t]; \dots\dots\dots Eq (9)$$

Where; *i* = IRR, *n* = number of periods; *P* = present value; *F* = Future value at year *t*.

3.2.9.5 Simple payback period method

This method measures the time required or the number of years required to recover the initial investment or cost by simple calculation. This method ignores the concept of the time value of money. Usually it is used for quick comparison or when the interest rate is zero. The payback must satisfies the following equation:

$$\sum CF_t \geq 0, \dots\dots\dots Eq (10)$$

where CF = cash flow.

3.2.9.6 Discounted payback period method

Discounted method is similar to the simple payback period method, except for the fact that time value of money is considered in the calculation. The discounted payback method must satisfy the following formula:

$$\sum CF_t (P/F, i, t) \geq 0, \dots\dots\dots Eq (11)$$

where is CF = cash flow at the end of year t; P = present value; F = Future value; i = discounted rate.

3.2.9.7 *Effect of inflation on the cash flow*

Inflation is the decrease of purchasing power of money over time; this means that cost of an item increases over time. Deflation is the opposite of inflation; however, the inflation is more common in the real world and deflation rarely occurs (Park, 2004,p.114). Hence, here we will highlight the inflation effect on the cash flow analysis. As we know that the present value of the cash flow will be reduced due to inflation, therefore, most of the investors should consider inflation during their analysis of the cash flow in order to compensate for inflation. Moreover, the present value of any cash flow also is reduced due to the time of value money by the discount rate as discussed above. Here, due to the combination of these two factors, *adjusted discount method* is introduced and represented in the following formula:

$$(i') = i + f + (i \times f), \dots\dots\dots \text{Eq (12)}$$

Where (i') = adjusted discount rate; i = original (market) discount rate; f = inflation rate .

3.2.9.8 *Alternatives selection and decision making*

The assumption in selecting between several alternatives is that these are mutually exclusive, which means that choosing one alternative will exclude the others. According to Park (2004, p.161) the projects are classified into service or revenue projects when comparing mutually exclusive alternatives. Revenue projects are projects that generate revenue that depends on the choice of alternative, therefore the selection of alternatives will depend on the largest net gain, such as the highest present worth (**PW**), the highest future worth (**FW**) or the highest equivalent uniform annual (**EUAW**). In contrast, in the **service project**, the most important information is to know how much it will cost to install or select the alternatives, so the selection will be based on the lowest cost, in this case the lowest of PW, FW, or EUAW will be selected.

In the topside facilities projects for offshore platforms, all projects are considered service projects. Most of the projects are related to maintenance and replacement work, these include the spare parts for pumps, separators, turbines, tanks, piping systems, mechanical systems and others. (Refer to components of topside modules in chapter 3).

In order, to make the selection in terms of *present worth method* or *future worth method* as described above, the alternatives should have equal economic life. Otherwise comparing alternatives for unequal life span would mean comparing different total cost. To solve this problem we have to **equalise** the length of the cash flow or lifetime of the alternatives so that they will have the same planning horizon. This can be achieved by finding the lowest common multiple of the lives for the planning horizon. The other solution is to use the **EUAW method**, which doesn't require finding a common multiple of lives and can be applied directly; this is the main advantage of this method.

Internal rate of return method (IRR) has many difficulties and limitations. Further, it requires complicated calculations. A trial and error method is used to determine IRR in its calculation. Mian (2011, p.316) mentioned that there are limitations to using the IRR method, such as IRR cannot be calculated when cash flow is all positive or all negative. According to Park (2004, p.238), to apply the IRR method we need to classify the type of investment into simple or non-simple investment. The cash flows in the simple investment are negative and only one sign change in the net cash flow occurs. On the other hand, in the non-simple investment more than one sign change in the cash flow series occurs, so multiple interest (i) could occur in the non-simple investment. In terms of comparing between mutually exclusive projects by using the IRR method, projects with unequal lives should be treated in a similar way to the PW and FW methods by finding the lowest common multiple of lives for the planning horizon. The main problem in comparing mutually exclusive projects is that the highest IRR doesn't mean the preferred alternative as the IRR is a relative (percentage) measure and cannot be applied in the same way as the PW or EUAW, which are considered as absolute measure of investment worth. Therefore, to overcome this problem, the **incremental analysis** is required for the IRR method. Incremental analysis can be done by subtracting the cost of one alternative from the cost of the other and generating new cash flow showing the difference between the two alternatives. Then, the normal calculation will be applied to determine the IRR for the new cash flow (alternative 2 – alternative 1). If the IRR for

cash flow (alternative 2 - alternative 1) is greater than MARR, then alternative 2 should be selected. If the result shows less than the MARR, then alternative 1 should be selected. However, if the analysis shows that $IRR = MARR$, then either can be selected. Schade (2007) compared all economic methods in terms of the advantages and disadvantages (refer to table 5).

Table 5 Comparison of appraisal methods (Schade, 2007)

Method	What does it calculate	Advantage	Disadvantage	Usable for
Simple payback	Calculate the time required to return the initial investment. The investment with the shortest pay-back time is the most profitable one (Flanagan et al., 1989).	Quick and easy calculation. Result easy to interpret (Flanagan et al., 1989).	Does not take inflation, interest or cash flow into account (Öberg, 2005; Flanagan et al., 1989).	Rough estimation if the investment is profitable (Flanagan et al., 1989).
Discount payback method (DPP)	Basically the same as the simple pay back method, it just takes the time value into account (Flanagan et al., 1989).	Takes the time value of money into account (Flanagan et al., 1989).	Ignores all cash flow outside the payback period (Flanagan et al., 1989)	Should only be used as a screening device not as a decision advice (Flanagan et al., 1989).
Net present value (NPV)	NPV is the result of the application of discount factors based on a required rate of return to each years projected cash flow, both in and out, so that the cash flows are discounted to present value. In general, if the NPV is positive it is worth while investing (Smullen and Hand, 2005). But as in LCC the focus is on cost rather than on income, the usual practice is to treat cost as positive and income as negative. Consequently, the best choice between two competing alternatives is the one with minimum NPV (Kishk et al., 2003).	Takes the time value of money into account. Generates the return equal to the market rate of interest. It uses all available data (Flanagan et al., 1989).	Not usable when the compared alternatives have different life length. Not easy to interpret (Kishk et al., 2003).	Most LCC models utilise the NPV method (Kishk et al., 2003). Not usable if the alternatives have different life length (Flanagan et al., 1989).
Equivalent annual cost (ECA)	This method expresses the one time NPV of an alternative as a uniform equivalent annual cost; therefore, it takes the factor present worth of annuity into account (Kishk et al., 2003).	Different alternatives with different life lengths can be compared (ISO, 2004).	Just gives an average number. It does not indicate the actual coast during each year of the LCC (ISO, 2004).	Comparing different alternatives with different life length (ISO, 2004).
Internal rate of return (IRR)	The IRR is a discounted cash flow criterion which determines an average rate of return by reference to the condition that the values be reduced to zero at the initial point of time (Moles and Terry, 1997). It is possible to calculate the test discount rate that will generate an NPV of zero. The alternative with the highest IRR is the best alternative (ISO, 2004).	Result gets presented as a percent, which gives an obvious interpretation (Flanagan et al., 1989).	Calculations need a trial and error procedure. IRR can only be calculated if the investments will generate an income (Flanagan et al., 1989).	Can only be used if the investments will generate an income, which is not always the case in the construction industry (Kishk et al., 2003).
Net saving (NS)	The NS is calculated as the difference between the present worth of the income generated by an investment and the amount invested. The alternative with the highest net saving is the best (Kishk et al., 2003).	Easily understood investment appraisal technique (Kishk et al., 2003).	NS can only be used if the investment generates an income (Kishk et al., 2003).	Can be used to compare investment options (ISO, 2004), but just if the investment generates an income (Kishk et al., 2003).

3.2.10 Risk and uncertainty in life cycle costing

According to Mian (2011, p.30), uncertainty and risk are complementary concepts. He defined risk as “a situation where a project has a number of possible alternative outcomes, but the probability of each outcome is known or can be estimated. Uncertainty refers to a situation where these probabilities are not known or cannot be estimated”. Boussabaine and Kirkham (2004,p.142) noted that there are uncertainties about every estimate or input data that is to be used in the life cycle costing calculation. They mentioned that several factors contribute to uncertainties in the whole life cycle costing calculation; for example, uncertainties due to the following: project scope, replacement cost, time schedule, operation conditions and investment parameters such as tax, inflation and interest rate. They emphasise the importance of assessing these uncertainties, as they will affect the whole life cycle costing budget, as well as the actual cost allocated to running and operating the asset. Kishk et al. (2003) highlighted the uncertainty issues in whole life cycle costing, which are due to many factors such as operation cost, maintenance cost, inflation and discounted rate, as well as all future factors as the future is unknown. They pointed out the importance of considering the uncertainty in information and data for the successful LCC implementation.

Boussabaine and Kirkham (2004, p.57) classified the techniques for treating uncertainty in economic evaluation into three categories: (1) deterministic techniques such as sensitivity analysis and break even analysis; (2) quantitative or probabilistic techniques such as monte carlo simulation, fuzzy sets theory, and mean variance criterion; and (3) qualitative or scoring techniques such as risk matrix and SWOT analysis. The simplest and most famous method is the sensitivity analysis, which will be described in the following section.

3.2.11 Sensitivity analysis

Sensitivity analysis, as described by Kishk et al (2003) “a modelling technique that is used to identify the impact of a change in the value of a single risky independent parameter on the dependent variable”. According to Marshall, cited in Boussabaine and Kirkham (2004, p.74), sensitivity analysis is the measurement of economic impact

resulting from alternative values of uncertain variables that affect the economics of operating and maintaining a building.

Park (2004, p.361) mentioned that in the analysis of cash flows, some items have a greater impact on the final result than others, therefore the sensitivity analysis determines the impact of variation in the input variables on PW such as operating cost used to estimate cash flow. He also stated that the sensitivity analysis is sometimes called “what-if-analysis” because it answers such questions. The major advantage of the sensitivity analysis, as noted by Kishk et al (2003) is that it shows the strength of the ranking of alternatives.

3.3 The Second Pillar – Environmental Impacts

In order to understand the environmental and social impacts of topside facilities, this section explores first the topside facility components and systems in offshore fixed platforms. Following environmental Impacts of topside facilities on the environment, marine life and offshore workers are discussed. Recommendations on how to mitigate the potential impacts are also presented.

3.3.1 Topside facilities components

Oil wells are drilled from topside facilities in order to penetrate the oil reservoir underneath the seabed by using the drilling rig in a predetermined sequence. There are two types of wells: (1) oil production wells; and (2) injection wells. Injection wells are drilled to transport either water or gas into the reservoir to maintain the pressure in the reservoir and maximise the production by pushing the oil up towards the production wells. The next step after drilling is the completion of the well. Well completion consists of several steps, comprising (1) well casing; (2) well completion; and (3) installing the wellhead (casing head, tubing head and the Christmas tree) (Devold, 2013).

The oil either reaches to surface under natural pressure, or an artificial lift is required using pumps. The wellhead pumping unit or “Christmas tree” is used to pump the oil to the surface flowlines and then to the production facilities for separation (Nolan, 2014, p.29). In the following sections, the components of the processing and utility modules will be presented.

3.3.2 Processing module

The well fluids or stream contain crude oil, gas, water and other contaminants. Therefore, the first step is to split this mixture into the required components in the processing module.

3.3.2.1 Production separators

The first step after extracting the produced fluid from the wells is sending the mixture to the separators for processing by the flowlines; the purpose here is to separate the hydrocarbons, or mixture, into a different stream of water, gas and oil. The mixture is separated either by a two or three phase separator. The two-phase separator is used to separate the gas from the fluids, while the three-phase separator is used to separate the water from the fluid as well. In the three-phase unit the separator has three outlets: a gas outlet, a water outlet and an oil outlet (Holmager, 2010, p.50).

The separated water is routed to the produced water conditioning unit, while the gas is routed to the gas compression module for further processing. The separated oil is then sent to the second stage separator in order to reduce the amount of water in the fluid.

3.3.2.2 The coalescer and electrostatic desalter

After the separation stages, the oil is directed to the coalescer for final removal of water where the water content can be reduced to below 0.1%. In some cases, if the separated oil has a high amount of salt, an electrostatic desalter is placed after the first or second stage of the separation based on the gas oil ratio from the well (Devold, 2013).

3.3.2.3 Produced water treatment

The produced water from the separation process contains a small amount of oil and different materials. The produced water will be treated before it is discharged into the marine or re-injected into the reservoir to maintain reservoir pressure. The treatment system (after long processing) separates the remaining trace of oil and gas from the produced water, where the gas is routed to the flare system and the collected oil sent back

to the separators. The impact of the produced water on the environment will be discussed in later sections (NORSOK-P002, 2014; Devold, 2013).

3.3.2.4 Gas compression unit

A compressor is a device that conveys energy to a gaseous fluid to export it onshore. The gas separated during the separation stages loses a lot of pressure, so it has to be compressed before it is exported. The compressed gas can be: (1) exported onshore; (2) re-injected into reservoir to maintain the pressure; (3) used for gas lifts in the produced wells as the gas lift increases the production flow rate; and (4) used as fuel gas on the platform. Nonetheless, before the gas even reaches the compressor engine, it needs to be treated, gas treatment involves cooling and then dehydration. This process is done through the heat exchanger and the scrubber (Devold, 2013).

3.3.2.5 Heat exchanger

The temperature of the gas when it comes out of the separators is relatively high. The heat exchanger is used to cool the gas. Water and corrosion inhibitors are often used for this process.

3.3.2.6 Scrubber and dehydration

The separated gas may contain some fluid droplets and gas hydrates may also be formed during the process of the gas from the heat exchanger cooling. The gas hydrates block the flow of gases in the flow lines. In this case, the scrubber, which contains many layers of glycol, is used to remove this small amount of liquid or moisture from the gas and to prevent the formation of the gas hydrates (Devold, 2013).

3.3.2.7 Water injection

The purpose of water injection into the reservoir is to prevent the reduction of the pressure level in the reservoir and to push the oil towards the wells. The main sources for the water injection is produced water (which has been explained above), and this can be injected after the treatment. A secondary source is lifted seawater as is explained in the following section (NORSOK-P002, 2014; Devold, 2013).

3.3.2.8 *Lifted seawater*

The system includes lifting pumps that lift the seawater from below the sea level. As seawater contains solids and particles, the first step is to direct the seawater to a filtration process to remove all the solids and particles through both coarse and fine filters. To prevent the formation of bacterial colonies in the water injection flow lines, the water injection steam must also be treated. The treatment includes de-oxygenating, which represents the removal of the oxygen by adding oxygen scavengers and other chemicals like biocide, antifoam and corrosion inhibitors. The de-oxygenating takes place in a vertical vessel/tower called a de-aerator. After the treatment is completed, the steam is routed and mixed with the treated produced water and it is then pumped to the injection pipelines through injection pumps. The main components of the lifted seawater system for water injection are therefore: lifting seawater pumps; coarse and fine filters for the filtration process; de-oxygenating vessel (de-aerator) for removal of the oxygen; routed/booster pumps; and injection pumps (Devold, 2013).

3.3.3 *Utility module*

The main processes and operations on the offshore platform require several different utility systems to perform their processes. The main utility systems are explained below.

3.3.3.1 *Power generation*

Electrical power is required for all production operation on the platform. Power offshore is generated by gas turbines, which operate by using the fuel gas generated by the platform. Diesel is used offshore for some systems and operations like crane operation. Diesel is also used for essential and emergency systems that require 24 hour operation in the event of the main power failure (Myhre, 2001, p.9). In cases when the platform is located close to the shore, an AC power cable can sometimes be provided.

3.3.3.2 *Seawater system*

As aforementioned, after the treatment of the lifted seawater, and based on the operation requirements, the seawater can be used for many purposes and especially for cooling requirements like in a HVAC system, air compressor coolers and gas coolers. The

seawater is also used for other purposes like water injection, in fire water systems, potable water and sewage water treatment (NORSOK-P002, 2014).

3.3.3.3 Flaring and venting system

The purpose of the flaring and venting system is to remove and safely dispose the unrequired gases resulting from the production processes. In the venting system, the gases are released directly into the air and they are not burnt. According to the International association of oil and gas producers (OGP) (2000, p.2), unrequired gas can be treated in three ways: (1) venting; (2) flaring; and (3) re-injecting. However, reinjection is not always suitable for all oil reservoirs.

The OGP (2000, p.3) states that even if the gas is sent to shore or injected into the reservoir there will still be a small amount of gas that needs to be burnt or vented to prevent any fires or explosions. For safety purposes, a separated platform is usually designed with a flare boom and pipes, where all production systems send the unrequired gases through two flare systems to the flare tip for burning. The two systems comprise a LP flare system for low-pressure gases and a HP flare system for high-pressure gases. Each system has its own set of components, such as flare collector, ignition system and the flare tip. Both the systems (LP and HP) can operate simultaneously. The design of the flare platform should consider remaining a safe distance from the processing and, or accommodation platform. There are several sources of unrequired gases; these include but are not limited to the following: separators, produced water system, gas turbine generators, glycol contactor, gas compressors and other sources.

3.3.3.4 Drainage system

Drainage system consists of two sub-systems: (1) an open drain system which collects all water or any spillage of liquid or solid from the non-processes area and divides it into hazardous and non-hazardous materials; (2) a closed drain system which collects all hydrocarbon liquids from the processes area (equipment or piping) and also divides it into hazardous and non-hazardous materials. The classification of hazardous and non-hazardous is a requirement to ensure that the water discharged into the sea has the minimum amount of hazardous materials and containments (NORSOK-P002, 2014).

3.3.3.5 Sewage system

The sewage system can be classified into grey and black water. The grey water comes from showers and the kitchen, while the drainage water from the toilets is called black water. A sewage treatment unit should be considered offshore in order to comply with the regulations for the prevention of pollution before the black water is discharged into sea.

3.3.3.6 Chemical injection system

Chemical injection includes all chemicals that need to be injected for the process systems. Examples of these chemicals are: corrosion inhibitors, antifoam, biocides, emulsion breakers, methanol, triethyleneglycol and others. The NORSOK-P002 (2014) standard states that the materials for the chemical injection facilities should be corrosion and chemical resistant. Moreover, separate piping for each chemical from loading station to storage tanks should be provided. Chemical facilities such as loading station, storage tanks, and injection pumps should be equipped with drip trays and flushing system underneath them to collect any chemical spillage during operation.

3.3.3.7 Other systems

Other systems include the HVAC system, compressed air systems, heating and cooling medium systems, smoke and gas detection systems, firewater and deluge systems, PA speakers and alarm system, control and safety systems and others.

3.3.4 Sources of environmental effects and pollutions

Patin (1999, p.32) considered marine pollution as the most dangerous factor of anthropogenic impact on the hydrosphere for two reasons: pollution occurs with all human activities including offshore oil and gas production and transportation, and pollution in the water environment spreads fast over a large distance from the source of the pollution. He mentioned several sources of pollution that enter the marine environment, such as direct discharge of effluents and solid wastes into the sea and atmospheric fallout of pollutants.

Hirst (2004, p.18) outlined the environmental impacts of offshore oil and gas platforms, stating that the impacts result not only from the drilling rig activity, but also from the installation activities and the associated support, referring to the topside facilities. Patin (1999, p.53) mentioned that the four main stages of oil and gas development: geological survey, exploration, production (platform emplacement) and decommissioning, involve some activities that realise environmental impacts. He pointed out that the most intense environmental impacts occur during the development and production stage. This research focuses on the environmental impacts of offshore topside facilities during the production stage.

Most of the researchers have classified the sources of environmental impacts of offshore topside facilities into five areas: (1) water pollution; (2) air pollution; (3) solid and liquid wastes; (4) oil and chemical spills; and (5) noise Pollution. The following sections of this chapter will focus on these areas (refer to figure 22).

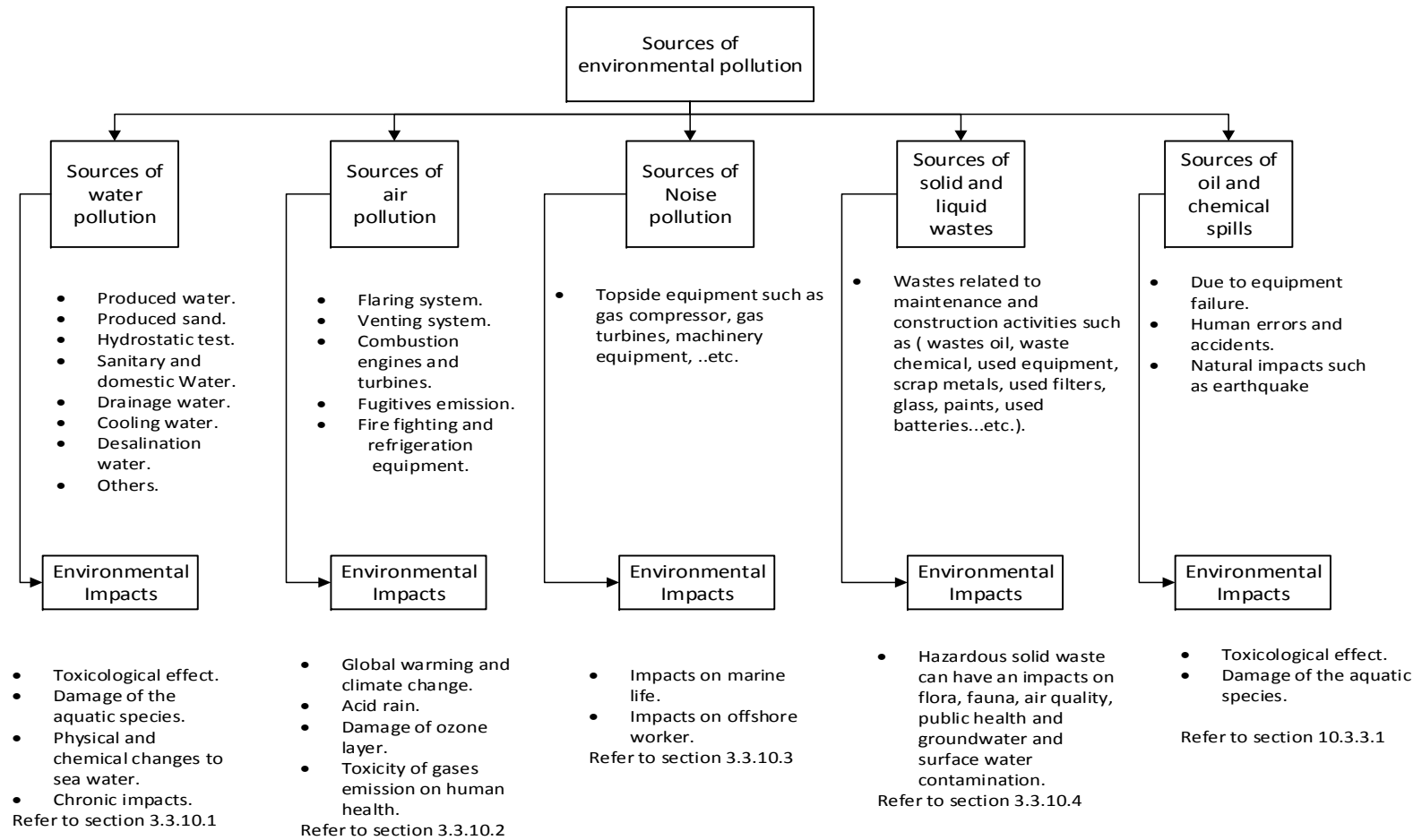


Figure 22 Sources of environmental sources

3.3.5 Discharges to marine (water pollution)

According to Speight (2015, p.258), there are many sources of topside facility discharging into the marine environment that can contaminate the sea and the surrounding area of offshore platform. Systems such as produced water, sanitary and domestic water, produced sand, the drainage system, or discharge for a short duration, for instance, chemical discharge during construction can have an impact.

3.3.5.1 Produced water

As mentioned in section 3.3.2.3, produced water is the water produced from the separation process as a result of oil production; Speight (2015,p.272) citing the EEA, noted that produced water which includes injection water and solutions of chemicals is considered one of the main sources of oil pollution offshore. Speight stated that the volume of discharged water and difficulty of its treatment will increase with the depletion of the hydrocarbon reservoir. According to Emam, Moawad, and Aboul-Gheit (2014), it has been estimated that 98% of the total waste generated in the oil and gas industry is from produced water. In 1999, it was estimated that 210 million barrels of water were produced worldwide daily, which represents about 77 billion barrels of produced water for the entire year. The quality of produced water varies based on the geographic location of the oilfield, the geochemistry of the producing formation, the type of hydrocarbon product and the type of the producing well, either oil or gas. Produced water is salty and includes harmful particles such as chemicals used in hydrocarbon extraction, heavy metals, suspended and dissolved solids, numerous organic species and others.

Hirst (2004, p.29) stated that in 2003, 266 million tonnes of water were discharged containing 5,190 tonnes of oil in the UK offshore alone. Webster (2012), citing OGP, suggested that for every tonne of hydrocarbon produced in 2010, 0.60 tonnes of produced water was discharged into the sea, and 1.0 tonne of produced water was re-injected into the reservoir. It was also noted that the mixture of the produced water contains organic and inorganic components, organic components in the form of dispersed oil and soluble oil such as aliphatic hydrocarbons, phenols, carboxylic acid, volatile aromatic hydrocarbons, benzene and others. In terms of inorganic components, concentrations of barium (Ba), lead (Pb), zinc (Zn), copper (Cu), iron (Fe), nickel (Ni), silver (Ag) and others are present. In addition, the production chemicals used in the production processes

could also affect the composition of the produced water; production chemicals include antifoam, corrosion inhibitors, wax inhibitors, H₂S removals, CO₂ removals and others. According to Patin (1999, p.77), the composition of the discharged produced water is very complex and changeable because reliable and complete analytical studies are very limited.

3.3.5.2 *Produced sand*

During the hydrocarbon separation of the fluids, which are extracted from the reservoir, the produced sand is separated; this sand contains hydrocarbon and other substances. From an environmental point of view, it is not good practice to discharge it into the sea. This removed sand should be sent onshore for treatment and disposal or rerouted into an offshore injection disposal well. If discharge into the marine environment is the only option, then it should comply with the international guidelines and procedures (World Bank Group, 2015).

3.3.5.3 *Hydrostatic water testing*

In order to verify equipment and piping systems, hydrostatic testing is required. This test involves pressure testing with water. However, in order to prevent the internal corrosion of the tested pipes and equipment, chemical additives are added to the tested water. Therefore, a discharging hydrostatic test should be avoided (World Bank Group, 2015).

3.3.5.4 *Sanitary and domestic water*

Sanitary and domestic water which includes the grey and black water, will be treated before discharging it via the sewage treatment unit. Small amount of residual chlorine and faecal coliforms will exist in the discharged water, and so even if this amount is within the allowable amount specified by the international regulations, pollution will still occur (Bahadori, 2014; World Bank Group, 2015).

3.3.5.5 *Drainage water*

Drainage water generated from process and non-process areas is separated into hazardous and non-hazardous materials (refer to section 3.3.3.4). Drainage water is polluted with oil

and chemical substances, therefore it should be treated before it is discharged into the sea in order to comply with international guidelines and codes.

3.3.5.6 *Desalination brine from potable water system*

Discharging the desalination brine from potable systems can poison marine life due to the high concentration of salt in the discharge. Chemicals are used in the desalination process, such as chlorine and other biocides, to stop bacterium from growing on the piping's interior. Salty and chemical components resulting from this process therefore become components of the discharging stream. According to the World Bank Group (2015), the desalination brine can be mixed with the cooling water or other effluent streams to reduce the concentration of the salt before discharging it.

3.3.5.7 *Cooling water*

Lifted seawater, as described in section 3.3.3.2, is used in cooling water systems for gas compressors and power generation turbine. Bahadori (2014, p.131) noted that the cooling water is not polluted since an indirect method is generally used. However, there are cases of liquid leakage from the tubes of a cooler due to a corrosion attack. Hence, contamination of cooling water can occur. The World Bank Group (2015), mentioned that antifoulant chemical dosing to prevent marine fouling of offshore cooling water systems should be cautiously considered; in order to reduce the use of chemicals, the seawater intake depth should be optimised and proper screens should be fixed to the seawater intake to avoid impingement of marina flora and fauna. Another aspect to consider is that the selection of the discharge stream depth is important to ensure that the temperature of the ambient seawater is within 3 degrees Celsius at the mixing zone.

3.3.5.8 *Other discharges into the marine environment*

Other discharges related to the pipelines and drilling activities are not covered since this research focuses on the topside of the fixed platform; these discharges include hydrostatic tests cleaning of pipeline systems, and drilling fluids and cuttings.

3.3.6 *Discharges to the air (air pollution)*

During the process and production of hydrocarbon, the contamination of air by noxious gases discharged into the air from topside facilities causes air pollution. The main sources of emissions from topside facilities are presented below (Jafarinejad, 2017; Bahadori, 2014; World Bank Group, 2015; and EIIP, 1999).

1. Flaring and venting systems: burning the unrequired gases from the production process is called flaring, whilst releasing the unburned gases directly into the atmosphere is called venting. Flaring and venting systems are widely used in the oil and gas industry to dispose of unwanted gases. Pollutants of concern are: nitrogen oxides (NO_x); hydrogen sulfide (H₂S); sulfur oxides (SO_x); carbon dioxides (CO₂); carbon monoxide (CO); volatile organic compounds (VOCs); polyaromatic hydrocarbon (PAHs); and methane (CH₄).
2. Combustion of power generation: this includes the emission of the exhaust gases produced by the combustion of gas, liquid, diesel in turbine generators, heaters, boilers, compressors, emergency generators and pumps. Pollutants of concern are: nitrogen oxides (NO_x); hydrogen sulfide (H₂S); sulfur oxides (SO_x); carbon dioxides (CO₂); carbon monoxide (CO); volatile organic compounds (VOCs); polyaromatic hydrocarbon (PAHs); and methane (CH₄).
3. Fugitive emission: the sources include equipment leaks of hydrocarbon process equipment. Leaks from different equipment components such as flanges, pumps, valves, compressors, separators, wellheads, pneumatic devices, process drain, oil storage and loading, and others. The main pollutants of concern are VOCs and CH₄.
4. Firefighting, refrigeration and air-conditioning equipment: released gases such as halons, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs).

3.3.7 *Solid and liquid wastes*

Topside facilities produce many types of solid and liquid waste due to the routine operation and construction activities of brownfield modification projects. This waste can have a significant negative impact if it is not treated and controlled. Waste related to maintenance, construction and operation activities include waste oil, hydraulic fluid, waste production chemical, used filters, used process equipment, scrap metals, heavy metals, paints, plastics, used cans and containers, batteries, used pipes and tanks, used glass, medical waste, spent chemicals from laboratory and others (World Bank Group, 2015; Jafarinejad, 2017). According to the World Bank Group (2015), these materials should be separated offshore into hazardous and nonhazardous materials and then sent onshore for disposal, recycling or other treatment.

3.3.8 *Oil and Chemical Spills*

Oil and chemicals spills can occur from topside facilities due to several resources. The main fluids are oil, diesel and production chemicals. Patin (1999,p.86) mentioned that the most common causes of oil spill accidents are equipment failure, personal or human error, and natural impacts such as seismic activity, hurricanes and so on. According to Bahadori (2014, p.124), equipment failure includes corrosion and leaking of piping or tanks and valves, while operating and human errors involve, for example, overfilling tanks and improper alignment of valves and piping. He pointed out that human errors, operating errors and equipment failure can be reduced by considering proper design, applying a maintenance and inspection strategy and select proper equipment. Fang and Duan (2014, p.340) stated that it is difficult to recycle the oil spilled offshore, which can spread a great distance causing ecological damage, and harmful effect on marine life and the environment. They mentioned some offshore accidents resulting in oil spills: “*BP’s platform deep-water horizon exploded in the Gulf of Mexico*” in April 2010; and “*the Dalian crude oil pipeline burst in China*” in July 2010.

3.3.9 *Noise pollution*

Noise pollution can occur throughout the life cycle of offshore development activities. Most of the activities, such as seismic operation, installation activities, drilling,

production and operation and decommissioning, can generate a high level of noise (Hirst, 2004, p.45; World Bank Group, 2015, p.14). The human ear can hear sound waves from 20 to 20,000 hertz (Hz); the intensity of sound is measured in sound pressure levels and the unit is decibels (dB); sound pressure level (SPL) in the range of 100 to 120 dB is considered uncomfortable, while above 130 dB is painful (Bahadori, 2014, p.217).

The sources of noise (unwanted sound) with respect to topside facilities during the operation and production stage vary due to the complicated components of topside facilities. Noises and vibrations are generated from several sources such as gas compression modules, gas turbines, piping systems, machinery equipment, construction activities related to brownfield modification and so on. Control of the noise offshore is very important for offshore workers as well as the surrounding environment (marine mammals). BOMEL LTD (2002) stated that the noise limit for individual equipment or machinery should be included as part of the general equipment specifications issued to the supplier and fabricator. In addition, the equipment supplier should provide evidence of the noise level generated by their equipment. The Factory acceptance test (FAT) for noise control should be requested by the client to make sure that the equipment complies with international standards such as ISO.

3.3.10 Potential impacts of offshore topside facilities on the environment

The potential environmental impacts of the oil and gas industry depend on several factors such as size and complexity of the project, stage of the process, toxicity of the materials and their concentration, the sensitivity and pollution in the nearby environment, and mitigation and control methods (E&P Forum cited in Jafarinejad, 2017, p.86). Pollution and waste as discussed in section 3.3.4, is related to all activities and stages of the oil and gas sector, from exploration, to development and construction, operation and production and finally the decommissioning. Offshore, the potential impacts can be generated from the water pollution, air pollution, solid wastes, and noise pollution.

3.3.10.1 Potential impact of oil and other discharges on ocean life

According to Emam, Moawad and Aboul-Gheit (2014), it is very important to analyse the produced water in order to provide reliable information about the source and characterisation of the water produced with oil, prediction of corrosion rate, prediction of

scale formation rate, quality check of the injection water, and monitoring the chemicals used for water treatment. The authors noted the impact of produced water on marine life, as the produced water is rich with dissolved ions, hydrocarbons and trace elements; the following harmful impacts will become of concern if produced water is discharged without proper treatment: (1) toxicological effects on aqua life; (2) damage of the aquatic species due to reduced oxygen level; (3) clay deflection due to the increase of sodicity; (4) dehydration and death of plants due to the increase of soluble salts; (5) other environmental impacts due to additives such as a corrosion inhibitor and H₂S scavenger. Hirst (2004, p.33) highlighted the potential toxicity of the produced water; the level of toxicity will be based on the concentration of the production chemicals such as corrosion inhibitors, oxygen scavengers and others.

Patin (1999, p.193) stated that oil consists of a complex mixture of hundreds of organic substances and when this mixture enters the marine environment it is separated into different fractions; the biogeochemical behavior and distribution of oil compounds in the marine environment depend on complicated interconnected processes. These include: aggregation, microbial degradation, sedimentation and bio-sedimentation, dissolving and emulsification, oxidation and decomposition and physical transport. Speight (2015,p.277), discussed the above process of chemical and physical changes, as will be presented below.

(1) Aggregation: after the light fractions of the crude oil evaporate, oil aggregates formed from emulsified oil residuals and resulting from microbial and chemical transformation, the chemical composition of the aggregates is changeable. Generally, however, aggregates are formed from heavy molecular weight constituents. In form, these look like sticky, grey or brown lumps that are uneven and range in size from 1mm to 10cm, although they can be much larger. They can take several years to degrade, depending on whether they sink, float, or are washed ashore.

(2) Biodegradation: here the substance is transformed into a new compound due to the actions of micro-organisms, a biochemical reaction, or a microbial organism altering the structure of the chemical after it enters the environment. Many of the marine micro-organisms in seawater are able to metabolise elements of crude oil; these organisms are more common in more polluted coastal waters. The rate of biodegradation is impacted by

three factors: availability of oxygen and nutrients, temperature, and oil characteristics. A wide range of micro-organisms are required for this process as each type degrades a particular group of constituents. Generally, these micro-organisms, which form communities and amass when there is oil available for degradation, are able to degrade a range of compounds, but there are some large complex molecules that resist. It is clearly noted by Speight that biodegradation will not be able to remove bulk oil accumulations however.

(3) Dispersion: on entering the water, turbulence or waves can break parts of the slick into various size droplets which are then mixed into the top parts of the water; larger droplets rise to the surface, while smaller ones may be suspended lower down; the larger ones then coalesce at the top to create a thin film. The smaller droplets at the lower level, kept there by the turbulence of the sea, mix and spread the oil into increasing amounts of seawater. This can, in turn, promote degradation. As with the above, the rate of dispersion is impacted by the type of oil and sea conditions.

(4) Dissolution: to a point, some elements of crude oil are water soluble; low-molecular-weight aliphatic and aromatic hydrocarbons are soluble, as are polar compounds that develop due to the oxidation of some oil fractions. Dissolution usually takes longer than evaporation and the conditions of the ocean have a very strong impact on this process, along with the oil composition and spreading. Whilst low molecular weight parts are slightly soluble in seawater, higher molecular components remain insoluble.

(5) Physical transport: the transport and spreading of crude oil following a spill is impacted by a number of factors, including: gravitation forces, oil viscosity, volume, currents, temperature and weather conditions. Temperature has a particular impact as it can increase viscosity to such a degree that the oil solidifies quickly. Impacted by the weather, the slick is generally driven by the wind and, on reaching the important thickness of 0.1mm, it begins to disintegrate into small fragments that spread over a larger area.

(6) Emulsification: dependent on water conditions and the oil composition, emulsification often occurs after a large storm and can persist for over three months. The stability of emulsions increases with decreasing temperatures.

(7) Microbial degradation: crude oil that enters the environment will ultimately be broken down or not based on microbial activity, with the rate of degradation decreasing with the complexity of the molecular structure. This rate of degradation is also impacted by oxygen, nutrient availability and oil characteristics; once degradation begins, a community of microorganisms develops.

(8) Oxidation: often colloquially referred to as weathering, oxidation involves the chemical transformation of the crude oil and usually begins about one day after the spill occurs. This process is inhibited by sulphur, catalysed by a number of trace elements and promoted by sunlight, among other factors. The final product of this process is usually more water-soluble.

(9) Sedimentation: in coastal and shallow areas in particular, where mixing is promoted to a greater degree, up to 30% of the oil is absorbed by suspended material and then deposited on the sea bottom. Simultaneously, bio sedimentation occurs; bio sedimentation refers to the process by which organisms such as plankton absorb the emulsified oil and make it sediment on the ocean floor. Due to the low levels of oxygen on the ocean floor, decomposition ceases when the oil reaches the ocean floor; this oil in sediments can therefore last for many months or even years.

From the ecotoxicological point of view, Patin (1999, p.185) noted that oil is a multicomponent toxicant that includes hundreds of substances with changeable properties. The complex structure and higher molecular weight of the hydrocarbons causes carcinogenic and mutagenic effects in benthic organisms. The impact of oil's toxicity also appears in its integrated nature, which means that every vital function, mechanism and process within a living organism is affected by oil in the marine life. In addition, the photochemical degradation of oil in the marine and metabolic transformation of oil compounds in living organisms can also lead to the formation of substances with higher toxicity than that of the original hydrocarbon. Chronic effects emerge due to oil accumulation in the bottom sediments and impacts may continue for 30 years after the oil entered the marine environment. Patin (1999, p.335) summarised the major biological effects of oil spills in the ocean, as shown in figure 23 below.

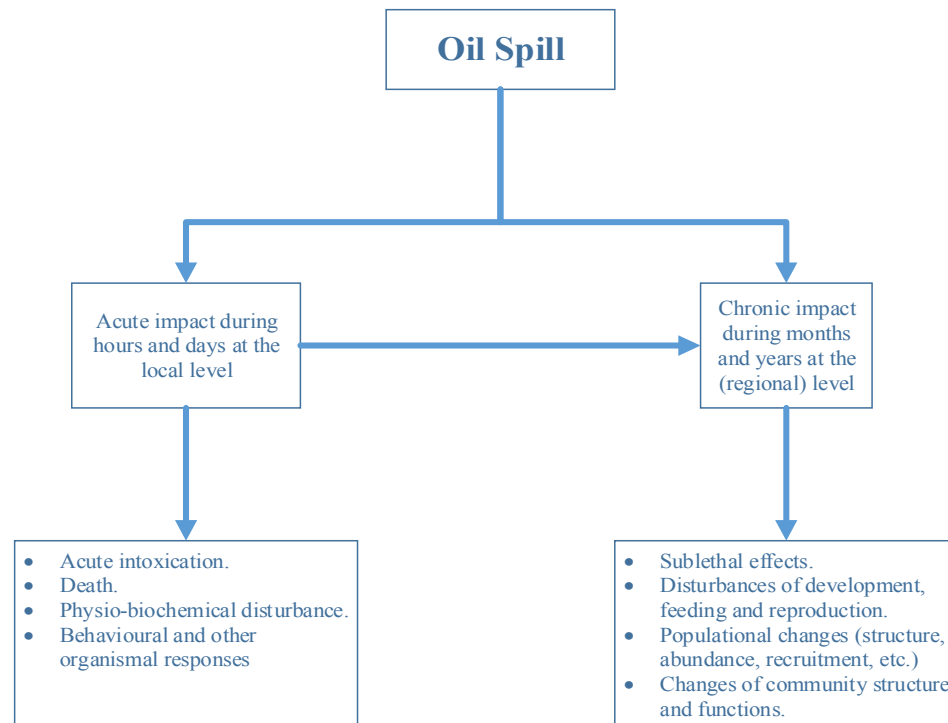


Figure 23 Effect of oil spills

3.3.10.2 Potential impacts of atmospheric emission on the environment

As discussed in 3.3.6, there are many types of gases released from offshore topside facilities and the environmental impacts depend on the toxicity and concentration of these gases. Global warming associated with the effects of greenhouse gases, acid rain and ozone depletion comprise the greatest impacts on the atmosphere.

3.3.10.2.1 Hazards and toxicity of emission gases

Bahadori (2014, p.37) discussed emission gases in the chemical and petroleum industry in terms of their potential toxicity and hazard.

(1) **Methane (CH₄)** is one of the most dangerous gases because of its flammability upon its release and contact with air; an explosive mixture can be formed. The flammability limit of the gas (concentration) in air is normally between 5 and 15%.

(2) **Carbon monoxide (CO)** is another of the most dangerous gases because of its high toxicity, explosiveness, and the fact that it has no colour and smell. The flammability limit of this gas in air ranges between 12.5 and 74.2%. In terms of the effects of carbon monoxide on human health, the haemoglobin in the body has an affinity for carbon monoxide 300 times greater than for oxygen, which makes it very dangerous. A small amount of CO causes the body to create a new substance in the bloodstream called carboxyhemoglobin, which leaves a reduced number of red cells to carry oxygen to vital organs such as the brain and heart. The physiological reactions will vary from case to case based on the gas concentration and the time of exposure. The effect on the body ranges from severe headache, dizziness, collapse, fainting, coma and death at high concentrations.

(3) **Sulfur dioxide (SO₂)** is a highly toxic gas; a small concentration of the gas (parts per million instead of percentage) causes severe irritation of eyes throat, and respiratory system; 400 parts per million (ppm) could cause immediate death.

(4) Similarly, **hydrogen sulfide (H₂S)** is highly toxic; the toxicity starts at 5 (ppm), and at 1000 (ppm) immediate death could occur.

(5) **Nitrogen dioxide (NO₂)** is very toxic; small concentration parts per million (ppm) cause pulmonary infections and can be fatal.

(6) **Hydrogen (H₂)** is considered the most explosive gas and can be ignited at any temperature below 580C⁰; the flammability limit is between 4 to 74.2% in the air.

(7) **Carbon dioxide (CO₂)** is also a harmful gas if the person is exposed to it for a long time; its solubility in the bloodstream is rapid and causes an increase in the respiration rate.

In this section, toxicity and impacts on offshore workers were highlighted; environmental impact will be discussed in the following section.

3.3.10.2.2 Greenhouse effects and global warming

It is well known that the emission gases from topside facilities contribute significantly in greenhouse gas (GHG) emission and have negative environmental impacts. The

majority of these emissions come from flaring, venting and combustion of power generation (refer to section 6.5.2).

In terms of fuel combustion, Emam (2016) and Mazzetti et al. (2014) mentioned that 75-80% of the CO₂ emissions from offshore are emitted from the combustion of fossil fuels and gas turbines used to produce energy. In terms of gas flaring, Emam (2016) and Svensson (2011) cited the World Bank, noting that over 150 billion cubic metres of natural gas related to oil production is being flared annually worldwide, and this contributes by adding 400 million tonnes of carbon dioxide (CO₂) to the atmosphere annually. Svensson (2011) stated that the volume of flared gas represents 5% of the natural gas production and the loss costs 25 billion dollars per year.

Ruta (2010), citing OECD outlook, noted that the global economy is expected to grow by 3 to 4%; as a consequence the resource extraction and fuel consumption will increase. Therefore, OECD cited in Ruta (2010), has predicted that resource extraction will increase from 58 billions tonnes in 2005 to 80 billion tonnes by 2020; the corresponding GHG emission will increase globally by about 37% from now to 2030, and by 52% between now and 2050.

Ruta (2010) mentioned that climate change is caused by several factors, one of which is the GHGs. World Bank (2012, p.23) stated that GHGs vary in their potential impacts and since CO₂ is the most common gas produced, the other gases are reported in terms of CO₂ equivalent (CO₂eq). Global warming is one of the GHG effects; the radiation emitted by the sun is trapped by the earth's atmosphere when the GHG allows the radiation to pass into the earth, but retains the heat radiation back from the earth's surface; as a result part of the sun's energy is retained within the earth's atmosphere (Jafarinejad, 2017, p.91). Ruta (2010), citing Dell, noted that global warming will have a major impact on both level and growth of GDP; it was observed that during the warm years, the level and growth rate of GDP in developing countries are reduced. Therefore, due to global warming and variation in rainfall, the major impact will be on agricultural yields. Further, Ruta (2010), citing World Bank, suggested that the temperature will raise between 3 and 4 degrees by 2099, and this will help in the spreading of diseases such as malaria in the African continent. Coastal areas will also be affected by the raising of the sea level and the higher concentration of CO₂ in the air will affect the ocean through

acidification, which will change the pH values; as a consequence corals will be damaged and marine mammals threatened.

Acid rain is another result of the effects of GHG on the environment. This occurs when the GHG emission from the petroleum industry reacts with rainwater in the atmosphere; for example, CO₂ is dissolved into rainwater to produce carbonic acid H₂CO₃, and similarly for other gases SO₂ and NO_x when they react with rainwater, sulphuric acid (H₂SO₄) and nitric acid (HNO₃) are produced. Acid rain has negative impacts on seawater, rivers, ecosystems, animals, soil, plants and human health (Jafarinejad, 2017, p.94).

The increase of the concentration of ozone gases (O₃) at the ground level of the atmosphere is another impact of GHG on the environment. Emam (2016) noted that the ozone increased as a result of the reaction between NO_x and O₂ in the air, or between VOC and NO_x; consequent effects can be seen on respiratory system health and lung cancer rates. According to Bolaji and Huan (2013), the ozone layer, which works as protection against the harmful ultraviolet rays of the sun, is affected by chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). As a consequence, the damage to the ozone layer will impact the environment and human health significantly. Exposure to ultraviolet rays can cause skin cancer and eyes damage and affect plant growth and the ecosystem.

3.3.10.3 Potential impacts of noise

The potential impacts of noise from topside facilities and activities can be classified into two types: impacts on marine mammals and impacts on offshore workers. Hirst (2004, p.45) noted that the potential noise source that will impact the marine mammals is generated during the seismic and piling activities (installation). Evan, cited in Hirst (2004, p.46) outlined that the hearing ability of marine mammals can be classified into three groups: baleen whales, toothed whales and pinnipeds. The potential effects range from changes in behaviour to temporary and permanent hearing loss.

Dolman et al. (2006), citing Jepson, highlighted that noise has both killed and deafened marine mammals, and forced them to move away from feeding areas. Noise can interact with marine animals, preventing them from sensing vessels and fishing gear and expose

them to injury (Nowacek, cited in Dolman et al., 2006). Recently, a new type of mass stranding was discovered involving beaked whales; the animals had spread out along several kilometers of coastline. They were disease free and had food in their stomachs; however, they were living very close to a noise event. The only explanation was that these animals had gotten acoustic trauma. The impact of noise can be extended to include all marine mammal types such as fish, invertebrates and sea turtles; noise can also be lethal to embryonic fish (Dolman et al., 2006). Wan (2005) highlighted that oil and gas exploration and military activities can have a significant effect on mammals in the ocean due to generated noise; stating that marine mammals are sensitive to sound and they depend on sound for finding food, communicating with each other and avoiding enemies. Noise pollution can deafen and disturb marine animals, which results in death in many cases. The majority of the literature indicates that the impact on marine life as a result of drilling, pilling and seismic activities. However, in terms of production facilities (topside), Richardson et al. (1995, p.432) stated that the underwater noise from offshore production has not been studied extensively. Moreover, they noted that the platforms powered by gas turbine produce more noise than those with shore power.

Noise from topside facilities has a major impact on offshore workers due to the routine operation and production activities. Bahadori (2014, p.217) mentioned several impacts of the noise on workers:

- It causes displeasure to hearing and annoyance.
- It causes physiological effects on humans such as increased blood pressure; heart beat rate; breathing amplitude and others.
- Long exposure to excessive noise levels causes loss of hearing.
- Some effects on human performance, such as reduction of the worker's concentration levels.
- Effects on the nervous system, such as ringing in the ears and feeling tiredness.
- Causes sleeplessness.

3.3.10.4 Potential impacts of solid wastes on the environment

Jafarinejad (2017, p.275) cited the US environmental protection agency in noting that the hazardous waste is solid waste that has at least one of the following features: corrosivity, toxicity, reactivity or ignitability. Hazardous solid waste can have an impact on flora, fauna, air quality, public health and groundwater and surface water contamination. Among the solid wastes described in section 3.3.7, careful attention should be given to oily sludge in particular as it is highly toxic. Oil sludge can cause mutagenic, carcinogenic, and lethal toxic effects on aquatic and terrestrial ecosystems (Bojes and Pope, 2007; Ubani et al., 2013 cited in Jafarinejad, 2017, P.275).

3.3.11 Recommendations to mitigate environmental impacts

Regulations, policies, standards, guidelines and procedures should be established and applied by countries in order to minimise potential environmental impacts and protect human health. The following are some recommendations that should be considered in the application of the environmental and health management system in terms of discharges to water, air emissions, noise pollution and solid wastes.

3.3.11.1 Recommendation for discharging and spills in the marine environment

Patin (1999, p.393) outlined the stages that should be included in the environmental control and management system:

- Determine the general goals and priorities of environmental protection; selecting environmental requirements and standards to achieve the goals;
- Describe and assess the background characteristics of the environment and establish a regulatory base for the protection;
- Identify and analyse environmental hazards and impacts at different stages of the project;
- Evaluate the possible consequences and risks of different impacts and establish measures to reduce these risks;
- Perform ecological monitoring and implement the most effective measures and methodology available.

Similarly, Jafarinejad (2017, p.108) cited E&P forum/UNEP that environmental legislation requires the following factors:

- Applicable international laws, guidelines and regulations;
- Clear methods for decisions on activities and projects;
- Clear determination of responsibilities and liabilities;
- Clear and applicable methods of monitoring;
- Motivated enforcement authorities;
- Availability of consultation and appeal procedures;

In terms of the international requirements and regulations, Patin (1999, p.393) classified the standards into two groups: the first group controls the volume and composition of discharges into the marine environment; the second group determines the extent of change in marine environment. The most famous international environmental conventions are: the international convention for the prevention of pollution from ships (MARPOL); the convention for the protection of the marine environment of the north east atlantic (OSPAR).

Oil spill responses include three phases: protection, recovery, and cleanup. In most responses, the protection and the recovery are immediate targets; protection involves keeping the oil out of a habitat and or reducing the amount that enters, while the recovery includes removing the oil from the sea surface. However, the main objective of the cleanup phase is to remove the oil spill from coastline habitats (API and NOAA, cited in Jafarinejad, 2017, p.118).

3.3.11.2 Recommendations for air emissions

As discussed in 3.3.6, the main sources of air pollution are generated from flaring and combustion engines used for power generation. In terms of reduction of emissions from flaring, Indriani, (2005) and the European Commission and Joint Research Centre (2013) cited in Jafarinejad, (2017, p.179), highlighted the following methods:

- Implementing a flare gas recovery system by considering correct designing of the plant.
- Using flaring only as a safety system rather than in normal operations such as start-up, shutdown, and emergency.
- Working on designing the parameters of flares, such as pressure, height, type of flare tips, etc., to create smokeless operation and ensure that efficient combustion of excess gases is achieved during flaring.
- Reinjection of the gas into the reservoir in order to increase the pressure within the reservoir and enhance the flow of oil.
- Transport the gas by pipelines to end users; use a natural gas liquid (NGL) recovery system, or use a gas to liquid (GTL) system.

HARC (2015) discussed several solutions such as: (1) gas to liquids process to create *synthetic crude ethanol, methanol or formalin*; (2) using flare gas to produce a *nitrogen fertilizer*; (3) turbines to produce electricity instead of diesel; and (4) converting gas to LNG (liquefied natural gas) to power and manage the drilling operations.

In terms of the combustion of gases in the gas turbine, Mazzetti et al. (2014) mentioned that the most effective method to improve energy efficiency on offshore platforms is by using compact bottom cycles to the waste heat from the gas turbines with potential of CO₂ reduction up to 25%. EIIP (1999) noted that for gas turbines, selective catalytic reduction can be used. Accenture (2012) mentioned that, electricity from the land-based grid can be used for offshore platforms rather than gas turbines, in order to reduce CO₂ emissions, and improve energy efficiency as well as utilize grid based renewable energy.

In terms of the effect of CFC and HCFC gases on the ozone layer, Bolaji and Huan (2013) suggested the use of natural refrigerants as a replacement for CFC and HCFC. Natural refrigerants, which can be used as alternatives, include water, ammonia and hydrocarbon; these refrigerants have zero ozone depletion impact with a lower global potential impact compared to CFC and HCFC.

Gas flaring and venting can be reduced and monitored through national or international standards and regulation. The convention for the protection of the marine environment of the north east atlantic (OSPAR) and global gas flaring reduction partnership (GGFR) both assist governments and countries in reducing flaring by providing guidelines (Worldbank, 2004). The American Petroleum Institute (API) has developed a methodology and guidelines for estimating GHG emission on oil and gas industry; Campbell et al. (2004) has recommended estimating gas flaring and venting based on the API.

3.3.11.3 Recommendation for marine noise

As aforementioned the impact of noise classified into effects on mammals and offshore workers. In terms of mitigating the noise effects on marine life and mammals, Richardson et al. (1995, p.417) provided general approaches that can be used and applied to mitigate the noise impacts on marine mammals. The first approach is to select the appropriate equipment and facilities. He stated that if the offshore area is important to ocean mammals, then the noise emission should be studied when determining which type of platform to use; he also emphasised the importance of equipment selection, stating that several equipment types can often perform the same required function, therefore, the less noisy equipment should be selected. The second approach includes adjusting the operational procedure to reduce the potential effects; for instance, some countries require visual monitoring for the presence of marine life, and postponing any activities when mammals are detected. Other approaches are related to adjusting the seasonal and hourly timing of noisy activities to avoid periods when mammals are sensitive.

In terms of the effects on offshore workers, Bahadori (2014, p.217) noted that noise control is very important to reduce the effects on workers and environments. He stated several means that can be considered in this regard:

- Reduction of the noise at source by redesign or replacing the noisy equipment; if not, mechanical modification or isolation can be considered.
- Proper maintenance and lubrication can mitigate the noise level.
- Increasing the distance between the workers and noisy equipment or installing barriers between the source of the noise and workers.

- Reducing the length of exposure to the noise source by, for instance, considering job rotation.
- Educating the workers in terms of effects of exposure to noise for a long time; providing them with means of protection, such as ear protection.

Bahadori (2014, p.223) further, pointed out the importance of local regulations to environmental noise, which should include noise limits and techniques for measurement. The supplier or vendor should always provide the equipment noise limitation sheets, which should meet the acceptable level of noise based on the regulations or international standards. BOMEL LTD (2002) specified the noise level of a specific operation area offshore, as shown in the following table 6.

Table 6 Noise limit of offshore area

Specific Area	Noise limit (dBA)
Workshops	70
General stores	70
Control rooms	55
Offices	55
Laboratories	55
Other 12 hour shift	88
Other 8 hour shift	90

3.3.11.4 Recommendation for solid wastes (waste management plan)

Wastes here are related to the solid and liquid surplus from service industries, manufacturing and treatment plants; wastewater and exhaust gases are not considered to be waste (Pollution Control Act cited in Haugan et al., 2013, p.2). Discharges to air and water can be considered as pollution, not waste.

3.3.11.5 Importance of a waste management plan

A waste management plan plays an important role in achieving sustainable development by reducing the environmental impacts and human health issues. Waste, especially in the oil and gas sectors, contains chemical substances and hazardous materials with potential effects on the environment and human health. From an economical point of view, prevention and minimising the production of waste is important in ensuring that the cost of waste generation by facilities does not exceed the value of using them. DEFRA (2011) mentioned that a green economy can be achieved and supported by reducing environmental damage, increasing energy security and sustainably managing natural assets. DEFRA (2011) further, emphasised that the direct greenhouse gas emissions from biodegradable waste in landfill are significant; therefore, energy recovery from wastes as an option can reduce the carbon impact and provide economic benefits. Renewable energy can also be derived from waste such as bio-methane, which can produce a greenhouse gas saving of between 66% and 92% compared to natural gas. Therefore, the need for sustainable waste plans and policies are important to protect the environment and human health.

3.3.11.6 Waste management hierarchy

The waste management hierarchy classifies the waste management option according to what is the most preferred option for the environment. The following hierarchy (Figure 24) should be considered when applying the waste management plan: (1) prevention; (2) source reduction or decreasing; (3) re-use; (4) recycling and recovery; (5) treatment; and (6) disposal (landfill). Therefore, when waste generation cannot be avoided, priority is given to preparing it to re-use, then recycling, then treatment and finally disposal. (Haugan et al, 2013; Jafarinejad, 2017; Borthwick, 1997).

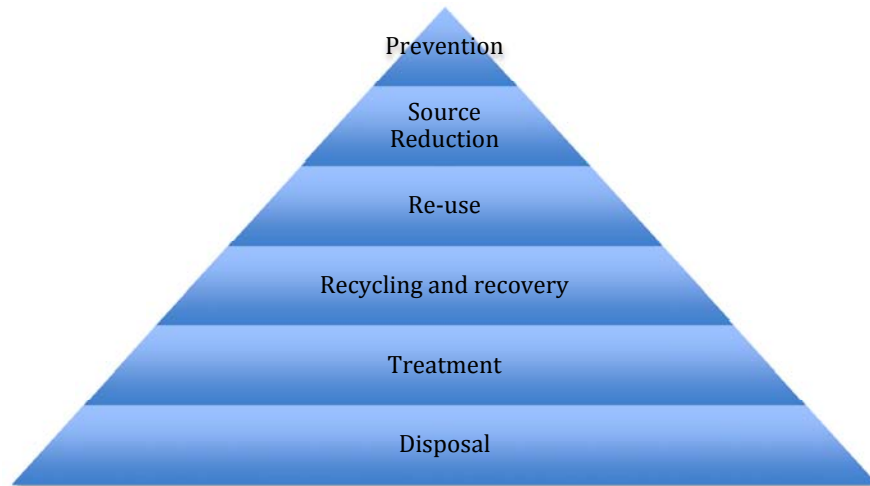


Figure 24 Waste management hierarchy (Jafarinejad, 2017; DEFRA, 2011)

3.3.11.6.1 Prevention

Waste management systems can begin with waste prevention. Prevention can be considered in the design at the conceptual stage, or during the planning process. For example, using bolting design connection offshore instead of cutting and welding, which generates a lot of waste and hazards. Jafarinejad (2017, p.101) stated that pollution prevention can be done by eliminating of operation practices that result in discharges into the environment.

3.3.11.6.2 Source reduction (minimising)

In this approach, during the conceptual stage of the project the activity is designed or selected to generate the minimum volume of waste or toxicity. Jafarinejad (2017, p.102), citing the E&P forum, suggested that selection and substitution that result in producing less toxic and waste should be considered. For instance, selection of additives that don't contain a high level of toxic compound is preferred. In a heat exchanger, replacing chromates with a low toxic option such as phosphate is an example of reduction.

3.3.11.6.3 Re use

The opportunities for re using waste materials should start at the conceptual stage; the designer should consider this approach in his design, debating the flexibility of re using

the same materials in their original shape. API 5E (1997) stated that the contractor or operator should consider reclaiming the waste materials, either in activities onsite or outside in other industries.

3.3.11.6.4 *Recycling and recovery*

Converting waste materials into usable materials is referred to as recycling, whereas extracting energy from waste materials is called recovery. Examples of materials for recycling include: used oil, hydraulic fluids, paper, plastic and metals. Recovery of hydrocarbons can be achieved onsite at production facilities or offsite, such as via recovery oil from produced water and separator sludges (API 5E, 1997; Jafarinejad, 2017, p.104).

3.3.11.6.5 *Treatment*

After source reduction, re use and recycling options, treatment as a solution should be considered. The main purpose of treatment is detoxification of waste materials through a specific process. Techniques such as filtration, centrifugation, thermal treatment and chemical treatment can be used to reduce the level of toxicity in wastes materials (API E5, 1997; Jafarinejad, 2017, p.105).

3.3.11.6.6 *Disposal*

All wastes that cannot be re used, recycled or recovered, will be disposed of. Waste disposal methods will be evaluated based on the type of waste, regulatory requirements and restrictions, environmental considerations, location, engineering limitations, and economics. Techniques such as secure landfill, surface discharges (onshore and offshore) and burial among others are reported in the oil and gas industry (Jafarinejad, 2017, p.305).

3.3.11.6.7 *Considerations in managing waste offshore*

The following points should be considered when a waste management plan is created or applied to any project:

- The roles and responsibilities should be clear for all parties: offshore platform manager (client), contractor and subcontractors.
- The waste management plan should include a clear system to segregate the hazardous and non-hazardous materials. Hazardous waste includes such materials as medical waste, chemicals, paints, batteries, flammable waste and so on; non hazardous waste includes domestic waste from accommodation platforms (foods, cans, papers etc.), scrap metals, and so on.
- Packing and labelling systems should be adhered to in order to separate hazardous and non hazardous waste. Segregation should consider recyclable items, reused items, recovery item and items for disposal.

3.4 The Third Pillar - Social Impacts of Topside Facilities

Mckenzie (2004) defined social sustainability as “*a life-enhancing condition within communities, and a process within communities that can achieve that condition*”. Vallance, Perkins and Dixon (2011) mentioned that although the concept of sustainable development includes aspects of social mandate; however, the human dimension was neglected. As similar meaning was given by Kandacher (2014), who stated that social sustainability is the least addressed or most neglected among the three main pillars of sustainability (economic, environmental and social) as most of the research focuses on environmental and economical sustainability. Kandacher noted that it is difficult to define and realise social sustainability; according to Bibbington and Dillard, cited in Kandacher (2014), the reasons for this difficulty are that there is no accepted scientific basis for the analysis and there is no common unit of measure, unlike with environmental and economical sustainability.

An offshore platform is a community for offshore workers, and offshore workers are the people who live there and thus the following definition can be extracted as social sustainability for offshore platform:

The condition at which offshore facilities operate safely and securely considering the human rights of the offshore worker in terms of health, safety, and professional training.

From the above definition, two main groups will be extracted and addressed in the following section: (1) offshore process (safety and security); (2) occupational health and safety (human rights).

3.4.1 Offshore process (safety and security)

Jones (2003, p.134) noted that offshore platforms are uniquely hazardous in that the offshore workers are surrounded by vast facilities containing multiple combustible materials. Jones indicated that accidents can occur because of the failure of structural members through corrosion, collision of vessels and leakage of hydrocarbons, which in turn can lead to ignition and the death of offshore workers. According to Fang and Duan (2014, p.184), an accident refers to a failure in the effectiveness of the project; failure is opposed to reliability, which guarantees the engineering system functioning, achieved by regular maintenance of the system's components. Sutton (2014, p.14) stated that process safety in particular needs to focus on processes related to failure, such as pipe ruptures, blowouts, or any other event that may have catastrophic consequences. This type of failure comes as a result of not implementing a proper safety management system or programme, which includes operating procedure, mechanical integrity, training and management of change. Fang and Duan (2014, p.183) highlighted the importance of the safety system engineering, which uses systematic methods to analyse and evaluate the safety from every angle and find a solution to achieve safety objectives.

3.4.1.1 Offshore events and impacts

Sutton (2014, p.54) discussed the most important incidents that have occurred in the last 40 years; these events are presented in the table 7 below. Sutton highlighted the importance of implementing a safety management system to avoid such accidents, save lives, protect equipment and production (asset), protect the environment and reduce losses. The components of the safety management system will be presented in the following sections.

Table 7 Offshore event (Sutton, 2014, p.54)

Event	Year	Location	Organisation type	Description	Environmental and economic Impacts	Number of fatalities
Santa Barbara	1969	California	Drilling	Blowout	Major environmental impact on local beaches and wildlife	0
Alexander L.Kielland	1980	North Sea	Flotel	Loss of vessel	Loss of major asset	123
Piper Alpha	1988	North Sea	Production	Explosion and fire	Loss of the platform (asset)	167
Snorre A	2004	North Sea	Drilling	Blowout	Minor environmental impact but long-term reduction in production	0
Mumbai High North	2005	India	Production	Vessel impact	Fatalities, many injuries, loss of facility	22
Blackbeard	2006	Gulf of Mexico	Drilling	Blowout	None	0
Montara	2009	Australia	Drilling	Blowout	Substantial spill of oil and extensive fire damage to the relief drill rig	0
Deepwater Horizon	2010	Gulf of Mexico	Completion	Release of gas and oil during drilling of a deepwater well	Major environmental damage. Loss of a world scale drilling rig, numerous penalties and clean up costs	11

3.4.2 Occupational health and safety

The consequences of the behaviour and performance of individuals (personal) either alone or in groups is referred to “occupational safety” (Sutton, 2014, p.14). According to Nolan (2014, p.378) human errors may occur during the life cycle of the facility or project related to the complexity of the equipment, personal training, worker-equipment interfaces, and operating procedures. It is difficult to entirely eliminate human errors. Human errors are often related to the personal attitude and tolerances. Tolerances refers to ability and how quickly the information can be accepted and understood by workers. The company management style and culture can negatively affect a personal’s attitude which may lead to an incident; therefore, it is important to consider safety aspects especially during the maintenance activity when most historical disaster events have occurred. In the following sections, safety and health issues will be discussed.

3.4.2.1 Safety issue

As mentioned above, offshore facilities use chemicals in oil production; these chemicals are both toxic and flammable. The releasing of flammable and toxic gases in offshore operation and activities means that offshore workers are working in hazardous areas and near ignition sources. Concerns related to this are presented below.

3.4.2.1.1 Escape route and muster area

In the case of fire or a smoke alarm, offshore workers move quickly to the muster area, which is the safest place on the platform. Nolan (2014, p.388) noted that during any emergency, panic or irrational behaviour might take place as a result of unfamiliarity or confusion. Panic affects individuals by preventing them from performing their job correctly; for example, failure to activate the emergency process to minimise the incident, or using the wrong escape route. Sutton (2014, p. 102) highlighted that offshore platforms are not like petrochemical plants onshore; offshore platforms are congested and there is no outside to escape to. Jumping into the water is risky and could cause death. Therefore, a clear escape route, evacuation plan and training in using lifeboats (survival craft) are required.

3.4.2.1.2 *Persons on board*

A major concern in offshore platform incidents is the offshore crew. In the case of a serious accident on onshore facilities, the number of affected people is limited to those who are on duty. However, this is not the case on offshore, where the workers who are not working are still present and live on the platform. Piper Alpha (refer to table 7) is an example of this; a large number of deaths were reported among those who were asleep in the living accommodation and could not escape (Sutton, 2014, p.103).

3.4.2.1.3 *Blowouts and explosion*

Blowouts can happen during the drilling activity; but they comprise a threat to the entire platform and production equipment, as well as the environmental and persons on board. A safety management system must be considered in this regard, paying a great deal of attention to avoiding such an event (Sutton, 2014, p.104).

3.4.2.1.4 *Dropped objects and mechanical handling*

Dropped objects from crane operation onto the platform can happen in a routine job such as erecting of brownfield projects, maintenance activities and so on. Dropped objects can cause asset damage if they fall on major equipment, which might lead to catastrophic events; or they may even hurt offshore workers if they fall on them (Sutton, 2014, p.106). Mechanical handling studies and removal and installing procedure studies must be prepared prior to the installation of any project.

3.4.2.1.5 *Ignition sources and hydrocarbon fires*

Combustible liquids and gases are present in many of the operation processes; therefore, any leak has the potential to create a huge explosion. Ignition sources include: offshore hot working, welding and cutting, radiant heat, hot surfaces, static electricity, electrical sparks, stray currents, and lightning. The ability of these sources to ignite a material is based on the availability of the energy (Nolan, 2014, p.229). Design considerations, materials and equipment selection are very important to mitigate this risk.

3.4.2.1.6 *Welding and hot work*

Hazards related to the welding as per HSE (2012) include: fire caused by sparks, heat and molten metal; explosions when repairing equipment containing flammable materials; explosions caused by gas leak, backfires and flashbacks; impact injuries when handling and transporting cylinders of gases.

3.4.2.2 *Health issues*

Offshore topside facilities produce various types of pollution that have a direct impact on offshore workers, including: noise impact; welding flame; and toxic emission gases.

3.4.2.2.1 *Noise impact*

Noise emitted by topside facilities equipment can damage the hearing of offshore workers (noise impacts on offshore workers were further discussed in section 3.3.10.3). Another aspect is that noise can prevent or disturb offshore workers in hearing the emergency alarm, announcement and instructions. Whenever the noise level is above that of emergency alarm, a flashing light, signals and beacons should be considered (Nolan, 2014, p.387).

3.4.2.2.2 *Welding flame*

Most of the brownfield projects are designed with a welded connection. Welding is the most common procedure for fixing and installing brownfield projects. However, there are concerns in terms of safety and health; welding is an ignition sources (as discussed in 3.4.2.1.6). In terms of health, HSE (2010) stated that welding operation produces fumes that contain a complex mixture of gases and particles, which can reach the lungs. Inhalation exposure to the welding fumes can cause asthma, pneumonia, chronic obstructive pulmonary disease (COPD), metal fume fever, lung cancer and lung function changes.

3.4.2.2.3 *Toxic gases and smoke*

The toxicity of emission gases and their effects on human beings were discussed in 3.3.10.2.

3.4.3 *Recommendations for offshore (occupational and asset) safety, and health*

Fang and Duan (2014, p.323) outlined six ideology guidelines for management of safety production in offshore engineering; these include:

1. “People oriented awareness”: the concept of protecting people by considering the safety, occupational health and vital interests of workers; ensuring all workers are involved in the management of safety production.
2. “System engineering awareness”: a harmonised system including economical, environmental, social and human factors to satisfy the needs of safely production and human security, increase social-economic development and reduce the impacts of accidents. Safety management for all project development stages and phases is required from basic design, to detailed design, construction, transportation, installation, and commissioning, through until decommissioning of the platform.
3. “Prevention oriented awareness”: based on preventative methods to prevent an accident from happening. The direct causes are traced and safety management strengthened in order to avoid any accident occurring again; the focus is on the prevention rather than handling and dealing with accidents.
4. “Risk management awareness”: implementing risk management in the management of production safety in order to avoid and mitigate the losses that risk bring to the organization with least amount of workforce, materials resources and economic input.
5. “Management awareness in accordance with law”: achieving the safety and occupational health of workers and running safety production; it is necessary for the management of safety production to be in accordance with the law, and to follow rules and safety standards and specifications outlined by the government.

6. “Cultural construction awareness”: indicates the importance of a security legal system for construction and safety education. This emphasises on evaluating the worker’s safety knowledge, attitude, safety skills, ethics, morals and human factors. A cultural awareness session should include safety materials and culture, and management and behaviour culture, in addition to implementing the security technology, safety engineering and safety equipment and tools.

According to the World Bank (2015), offshore facilities should be designed to reduce and eliminate the potential risk and hazard of an accident. Gibson (2009) indicated that providing training and safe working area are important factors for increasing the productivity. The following points should be considered in the design of offshore facilities as per World Bank (2015).

General health and safety consideration:

- Proper selection of materials and providing a monitoring plan to protect the equipment from corrosion.
- Environmental conditions at offshore location such as earthquakes, seismic, wave load, ice, etc., should all be considered in the design.
- Providing adequate living accommodation for outside environmental conditions; space for social activities and recreation should be considered.
- Clear escape route and sufficient number of escape routes from facilities to the muster area.
- Temporary refuges or safe shelters in a protected area must be considered in the design to be used in emergency events.
- The position of the laydown area during design stage must be selected carefully in order to avoid moving loads by crane over critical equipment and piping.

- An alarm system should be installed and heard clearly throughout the offshore platform. A specific alarm should be assigned to each case with alarms for fire, H₂S and gas leak, person on board and so on.
- Offshore platforms should be equipped with a medical unit with specialised first aid; a general doctor must be considered based on the number on board.
- Due to the hazard of gas releases on offshore platforms, ventilation in closed areas and in areas that need to be operated during an emergency situation is required.
- Smoke and gas detection should be installed and located to enable quick and effective responses.

Fire and explosion prevention and control:

- Design the structures to protect against fire and explosion and evaluate for the need for a blast wall; consider explosion venting or blast panel and fire protection for wellheads, living areas and safe areas.
- Passive fire protection on load bearing structures, fire rated walls and partitions between rooms should be provided or considered.
- In the design of a load bearing structure or blast wall, explosion load should be accounted for.
- Accommodation should be located in a safe area and protected by a distance from hazardous areas; the ventilation air intakes must be designed to prevent smoke and hazardous materials from entering the accommodation area.
- The fire water system components such as firewater pumps and control room should be located in a safe area and insulated from hazardous areas by distance or by fire wall protection.
- To avoid an explosive atmosphere in restricted and narrower spaces, ventilation should be included or the space made inert.

- A combination of manual and automated fire alarm systems must be provided; a combination of active fire mechanism can be used depending on the type of fire, for example, fixed fire water system, CO2 extinguishing system, fixed foam system, water, water mist system, fixed dry chemical system, gaseous extinguishing system, fixed wet chemical system, live hose reels, fire water monitors, and portable fire extinguishing equipment.

Hazardous materials:

- The exposure of offshore workers to hazardous chemical materials should be reduced and considered in the design offshore facilities. Hazardous materials should be classified clearly, for instance, carcinogenic, toxic, mutagenic and so on.
- A materials safety data sheet should be provided to prevent any impacts from chemical materials on personal or offshore assets.
- Radioactive sources used offshore should be managed and controlled; a procedure must be developed for controlling and storing when the source is not in use.
- Where naturally occurring radioactive materials (NORM) are detected in processing and production equipment, annual dosage and potential exposure must be assessed for the workforce; NORM can have dangerous health effects through external or internal exposure via inhalation. The procedure should identify where NORM is located and the level of control is required.

Dropped object and materials handling:

- Assessing the loads falling from platform cranes and handling devices is very important to reduce the impact of dropped loads on platform and workers. A mechanical handling study and procedures must be provided.

Personal transfer from and to offshore platform:

- Safety procedures should be followed for personnel transfer from onshore to offshore either by helicopter or boat/vessel.

- Personnel should have completed safety courses required for offshore transportation; equipment used for transportation should be certified.
- In case where personnel are transferred from boat to offshore platform by crane, the crane cable and basket used for this operation should be certified.

Preparedness for emergency and response:

- A high level of emergency preparedness plan should be available to ensure that response to incidents is immediately effective. The emergency response team must have received training to perform well in emergency responses and actions.
- An emergency and evacuation plan should be available; Personnel on board should be provided with sufficient emergency equipment including medical emergency equipment, lifeboat, rafts and evacuation devices. Lifeboats should be equipped with lifejackets, lifebuoys and survival suits.
- Frequent exercises in emergency responses should be carried out, such as evacuation drills with equipment deployment and training in leaving the platform under different weather conditions; regular training and continuous evaluation should be undertaken.

An emergency response plan should include the following as a minimum:

1. Description of the response structures (rules, responsibilities and decision makers).
2. Description of the response procedures (equipment location, training requirements and duties).
3. Description of alarm systems and communication.
4. Description of on-site first aid supplies and medical supports.
5. Description of emergency facilities such emergency generators and fuelling sites.
6. Description of survival equipment and gear.
7. Evacuation procedures and procedures for person overboard.

8. Policies identifying when the events will stop and termination of action.

3.4.3.1 Importance of fire and explosion design strategy

Alderman and Carter (2002) stated that a fire and explosion design strategy should be integrated into hazard management system for each company. This strategy should be applied to every decision at the early design stage from the type of hydrocarbon processing, to the type, location and the need for equipment or materials. This must be considered before the decisions are made so that the opportunity can be taken to minimise the hazard; a fire and explosion design strategy should be created for each new project. Further, Alderman and Carter (2002) noted that fire and explosion design strategy is a “systematic approach to identifying, reducing, and managing hazards” and they highlighted the objectives and the importance of this strategy:

- To ensure that the protection of the personnel is considered in the design;
- To ensure that all types of hazards are identified, evaluated and reported;
- To ensure the negative effects and impacts on the community and the environment will be controlled;
- When minimising the hazards, to ensure the capital investment is optimized;
- To allow business goals to be achieved during the facility’s lifetime.

UKOOA (2003) emphasised that fire and explosion assessment should start very early in the design and everyone should have sufficient knowledge of the hazards that can be involved in the process; safety systems should be designed and selected based on the hierarchy of ***prevention, detection, and control and mitigation***.

Prevention means avoiding fires and explosions from ignition sources and avoiding the uncontrolled releases of hydrocarbons. This depends on various aspects, such as use of appropriate standards and design codes and implementing good operating practice. Prevention measures involve, for example: consider the reduction of possible release points in the design; process control and shutdown system; materials selection, inspection and protection; corrosion allowances; breach of containment control; isolation valve;

overpressurisation protection system; use non-flammable materials; avoid fired heaters or electrical equipment in hazardous area (UKOOA, 2003).

Detection measures use for identifying hazardous condition such as excess process pressure or release of gas or fire. The following detection systems should be considered: fire detection; heat detection; smoke detection; and gas detection systems.

Control measures are systems that prevent fires or explosions from spreading to other places; these include systems such as:

1. Emergency shut down systems to limit the inventory release in an incident;
2. Depressurisation systems to reduce the pressure within the system;
3. For liquid releases in some areas, bunding and drainage systems are required to collect the liquid released;
4. Well controlled systems;
5. Explosion control, which includes, for example: blast resistance walls, suppression systems, blast relief vent panels and design of layout.

Mitigation options include systems that which provide protection to personnel and equipment from fire and explosions. These systems include: a water deluge system; foam system; sprinklers system; fixed extinguishing; hose reels; hydrant pipe; and others.

API standards and UKOOA such as “fire and explosion guidance part 0 and part 1” can be followed as guidance for fire and explosion protection systems.

3.4.4 Recommendation for offshore process safety and security

For process and facility safety, Sutton (2014, p.34) described the structural components of safety management systems (SMS):

1. Facility or system description: for example, physical location and function of the facility, and the regulatory regime that the facility operates;
2. Technical information: all documents required for performing safety analysis, such as technical drawings for the facility;

3. Risk assessment, which includes hazard analysis, is the next step after describing and gathering all information for the facility;
4. Risk acceptance: based on the results from the risk assessment, the management should decide whether the level of risk is acceptable or not. If not, what is the action that should be taken to reduce it;
5. Report the results and how the risk will be managed;
6. Audit procedure: audit is required as part of the safety management system in order to learn any bad news as well as to make sure that the elements of the safety management system are implemented and conducted properly.

Risk assessment is the most important step in process safety; this step will be explained in greater detail below.

3.4.5 Risk and hazard assessment

Hazard assessment involves a review of accidents that are likely to occur; risk assessment includes various techniques and methods for determining the range of hazards on the facility and suggesting appropriate prevention or mitigation and control actions. There are several techniques reviewed by the *Centre for Chemical Process Safety (CCPS)*, such as hazard checklist, what if analysis, hazard identification (HAZID), failure modes effects and criticality analysis (FMECA), and hazard and operability (HAZOP) (Spouge, 1999, p.39).

The recommended practice for design and hazards analysis for offshore production facilities API RP 14J (2001) highlights the importance of conducting the hazard assessment as early as possible, especially at the conceptual or design phases when modification can be incorporated with minimal cost and effect. API RP 14J (2001) mentioned that the potential hazards come from processing systems, fluids being produced, procedures used for operating and maintaining the facilities; sources of hazards are flammable and toxic materials, and the consequences include explosions, personnel

injury and pollution. As this research focuses on the conceptual stage of offshore projects, the most useful techniques for risk assessment during the conceptual and design phases are considered to be HAZID and HAZOP.

3.4.5.1 HAZID study

Hazard identification (HAZID) is a tool for identifying early stage hazards that projects can be exposed to; this is a qualitative exercise undertaken by a group of experts based on judgement. Hazards at the early stage involve offshore installation procedure, blowout, fire and explosion, gas releases, dropped objects, process operation, and ship collisions. Spouge (1999, p.40) defined HAZID “as systematic review of the possible causes and consequences of hazardous events”. Veritas (2002) Marine Risk Assessment suggested the following considerations in conducting HAZID study:

- To encourage the identification of new hazards that have not previously been considered, HAZID should be creative (brainstorming);
- In order to cover all relevant hazards, the HAZID process should use a structured approach;
- The scope of HAZID should be clearly defined;
- Captures of lessons learned from previous accidents;
- The leader of the session should be an external consultant;
- Conclusions and recommendations should be discussed and documented during the group session.

For each hazard addressed, it has to be outlined how to remove or prevent it; if it cannot be removed, then action on how to mitigate and control it must be shown. Veritas (2002) pointed out that the *Centre for Chemical Process Safety* CCPS (1992) and the *Centre for Maritime and Petroleum Technology* (CMPT) (1999) have provided a detailed description of a HAZID technique that can be used for the process and offshore industry.

3.4.5.2 *HAZOP study*

In the design phase, and after completing the preliminary process and instrumentation diagrams, a *hazard and operability* study (HAZOP) is required to identify all hazards that might affect the safety and operability of a design in all type of processes, plants and facilities (API RP 14J, 2001; Spouge, 1999; Veritas, 2002). According to Spouge (1999, p.36), a HAZOP study involves each subsystem of the process in turn to evaluate the consequence of deviations in the design; the deviation is structured by a specific set of “guide word” to ensure all types of problems are covered. API RP 14J (2001) stated that the team leading during a HAZOP workshop should be experienced and able to guide the team through the analysis using “guide words” and process parameter”.

A HAZOP team comprises an engineer from each discipline, as well as, a member from the health, safety and environmental department. For each subsystem to be tested by HAZOP, deviations will be identified using “guide words”, then possible causes and consequences will be determined. After each “guide word” and deviation is tested for a subsystem, the team then moves onto the next subsystem and so on. Recommendations and actions for each consequence will be reported for further action. Guidance on HAZOP is given in CCPS (1992a) (Spouge, 1999, p.36).

3.5 Summary and Research Gap

This chapter aimed to provide the required knowledge background related to the research objectives in order to develop a sustainable framework for offshore topside projects. The literature was conducted by considering the main concerns and issues of the topside facility projects under the three main pillars of the sustainability.

Under the economic pillar, field development cost during FEED (conceptual stage) was highlighted as this stage has the most significant impact on cost, quality and schedule. Field development of offshore projects go through several stages and phases, starting with the exploring, engineering and construction, then operation and production, and finally the commissioning and start up stages. It was proposed of using and implementing the value engineering and life cycle costing concepts at the conceptual stage of any project as these concepts have big influence in the OPEX.

The value engineering concept and stages were discussed in this chapter and the importance of the function, creative and evaluation phases were reviewed. Moreover, the chapter recommended techniques for each phase. It was recommended to use the paired wise comparison method to weight the required function during the function analysis phase. With regard to the creative phase, the random identification technique is the most famous method and it adopted for this phase. Finally, an evaluation matrix was recommended as a practical and useful tool to evaluate and rank the alternatives.

The fundamentals of the life cycle costing approach were also presented. The concept of time value of money and the economic appraisals such as PW, FW, EUAW and IRR were discussed. It was found that there are some restrictions and disadvantages to using some of these methods in life cycle costing model. Use of the EUAW method in the calculation of the life cycle costing was recommended, since this method is easy to apply and doesn't require common multiples of lives between the alternatives. Uncertainty in life cycle costing analysis is always an issue due to many factors, such as cost, operation condition, inflation and so forth. The sensitivity analysis approach is a useful technique that can be applied to measure the impact of the uncertainty.

There was no evidence found of the application of value engineering and life cycle costing in topside facility projects. This lack of information will be considered and also approved through the interview questions presented in chapter 6. The author of this research has also not experienced any application of value engineering and life cycle costing concept over 15 years of his job as a topside project engineer.

In terms of the environmental Impacts (second pillar), the existing literature and its relation to the impacts of topside facilities on environments have been reviewed. Although there are some limitations to the literature on this subject, this study attempts to cover all aspects of platform topside impacts. The findings have revealed that the main impacts on environments from topside facilities can be divided into five main areas: water pollution due to discharging into the marine; air pollution due to gas emission into the air; oil and chemical spills due to accidental or human errors; noise pollution and its effects on offshore workers as well as the marine life; and finally solid and liquid wastes from topside facilities. Recommendations on how to mitigate these impacts on the environment have been discussed, however, these recommendations still lack clear guidance on how to

achieve zero impact. Greater effort is required by oil operators and international authorities to do more in this subject.

The social impacts of topside facilities (third pillar) mainly focus on the safety and security of offshore assets and on occupational health and safety. It has been shown throughout this chapter that there are many sources of hazards that threaten offshore assets and workers, such as types of materials, flammable materials, ignition sources, dangerous and flammable gases, design errors, human errors, etc. These points necessarily require more attention during the design through selecting proper materials, considering the explosiveness design strategy at the conceptual stage of projects and performing risk assessment, and in fact some of these aspects are missing in designs.

Therefore, this study, and in particular this chapter, proposes addressing these impacts and considering how to mitigate them in order to extract the main criteria for a sustainable framework, as presented in the following chapter. This chapter has addressed the research objective by identifying the potential impacts of topside facilities.

Chapter 4

Research Methodology

4.1 Introduction

This chapter discusses the research philosophy, types of research, methods and the data collection techniques generally. It presents in detail how the research is conducted and how the methodology is used to achieve the research objectives. The chapter outlines the most suitable research approach and the method considered to perform this research. The research design process is also presented. Finally, a brief explanation of the suggested offshore sustainable design framework and framework validation are discussed.

4.2 Research Definition

Research is defined by many sources as the technique of scientific investigation in order to gain new knowledge in any field. The Oxford Advanced Learners' Dictionary defined research as "a careful study of a subject especially in order to discover new facts or information about it". According to Clifford Woody, cited in Sarangi (2010, p.8) research can be defined as "a careful inquiry or examination in seeking facts or principles, a diligent investigation to ascertain something" and Blaxter, Hughes and Tight (2010, p.63) defined research as "a systematic investigation to find an answer to a problem". In Zikmund's *Business Research Methods* (2003, p.6), research is defined as "a systematic and objective process of gathering, recording, and analysing data for aid in making business decisions". Therefore, research process and methodology for collecting data and analysis will be discussed below.

4.3 Research Philosophy and Approaches

According to Remenyi, cited in Fellows and Liu (2015,p.69), researchers should consider and remain aware of which research community they belong to. Further, research assumptions like epistemological, ethical and ontological should be considered. It is very important to understand research positions in terms of the epistemological and ontological

approaches, as this is generally the basis for the research methodology. This was also supported by Naslund, cited in Woo (2011, p.669), who suggested that in order to identify the limitations and potential of any research method, the research paradigm should first be discussed.

Bryman (2012, p.6) mentioned that assumptions and views about how research should be conducted and followed are referred to as “**epistemological**”, whilst, assumptions about how the social phenomena influence the research process are referred to as “**ontological**”. Fellows and Liu (2015, p.70) stated that ontology is concerned with assumptions in conceptual reality, while epistemological, is therefore concerned with the origins, nature, methods and limits of human knowledge. Epistemological is therefore asking questions about how knowledge is acquired, and ontology is inquiring about the nature of reality and what it means to be or to exist (Lapan, Quartaroli and Riemer, 2012, p.76).

Falqi (2011, p.79), citing Burrell and Morgan, stated that the **ontological** is based upon two assumptions, *realism and nominalism*; and the **epistemological** is based upon *positivism (objectivism)* and *anti-positivism (subjectivism)*. Falqi also provided an overview of the research paradigms. The three methodological paradigms (approaches) in construction management are identified as *positivist, interpretivist and pragmatic*. According to Lapan, Quartaroli and Riemer (2012, p.76), the term paradigm “drives from the work of Thomas Kuhn (1970) who suggested that the researchers are influenced by dominant ways of or frameworks for conducting science”. Fellows and Liu (2015, p.18) defined **paradigms** as “a theoretical framework, which includes a system by which people view events”. Another definition was provided by Guba and Lincoln, cited in Denzin and Lincoln (2011, p74), as “the basic belief system or world view that guides the investigator, not only in choice of method but in ontologically and epistemologically fundamental ways”. Creswell (2009, p.6) further introduced a new term with regard to paradigms “worldview”. Therefore, *paradigms* and *worldviews* all refer to the same point.

Most researchers in construction management refer to the *positivist, interpretivist and pragmatic* approaches whereas the ontological and the epistemological approach are not common.

4.3.1 Positivist paradigm

The positivist paradigm uses scientific methods or experimental testing to research and find the required knowledge. Falqi (2011, p.80) stated that the positivist paradigm is based on realist **ontology** and objective **epistemology** and uses quantitative techniques. Arab (2011, p.119), citing Cohen, stated that in this approach knowledge is achieved within a framework of principles and assumptions of science. According to Fellows and Liu (2015, p.18), there is a strong relationship between this paradigm and quantitative approaches. From the above, it can be clearly seen that the following terminologies – objective, positivist, quantitative, scientific, experimentalist and traditionalist – belong to the same approach (Barker, Nancarrow and Spackman, 2001, p.3).

4.3.2 Interpretivist paradigm

The interpretivist paradigm assumes that people seek realization and the recognition of the world in which they live (Bryman, 2012). According to Saunders, cited in Arab (2011, p.120), interpretivism refers to how people feel or view their surrounding world and how they behave towards each other. The interpretivist paradigm is based on nominalist **ontology** and subjectivist **epistemology** and uses qualitative techniques (Falqi, 2011, p.80). This paradigm has become clearer in qualitative researches and studies. Therefore, the following terminologies – qualitative, subjectivist, interpretivist and humanistic – belong to the same approach.

4.3.3 Pragmatic paradigm

The pragmatic paradigm is not aligned to any system; in this method, researchers are concerned with the “what and how” of the research problem (Creswell cited in Arab, 2011 p.121). The pragmatic approach includes both positivist and interpretivist paradigms in a single research (Falqi, 2011, p.80). This paradigm mainly uses the mixed method approach for collecting and analysing the data. Tashakori and Teddlie, cited in Awodole (2012, p 104), mentioned that a number of different authors use pragmatism as the paradigm for the mixed methods research.

With this approach the researchers are free to choose the methods, techniques and procedures that best suit their needs. Thus, the researchers in mixed methods use both

qualitative and quantitative data to provide the best understanding of their research problem. Moreover, pragmatic approaches allow for multiple methods, assumptions and different worldviews in addition to different forms of data gathering and data analysis (Creswell, cited in Awodole, 2012, p 104).

4.4 Strategies of Inquiry in Construction Research

The techniques, tools and procedures used for collecting and analysing the data are referred to as research methods. The research method is not the same as the research methodology. The research methodology is a comprehensive design and framework, used in investigation. Thus, methods can be described as “a way of doing” and the methodology as “a way of thinking”. The research methodology is sometimes referred to as the research approach or research design (Lapan, Quartaroli and Riemer, 2012, p.3,11,71).

Creswell (2009, p.11) stated that **strategies of inquiry** are types of qualitative, quantitative and mixed methods design or models that provide specific procedures in a research design, further noting that other researchers have referred to these as **approaches to inquiry**. The most common research methods in construction management are *qualitative*, *quantitative* and *mixed* methods.

4.4.1 *Qualitative and quantitative methods*

Qualitative methods seek to understand people’s perceptions of the world and so the views, opinions and beliefs of experts are analysed and investigated. The analytical techniques for qualitative data, however, are sometimes very problematic due to the need to analyse conversations and the interview content (Fellows and Liu, 2015, p.28). Lapan, Quartaroli and Riemer (2012) noted that qualitative research involves studying the phenomena from the perception of insiders by using an interpretive framework. This method also depends on the ability of the researcher to interact efficiently with the insiders in order to collect the required data. In this way, the researcher interacts with what is being researched. This method uses a deductive process as a methodology. The main methods for data collection are in-depth interviews, observations and documentary analysis. Creswell (2009, p.13) outlined several ways to conduct qualitative research

including grounded theory, ethnography, case studies, phenomenological and narrative research.

According to Fellows and Liu (2015, p.28), **quantitative** methods relate to positivism and aim to collect real data in order to study relationships between facts and relationships in accordance with theories and findings from previous research. This method uses scientific techniques to get the quantified data. Lapan, Quartaroli and Riemer (2012) stated that quantitative researchers attempt to remain independent of the phenomena they study with the aim of generalizing the findings. An inductive process is therefore used as a methodology for researching. Experiments and surveys are the most common tools for data gathering in this method.

The differences between the two methods can be summarised as follows: the qualitative method is based on the interpretivist paradigm, while the quantitative method is based on the positivist paradigm. The reality in the quantitative method is objective, whilst the reality in the qualitative method is subjective. Researchers are independent from what is being researched in the quantitative method, while in the qualitative method the researchers interact effectively with insiders. According to Forman et. al. (2008, p.765), the aim in the qualitative method is discovery oriented and data collection is open ended, while the aim of the quantitative method is to determine the relationship between the variables and the data collection is not open ended. Forman et.al (2008, p.765) also outlined that the research process is iterative and emerging in the qualitative method, whilst, the research process is sequential and fixed in the quantitative method. Mukherji and Albon (2010, p.14) stated that the quantitative method aims to measure and quantify, whilst the qualitative method is usually more concerned with describing an experience and exploring the nature of an issue. Therefore, qualitative researchers describe and quantitative researchers compute. Eliot (2010, p.1) mentioned ten distinctions between quantitative and qualitative methods. These differences are presented in table 8 below.

Table 8 Difference between qualitative and quantitative methods (Eliot, 2010, p.1)

Methods Differences	Qualitative	Quantitative
Understanding vs. Explanation	Seek to understand the interrelationships.	Seek to explain and control.
Non Causal vs. Causal	No expectation of causal explanation.	Establish cause and effect.
Unique vs. Generalisable	Consider the uniqueness of individual cases and contexts as important to understanding.	Nullify the context to find the most general and pervasive explanatory relationships.
Continual vs. Summative Interpretation	During data collection the qualitative researcher continually exercises subjective judgment, constantly analysing and synthesising data.	In standard quantitative designs interpretations are stifled until all the data are collected and statistically analyzed.
Limited vs. Unlimited Variables	Qualitative research questions are designed to seek unanticipated as well as expected relationship among a broad set of variables.	Quantitative questions examine relationships among a small number of predetermined variables.
Field vs. Design Talent	Talented researchers must be the ones out in the field “directly in contact with the phenomenon” and making subjective claims as to the meaning of the data.	Talent is most beneficial when allocated upfront in instrument development and controlled questioning.
Holistic vs. Targeted	Qualitative inquiry is distinguished by its emphasis on a holistic treatment of phenomena.	Quantitative studies target one discrete piece of the whole.
Allow vs. Create	Qualitative researchers allow things to happen naturally.	Quantitative researchers create situations to test their hypotheses.
Critical vs. Comparative Uniqueness	In qualitative research, uniqueness is established through the "collection of features and sequence of happenings critical to understanding a particular situation”.	Uniqueness in quantitative research is established by comparisons made to a number of other pre-determined variables.
Patterns vs. Co-variation	Qualitative research is grounded in patterns and themes.	Quantitative researchers rely on correlation and co-variation to validate findings.

4.4.2 *Mixed methods*

The application of quantitative as well as qualitative methods in one study is referred to as mixed methods. This method is based on the pragmatic approach. Harrison (2013, p.2153) noted that this method is given various different names such as multiple methods, blended research, multi-method or triangulated studies, but the most common name is mixed method. Johanson et al. cited in Harrison (2013, p. 2153) defined mixed methods as:

..... “the type of research in which a researcher or team of researchers combine elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inferences techniques) for the broad purpose of breadth and depth of understanding and corroboration”.

Creswell and Plano, cited in Stentz.et.al (2012) defined mixed methods research as a:

..... “a research design with philosophical assumptions as well as methods of inquiry. As a methodology, it involves philosophical assumptions that guide the direction of the collection and analysis and mixture of qualitative and quantitative approaches in many phases of the research process. As a method, it focuses on collecting, analyzing and mixing both quantitative and qualitative data in a single study or series of studies. Its central premise is that the use of quantitative and qualitative approaches in combination provides a better understanding of research problems than either approach alone”.

Bloch (2014, p.106) stated that the particular value of mixed methods is in its ability to address problems from different points of view in order to provide a more comprehensive analysis. This was supported by Mengshoel (2012, p.373) who noted that findings of mixed methods are generally believed to be more comprehensive and valid than the findings of qualitative or quantitative methods when they are undertaken separately. Quantitative and qualitative methods have different restrictions and strengths, and combining these two approaches within mixed methods can maximise the strength of each. In this way, the weakness of one approach can be compensated for with the strength of the other (Mengshoel, 2012, p.373; Stentz et al. 2012).

Creswell (2009, p.15) emphasised that mixed methods involves the use both open and closed ended questions, statistical analysis, text analysis, and multiple forms of data, drawing on all possibilities; therefore, in general it can be said that this type uses a combination of qualitative and quantitative tools.

4.4.3 Design typologies of mixed methods

According to Johanson and Onwuegbuzie, cited in Bloch (2014, p.106), mixed methods research faces a number of challenges during the method design, such as whether to conduct the qualitative and quantitative stages concurrently or separately, whether both methods should be given equal priority, at what stage of the work the methods are mixed and how interaction between the methods is undertaken. This was supported by Creswell and Plano Clark (2011) and Stentz et al. (2012) who identified four basic elements involved in designing a mixed method research, which are as follows: *the extent of interaction, the relative priority, timing, and where and how they are mixed*. These elements are further explained in the table 9 below:

Table 9 Element in designing a mixed method

Interaction	Whether the two methods (qualitative and quantitative) are kept independent from one another or interact with one another.
Priority	The most relevant component to answer the research question; there are three possible priority choices: equal, quantitative, or qualitative.
Timing	The order in which the data is collected and analysed is referred to as timing by Morse, cited in Stentz et al., (2012). Three timings are identified: concurrent, sequential and multiphase combination timing. When both qualitative and quantitative data are executed during a single stage of the research, this is referred to as concurrent timing . In contrast, when the data for one type is collected and analysed before the other type, this is referred to as sequential timing . When both concurrent and sequential timing are applied in multiple phases of the study, this is referred to multiphase combination timing .
Mixing	When and how the two different data types are combined and integrated.

Sources: (Creswell and Plano, 2011; Stentz, 2012; Greene, 2007)

Four common designs typologies of mixed methods were identified by Creswell and Plano Clark, cited in Harrison (2013, p.2156), Stentz et al. (2012) and Albright et al. (2013, p.403). These are *exploratory designs*, *explanatory designs*, *embedded designs* and *convergent designs*. Moreover, Stentz et al. (2012) discussed two more designs: *transformative* and *multiphase* designs. Table 10, identifies the four common design typologies of mixed methods.

Table 10 Typologies of mixed method

Design Type	Description	Timing	Priority
Exploratory	This design is carried out in two phases. First, the qualitative data is collected and analysed. Second, the quantitative data is gathered and considered. This type of design is useful when the qualitative results require further testing or quantification.	Sequential	Qualitative
Explanatory	This design occurs in two phases. First, the quantitative data is collected and analysed. Second, the qualitative data is followed and considered to explain in depth the quantitative results.	Sequential	Quantitative
Embedded	Both qualitative and quantitative data are collected either sequentially or concurrently within a general quantitative or qualitative research design.	Sequential or concurrent	Quantitative or qualitative
Convergent	Both qualitative and quantitative data are collected together, analysed separately, and mixed in the result stage where the conclusion is drawn.	Concurrent	Equal

4.5 Selected Research Approach/Strategy

The main objective of this research is to provide a sustainable design framework for the offshore industry, which can be used at the early stage of any project to help the decision maker to evaluate and select the materials from a sustainability perspective (social, environment and economic). The research will be conducted in phases, as described in section 4.6 below. It will begin with qualitative research and end with a quantitative study to test the qualitative results and approve them. Therefore, it is clear that the *exploratory sequential design* is the best research design method to describe the general framework methodology for this study. Stentz et al. (2012) stated that this design is conducted in two phases, starting with qualitative methods and followed by quantitative methods, built on the initial qualitative results, and this design is useful when the qualitative results need more testing. Table 11 below summarises the research philosophy adopted for this research.

Table 11 Research approach for this study

Paradigm	Strategy/Method	Type	Timing	Priority
Pragmatic	Mixed Method	Exploratory	Sequential	Qualitative

4.6 Research Design

The research is designed to find a solution to the problem statement and to achieve the research objectives, which are mentioned in chapter 1. Therefore, the research design includes the methodology and framework for the investigation as well as the procedures that should be followed to achieve the required objectives and targets. The research design is divided into four stages in order to achieve the objectives; two stages include the data collection and analysis, and the other two involve the output and achievement of this research.

Data collection and analysis includes the following stages:

- Stage one: exhaustive literature review
- Stage two: semi structured Interviews

Output and achievement of this research includes the following stages:

- Stage three: framework development
- Stage four: framework validation and evaluation

4.7 Stage One: Exhaustive Literature Review

The literature review helps the reader to determine whether the subject is worth studying, and provides understanding of ways in which the researcher can limit the scope to a needed area of study (Creswell, 2009, p.23). The literature review should prove that the author has a full understanding of the existing knowledge, demonstrating his capacity to make an original contribution to knowledge in this research area; in addition, the literature helps the researcher by giving him guidance on how he can design and conduct his study effectively (Naoum, 2012, p.18). Therefore, the literature review was conducted in two phases, as outlined below:

4.7.1 *General literature review*

In the general literature review, academic literature were considered to clarify the main concepts of the research, such as construction in the offshore industry, sustainability in

the construction industry, requirements for green design and eco materials, and requirements for offshore materials; this was presented in chapter 2. Moreover, the importance of conceptual stage offshore field development and using value engineering and life cycle costing techniques within the conceptual stage were presented in chapter 3.

4.7.2 In depth literature review (secondary data)

This research is considered an original research as no sustainable framework for offshore topside facility projects exists that can provide a foundation for this study. One advantage of this research is that the author is the end users and has an experience more than 15 years' experience in the field.

The aim of this part is to explore the main factors or criteria that affect the sustainable design of offshore topside projects. In order to achieve this objective, the literature was used to provide a rigid background in certain areas that will help to drive and explore these factors. Topside facilities systems, the environmental and social impacts of topside facilities systems and the importance of materials selection as part of the sustainable design are all areas that have been covered in chapter 3. The strategy was used for conducting the literature reviews has considered various reliable sources of information, such as international journals, textbooks, international standards and codes in offshore fields, conference papers, articles, guidelines and PhD theses. Creswell (2009, p.34) stated that one important task for a researcher working with a new topic is to organise the literature through a map. Therefore, literature map is presented below in figure 25.

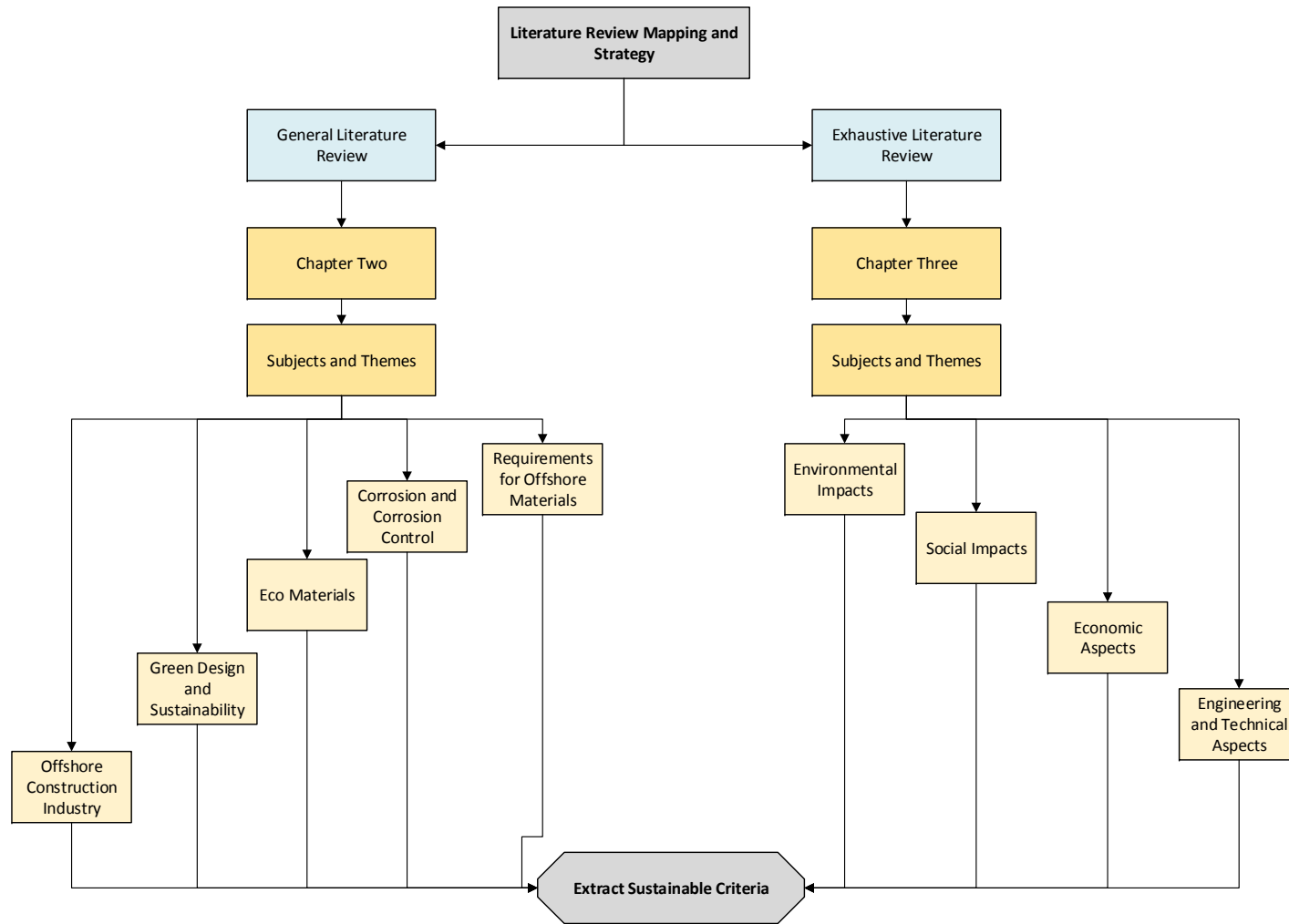


Figure 25 Literature mapping

4.7.3 Analysis of the literature review (secondary data)

Thematic and narrative approaches were used for gathering the factors affecting the sustainable design. Four main themes were introduced which represent the three main pillars of sustainability (economical, environmental, and social) alongside the engineering and technical aspect. The main themes were also divided into sub-themes as shown in the following figure 26. This is further discussed in chapter 5 (extracting and deriving the criteria).

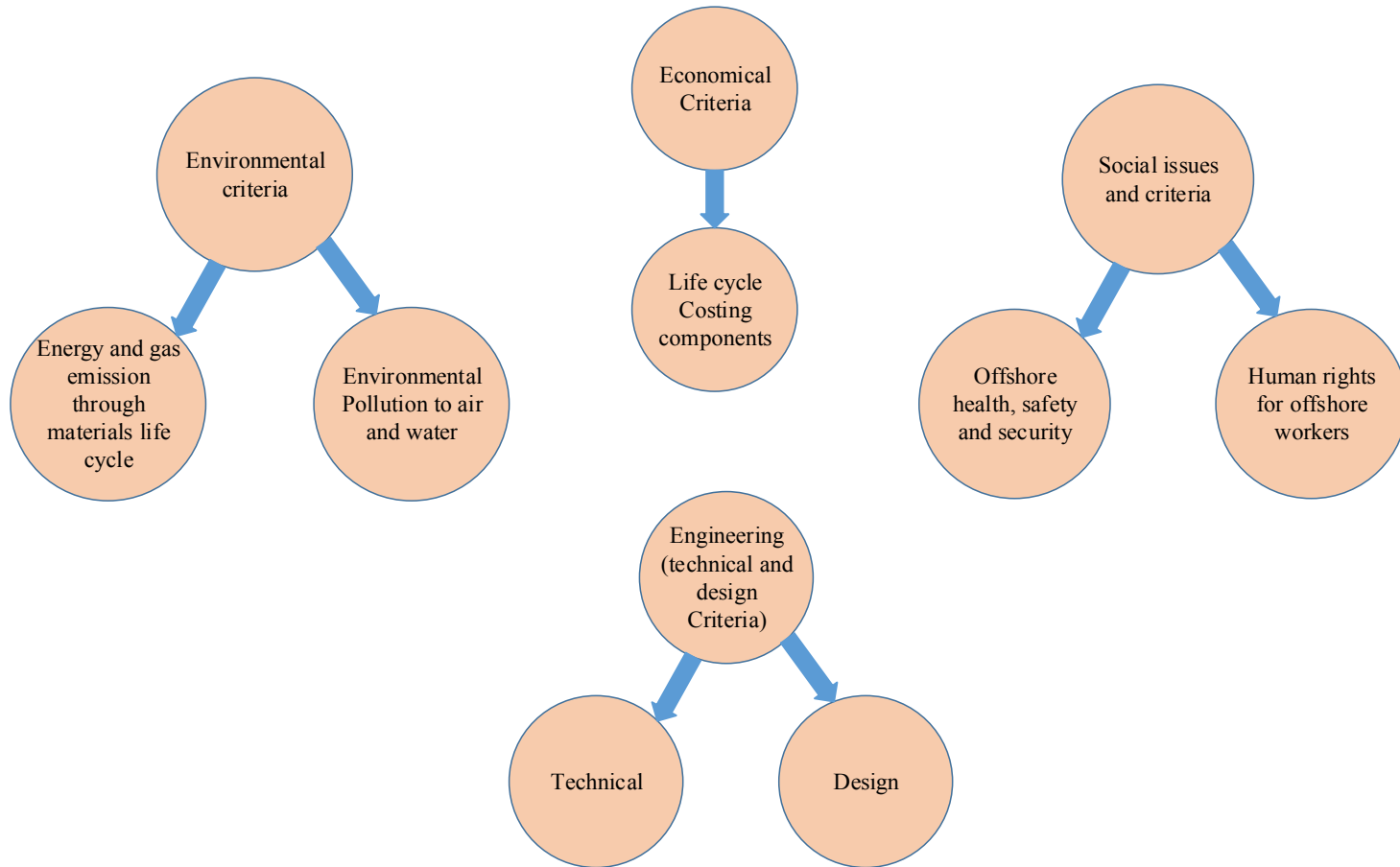


Figure 26 Themes analysis

4.8 Stage Two: Semi-Structured Interview (Primary Data)

The main tools for collecting qualitative data, as mentioned in section 4.4.1 above, are interviews, observations and documentary analysis. Fellows and Liu (2015) mentioned that interviews are one of the most common methods used in the construction industry. They mentioned three types of interviews: structured, unstructured and semi-structured interviews. They also categorised the data collection into either one-way or two-way communication. One-way communication includes questionnaires, structured and unstructured interviews. However, the importance of the two-way communication, such as semi-structured interview, provides feedback and transferring the meaning rather than just the data, as in one-way communication. Leech (2002) asserted that semi-structured interviews provide more detail and an insider's view. In contrast, the structured interview could backfire if the questions are asked in the wrong way; as a consequence, content validity would be lost. Elliott and Timulak (2005) mentioned that in qualitative research, questionnaire is used in small scale as it does not provide detailed information about a specific experience. Arab (2011, p.150), citing Punch, mentioned that semi-structured qualitative interviews cover several themes and topics in an interview guide and this kind of interview is also considered the best tool for researchers seeking comprehensive information. Questions in a semi-structured interview can be changed or added depending on the interview situation, and this can be managed and controlled to get the necessary information from the interviewees (Falqi, 2011, P.151). Moreover, Naoum (2012, p.56) highlighted the main characteristics of this kind of interview. Semi-structured interviews include both open and closed ended questions; the interviewer has flexibility with regard to the order of asking the questions as there is no specific order or schedule to be followed. This type of interview focuses on the respondent's experience in specific area, as well as referring to situations that have been analysed prior to the interviews.

Therefore, due to the lack of research in offshore topside facilities in terms of sustainable engineering design and materials selection, the best method for this study was found to be semi-structured interviews, which is appropriate for exploratory research and facilitates the gathering of comprehensive information.

4.8.1 Purposes of the interviews

The interviews aimed to verify and evaluate the factors and criteria that identified through the literature review by investigating the respondents' understanding of these criteria and investigating the gaps in the current practice in engineering design and materials selection for offshore topside facilities in order to develop an effective sustainable framework for offshore topside projects. The main objectives of semi-structured analysis are: (1) to rate the derived criteria from the literature review based on their importance; (2) to prove and confirm the findings of the literature review; (3) to provide any additional comments based on the expert's experience; (4) to explore and identify the gaps in the current practice of engineering design and materials selection by determining the required principles, concepts and themes to be considered in the proposed framework; (5) to provide the main requirement for the framework creation; and (6) to address the objective 3 of this study (refer to section 1.6).

The interview method was face-to-face interaction; the strategy for sample selection was considered 40 experts from the oil and gas industry, and in order to enrich the research and get the most effective results, the selection of the interviewees considered both views of oil operator companies and consultancy offices. Further details about the process of the interviews and sample selection strategy are explained in next sections.

4.8.2 Interview design and methods

The interview was designed to achieve the objectives mentioned above in section 4.8.1, as well as to collect as much data as possible. The questions were designed based on the information and data obtained from the literature review. The questions were ordered in a way that researcher could control the conversation and to ensure that all research concepts and principals were discussed.

The interview was designed to last 90 minutes to give the interviewees the freedom to express their ideas, thoughts and opinions on sustainability, engineering design and materials selection for offshore topside facilities, as well as, allowing them to rate the determinant factors from the literature review. To ensure effective qualitative interviews

were conducted, a combination technique of closed ended and open ended questions was designed. Naoum (2012) mentioned that the semi-structured interview starts with indirect questions in the form of open ended questions, which provides the opportunity for the respondent to express their view and encourages them to consider the problem.

Zikmund (2003) mentioned several important points for developing and designing the questions: (1) the questions must avoid complexity, and should use simple words; (2) the questions should avoid leading and loaded questions, which are the major source of bias; (3) the questions should be specific to avoid any ambiguity; and (4) double barreled questions should be avoided.

Therefore, the interview included three main parts, starting with open ended questions, then closed ended, and finally concluding with open-ended questions as shown in **appendix A**. The first part of the interview questionnaire comprised open ended questions and two sections. The first section was concerned with the background of the interviewees, such as job position, academic level, years of experience in the oil and gas industry, type and size of company. This information will be used to describe and identify the respondents' attributes. The second section of the first part included general questions where the respondents were asked to provide their opinion and evaluation of some concerns about topside facilities for fixed offshore platforms.

The second part included closed ended questions, where the respondents were asked to rate the level of importance of the seventy seven criteria derived from the literature review based on a Likert scale of 1 to 5, where 5 is the "most important" and 1 is the "least important".

The final part comprised open ended questions where the respondents were asked to provide their thoughts, ideas and knowledge about important concepts and principals that will help in creating the proposed sustainable framework. These concepts and principals included life cycle costing, time value of money and value engineering. Moreover, the respondents were asked to provide any additional criteria or factors that might influence sustainable design but had not been mentioned or listed in the previous parts.

4.8.3 Method of interaction

Face to face interviews and telephone interviews are the main methods for collecting data in the qualitative interviews. Face to face interviews have several advantages, for example, they can help the researcher collect precise information and allow for feedback from both parties as required. This kind of method also allows for probing complex answers when they are not clear to the researcher. Face to face interviews allow for a longer time to get more comprehensive information; a telephone interview, on the other hand, which could last for just 10 minutes (Zikmund, 2003, p.201). Rosnow and Rosenthal (2013) stated that face to face interviews provide the opportunity to establish a relationship and encourage the cooperation needed to explore the problems. Although face to face interview is considered more expensive than other methods, this method has therefore been adopted for this study.

4.8.4 Strategy for the sample selection

Sampling in qualitative research should be flexible and should cover all important aspects of the research question, no matter the size of the sample, whether 8 or 100 (Elliott and Timulak , 2005, p.151). The interviewees were selected based on their experience and background in the topside area of fixed offshore platform.

To get the most effective results from this study, two types of organisation were involved, one international operator company from the oil and gas industry, and an international consultancy office in the oil and gas industry. This strategy will provide both the views of oil operator companies and consultancy offices.

There were several considerations necessary in selecting the interviewees, as a response to which the following criteria were applied: (1) extensive knowledge in their field; (2) experience in the offshore industry, especially the topside part of the fixed offshore platform; (3) selection ranging from all engineering disciplines; and (4) considering the different job positions within the same discipline (such as head of department, lead engineer, senior engineer, etc.).

Tables 12 and 13, show that 40 experts and professionals across all engineering disciplines in the oil and gas industry were interviewed. 24 experts from an international

oil operator company and 16 experts from an international consultancy office took part in the study.

Table 12 Profiles of the participants (oil operator company)

International Oil Company		
Department	Position	Years of Experience
Process	Lead process engineer	19
	Senior process engineer	10
	Process engineer	7
Structural	Head of structures and pipelines	35
	Lead structure engineer	14
	Senior structural engineer	30
	Senior structural engineer	25
Piping	Head of piping department	27
	Lead piping engineer	25
	Senior piping engineer	10
	Piping engineer	14
Electrical and Instrumentation	Head of electrical and instrumentation	21
	Senior control and instrument	22
	Lead instrument engineer	12
Materials/ welding	Lead metallurgist engineer	18
	Materials and welding engineer	25
	Materials and corrosion engineer	18
Mechanical	Head of mechanical department	24
	Lead mechanical engineer	23
Projects	Senior project engineer	25
	Senior project engineer	14
FDP	Facilities manager	22
	Project manager	24
HSE	Senior environmental advisor	20

Table 13 Profiles of the participants (oil consultancy office)

International Consultancy Office		
Department	Position	Years of Experience
Management	Engineering manager	25
Process	Chief process engineer	26
	Senior process engineer	12
	Loss prevention engineer	7
Piping	Lead piping engineer	12
	Senior piping engineer	12
	Piping engineer	12
Structural	Chief structural engineer	18
	Principal structural engineer	28
	Principal structural engineer	24
	Lead structural engineer	18
Electrical and Instrumentation	Chief instrumentation and control	16
	Lead instrument engineer	16
	Senior instrument engineer	15
Projects	Lead project engineer	26
	Project engineer	10

4.8.5 Pilot Study for qualitative research

Tashakkori and Teddlie, cited in Dikko (2016), noted that a pilot study is important for both qualitative and quantitative research. Naoum (2012) stated that a pilot study is useful for testing the wording of the questions, checking the length of the questionnaire and making sure that all questions are clear and not ambiguous. Teijlingen and Hundley (2001), citing Holloway, suggested that in qualitative research a pilot study is not necessary as for example, in the interview approach the researcher can simply use the first three interviews to improve the questions or add new topics.

Therefore, the first three interviews were treated as a pilot study for this qualitative research. The interview schedule was thereby checked in terms of clarity, understandability, and the time required to complete the interview. The results of the pilot study showed that there were no major changes to be made. The only change was to the time allocated to each interview; the time allocated increased from 60 to 90 minutes.

4.8.6 Reliability of the qualitative part (open ended part)

According to Ikediashi (2014, p.178), citing Bagies and Creswell, the reliability of the qualitative research is related to the quality of the interview context, the interviewer experience and the interviewee's background. Alshenqeeti (2014) outline several methods by which to achieve reliability and validity when interviewing, such as avoiding leading questions, conducting pilot interviews, and giving the participants a chance to present and clarify the points they have made.

In terms of the interview context, the pilot study was conducted with the first three participants to check the clarity and understandability of the interview context. In terms of the interviewee's background, the strategy for sample selection is presented in details in section 4.8.4. Most of the interviewees have masters and PhD degrees, as well as occupying high level positions in the oil and gas industry, such as heads of departments, managers, leadership roles etc. Therefore, there is no doubt that they are not providing reliable information. In this regard, reliability of the qualitative part of the semi-structured interviews was achieved.

4.8.7 Reliability of the measuring instrument (closed ended part)

Carmines and Zeller (1979) defined reliability as “the extent to which an experiment, test, or any measuring procedure yields the same results on repeated trials”. There are four techniques for estimating the reliability of empirical measurements: (1) test and re-test method; (2) alternative form method; (3) splits halves method; and (4) internal consistency method (Carmines and Zeller, 1979; Oppenheim, 2003). However, Carmines and Zeller (1979) provided an evaluation of the four mentioned methods; they concluded that neither the re-test nor splits halves method is recommended for calculating reliability, and there are some difficulties with using the alternative form method. In contrast, the internal consistency method has more general reliability and is easy to compute. Hence, the internal consistency reliability was considered for this study. The analysis and results of the reliability are discussed in chapter 6.

4.8.8 *Validity of the measuring instrument*

The validity test refers to whether a measure of a concept really measures what it is supposed to measure (Bryman, 2016; Oppenheim, 2003). In the existing literature on research methods, six types of validity were mentioned. These are: face validity, content validity, concurrent validity, predictive validity, construct validity and convergent validity. Carmines and Zeller (1979), citing Cronbach, noted that “one validates, not a test but an interpretation of data arising from a specified procedure”. So the measuring instrument could be valid for testing one phenomenon but could be invalid for testing another. However, Oppenheim (2003) argued that “each measurement technique can have more than validity depending on the conclusion we want to draw from it”. Oppenheim (2003, p.162) further indicated that, with regard to content validity, the questions or items need to cover the concept and provide a well-balanced sample of the content to be tested. Face validity refers to the degree to which the instrument “looks as if” it is measuring what it is supposed to measure (Rosnow and Rosenthal, 2013, p.107). On the other hand, Bryman (2016) specified that face validity can be determined by asking experts in the field whether the measure or questions have been well designed to cover the concept concerned. Therefore, face and content validity were adopted in this study.

Face and content validity were established by consulting the experts during the pilot study and interviews. The experts were asked to check whether the questions consider what they are designed to measure. They were also asked if the questions represent the research domain. During the pilot study, all the questions were examined and the only resulting change was in the time allocated for each interview, which was changed to 90 minutes instead of 60 minutes. In the open-ended questions, the interviewees were asked to provide any additional criteria or factors that might influence sustainable design that had not been mentioned or listed in the questionnaire. They were also asked to comprehensively provide any general suggestions or comments on the themes and concepts discussed in the questions. However, no additional relevant criteria or comments on the interview questionnaires were noted; consequently, the questionnaire was treated as content validated.

4.8.9 Analysis of the semi structured interviews

The semi-structured interviews included three main parts: the first part was open-ended questions where the respondents were asked to provide background about their experience, job title, educational level and so on. The second part included closed ended questions, where the interviewees were asked to rate the identified factors from the literature review based on their importance on a Likert scale from 1 to 5, where 5 is the most important and 1 is the least important. The last part comprised open ended questions where the respondents were asked to give their thoughts, ideas and knowledge about the research themes and concepts, as well as the requirements of the framework creation. The analyses of the answers to both open and closed ended questions are carried out as shown below.

4.8.9.1 Relative importance index

The closed ended questions for the semi-structured interviews were statistically analysed. The relative importance index (RII) was used to rank the determinant factors and criteria based on the literature review. 40 responses were received and analysed by the RII (for the analysis refer to chapter 6).

4.8.9.2 Thematic and narrative analysis

It is very important in qualitative interviews to determine the context of the interview by identifying the interview themes. There are several methods for establishing the context of the interview. Themes can be derived from theories discussed in the literature, or the researcher's experience of the specific topic, research participants or co-workers (Saunders, Lewis and Thornhill, 2009). In this study, the interview themes were identified based on the research questions and concepts. Four main themes were derived and divided into subthemes as shown below in figure 27. The main themes are: (1) general sustainability understanding and requirement, which includes three subthemes, (A) environmental aspects, (B) social aspects and (C) economical aspects; (2) engineering aspects, which include the subthemes, (A) design practice and (B) materials selection practice and consideration; (3) project evaluation and appraisal, which includes (A) value

management, and (B) life cycle costing management; and (4) framework requirement and components. The analysis of the questions are presented in chapter 6.

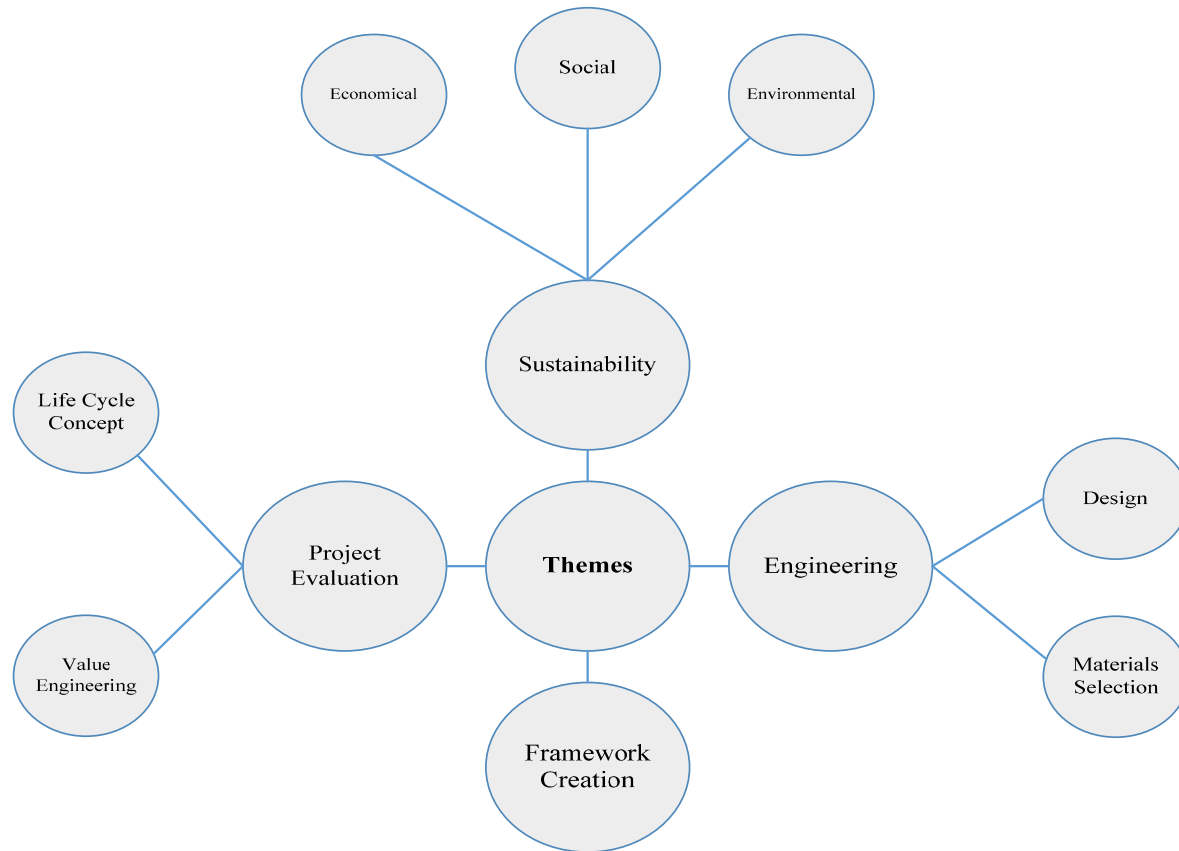


Figure 27 Themes grouping for semi structured interviews

4.9 Stage Three: Framework Development

As mentioned above, this study is considered an original study, as there is no existing framework for offshore topside projects that can be used as a foundation for this research. Therefore, the creation of the framework is based on the criteria derived from the literature review, the results from the semi structured interviews with 40 professional experts in offshore oil and gas platforms, and the author's 15 years' experience in the offshore field. On the basis of the results and findings from the interviews, it is essential to develop a sustainable framework for offshore topside projects. The philosophy of the framework is considered in the creation, the *sustainability, value engineering and life cycle costing concepts*. The framework is presented in three main stages: (1) environmental and social evaluation; (2) materials and equipment evaluation; and (3) life cycle costing evaluation (refer chapter 7).

4.10 Stage Four: Framework Validation and Evaluation

In order to ensure that the framework is structured well and meets all the intended requirements, as well as to convince the stakeholders/ end users to implement and use the proposed framework, the framework needs to be demonstrated and validated. Therefore, it is important to establish a methodology for validating and evaluating the framework. Sargent (2005) mentioned several approaches to decide whether the framework or model is valid or not. In this study, two approaches were used in combination: (1) involving end users in determining the framework validity; and (2) the scoring model approach. According to Sargent (2005), the validation process is carried out in a conceptual framework to ensure that the framework is structured correctly without mistakes, the assumption and specifications are clear and the model or framework representation meets the intended purpose of the model. Sargent mentioned that there is no formalised guide or procedure for selecting the best approach to use in the validating framework as each modeling guide presents a set of challenges. Sengupta (2004) also noted that it is the researcher who can decide what is the best means to validate the model based on the nature of the research.

Sargent (2005) outlined four basic approaches to decide whether the framework or model is valid or not:

- A subjective decision can be made based on the results of the various tests and evaluations conducted as part of the model development process by the model development team.
- Involving end users with the development team (researchers) in determining the validity of the model/framework. Hence, the determination of validity will move from the development team to the end users. This approach is used to help in model credibility.
- A third party (independent) can be used to decide whether the model is valid or not. There are two different ways to conduct the validity in this approach: either the validity is conducted concurrently with development of the model, or it is conducted after the model has been developed.
- A scoring model can be used in this approach when conducting the validation process; scores are used to evaluate the model. The model/framework is considered valid if the overall scores are greater than some passing scores.

There are various techniques that can be applied to validate the model/framework; however, Sargent (2005) mentioned that the primary validation technique or method used in validating the conceptual model is the *face validity* method. Face validity involves asking experts to evaluate the conceptual model/framework in order to determine if it is correct and reasonable for its purpose. This sometimes involves examining the flowchart, graphical model, or model equations.

4.10.1 Selected approaches and methods

In order to get more credible results and valid framework, it has been decided to use a combination approaches. Therefore from the previous section, approaches 2 and 4 have been chosen.

1. **The first approach:** involving end users in determining the framework validity.

- Method: face validity; through performing case application, to check the applicability and workability of the framework with real data and to check the framework's logic and structure.

2. **The second approach:** scoring model.

- Method: semi structured interviews comprise of closed ended and open ended questions to evaluate the framework and get feedback from the end users. It was decided to select the interviewees from the same sample who took part in the first interviews as part of data collection (refer to section 4.8), as they will be the end users of the developed framework. Figure 28 shows the process of the framework validation.

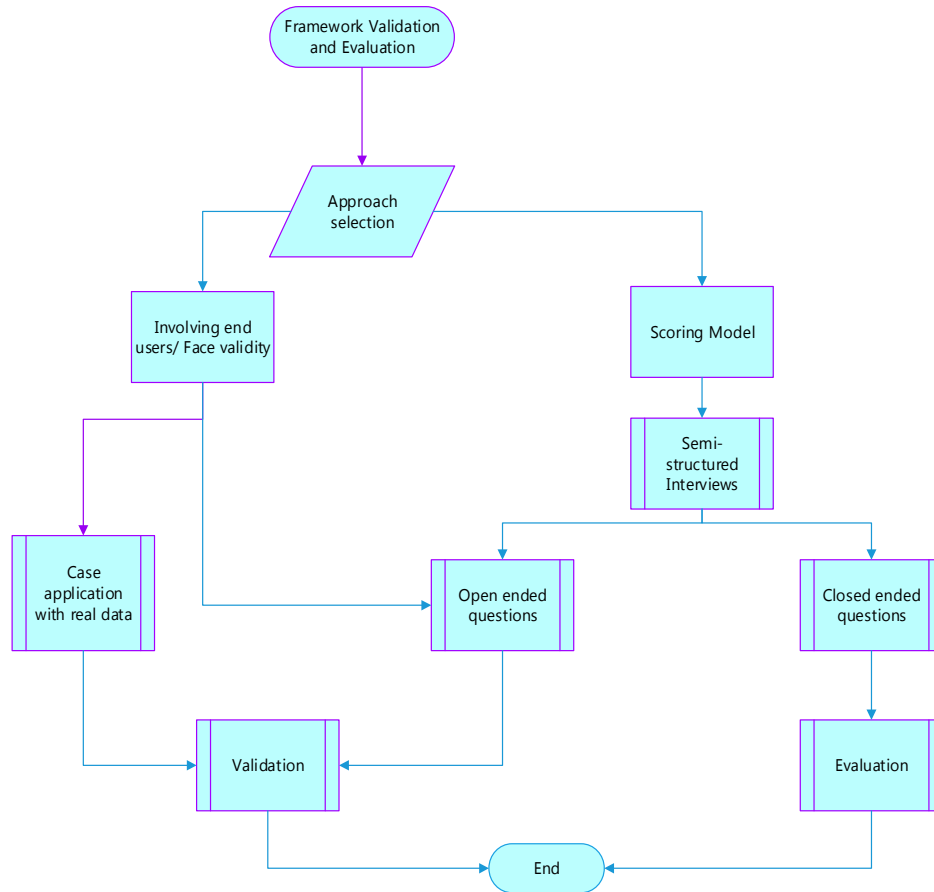


Figure 28 Framework validation process

4.10.2 Involving end users through case application

The proposed framework was tested and examined through a case application in order to check the applicability and workability of the framework with real data, as well as to check the framework's logic and structure. The framework was used to rank and select among four alternatives. Offshore experts participated in this validation stage (for more detail refer to chapter 8).

4.10.3 Scoring model approach

The evaluation was carried out by using semi-structured interviews (face to face). Participants from the first round semi-structured interviews (data collection, section 4.8.4) were selected to study the proposed framework and provide feedback on and evaluation

of some assessment criteria. The selection of the sample size considered two engineers from the main disciplines in the engineering department. The interview included two parts: the first part was closed-ended questions where the participants were asked to rate the developed framework based on assessment criteria. The second part included open-ended questions and the interviewees were asked to provide their opinion on the potential weaknesses, limitations and the strengths of the framework (refer to chapter 8 for more detail).

4.10.3.1 *Semi-Structure Interviews*

The selection of the sample size considered two engineers from the main disciplines in the engineering department, as shown in table 14. In total, eight engineers were interviewed based on closed ended and open ended questions.

Table 14 Profile of the interviewees

<i>Discipline</i>	<i>Positions</i>	<i>Years of experience</i>
Structural Department	Lead Engineer	14
Structural Department	Senior Engineer	25
Piping Department	Senior Piping Engineer	10
Piping Department	Piping Engineer	14
Mechanical and Materials Departments	Lead Engineer	23
Mechanical and Materials Departments	Materials and Corrosion Engineer	18
Process Department	Senior Engineer	10
Process Department	Process Engineer	7

In the closed ended part, the respondents were asked to rate the proposed framework based on the assessment criteria, as shown in table 15, by using a scale of (1 to 5), where (1) is poor, (2) below average, (3) moderate, (4) above average, and (5) excellent.

Table 15 Framework assessment criteria

<i>Framework Assessment Criteria</i>
<ul style="list-style-type: none"> • Clear and easy to understand • Systematic and well structured • Comprehensiveness (includes all aspects of sustainability and engineering) • Framework applicability • Framework efficiency • Framework practicability • Appropriate to the construction projects for offshore topside facilities • Helps to understand the concept of sustainability • Helps to understand the concept of life cycle costing and its application • Easy to use without complicated software

In the second part of the interviews, which comprised the open-ended questions, the interviewees were asked to provide their opinions about the potential weaknesses, limitations and the strengths of the framework, as well as providing any comments or suggestions that might help in implementing the developed framework. The analysis was presented in chapter 8.

4.11 Research Design and Process Alignment with Research Objective

Research process and design is presented below in figure 29.

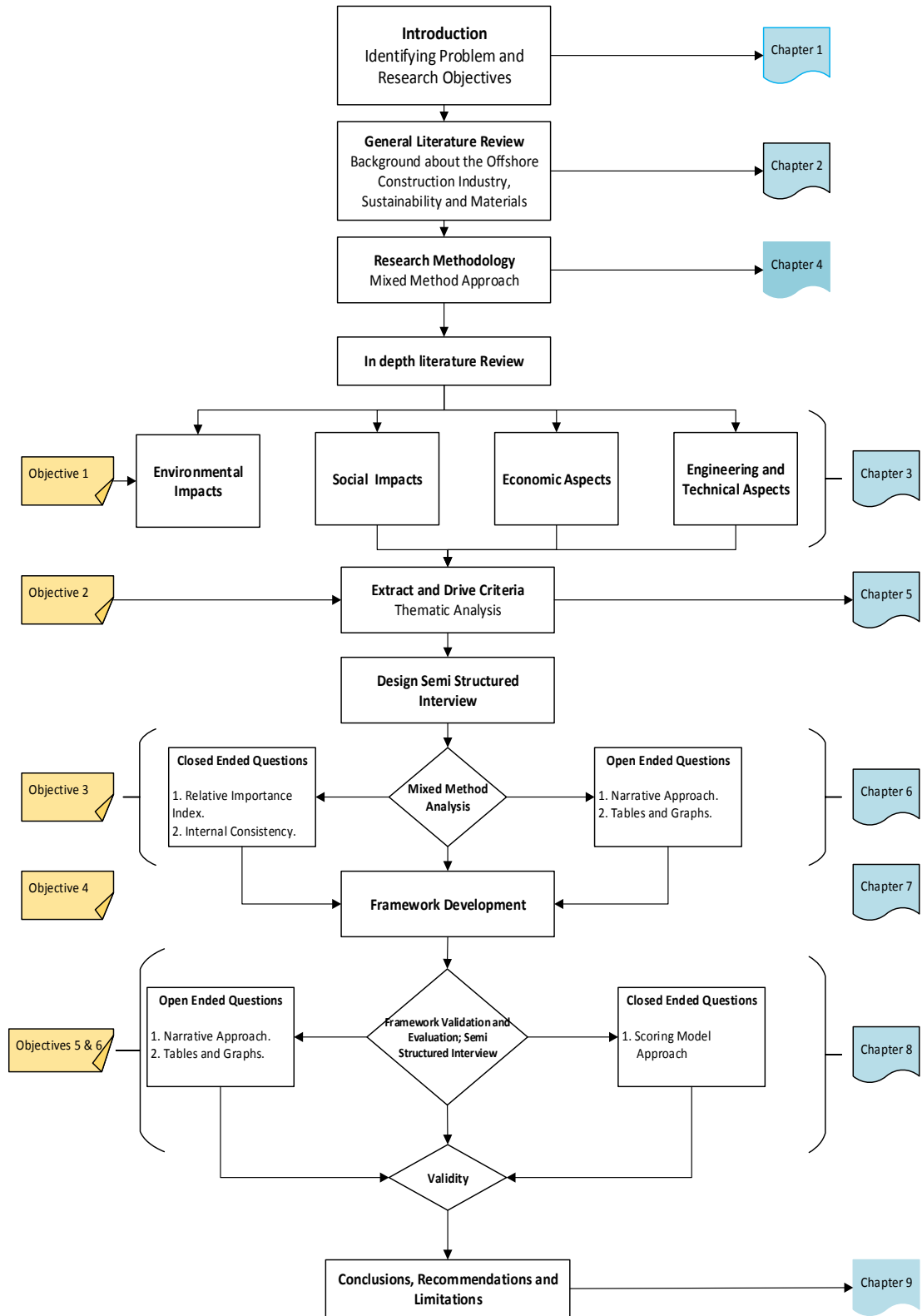


Figure 29 Research design process

4.12 Summary

This chapter presented the general themes, concepts and procedures for the research design in construction management, and discussed the approach and strategy adopted for this study. The research uses the pragmatic paradigm and a mixed method strategy; the data collection and analysis is conducted sequentially; the research type is exploratory with priority given to the qualitative strand. Refer to table 16 below.

Table 16 Research approach

Paradigm	Strategy/Method	Type	Timing	Priority
Pragmatic	Mixed Method	Exploratory	Sequential	Qualitative

In order to achieve the research aims and objectives, four main stages were designed: (1) stage one included collecting secondary data by conducting an in depth literature review, involving thematic analysis at this stage; (2) stage two included collecting the primary data, in this stage semi structured interviews were performed with experts in oil and gas industry, a pilot study was considered before conducting the interviews, thematic analysis was carried out for the open ended questions, and statistical methods were applied for the closed ended questions, such as the relative importance index and the internal consistency by calculating Cronbach's alpha; (3) stage three discussed the framework development; and (4) stage four included validating and evaluating the proposed framework as an effective tool for an offshore oil and gas platform.

Chapter 5

Extracting and Deriving the Criteria

5.1 Introduction

This chapter aims to address and achieve objective 2, as presented in section 1.6. The chapter presents analysis and results based on data carefully extracted from the literature reviews; how the data was extracted is also presented in this chapter. 77 criteria/factors were extracted from the literature review, reflecting that we believe these factors to be the most important for the sustainable design of offshore topside projects; these factors are divided into groups and subgroups.

5.2 Literature Mapping and Analysis

Creswell (2009, p.28), citing Cooper, noted that literature reviews can be integrative, involving the researcher summarising broad themes in the literature, and this approach is popular in dissertation. Creswell (2009, p.184) also mentioned that the basic approach for the researcher in analysing the literature is to collect data, analyse it for themes and then report four to five themes. Creswell (2009, p.34) stated that one important task for a researcher working with a new topic is to organise the literature through a map. The literature map in section 4.7.2 (figure 25) was developed when the literature review was conducted at the start of this research.

5.3 Themes Analysis

The main themes for this study, as mentioned in chapter 1, are pillars of sustainability and engineering and technical aspects. Therefore, the following themes (groups) were created in order to identify and gather the criteria for each theme or group (refer to section 4.7.3).

1. Environmental criteria, which includes two groups: (a) environmental pollution into air and water; and (b) energy and gas emissions through materials' life cycles.
2. Social issues and criteria, which includes two groups: (a) offshore health, safety and security; and (b) human rights of offshore workers.
3. Engineering criteria, includes two groups: (a) engineering and technical aspects; and (b) design aspects and considerations.
4. Finally, the economic criteria, which involves one group: life cycle costing components.

5.4 Environmental Criteria

As was noted from the themes outlined above, the environmental criteria are distributed into two groups: (a) **environmental pollution into air and water**; and (b) **energy consumption and gas emissions through materials' life cycles**. In chapter 3, the impacts of topside facilities on the environment were discussed and five main areas were identified from the literature: discharge into water; discharge into air; solid and liquid waste management; noise pollution; and oil and chemical spills. It was also found that in order to reduce the CO₂ emissions and energy consumption during the operation, the energy efficiency of the product and the equipment is a very important factor that should be taken into account when any product or equipment is selected.

Therefore, in the first group – *environmental pollution into air and water* – the following criteria can be extracted in order to achieve the environmental aspect of sustainability: (1) minimum discharge into water (marine); (2) minimum discharge into air (atmosphere); (3) providing of solid, liquid and construction waste management plan; (4) energy consumption and efficiency for products and equipment; (5) noise and vibration control

due to offshore operations and offshore transportation; and (6) risk of oil and chemical spills from topside facilities should always be assessed for each project.

Energy consumption and gas emissions through materials' life cycles are very important aspects due to the potential negative effects of these factors can have on the environment. The requirement for eco materials and green design implies the need to use friendly materials and equipment. In chapter 2, life cycle assessment was discussed as an environmental tool for determining the environmental impacts of materials and products from 'cradle to grave'. However, due to the limitations and difficulties that this tool entails, as discussed in section 2.8, the Ashby strategy was adopted for this study because of its simplicity. Therefore, the following factors/criteria can be extracted based on the Ashby method: (1) embodied energy during materials extraction; (2) CO₂ equivalent during materials extraction; (3) energy consumption during materials manufacture; (4) CO₂ equivalent during materials manufacture; (5) energy consumption during transportation and use; (6) CO₂ equivalent during transportation and use.

The environmental criteria and the associated literature sections are presented in the following tables 17 and 18.

Table 17 Environmental criteria group 1

Group 1: Environmental Pollution to air and water	Related sections
1. Minimum discharge to air.	3.3.6/3.3.10/3.3.11
2. Minimum discharge to water.	3.3.5/3.3.10/3.3.11
3. Energy consumption and efficiency for products and equipment.	2.9.1/3.3.11.2
4. Solid, liquid and construction waste management plan.	3.3.7/3.3.10/3.3.11
5. Noise and vibration due to offshore operation and offshore transportation.	3.3.9/3.3.10/3.3.11
6. Risk of oil and chemical spill from topside facilities.	3.3.8/3.3.10/3.3.11

Table 18 Environmental criteria, group 2

Group 2: Energy and Emission through Materials Life Cycle Process	Related sections
7. Embodied energy during materials extraction.	2.9.1
8. CO ₂ equivalent during materials extraction.	2.9.2

9. Energy consumption during materials manufacture.	2.9.1
10. CO2 equivalent during materials manufacture.	2.9.2
11. Energy consumption during transportation and use.	2.9.1
12. CO2 equivalent during transportation and use.	2.9.2

5.5 Social Issues and Criteria

The social impacts of offshore topside facilities were discussed in detail in chapter 3. The safety and security of the offshore process, as well as occupational health and safety, were the main aspects considered in this regard. As a result of this work, in this part we propose two groups: the criteria related to all *health and process safety and security* in one group; and *offshore human rights* in terms of their health and safety in the other.

For the **first group** – health and process safety and security – the aspects of process safety and security were described in section 3.4.1. Offshore accidents can occur due to failure of structural members, leakage of hydrocarbon, pipe rupture, etc. So, the first factor involves achieving process safety and security through safety system engineering (criterion one). In chapter 3, it was also discussed that there are many sources of hazard on an offshore platform, including various ignition sources, radiant heat, hot work, etc. In order to protect the personnel on board, as well as offshore assets, the approach of prevention, detection and control should be applied (as discussed in 3.4.3.1); using this approach requires a comprehensive fire and explosion design strategy to be applied (criterion two). In 3.4.3, hazardous materials were discussed; it was recommended that use of hazardous materials should be reduced as much as possible during the design stage and, moreover, these materials should be classified and a procedure applied for storing them. Materials such as radioactive materials used in this stage also have health effects on offshore workers. Therefore, the chemical properties and safety aspects of the materials are important criteria to be considered in the design (criterion three). Another aspect to consider is the explosiveness of the materials and equipment that contain significant potential energy; they must be selected carefully as the offshore atmosphere has many sources that can ignite this energy (criterion four). In sections 3.4.2.1.4 and 3.4.3, it was also noted that objects can be dropped from a platform or crane during routine jobs such

as maintenance and replacement works, or during the installation and construction of new brown field projects. Dropped objects can cause asset damage if they fall on major equipment, which might also lead to catastrophic events; therefore installation and removal procedures and mechanical handling studies are significant aspects that need to be taken in account during the design (criterion five). The current practice in designing new projects is to use offshore welding to install and fix the equipment and steel structures. Offshore welding involves two main aspects: health and safety. In terms of health effects, the welding operation emits fumes which contain a toxic mixture of gases; these can have dangerous effects on human beings, such as lung cancer, etc. In terms of safety, welding sparks and flames comprise major ignition sources on offshore sites. Therefore, avoiding and mitigating offshore welding at the design stage is another important factor (criterion six).

In the **second group**, criteria and factors related to the human rights of offshore workers were identified and extracted. As noted in the literature review, the nature of work in the offshore area is different from other industries. Small human errors can cause major disaster events; such human errors are often related to personal attitude and tolerance, working under stress and long shift working hours. Offshore workers are working in a hazardous area near ignition sources and there are fewer entertainment activities on offshore platforms that there would be onshore. Based on these facts and discussions in chapter 3, the following criteria and factors can be extracted: (1) working in hazardous conditions – as far as possible, provide suitable and safe working conditions; (2) workforce protection – provide easy access to safety protection equipment. (3) It is also important to provide an evacuation plan and clear escape routes to the muster area. (4) In order to reduce conflict and misunderstandings between the workers, effective communication and clear roles and responsibilities are also very important aspects to implement. (5) It is essential to provide professional training to offshore workers as skilled labourers are the main source of safe operation. (6) Adequate offshore accommodation with various entertainment facilities is also necessary. I have visited a number of offshore platforms where workers live in small, limited containers, but I have also visited platforms where the accommodation is on the level of a five star hotel, with recreation, canteen, gymnasium and other facilities available. (7) Encourage oil companies to employ local people in such jobs; this will support the local economy.

The social criteria and associated literature sections are presented in the following tables 19 and 20.

Table 19 Extracted social criteria, group 3

Group 3: Offshore Health, Safety and Security	Related Sections
13. Process safety and security	3.4.1/3.4.2/3.4.4
14. Fire and explosive strategy	3.4.3/3.4.3.1
15. Chemical properties of materials (Flammability and Toxicity)	3.4.2/3.4.3
16. Explosiveness of the materials	3.4.2.1.3/3.4.2.1
17. Safe installation and removal procedures for product, equipment and system.	3.4.2.1.4/3.8.3
18. Avoid or mitigate offshore welding	3.4.2.1.6/3.4.2.2.2/3.4.3

Table 20 Extracted social criteria, group 4

Group 4: Human Right for Offshore Workers	Related Section
19. Working hazard (safe and suitable work condition)	3.4.2/3.4.3
20. Workforce protection (provide easy access to safety protection equipment)	3.4.2/3.4.3
21. Evacuation plan and clear escape route to muster area	3.4.2/3.4.3
22. Effective communication and clear roles and responsibilities between workers.	3.4.3
23. Use local labor.	3.4.3
24. Well skilled labor and provide training for them.	3.4.3
25. Adequate offshore accommodation	3.4.3

5.6 Engineering Criteria

The engineering criteria were studied in depth in chapters 2 and 3, and as proposed in the themes analysis, these criteria can be divided into two groups: *technical aspects* and *design aspects*. For the **technical group**, in chapter 2 the requirements of offshore

materials were discussed and based on that, the following factors and criteria are considered to be the most important factors, also considering international standards such as ISO and NORSOK (refer to sections 2.11 through 2.16): (1) conformance to standards, codes and specifications; (2) mechanical properties; (3) physical properties; (4) chemical and electrochemical properties; (5) electrical properties (conductivity and resistivity); (6) corrosion and erosion; (7) corrosivity evaluation and system contents (CO₂, H₂S, O₂, SO_x, etc.); (8) inspection strategy and corrosion control; (9) durability; (10) reliability; (11) operation environment; (12) chemical resistance; (13) swelling and shrinkage by gas and liquid; (14) thermal properties (expansion, conductivity, thermal stress); (15) thermal stability; (16) thermal radiation; (17) heat and thermal resistance; (18) weldability; (19) wear and abrasion resistance; (20) operating pressure and temperature; (21) fire performance and resistance; (22) free of harmful contaminants; (23) dimensional properties (size and shape) due to the limited area and space on the offshore platform; (24) design life of the product or system; (25) coating and corrosion methods; (26) weight reduction (due to the limited capacity of the platform, weight is an important factor); (27) easy offshore installation; (28) reduced hot work offshore; (29) decommissioning plan. This is final point (29) is applicable to green field projects; when designing green field projects, decommissioning methods for easy disassembly and consideration of how to transport it to the onshore must be undertaken.

The requirements of green design were also considered (as described in section 2.6 and 2.7), including: (30) availability in the local market; (31) easy to use (this is important to reduce human error and thus the risk of hazards); (32) safe to use; (33) recyclable materials content; (34) reused content.

The second group for the **engineering design** includes the criteria most related to the design aspects, such as: (1) prefabrication flexibility (as discussed in section 2.7); (2) it was discussed in section 2.7 that offshore installation is very expensive, therefore the designer should take into account the need to design any project with minimum offshore installation hours; (3) a bolting design connection should be considered in relation to safety in order to avoid hot works on the offshore site, as well as to minimise the installation hours; (4) designing for easy inspection is important as the space within the platform is limited and crowded with pipes and equipment; (5) designing with a view to easy maintenance and replacement should also be considered; (6) as discussed in chapter 2, there are many types of platform based on the function requirements, therefore, in

terms of designing the accommodation platform, designing for indoor environmental comfort and water consumption efficiency is very important. Further, there are particular requirements for green design (as explained in sections 2.6 and 2.7), such as: (7) design for easy assembly; (8) design for easy disassembly; and (9) design for re-use.

The engineering criteria and associated literature sections are presented in the following tables 21 and 22.

Table 21 Extracted engineering criteria, group 5

Group 5: Engineering/Technical Criteria	Related Section
26. Conformance to standards, codes and specification	2.11/2.12
27. Mechanical properties	2.11/2.12
28. Physical properties	2.11/2.12
29. Chemical and electrochemical properties	2.11/2.12
30. Electrical properties (conductivity and resistivity)	2.11/2.12
31. Corrosion and erosion	2.13 to 2.15
32. Corrosivity evaluation and system contents (CO ₂ , H ₂ S, O ₂ , SO _x , CL..etc)	2.12/2.15
33. Inspection strategy and corrosion control	2.12/2.16
34. Durability	2.11/2.12
35. Reliability	2.11/2.12
36. Operation environment	2.11/2.12
37. Chemical resistance	2.11/2.12
38. Swelling and shrinkage by gas and liquid	2.11/2.12
39. Thermal properties (expansion, conductivity, thermal stress)	2.11/2.12
40. Thermal stability	2.11/2.12
41. Thermal radiation	2.11/2.12
42. Heat and thermal resistance	2.11/2.12
43. Weldability	2.11/2.12
44. Wear and abrasion resistance	2.11/2.12
45. Operating pressure and temperature	2.11/2.12

46. Fire performance and resistance	2.11/2.12
47. Availability in local market	2.11/2.12
48. Recyclable materials content	2.6/2.7
49. Reused content	2.6/2.7
50. Free of harm contaminants.	2.12/3.4.3
51. Dimensional properties (size and shape)	2.12
52. Easy offshore installation	3.4.2/3.4.3/2.7
53. Less hot works in offshore	3.4.2/3.4.3/2.7
54. Easy to use.	2.6/2.7
55. Safe to use.	3.4.2/3.4.3/2.7
56. Design life of the product or system	2.12
57. Coating and corrosion methods	2.16
58. Weight	2.12/3.4.2/3.4.3
59. Decommissioning plan (greenfield project)	General

Table 22 Extracted engineering criteria, group 6

Group 6: Engineering/Design Consideration	Related Section
60. Prefabrication flexibility	2.6/2.7
61. Minimum offshore installation hours	3.4.2/3.4.3/2.7
62. Bolting design connection	3.4.2/3.4.3/2.7
63. Design for easy assembly	2.6/2.7
64. Design for easy disassembly	2.6/2.7
65. Design for flexibility to re-use	2.6/2.7
66. Design for easy inspection	3.4.2/3.4.3/2.12
67. Design for easy maintenance	3.4.2/3.4.3/2.12
68. Design for indoor environmental comfort and water consumption efficiency in case of accommodation and offices spaces in offshore.	3.4.2/3.4.3/2.7

5.7 Economic Criteria

The economic criteria mainly involve the life cycle costing components. In chapter 3, the concept of life cycle costing was presented and components of cost, such as capital cost, operating cost, demolition and salvage cost, were described. Therefore, the economic criteria should entail all components related to the costs and should include but not be limited to the following: (1) design and engineering cost; (2) initial cost for the materials and equipment; (3) prefabrication and fabrication cost; (4) total offshore installation cost (including transportation and shipping to offshore); (5) operating cost of the equipment or material during its life cycle; (6) maintenance cost; (7) replacement cost; (8) offshore demolition cost; and (9) disposal cost.

The economic components /criteria and associated literature sections are presented in table 23.

Table 23 Economic criteria

Group 7: Economical criteria	Related Section
69. Design and engineering cost	3.2.6.4
70. Initial cost for the materials and equipment	3.2.6.4
71. Prefabrication and fabrication cost	3.2.6.4
72. Offshore installation cost (including transportation and shipping to offshore)	3.2.6.4
73. Operating cost during life cycle	3.2.6.4
74. Maintenance cost	3.2.6.4
75. Replacement cost	3.2.6.4
76. Offshore demolition cost	3.2.6.4
77. Disposal cost	3.2.6.4

5.8 Chapter Summary

In this chapter, 77 identified factors were extracted from the exhaustive literature review to align with objective 2 of this study. The 77 determinant factors were distributed into four main groups and seven subgroups. The first group identified 12 criterions for the environmental criteria and distributed these into two subgroups; six criterions under environmental pollution to air and water, and six criterions under energy consumption and gas emissions through materials' life cycles. The second group identified 13 criterions for the social criteria and these distributed into two subgroups: six criterions under offshore health, safety and security, and seven criterions under human rights of offshore workers. The third group identified 43 criterions for the engineering criteria and distributed these into two subgroups: 34 criterions under engineering and technical aspects, and nine criterions under design considerations and aspects. The fourth group for the economic criteria included nine criterions, which, as one group, presented the components of life cycle costing aspects.

These identified factors will be validated by offshore experts through semi-structured interviews in the following chapter. These factors will be used for the creation of the proposed framework.

Chapter 6

Interview Design and Analysis: Proving the Criteria Through Stakeholders

6.1 Introduction

It was mentioned and discussed in chapter four (the research methodology) that the data collection for this study, as an exploratory research, would be conducted in two parts. The first part involved an exhaustive literature review in order to determine the main factors and criteria for sustainable design that would help to develop the proposed framework. Following this, it was very important to prove and validate the findings from the literature review, as well as checking the data for veracity by consulting offshore experts (stakeholders). Moreover, to increase the effective results produced by this study, as well as to develop a framework that could be easily and effectively used by the offshore industry, it was decided to carry out semi-structured interviews with experts in the offshore industry; this represents the second part of the data collection.

In this chapter, the aim and objectives of the interviews, the design of the interviews and the selection of the participants will first be discussed. Second, the responses from the participants will be analysed and presented. Finally, the findings and results from the interviews will be discussed and presented to outline how they affect the development of the proposed framework.

6.2 Analysis of The Sample Size (Participants)

As mentioned in section 4.8.4 (strategy for the sample selection) there were several considerations necessary in selecting the interviewees, as a response to which the following criteria were applied: (1) extensive knowledge in their field; (2) experience in the offshore industry, especially the topside part of the fixed offshore platform; (3) selection ranging from all engineering disciplines; and (4) considering the different job

positions within the same discipline (such as head of department, lead engineer, senior engineer, etc.).

From tables (12 & 13) in section 4.8.4 (profiles of the participants), all of the participants are experts in the offshore industry, where 47.5% have experience between 10 to 19 years, and 42.5% have experience between 20 to 29 years. The level of education of the participants shows that 5% of the interviewees have PhD degrees, 37.5% have master degrees and 57.5% have bachelor degrees (refer to table 24).

Table 24 Analysis of participants

Items	Number	Percentage %
Managers and head of departments	7	17.5
Lead, principal and chief engineers	15	37.5
Senior engineers	11	27.5
Engineers	7	17.5
Experience		
Between 5 and 9 years	2	5
Between 10 and 19 years	19	47.5
Between 20 and 29 years	17	42.5
30 years and above	2	5
Level of Education		
Bachelor degree	23	57.5
Master degree	15	37.5
PhD	2	5
Department Involved		
Department name	Number	
Structural	8	
Piping	7	
Electrical and Instrumentation	6	
Process and Safety	6	
Mechanical, Materials and Welding	5	
Projects	4	
Field Development Plan	2	
Engineering Management	1	
HSE (Health, Safety and Environment)	1	

6.3 Analysis and Discussion of the Closed Ended Part

Ranking the criteria, groups of criteria and the top ten ranked criteria are presented below.

6.3.1 *Ranking the criteria based on the relative importance index*

The data received from the interview questionnaire (appendix B) were analysed using the relative importance index (RII) method in order to rank the identified criteria according to their importance.

RII was calculated as illustrated in Equation 1 (Khan, 2015).

$$\text{RII} = \text{Sum of weights } (W_1+W_2+\dots+W_n)/A*N \dots\dots\dots \text{Eq.13}$$

Where W is the weight given to each factor by the respondents, ranging from 1 to 5 (where 1 is “least important” and 5 is “extremely important”), A is the maximum weight (A = 5 in this research) and N is the total number of participants.

Table 25 shows the ranking results for the identified criteria (environmental, social, engineering and economic) by using the RII. The level of significance of the criteria can be categorised based on the RII results as the following: (1) “extremely important” ($0.800 \leq \text{RII} \leq 1.00$); (2) “very important” ($0.600 \leq \text{RII} \leq 0.799$); (3) “important” ($0.400 \leq \text{RII} \leq 0.599$); and (4) “moderately important” ($0.200 \leq \text{RII} \leq 0.399$). The results show that the minimum RII value is 0.640, which means that all the criteria fall within the two levels of significance, either extremely important or very important.

Table 25 Ranking the Identified Criteria

<i>Rating and Ranking The Identified Criteria</i>				
Criterion	Relative Importance Index	Group	Overall Ranking	Level of Importance
1. Evacuation plan and clear escape route to muster area	0.995	Human right for offshore workers (Social)	1	Extremely important
2. Process safety and security	0.990	Offshore health and safety	2	Extremely important
3. Conformance to standards, codes and specification	0.980	Engineering (Technical)	3	Extremely important
4. Fire and explosive strategy	0.970	Offshore health and safety	4	Extremely important
5. Risk of oil and chemical spill from topside facilities	0.960	Environmental pollution to water and air	5	Extremely important
6. Operating pressure and temperature	0.955	Engineering (Technical)	6	Extremely important
7. Workforce protection (provide easy access to safety protection equipment)	0.955	Human right for offshore workers (social)	6	Extremely important
8. Minimum discharge to water	0.945	Environmental pollution to water and air	8	Extremely important
9. Safe to use.	0.940	Engineering (Technical)	9	Extremely important
10. Minimum discharge to air.	0.935	Environmental pollution to air and water	10	Extremely important
11. Corrosivity evaluation and system contents (CO ₂ , H ₂ S,	0.935	Engineering (Technical)	10	Extremely important

O2, SOx, CL..etc).				
12. Working hazard (safe and suitable work condition).	0.930	Human right for offshore workers (social)	12	Extremely important
13. Effective communication and clear roles and responsibilities between workers.	0.930	Human right for offshore workers (social)	12	Extremely important
14. Fire performance and resistance.	0.930	Engineering (Technical)	12	Extremely important
15. Offshore installation cost (including transportation and shipping to offshore).	0.925	Economic	15	Extremely important
16. Mechanical properties.	0.920	Engineering (Technical)	16	Extremely important
17. Corrosion and erosion.	0.920	Engineering (Technical)	16	Extremely important
18. Operating cost during life cycle.	0.915	Economic	18	Extremely important
19. Inspection strategy and corrosion control.	0.910	Engineering (Technical)	19	Extremely important
20. Maintenance cost.	0.905	Economic	20	Extremely important
21. Explosiveness of the materials.	0.905	Offshore health and safety	20	Extremely important
22. Chemical properties of materials (Flammability and Toxicity).	0.895	Offshore health and safety	22	Extremely important
23. Well skilled labor and provide training for them.	0.890	Human right for offshore workers (social)	23	Extremely important

24. Design life of the product or system.	0.890	Engineering (Technical)	23	Extremely important
25. Reliability.	0.880	Engineering (Technical)	25	Extremely important
26. Coating and corrosion methods.	0.880	Engineering (Technical)	25	Extremely important
27. Free of harm contaminants.	0.870	Engineering (Technical)	27	Extremely important
28. Minimum offshore installation hours.	0.865	Engineering (Design)	28	Extremely important
29. Design for easy maintenance	0.860	Engineering (Design)	29	Extremely important
30. Durability.	0.860	Engineering (Technical)	29	Extremely important
31. Physical properties	0.855	Engineering (Technical)	31	Extremely important
32. Safe installation and removal procedures for product, equipment and system.	0.855	Offshore health and safety	31	Extremely important
33. Operation environment.	0.845	Engineering (Technical)	33	Extremely important
34. Design for easy inspection.	0.840	Engineering (Design)	34	Extremely important
35. Adequate offshore accommodation.	0.840	Human right for offshore workers (social)	34	Extremely important
36. Design for indoor environmental comfort and water consumption efficiency in case of accommodation and offices spaces in offshore.	0.835	Engineering (Design)	36	Extremely important
37. Solid, liquid and construction	0.835	Environmental pollution to	36	Extremely important

waste management plan		water and air		
38. Less hot works in offshore.	0.835	Engineering (Technical)	36	Extremely important
39. Weldability.	0.830	Engineering (Technical)	39	Extremely important
40. Chemical resistance.	0.815	Engineering (Technical)	40	Extremely important
41. Design for easy assembly.	0.805	Engineering (Design)	41	Extremely important
42. Chemical and electrochemical properties.	0.800	Engineering (Technical)	42	Extremely important
43. Prefabrication flexibility.	0.795	Engineering (Design)	43	Very important
44. Replacement cost.	0.790	Economic	44	Very important
45. Easy offshore installation.	0.785	Engineering (Technical)	45	Very important
46. Easy to use.	0.785	Engineering (Technical)	45	Very important
47. Avoid or mitigate offshore welding.	0.785	Offshore health and safety	45	Very important
48. Thermal radiation.	0.785	Engineering (Technical)	45	Very important
49. Bolting design connection.	0.785	Engineering (Design)	45	Very important
50. Initial cost for the materials and equipment.	0.785	Economic	45	Very important
51. Decommissioning plan (greenfield project).	0.780	Engineering (Technical)	51	Very important
52. Prefabrication and fabrication cost.	0.775	Economic	52	Very important
53. Energy consumption and efficiency for products and	0.770	Environmental pollution to water and air	53	Very important

equipment.				
54. Electrical properties (conductivity and resistivity).	0.765	Engineering (Technical)	54	Very important
55. Heat and thermal resistance.	0.765	Engineering (Technical)	54	Very important
56. Weight.	0.765	Engineering (Technical)	54	Very important
57. Design for easy disassembly.	0.765	Engineering (Design)	54	Very important
58. Thermal properties (expansion, conductivity, thermal stress).	0.760	Engineering (Technical)	58	Very important
59. Wear and abrasion resistance.	0.760	Engineering (Technical)	58	Very important
60. Swelling and shrinkage by gas and liquid.	0.760	Engineering (Technical)	58	Very important
61. Noise and vibration due to offshore operation and offshore transportation	0.760	Environmental pollution to water and air	58	Very important
62. Thermal stability.	0.750	Engineering (Technical)	62	Very important
63. Dimensional properties (size and shape).	0.750	Engineering (Technical)	62	Very important
64. Recyclable materials content.	0.750	Engineering (Technical)	62	Very important
65. Offshore demolition cost.	0.745	Economic	65	Very important
66. Design and engineering cost.	0.740	Economic	66	Very important
67. Reused content.	0.735	Engineering (Technical)	67	Very important
68. Disposal cost.	0.725	Economic	68	Very important

69. Use local labor.	0.720	Human right for offshore workers (social)	69	Very important
70. Availability in local market.	0.710	Engineering (Technical)	70	Very important
71. Design for flexibility to re-use.	0.675	Engineering (Design)	71	Very important
72. CO2 equivalent during materials manufacture	0.675	Environmental pollution to water and air	71	Very important
73. Energy consumption during materials manufacture	0.670	Environmental pollution to water and air	73	Very important
74. CO2 equivalent during transportation and use	0.650	Environmental pollution to water and air	74	Very important
75. CO2 equivalent during materials extraction	0.645	Environmental pollution to water and air	75	Very important
76. Energy consumption during transportation and use	0.640	Environmental pollution to water and air	76	Very important
77. Embodied energy during materials extraction	0.640	Environmental pollution to water and air	76	Very important

6.3.2 Ranking the subgroup

In the same way, the participants were asked to rate the subgroups of the criteria; table 26 shows the ranking result of the subgroups by using the RII.

Table 26 Ranking subgroups

<i>All subgroup</i>		<i>Relative Importance Index</i>	<i>Overall Ranking</i>
1.	Offshore health and safety	0.980	1
2.	Environmental pollution to air and water	0.940	2
3.	Engineering and technical aspects	0.895	3
4.	Human right for offshore workers	0.890	4
5.	Design consideration	0.885	5
6.	Economical criteria and aspects	0.805	6
7.	Energy consumption and gas emissions through materials life cycle	0.710	7

6.3.3 The top ten criteria based on RII

According on the analysis of the result, table 27 summarizes the top 10 criteria, which have been rated by the experts. It is observed that four criteria from social category, four criteria from engineering category and three criteria from environmental were recorded among the top ten. This result is an evidence and support the results in table 26 (the previous one), where two subgroups from social category, one subgroup from environmental and one subgroup from the engineering were recorded among the highest four subgroups.

Table 27 Top ten criteria

<i>Criteria</i>	<i>RII</i>	<i>Main Group</i>	<i>Subgroup</i>	<i>Rank</i>
1. Evacuation plan and clear escape route	0.995	Social	Human rights for offshore workers	1
2. Process safety and security	0.990	Social	Offshore health and safety	2
3. Conformance to standards, codes and specifications.	0.980	Engineering	Technical	3

4. Fire and explosive strategy	0.970	Social	Offshore health and safety	4
5. Risk of oil spill and chemicals from topside facilities.	0.960	Environmental	Environmental Pollution to air and water	5
6. Offshore workforce protection (easy access to safety equipment)	0.955	Social	Human rights for offshore workers	6
7. Operating pressure and temperature	0.955	Engineering	Technical	6
8. Minimum discharge to marine (water) from topside facilities.	0.945	Environmental	Environmental Pollution to air and water	8
9. Safe to use (for material and equipment selection)	0.940	Engineering	Technical	9
10. Corrosivity evaluation and system content	0.935	Engineering	Technical	10
11. Minimum discharge to air from topside facilities.	0.935	Environmental	Environmental Pollution to air and water	10

6.3.4 Reliability of the measuring instrument (closed ended part)

The internal consistency method refers to the degree of relatedness of the single items in a test and it reflects how well the separate items are homogeneous (Rosnow and Rosenthal, 2013, p.111). Internal consistency can be determined by calculating the reliability coefficient, which is called Cronbach's alpha. Sethi and King (1991) mentioned that Cronbach's alpha is the most important method for estimating the reliability of instruments. The Statistical Package for Social Science software (SPSS) was used to calculate the Cronbach's alpha for the responses to the closed ended part of the interview questionnaire. The reliability coefficient Cronbach's alpha ranges from 0 to 1, with values closer to 1 representing higher internal consistency reliability ratings. A Cronbach's alpha value of 0.70 or higher is considered to be acceptable, and this means that all elements are homogenous enough.

The results of the alpha for the economic, social, environmental, and engineering criteria, and for all the criteria combined are 0.788, 0.728, 0.889, 0.949 and 0.959 respectively, as

shown in table 28. All values are greater than 0.70, representing that all the “Cronbach's alpha” are acceptable, and the “internal consistency” of the factors included in the scale are perfect.

Table 28 Cronbach's alpha

<i>Criteria</i>	<i>Number of Factors</i>	<i>Cronbach's alpha</i>
1. Environmental	12	0.889
2. Social	13	0.728
3. Economical	9	0.788
4. Engineering and Technical	43	0.949
5. Overall	77	0.959

Below are the screen shots of the output of SPSS analysis for the Cronbach's Alpha.

Reliability Statistics Social Criteria

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.728	.706	13

Reliability Statistics Engineering

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.949	.948	43

Reliability Statistics Environmental Criteria

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.889	.862	12

Reliability Statistics Economic Criteria

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.788	.771	9

Reliability Statistics Overall

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.959	.956	77

6.4 Analysis and Discussion of the Open Ended Part

As discussed above in section 6.2, the interviewees were carefully selected from the top level of engineering and design management, for example, head of departments, team leader, senior engineers across all engineering departments for the purpose of providing useful and reliable information about designing topside facilities for offshore platforms. This also served the purpose of creating a sustainable design framework.

Creswell (2009, p.183) mentioned three potential methods of recording information during interviews; hand written notes, audiotaping and videotaping. He recommended that the researcher take notes. Therefore, taking notes during the interviews was used for the open ended part of this research. Moreover, Creswell (2009, p.184) stated that data analysis includes making sense of text and image data; as well as in qualitative data the researcher collects the data, and analyses it for themes or perspectives and reports on them.

6.5 Themes Grouping

The following sections discussed the findings from the content analysis of the interviews for the open-ended questions. The questions and discussions were grouped into four main themes that reflected the original themes of this research. The main themes are: (1) general sustainability understanding and requirement, which includes three subthemes: (A) environmental aspects, (B) social aspects, and (C) economical aspects; (2) engineering aspects, which includes two subthemes: (A) design practice, and (B) materials selection practice and consideration; (3) project evaluation and appraisal, which includes (A) value management, (B) life cycle costing management; and (4) Framework requirements. The main themes and subthemes are presented in figure 27 in section 4.8.9.2.

6.5.1 General understanding of sustainability for offshore topside facilities

The knowledge of the general understanding of sustainability for offshore topside facilities is important for establishing the basic requirements for creating the sustainable framework in the later stage, as well as understanding what the offshore experts are thinking in terms of sustainability. In this context, the interviewees were asked to provide and comment on sustainability aspects for offshore topside facilities, as shown below.

Question 1: *How would you describe the sustainability of topside facilities in offshore oil and gas platforms?*

Sustainability is a new concept for the respondents. One reason for this is that the term sustainability in oil and gas in fact refers to sustaining production of oil as the first concern in the oil industry is how to produce oil as early as possible. Another reason for this is that although the national and international laws note the importance of considering sustainability in oil operation, most of the engineering and design standards and codes at the design level lack the concept of sustainability; this creates unfamiliarity with the concept within this field. This situation should not continue as it is. The meaning of sustainability should include more aspects, such as maintaining production in a safe manner at an economical cost with less environmental impact. It was not a surprise that many definitions were given for sustainability. Each respondent defined sustainability from his or her perspective based on the importance of the criteria that he or she thought should be achieved during the early design stage. From the 40 interviews, six main understandings of sustainability were revealed: (1) proper design for topside facilities considering the selection of the correct materials; (2) meeting the environmental regulations and requirements; (3) safe design to eliminate future risk during the life cycle of the project; (4) safe operation procedure with offshore equipment, work tasks, and offshore processes that might cause injuries or risk to offshore facilities or people; (5) having a component or system that meets the requirements and lasts for its design life; and (6) less maintenance and life cycle cost. Most of the definitions refer somehow to sustaining production, as mentioned above. The concept of sustainability should be

introduced by oil companies in the design and engineering. The responses are summarised in figure 30 below and they indicate that the majority of interviewees defined sustainability as lower life cycle costing and lower maintenance cost.

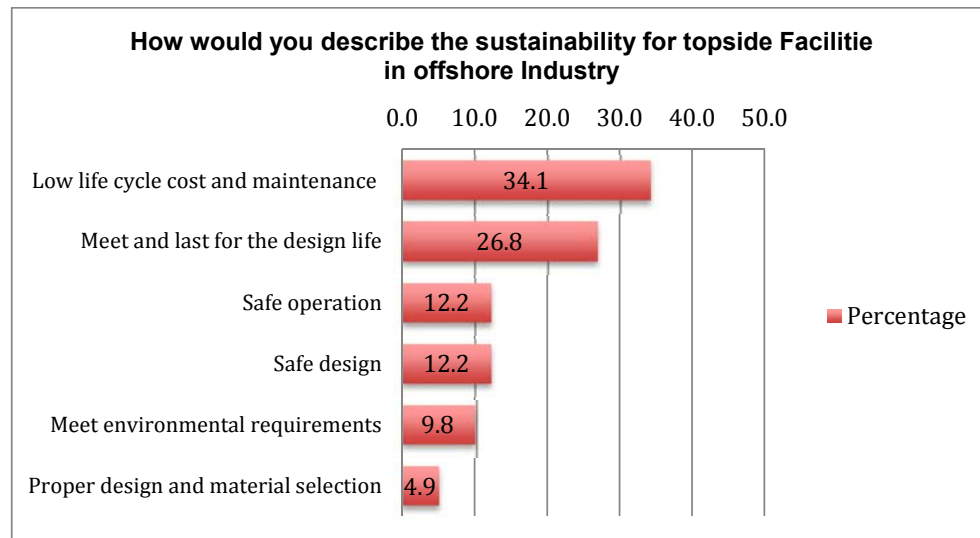


Figure 30 Sustainability definition by interviewees

Question 2: How would you describe the environmental and social impacts of topside facilities?

In terms of the environmental impacts, most of the respondents focused on gas flaring, as flaring is something visible for them and can be seen daily. Moreover, some of the interviewees mentioned the discharge of the produced water and its harmful components. Regarding, the social impact, it was difficult for the participants at the beginning to define the social impacts of topside facility; it was a new term or concept to them. However, after defining and explaining to them what is meaning by social sustainability, most of the responses were focused on providing professional training for offshore workers, maintaining safe production and safe operation, and providing all safety gear for offshore workers. Some of the issues which are facing the offshore workers, are nature of offshore tasks, and effects of fatigue due to long working hours. Normally, the daily shift in offshore is 12 hours, and each rotation (trip) is 28 days offshore. Definitely the intensive offshore works and effects of fatigue are potential source of hazards to workers' health

and offshore safety in general. This can be overcome by providing adequate offshore accommodation equipped with all entertainment facilities and recreation.

Question 3: Do you think the current platform systems are environmentally friendly?

It was generally found to be difficult to answer this question; as topside facilities have a great deal of complicated equipment and systems, as described in chapter 3. The interviewees had three different opinions. The first group, which represented 24% of the participants, considered that all systems for topside facilities are environmentally friendly as what this requires is following the international environmental regulations. Secondly, 22% of the participants suggested that the amount of discharge from the topside facilities is not environmentally friendly. The third and largest group, however, which represented the majority of the respondents (54%) commented that although there is a commitment to follow the environmental regulations, and even though a small amount of platform discharge goes to the air or water, this should still be taken into consideration and improved in future (refer to figure 31).

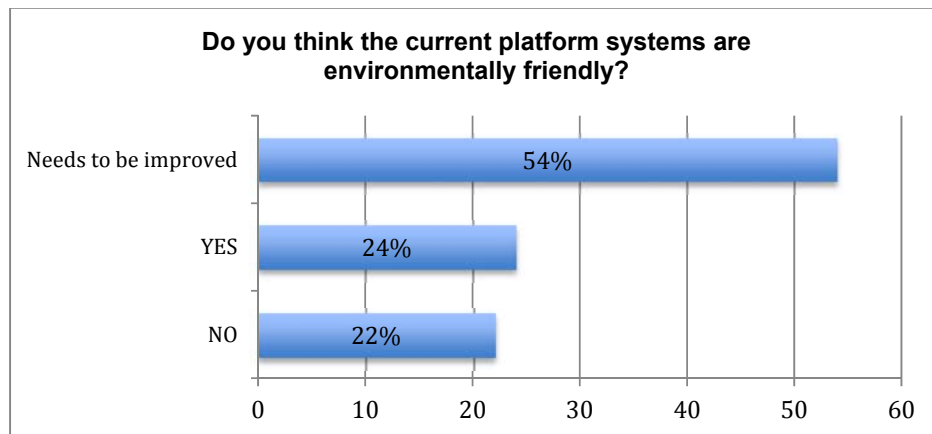


Figure 31 Offshore systems as environmentally friendly

6.5.2 Engineering and design considerations

In this section, the respondents were asked to provide their opinion on the current practice of materials selection during the design phase of a project. They were asked whether in

their job have experienced any sustainable engineering design framework or sustainable procedure for engineering design in offshore in an offshore topside facility.

Question 4: How would you describe the materials selection during the early design phase in your organisation (copy and paste, standards, guidelines, procedures etc.?)

Proper materials selection is a very important step towards achieving sustainability in any project. Materials selection is part of sustainable development when the embodied energy, CO₂ equivalent and recyclable contents are considered in the design as explained in chapter 3. Here, the participants were asked to share their experience of the current practice of materials selection for both brown field and green field projects. There was agreement between all the respondents that materials selection is an integral part of engineering design and it was generally considered the most important part. On the other hand, the interviewees stated that there is no clear policy or procedure that considers the sustainability perspective; the current practice is based on international standards or company procedures, but it lacks consideration of sustainability aspects such as embodied energy during the materials' life cycles. 90% of the respondents suggested that the current practice follows international standards, company procedures and guidelines, whilst 10% mentioned that this is a matter of copying and pasting from similar projects; in both cases, however, this lacked most of the sustainability aspects (refer to figure 32).

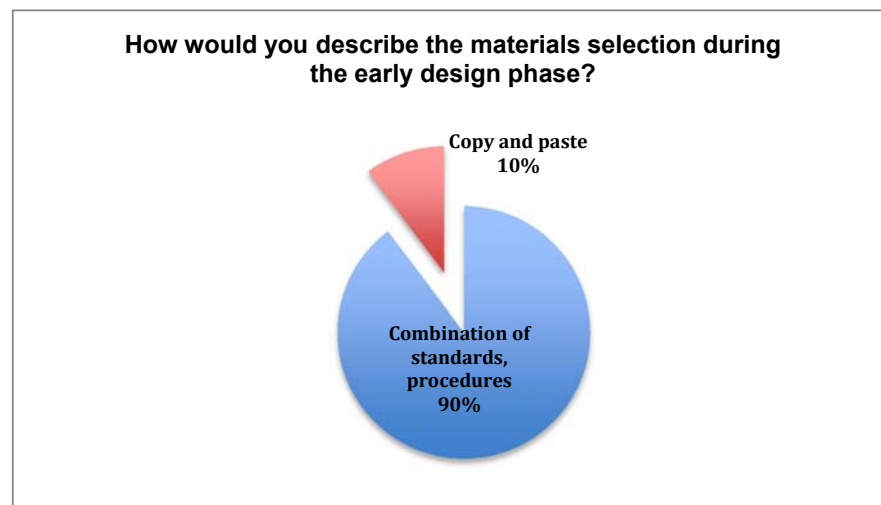


Figure 32 Describing materials selection procedures

Question 5: *From the sustainability perspective, do you think a proper materials selection framework will influence the platform design and consequently reduce the environmental, economic and social impacts related to the offshore industry?*

There was an agreement between all the participants that without a doubt, that if there was a proper materials selection framework, this would definitely reduce the negative impacts of the topside facilities. One of the interviewees said: “OPEX is one of the major challenges that faces the offshore industry; proper materials selection could be the way for reducing OPEX”.

Question 6: *Have you experienced sustainable framework for materials selection or engineering design for offshore topside facilities?*

There was a consensus among all the respondents that they had not experienced a fully sustainable framework considering, all sustainability aspects in one framework. However, a few respondents mentioned that some aspects of sustainability are covered in the company procedures, or design guidelines, but these guidelines deal with one aspect, for example, either focusing on environmental issues or economic issues separately, so there is a need to gather and consider all aspects in one framework.

6.5.3 Project evaluation for topside facilities

Capital and operating expenditures (CAPEX and OPEX) are always an issue for projects in the oil and gas industry. Evaluation concepts and techniques such as value engineering, life cycle costing, time value of money, and economic appraisals such as internal rate of return (IRR), net present value (NPV) and others, all integrated together in a specific framework could significantly reduce the CAPEX and OPEX significantly. In this section the respondents were asked to comment on these methods and techniques.

Question 7: *Please indicate the ones which you are familiar with (you may select more than one): (A) life cycle costing concept; (B) life cycle costing analysis; (C) time value of money; (D) value engineering; and (E) value engineering matrix.*

The outcome of the participants' responses regarding the above themes and concepts are shown in (figure 33). 70.70% of the respondents mentioned that they know the meaning of the life cycle costing concept, at least in part, or they have heard of it; however, only 26.8% of the participants have basic knowledge of time value of money and its techniques in calculating the life cycle costing. Further, only 34.1% of the participants are able to perform the life cycle analysis. Plausible explanations for this could be: (a) life cycle costing is not frequently used in the industry, especially for brown field projects; or (b) life cycle costing is not within the normal responsibilities of the respondents in the interviews. 68.3% of the participants indicated that they know the value engineering concept, but when they were asked about how to perform value engineering analysis or if they know the value engineering steps and procedures, only 22% who said they know the value engineering matrix and how it can be used for ranking and evaluating the alternatives for any projects or items.

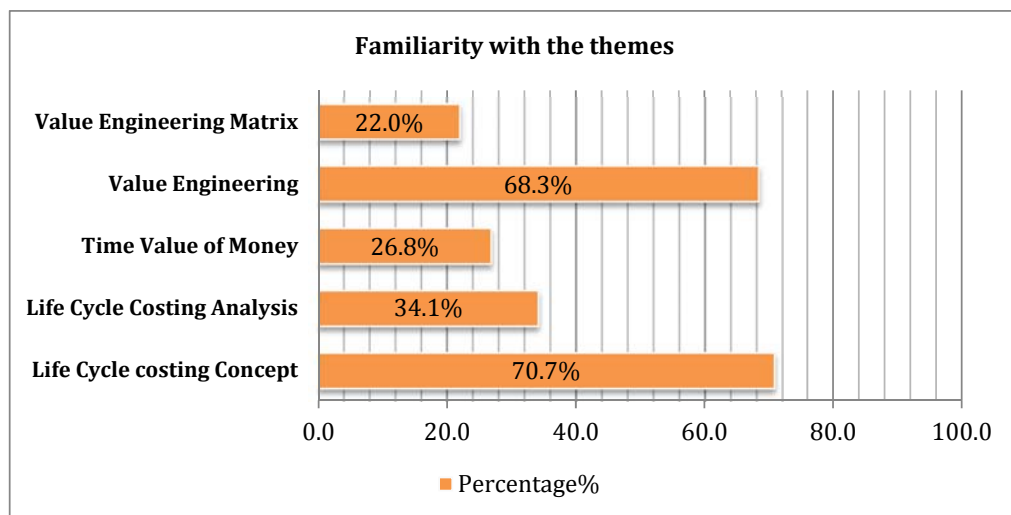


Figure 33 Familiarity of evaluation themes

6.5.4 Framework requirement

The purpose of this section is to obtain the interviewees' opinions, perspectives, and ideas on what the framework should look like and how it works. The respondents were asked to suggest components and characteristics for the proposed framework based on the 77 criteria and the overall discussion in the interviews.

Question 8: *Do you now think a materials selection framework in terms of sustainability dimensions is required for topside offshore platforms for both green field and or brownfield projects?*

There was agreement between all the respondents that a materials selection framework is required for both brownfield and greenfield projects; however, the benefits and the positive impacts will be greater if this is implemented in larger projects such as green field projects where the impact is greater.

Question 9: *Now, understanding the meaning of sustainability, and after discussing the 77 identified criteria, what are the components and outcomes required from the sustainable design framework?*

The following comments provided by the respondents reflect their perspectives and opinions on the creation of the framework. In general, they provided positive comments in terms of the derived criteria, and they agreed that the determinant criteria (as discussed in closed ended part), were comprehensive and sufficient to develop a comprehensive framework. Some of the comments and suggestions are shown below:

- Suggestions were made to consider corrosion control and life cycle costing; most of the respondents said that they have no experience using life cycle costing in their design or even implemented in the company procedure.
- Systematic tool for economic evaluation was required to reduce operating future cost (OPEX). There is no technique to estimate the future cost, even the estimated initial cost at the early stage is rough and based on previous projects. This part should be improved in the framework.
- Offshore process safety and security was mentioned as being as very important element to be considered first; materials evaluation in terms of toxicity, flammability and ignition must be evaluated first.
- It was noted that as we are engineers, we look for the materials and equipment that meet the requirements of the international standards in terms of safety and function, and then we look at the initial costs. It is a good idea to introduce

environmental and sustainability aspects such as embodied energy and CO₂ emissions throughout the materials' life cycle into the design; this requires the implementation of a clear and easy procedure.

- In terms of the cost estimation for single project or material, we consider the cheapest initial costs that meet the function required; life cycle costing is fully ignored.
- It was mentioned that many projects require replacement within a couple of years due to corrosion and offshore weathering, even when the expected lifetime is more than this. So it is important to find a mechanism to create a balance between quality, function and maintenance cost.
- Some responses stated that most engineers rely on the international standards and company procedures; these standards and procedures lack some aspects of sustainability.
- Responses mentioned that project engineers have a budget for each project; designing for sustainability requires greater spending in terms of selecting materials and designing the system. However, when considering life cycle costing for long term saving, this is a good idea, and should be implemented in the framework.
- Fire and explosion strategy in the design is mainly considered in green field projects; this is neglected sometimes for brown field projects. It is important to capture this and implement it within the framework.

6.5.5 Conclusion of the semi-structured interview

At the end, the interviewees were asked to provide any additional criteria that they consider to have an influence on the sustainable design and materials selection, which had not been listed or discussed in either the closed ended or open ended questions; they were also asked if they had any additional comments to be added (question 10 in the interview, appendix A). All the respondents agreed that the 77 criteria identified from the literature review are sufficient to create an efficient framework. No additional comments are reported.

6.6 Chapter Summary

This chapter presented the data collection, analysis and discussion of the semi structured interviews. The following findings summarise and highlight the most important points from this chapter:

1. The findings revealed that all the 77 derived factors are highly important with a minimum RII value of 0.640. All criteria were rated as “extremely important” or “very important” and no criterion was rated less than very important. This means that, for the offshore experts, all the determinant criteria are very important in terms of sustainability.
2. The criterion “offshore evacuation plan and clear escape route” was considered the most important criterion of the 77 factors.
3. The group “offshore health and safety” was considered the most important of all the groups.
4. The lowest five ranked criteria were recorded in one group: “energy and emissions through the materials’ life cycles”. This is not surprising because of the lack of knowledge about the embodied energy and gas emissions during the materials’ life cycles and the importance of this with regards to the sustainability.
5. Most of the respondents agreed that topside facilities need more improvements in order to be more environmentally friendly.
6. There was agreement between all the participants that providing proper materials selection and an engineering design framework are the most important steps in achieving sustainability.
7. There was a consensus among all the interviewees that they had not experienced any sustainable framework in topside engineering design, and there is a need for such a framework.
8. There are some barriers to achieving economic sustainability, such as lack of awareness and knowledge of the life cycle costing concept and analysis. Although the levels of education of the interviewees are high (37.5% have master degrees), the results show that 69.5% of the interviewees cannot perform life cycle costing analysis.

9. In terms of framework requirements, the interviewees agreed with the author that the following components should be considered in the framework: (A) the framework should consider the environmental and social aspects by implementing the 77 factors; (B) the framework should be systematic and easy to apply, avoiding any complexity, so the value engineering procedure and technique can be integrated in the framework in order to evaluate materials selection; (C) the life cycle costing approach could help in reducing the OPEX for both brown field and green field projects and this currently neglected concept should be considered in the early design.

Chapter 7

Development of Sustainable Engineering Design and Materials Selection Framework For Offshore Topside Facilities

7.1 Introduction

The aim of this study is to develop a framework that can be utilised as an effective tool in engineering design and materials selection in terms of sustainability for offshore topside projects. The development of this framework is based on the findings from the previous two chapters, which show that there is a significant need for a sustainable framework for offshore topside projects. The proposed framework was established based on the identified factors and the key elements discovered in the course of the literature review and semi-structured interviews, the latter of which included two components: open ended and closed ended questions. This chapter presents the concept of the proposed framework, as well as a detailed description of the framework phases and its components in line with the sixth objective of this research.

7.2 Framework Construction

Framework is created based on the identification of key concepts and the relation between them. The following steps were considered when developing the framework as shown in the below chart (figure 34) : (1) set an objective; (2) define concepts and relation between the concepts; (3) engage the stakeholder; and finally build the framework.

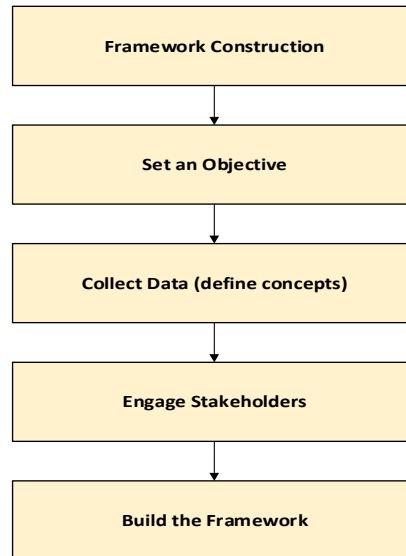


Figure 34 Steps to build framework

7.2.1 Step one: Set an objective

The first step in order to create a framework is to set an objective which include the requirements that are required to be achieved as an output from the framework. Objective of the framework was mentioned clearly in section 1.6.

7.2.2 Step two: Define concepts (philosophy of the proposed framework)

According to the in-depth literature review and findings of the semi-structured interviews, there is no clear sustainable framework for engineering design and materials selection that has implemented and integrated all aspects of sustainability within the same framework in an offshore topside facility. Moreover, in section 1.5 (research gap), it is found that no sustainable framework for offshore topside facility projects exists that can provide a foundation for this study. Hence, the proposed framework will consider the integration of three concepts: (1) *sustainability*; (2) *value engineering*; and (3) *life cycle costing*. For any project, there are always practical and optimal alternatives that consider sustainable development criteria in terms of environmental and social issues, such as recycled materials content, embodied energy, toxicity content, flammability and so on. Therefore, sustainability addresses and identifies environmental and social concerns; value

engineering is used to evaluate and assess these criteria in order to identify the best alternatives that satisfy the function and sustainability requirements. Finally, life cycle costing addresses the economic side of the alternatives in order to select the best value alternative in terms of the lower life cycle cost (refer to figure 35 and 36).

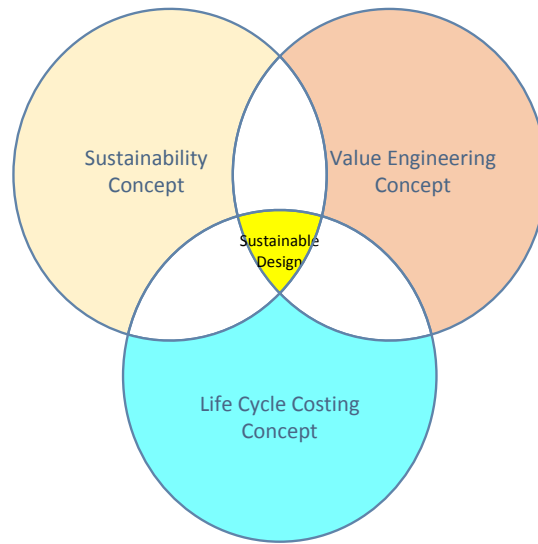


Figure 35 Framework philosophy

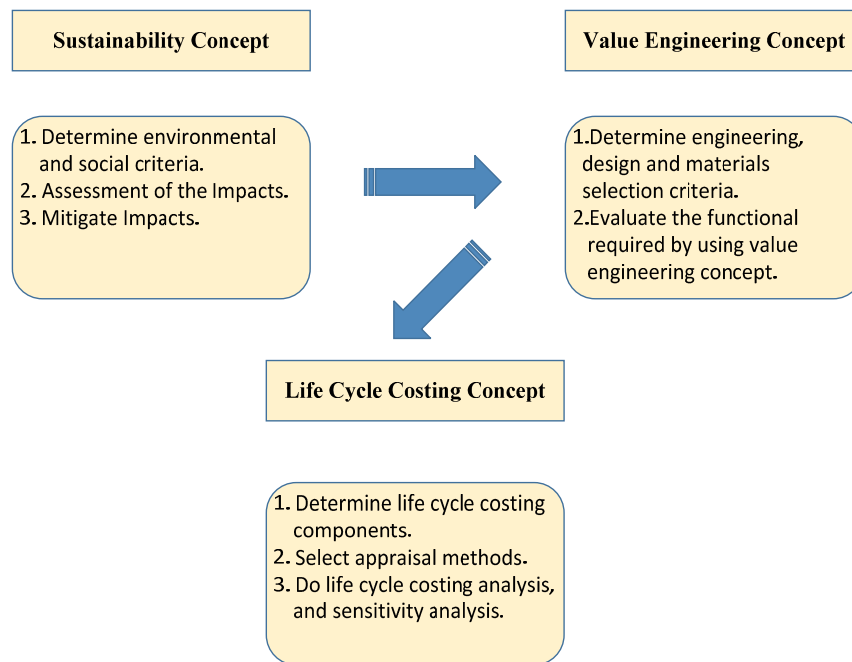


Figure 36 Framework explanation

7.2.3 Step three: engage stakeholders

Stakeholders engagement is a key part of creating the framework. Any organisation involves their stakeholders in order to find out what issues matter are important and should be considered during the framework creation; stakeholders are the people who will be involved in implementing the framework as well as may be affected by the decision it makes. Thus, stakeholders were involved in the semi-structured interviews as explained in chapter 6. The defined concepts from the previous step were discussed and the followings were agreed to be considered during the creation of the framework:

Therefore, based on the discussion with the stakeholders during semi-structured interviews, the key elements of the framework can be summarised as follows:

- The framework should incorporate all of the three pillars of sustainability, including social, environmental and economic aspects within the same framework;
- The framework should be designed to eliminate or mitigate the negative environmental and social impacts of topside facility projects;
- The framework should consider all the 77 factors/criteria identified through the literature review and substantiated by the offshore experts in the semi-structured interviews;
- The framework should consider the value engineering technique in terms of materials selection and evaluation;
- The framework should implement the concepts of life cycle costing and time value of money in order to economically evaluate the materials or the product with reference to the product's life of service.

7.2.4 Step four: build the framework

All the findings and recommendations from the semi-structured interviews (explained in chapter 6) were integrated along with the life cycle concept and value management techniques, to produce a generic sustainable framework that can be applied in all offshore industry sectors for topside facility projects. The proposed framework consists of three main stages: (1) environmental and social evaluation; (2) evaluation of the materials and

equipment; and (3) life cycle costing evaluation. The schematic process of the developed framework is illustrated in figures 37, 38, 39 and 40.

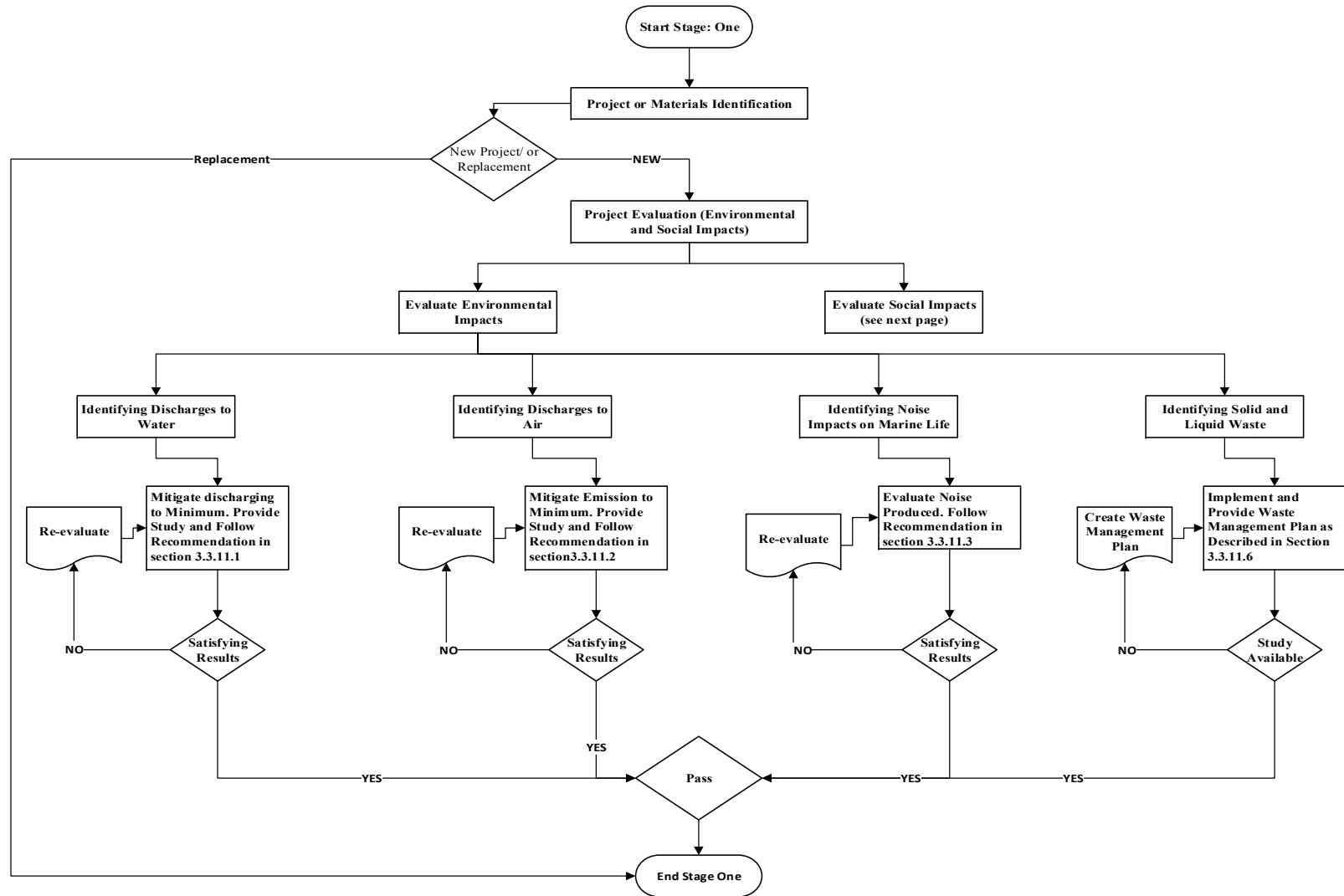


Figure 37 Stage one: environmental and social evaluation

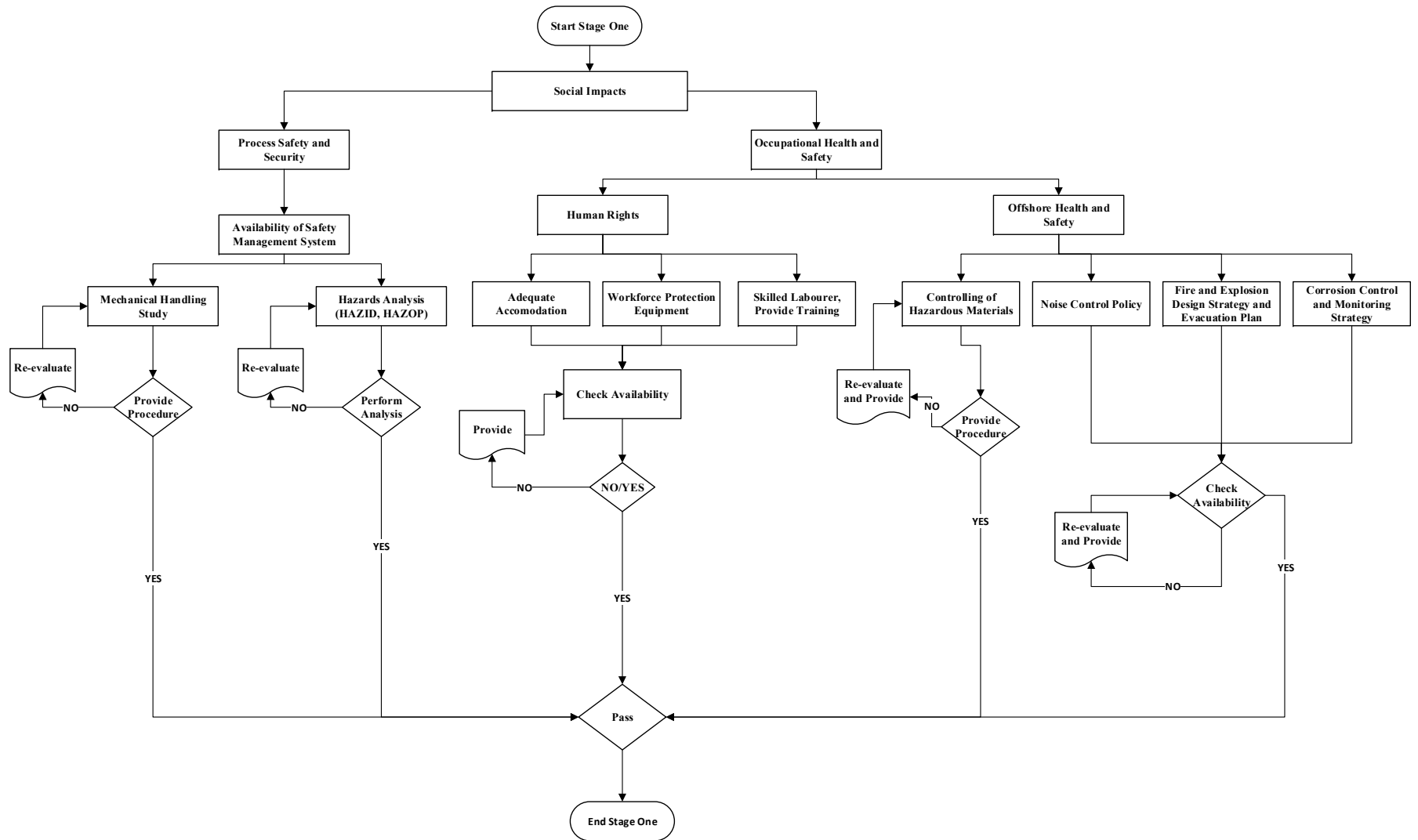


Figure 38 Stage one: environmental and social evaluation

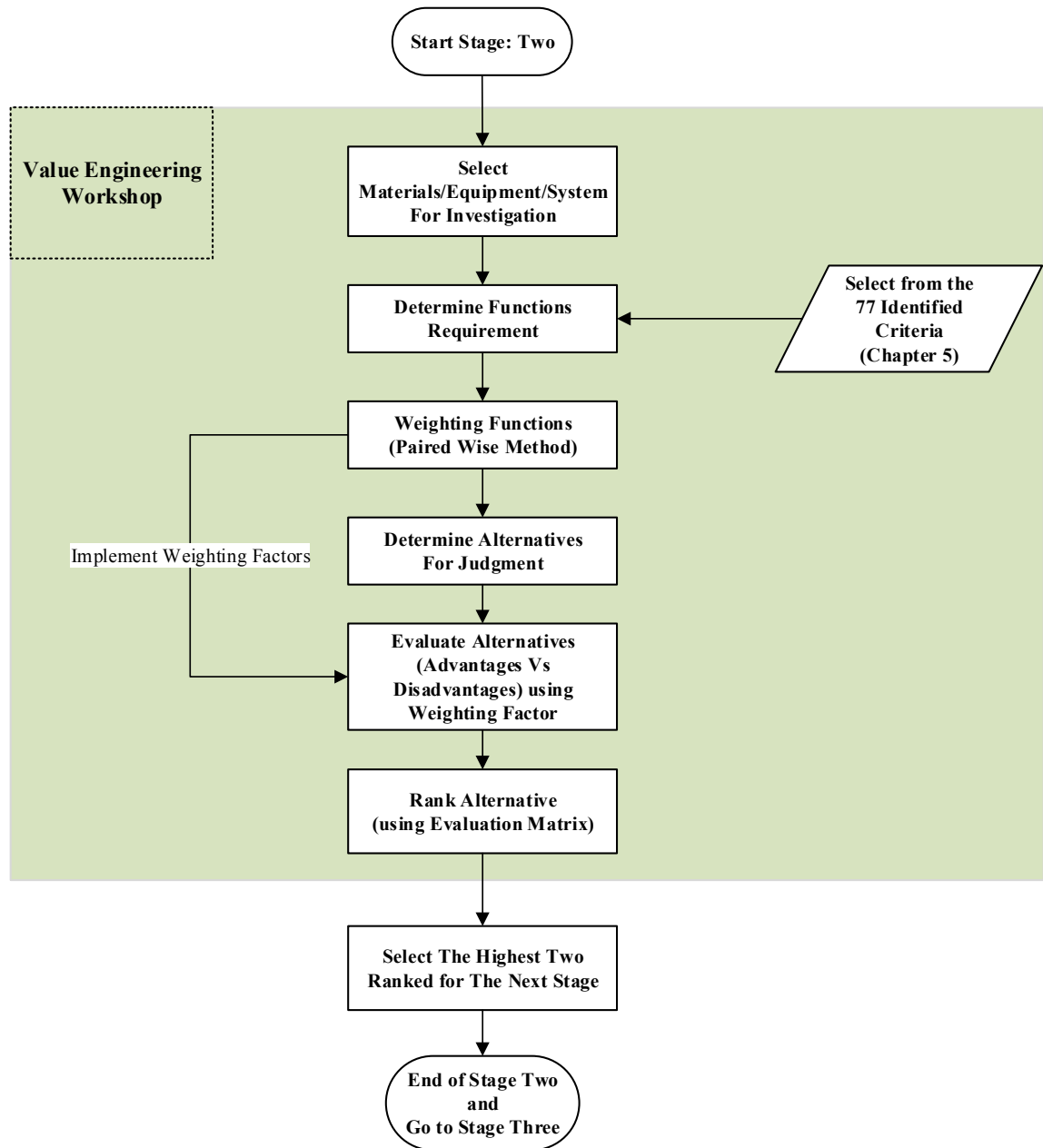


Figure 39 Stage two: evaluation of the materials and equipment

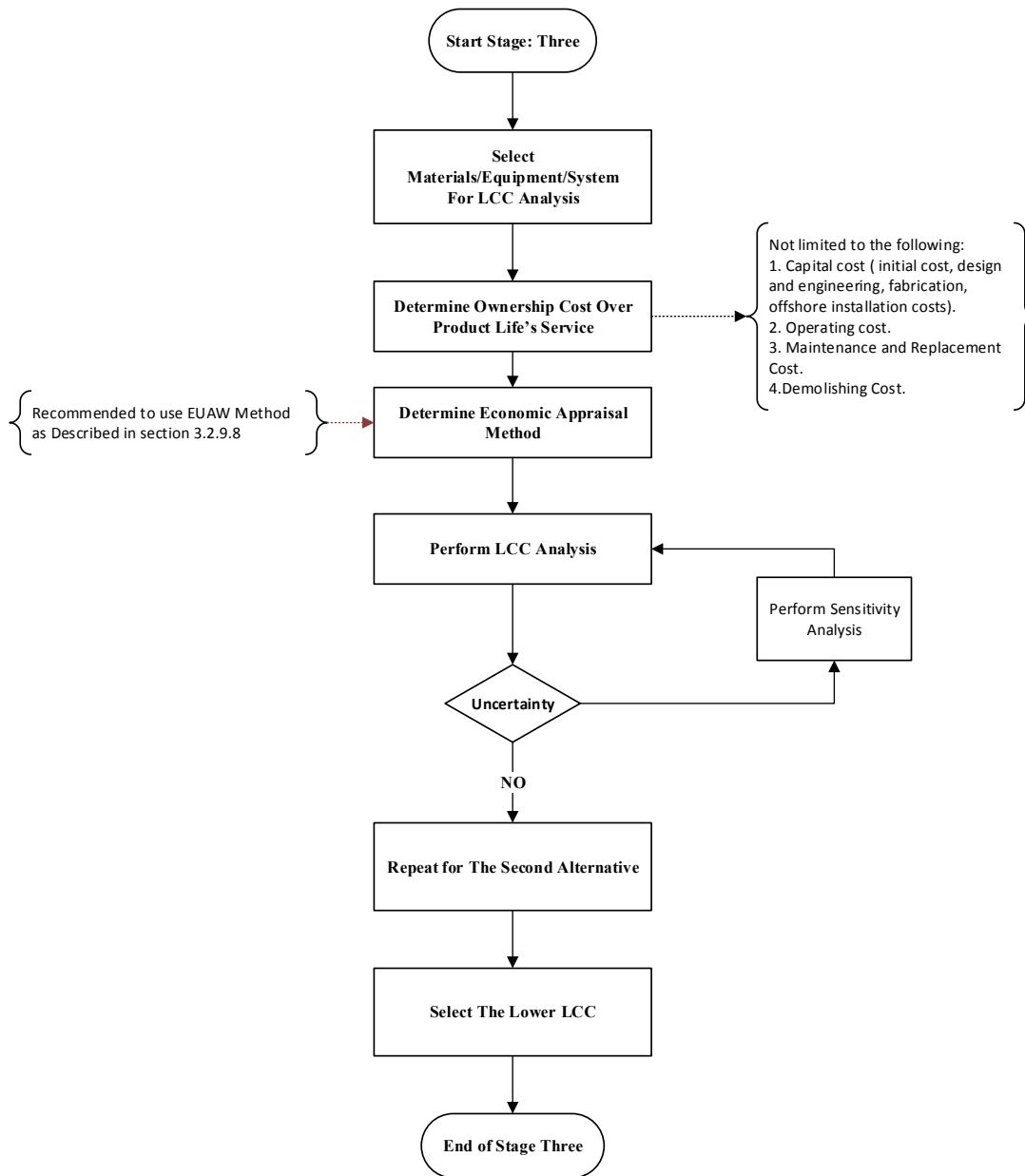


Figure 40 Stage three: life cycle costing evaluation

7.3 Stage One (Environmental and Social Evaluation)

This phase includes the evaluation of the entire project (as a whole) at the early stage, considering the environmental and social aspects. From the previous chapter, the subgroups ranked as the top two were the environmental pollution to air and water and offshore health and safety. Moreover, some criteria, under human rights for offshore workers, were ranked among the top ten criteria. Therefore, this phase addressed these criteria as they are very important to offshore experts and the offshore industry as a whole. The activities and functions of this phase are presented below:

7.3.1 Project or materials identification

This function involves determining the project type: whether it is a new project (either brown field or green field), or classified as a replacement and maintenance project. Usually all maintenance and replacement work in topside facilities is treated as like-to-like replacement. Therefore, the first activity stage of the framework will exclude maintenance and replacement jobs. If this is a new project, then it will go through all three stages of the framework; if it is maintenance and replacement work and the scope of the project only requires replacement, then it will go directly to the second stage of the framework.

7.3.2 Identification of the environmental impacts

The purpose of this activity, as explained in chapter 3, is to evaluate and assess the impacts of new projects on the environment. Considering the environmental impacts of topside facilities at the early stage of any project will significantly reduce its environmental pollution. Water pollution, climate change, global warming and ozone depletion are the major challenges contributing to destroying air quality, marine life and the ecosystem. Therefore, the plan for any project should be checked against potential environmental issues. Below, the major environmental issues based on the findings from the literature review and the semi-structured interviews are divided into four main activities.

A. Identifying discharges to water

This activity will address the discharges from topside systems into the marine environment. As mentioned in chapter 3, there are many sources of these discharges, such as produced water, oil spills, chemical spills, sewage and drainage systems, and other systems. The potential impacts and toxicological effects on aqua life were discussed in section 3.3.10.1. The level of discharges from topside facilities into water should be kept at zero level in order to maintain the marine life and ecosystem. However, it is difficult to achieve zero discharge into the marine environment as international regulation allows for a certain amount of discharge from sewage, drainage systems and produced water. The target is to minimise and mitigate the discharge level to the lowest possible value. Therefore, in this activity we recommend providing a process study outlining how to deal with the pollutants and discharges from topside facilities, either eliminating the discharges, or reducing them to a minimum. Some recommendations and suggestions are given in section 3.3.11.1 in this regard.

B. Identifying discharges to air

For this activity, all systems within a single project should be checked against greenhouse gases such as CO₂, CH₄, NO_x, SO_x and other gases, all of which are released from topside systems. As described in chapter 3, the main sources of air emissions are flaring unrequired gases, venting, combustion fuel from diesel engines and turbines, and fugitive gases from process systems. Hazards and toxicity of the emission gases, as well as the effect of greenhouse gases on the climate were discussed in section 3.3.10.2. Analysis of the greenhouse gases is required for each new system (release gases) to make sure that these gases do not carry any toxic or flammable components and they do not exceed international environmental regulations, which consequently could deliver harmful effects to offshore workers and working areas. Most companies comply with environmental law and regulation; however, this compliance still allows for a small amount of discharge into the air. Therefore, new technology and solutions have been introduced to the industry to prevent or mitigate air pollution. In this regard, recommendations to mitigate air pollution were presented in section 3.3.11.2.

C. Identifying noise impacts on marine life

Noise impacts from topside facilities affect both marine life and offshore workers. The effects on offshore workers will be addressed later under the social activities of the framework. The major impacts on marine life, as explained in section 3.3.10.3 occur during the installation of the topside module (refer to section 2.4.3.4). Therefore, a noise impact study on marine life should be considered only during the green field project. In section 3.3.11.3, recommendations on how to control and mitigate the impact of noise on marine life were discussed.

D. Solid and liquid waste

Topside facilities produce many types of solid and liquid waste due to the routine operation and construction activities of brown field modification projects. This waste can have a significant negative impact if it is not treated and controlled; potential impacts were discussed in section 3.3.10.4. A waste management plan plays an important role in achieving sustainable development by reducing environmental impacts and human health issues. Therefore, a waste management plan should be created for each new project, as well as for routine and maintenance jobs. A strategy on how to apply the waste management plan is described in section 3.3.11.4.

7.3.3 Identification of the social impacts

Social impacts in the framework are presented in two groups: (1) **process safety and security**; and (2) **occupational health and safety**. The first group includes the following activities and sub activities.

A. Safety management system

For topside facility projects on offshore platforms, the safety management should consider the project from two angles: the first part should include the safety of the process and operation of the project (HAZID and HAZOP study); the second part should look at the safety during the installation and construction of the project on the platform (mechanical handling study). Therefore, the following studies should also be provided and performed for each brown field and green field project.

- 1) HAZID and HAZOP studies: risk assessment includes a range of techniques and methods for determining various hazards on the facility and suggesting appropriate prevention or mitigation and control actions. As described in section 3.4.5, the potential hazards come from processing systems, fluids being produced and procedures used for operating and maintaining the facilities; the sources of hazards are flammable and toxic materials, where the consequences are explosions, personnel injuries and pollution. HAZID and HAZOP studies should be conducted at the early stage of the project (refer to section 3.4.5).

- 2) Mechanical handling study: sometimes called removal and installation procedures, this study is critical for all new projects as well as for maintenance jobs. The scope of the study is to show the best and safest method for handling the equipment for the new project and/or removing the old equipment for replacement purposes. Topside facilities have limited and narrower spaces between the facilities (tanks, pipes, vessels, pumps, etc.). Therefore, moving loads and equipment within the platform is difficult and in many cases the new projects are cancelled if the mechanical handling shows that installation has some restrictions. The study will show the route for moving equipment; if it is clear and strong enough or needs to be reinforced by adding temporary supports. It is necessary to check the crane capacity and how the equipment will be lifted from the vessel (boat) to the platform, and investigate if lifted equipment will pass above the critical process equipment or not (the requirement for adding a dropped object protection frame in some cases). It should be checked whether the new equipment needs additional space on the platform and the requirements for designing a new deck extension for that purpose. The final proposed location for the equipment should also be checked, if the proposed location is strong enough to carry the new loads, or structural reinforcement is required. In general, the full path from lifting up the equipment until installing it will be studied from the structural and safety point of view (refer to section 3.4.2.1.4).

The second group, **occupational health and safety** will have the following activities that should be considered during the early stage of any project:

A. Offshore health and safety

The health and safety for offshore workers is threatened by several sources of hazard on offshore platforms as explained in section 3.4.2. A clear procedure and strategy should be provided for the following issues at the time of the creation of a new project:

- 1) Controlling of hazardous materials: a procedure should be developed to reduce the exposure of offshore workers to hazardous materials and radioactive sources. The procedure should include how to handle, manage and store the hazardous materials offshore (refer to 3.4.3). In addition, hot works (welding) should be replaced by bolting design for both health and safety purposes (refer to 3.4.2.1.6 and 3.4.2.2.2).
- 2) Noise control: noise from topside facilities has a major impact on offshore workers due to routine operation and production activities. Procedures and policy should be available for brown field projects in terms of equipment selection and exposure of offshore workers to the noisy area. In this regard, some recommendations were given in section 3.3.11.3.
- 3) Fire and explosion design strategy and evacuation plan: this strategy should be created for each new project at the early design stage to prevent or minimise the hazards. The objective is to protect the personnel as well as the company offshore assets. The approach of prevention, detection and control and mitigating should be applied (refer to section 3.4.3 for general considerations, and to section 3.4.3.1 for the explosion design strategy).
- 4) Corrosion control and monitoring strategy: process safety, failure of structural members, pipes and valves can occur due to the corrosion; most of the replacement work offshore and the majority of the OPEX cost goes on corrosion issues and problems. A clear strategy of corrosion control and monitoring should be developed; types of corrosion and corrosion control and monitoring were discussed in chapter 2 (refer to sections 2.13 through 2.17).

B. Human Rights

As noted in the literature review, the nature of work in the offshore area is different from other industries. Small human errors can cause major disaster events; such human errors are often related to personal attitude and tolerance, working under stress and long shift working hours. Offshore workers are working in a hazardous area near ignition sources and there are fewer entertainment activities on offshore platforms that there would be onshore. Based on these facts and discussions in chapter 3, the following activities should be considered for each project:

1. Provide adequate accommodation.
2. Provide protection equipment.
3. Use skilled workers and provide them professional training as require.

7.4 Stage Two (Evaluation of the Materials and Equipment)

After assessing the entire project's systems in terms of the environmental and social impacts in stage one, the second stage will focus on the evaluation of the materials or equipment selection for the new project. This stage will provide a systematic process on how to create an evaluation base by using a value engineering technique, when the target is to evaluate between alternatives. The main focus of value engineering is to maximise the value of the product by confirming that the functionality is provided, but with the least cost possible (refer to sections 3.2.3 and 3.2.4). The following functions and activities represent how stage two will be conducted (refer to figure 39).

7.4.1 Select materials or equipment for investigation

Offshore projects normally involve the integration of multiple systems and disciplines (such as piping, structural, mechanical, electrical, instrumentation and process systems). Each discipline has different applicable materials, equipment or products that can be used for its system. In some situations (as explained in chapter 2), the engineer faces difficulties in selecting from several options or alternatives. Therefore, the first step is to identify the system or the equipment required for the investigation in terms of materials selection. An example of a system is (an open drain system) within the piping discipline.

7.4.2 Determine functions requirement

In this activity, the project manager or project engineer will first identify the value team (members) who will participate in the value engineering workshop. The first objective of the value team is to determine the list of functions required based on the engineering requirements. The value engineering methodology suggests using two words (active verb and measurable noun) in order to determine the list of functions (refer to chapter 3 and in particular section 3.2.5.1.1). To make this activity easy, the engineers can use the 77 identified factors described in chapter 5 to create the list of functions. These determinant factors cover most of the engineering functions.

7.4.3 Weighting functions (paired wise method)

The paired wise comparison method is a weighting and scoring technique. This technique will be used, as explained in 3.2.5.1.2, to give weight to each criterion. The weighted criteria/factors will be used later in the evaluation stage.

7.4.4 Determining alternatives (creative process)

In the creative process, the value team generates and develops a list of alternative technical solutions to achieve the identified functions from the previous activities. In the above activity (7.4.1), (open drain system) in the piping discipline is mentioned as an example. Now in this activity, the value team will try to develop a list of alternative materials for open drain system, such as (carbon steel, stainless steel, glass reinforced plastic, etc.).

7.4.5 Alternatives evaluation

In this activity, advantages versus disadvantages for each material will be discussed and based on this the value team will use the evaluation matrix and the weighted factors from the above activity (7.4.3) to rank the materials (refer to section 3.2.5.3).

7.4.6 Ranking alternatives

The alternatives will be ranked based on their score from the evaluation matrix; the highest score the highest ranking.

7.4.7 Selecting the alternatives for the next stage

It is suggested here that the two highest ranked materials should be lifted to the next stage for more investigation; other materials that fail will be ignored.

7.5 Stage Three (Life Cycle Costing Evaluation)

This stage focuses on evaluating the alternatives from an economic point of view. The concepts of the life cycle costing and time value of money will be used for this stage (for more detail in LCC refer to chapter 3). Figure 40, shows the schematic process diagram for this stage.

7.5.1 Selecting alternatives

The first step in this stage is to select alternatives for comparison; as explained in the previous stage, only the highest two ranked materials/alternatives from stage two will be entered into LCC analysis.

7.5.2 Determining ownership cost

This is the most important activity in the life cycle costing components; ownership cost is the total cost of the product or equipment over its life cycle. In offshore projects, the ownership cost is not limited to the following: (1) capital costs, which include the initial cost of the product or materials, engineering and designing cost, offshore shipping and installation cost; (2) operating and running cost (such as fuel); (3) maintenance and replacement cost (such as spare parts, corrosion control, corrosion monitoring, etc.); (4) demolishing cost (in some replacement projects, old projects should be removed to install a new project in its place; therefore, the cost of demolishing of the old project should be calculated); and (5) disposal cost (refer to section 3.2.6.4).

7.5.3 Determining the economic appraisal method

There are several techniques involved in performing the analysis of the life cycle costing methods. Some methods and techniques have limitations as described in 3.2.9.8;

therefore, it is recommended to use the equivalent uniform annual worth method (EUAW), as described in section 3.2.9.3.

7.5.4 Performing LCC analysis

LCC analysis will be performed based on the analysis of the cash flow diagram components; determinant cost, interest rate, service life of the product and economic appraisal methods (more detail on LCC in chapter 3).

7.5.5 Uncertainty and sensitivity analysis

There is always some uncertainty about the input data to be used in LCC calculation; uncertainties are due to the project scope, replacement cost, time schedule, operation conditions and investment parameters such as tax, inflation and interest rate. Therefore, sensitivity analysis is performed to test the outcome of LCC analysis when one variable of LCC components is changed (more detail in section 3.2.10).

7.5.6 Repeat the process for the second alternative

The above process will be repeated for the second alternatives to perform the LCC analysis with sensitivity analysis if required.

7.5.7 Selecting the lower LCC

After performing the LCC analysis and sensitivity analysis for the two alternatives selected from the previous stage (stage 2), a comparison of the results will be made to select the lower LCC.

7.5.8 End of stage three and framework

This is the end of the stage 3 and the framework, where the project engineer makes recommendations and suggestions to engineering management based on the results of this framework.

7.6 Summary

This chapter presented the sustainable design framework for offshore oil and gas platforms at the conceptual stage of topside facility projects. The framework consists of three stages: (1) environmental and social evaluation; (2) evaluation of the materials and equipment; and (3) life cycle costing evaluation. The components, process and activities for each stage were described. However, this framework can not be considered complete until it has been validated and evaluated by experts. The following chapter presents the validation and evaluation process adopted for this framework.

Chapter 8

Framework Validation and Evaluation

8.1 Introduction

Verification and validation are used to check the quality, workability and accuracy of the developed framework or model. There is sometimes confusion in distinction between verification and validation. Dasso and Funes (2007), citing Bohem suggested that we undertake validation when answering question, “Are we building the right product”; and verification when answering the question “Are we building the product right”. Moreover, they noted that verification techniques aim to detect mistakes and aid the designer in correcting them during the development of the model, while validation is related to the requirement specification in that it validates the user requirement. Al-Thani (2002) stated that the purpose of verification is to determine whether the model is “functioning as designed”, for example, checking if there are coding errors that could lead to improper results, while validation seeks to find weather the generated information provides a suitable basis for evaluating options, answering questions such as “does the model capture the desired interaction”.

From the above, we can see that verification is more related to the computerised model, which requires verifying mathematical equations or coding before validation, which is not the case in the conceptual framework. Preece (2001) suggested that verification can be viewed as part of the validation. Therefore the validation process only will be adopted for this study. This chapter presents the validation and evaluation process carried out for the sustainable design framework of offshore topside projects.

8.2 Validation Methodology and Approach

The validation methodology and approaches were discussed in section 4.10 in the methodology chapter. Two approaches were selected for the validation and evaluation process: (1) involving end users through performing *case application* to check the applicability and workability of the framework with real data and to check the

framework's logic and structure; and (2) scoring model by using semi structure interviews to evaluate the framework and get feedback from the end users.

8.3 Case Application

This case application examines the developed framework in terms of its applicability and shows the end users how to use it, also gathering reliable feedback from the end users. The case application gives the end users an opportunity to check every step and component of the proposed framework.

8.3.1 Problem statement

As mentioned (in previous chapters) the offshore environment is extremely corrosive due to high temperatures, humidity and airborne oxidants, especially in the Arabian Gulf. The normal (traditional) materials used for walkways are galvanised steel grating. However, galvanised steel grating has proven inadequate to cope with corrosion resistance (refer to figure 41 and 42).

The project (problem) is therefore:

‘ to resolve the issue of corrosion attacking an existing galvanized steel grating 38mm thickness, covering an area of 100 m2 and located on an accommodation platform. It is recommended to study other options and alternatives, considering the life cycle costing and aspects of sustainability’.



Figure 41 Steel grating, attacked by corrosion



Figure 42 New gratings for staircase

Framework implementation process as follows:

8.3.2 Stage one of the framework

As explained in the previous chapter, stage one will be applicable for new projects in order to evaluate the environmental and social impacts. The first step of stage one as described in section (7.3) is to identify the type of project. Therefore, as replacement and maintenance jobs, stage one will be excluded and will move directly to stage two.

8.3.3 Stage two of the framework (materials and system evaluation)

In this stage, the value engineering methodology will be applied step by step, in order to help the end users to list and establish alternatives based on the required functions. The three main phases of value engineering methodology: function analysis, creative, and evaluation will therefore be applied.

8.3.3.1 Value Engineering Team

The first step is to select the right participants for the workshop. As the offshore grating is a structural material, and the structural department is responsible for selecting such materials, it has been decided to involve three structural engineers from the structural department, and two project engineers. The author has participated as the second of these two project engineers in this workshop. The reason for involving project engineers in the workshop is that the project engineer is the one responsible for the project management of any project assigned to him, and also functions as the link between all engineering

disciplines and the construction department. Hence, feedback from project engineers is significant in learning about, for example, offshore installation hours, cost estimation, availability of the materials in the local market, fabrication process, etc. The profiles of the participants are shown below in table 29.

Table 29 Value engineering team profiles

<i>Job Position</i>	<i>Years of Experience</i>
Lead Structural Engineer	22
Senior Structural Engineer	25
Senior Structural Engineer	10
Senior Project Engineer	13
Senior Project Engineer (Author)	15

8.3.3.2 Agenda of the value engineering workshops

The value engineering methodology was carried out in two workshops on two separate days; the workshops were held in Qatar in one of the Oil Operator Companies in June 2016. The first workshop included the *function analysis phase*, and took about three hours. The second workshop included the *creative and evaluation phases*, and took about four hours.

Agenda of workshop one as follows:

- Confirmation of the problem statement.
- Establish and list functional requirements.
- Evaluate and assign weight for the functional requirements by using the paired wise matrix.

Agenda of workshop two as follows:

- Establish and list alternatives.
- Present and discuss the advantages versus disadvantages of all alternatives with regard to functional requirements.

- Evaluate and judge between the alternatives based on the advantages and features of each alternative compare to the others. Evaluation matrix will be used to rank the alternatives based on the weighted functions (criteria).
- List of the final recommendations.

8.3.3.3 *Function analysis phase (workshop one)*

This phase, as described in chapter 3, comprises of two main parts: (1) function identification and classification, and (2) function analysis by using the paired wise comparison method.

One of the research objectives is to determine the factors/criteria affecting sustainable design and materials selection for offshore topside projects, as explained in chapter 5. These factors make the function identification of any offshore projects easier and more straightforward as these factors consider many aspects as explained. Therefore, the value team established the function requirement based on these factors using the two-word technique: “active verb” and “measurable noun”. Twenty-five functions were identified for this situation, as shown in table 30.

Table 30 Function analysis

Environmental Criteria		
Verb	Noun	Classification
Reduce	Embodied energy throughout the material's life cycle	Secondary
Reduce	Co2 emission throughout the material's life cycle	Basic
Social Criteria		
Verb	Noun	Classification
Mitigate	Flammability and toxicity content	Basic
Secure	Installation and removal	Basic
Reduce	Offshore welding	Basic

Engineering and Technical		
Verb	Noun	Classification
Confirm	Standards and codes	Basic
Support	Mechanical properties	Basic
Prevent	Electrical conductivity	Basic
Resist	Corrosion and erosion	Basic
Facilitate	Corrosion control	Basic
Enhance	Durability	Basic
Enhance	Reliability	Basic
Ensure	Chemical resistance	Basic
Resist	Heat and thermal	Basic
Resist	Fire	Basic
Consider	Safe usage	Secondary
Consider	Easy usage	Secondary
Enhance	Design life	Secondary
Reduce	Weight	Basic
Contain	Reused materials	Secondary
Contain	Recyclable materials	Secondary
Obtain from	Local market	Secondary
Control	Coating method	Secondary
Facilitate	Prefabrication process	Secondary
Reduce	Installation hours	Basic

From the above table, 25 criteria were selected for this project. The criteria related to the economic aspects were not considered at this stage, because economic factors and criteria will be considered in the following stage of the framework (life cycle costing evaluation).

The next step is to assign weight to each function or criterion by using the paired wise comparison method as described in chapter 3. To make the comparison easier, each criterion will be given an alphabetical letter as shown in table 31 below.

Table 31 Function identification letter

Assigned Letter	Required Function
A	Reduce energy consumption throughout the material's life cycle.
B	Reduce CO2 emission throughout the material's life cycle.
C	Mitigate flammability and toxicity content.
D	Secure installation and removal
E	Reduce offshore welding
F	Confirm to standards and codes
G	Support mechanical properties
H	Prevent electrical conductivity
I	Resist corrosion and erosion
J	Facilitate corrosion control
K	Enhance durability
L	Enhance reliability
M	Ensure chemical resistance
N	Resist heat (thermal)
O	Resist fire
P	Consider safe usage
Q	Consider easy usage
R	Enhance design life
S	Reduce weight
T	Contain reused materials
U	Contain recyclable materials
V	Obtain from local market

W	Control coating method
X	Facilitate prefabrication process
Y	Reduce installation hours

The value matrix in table 32 (paired wise comparison) as described in chapter 3, will be applied to assign weight for each criterion. Each criterion is compared for importance and preference with each other criterion based on the following measures: 4 = major importance and preference; 3 = medium preference; 2 = minor preference and importance; 1 = slightly preference. So, for example, this will reflect how much criterion A is more important than B on a score of 1 to 4.

In table 32 below, for instance, in the comparison between criterion A (reduces energy consumption throughout the material's life cycle) and criterion B (reduces CO2 emissions throughout the material's life cycle), minor preference is given to criterion B over criterion A, and thus criterion B is assigned a score of 2 (B2), and so on until all the criteria have been compared with one another.

Table 32 Paired wise comparison matrix

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	
A	B2	C4	D4	E3	F4	G4	A/H	I4	J4	K4	L4	M2	N4	O4	P3	Q3	R3	S3	A/T	A/U	V3	W3	X2	Y4	
B	C4		D3	E3	F4	G4	B/H	I4	J4	K4	L4	M2	N4	O4	P3	Q3	R3	S3	B/T	B/U	V3	W3	X2	Y4	
C	C4			C4	F4	C3	C4	C2	C2	C2	C2	C2	C3	C2	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	
D	D/E				F4	G2	D3	I4	J1	K1	L1	M1	N2	O4	D1	D1	R2	S1	D4	D4	D4	W2	D2	D/Y	
E	F4					E1	E3	I4	J1	E/K	L/K	M1	N2	O4	E2	E2	E2	E3	E4	E4	E4	W1	E4	E1	
F	F4						F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4	F4
G	G4							I2	J1	G2	L2	G2	G/N	O2	G2	G2	G2	G2	G3	G3	G3	G1	G1	G3	
H	I3								J3	K3	L3	M3	N3	O4	P3	Q3	R3	S3	T2	U2	V2	W3	X3	Y3	
I	I4									I4	I4	I3	N2	O2	I4	I4	I4	I4	I4	I4	I4	I4	I4	I4	
J	J1										J1	J/M	N2	O2	J1	J1	J1	J1	J1	J1	J1	J1	J1	J1	J1
K	K1											K/M	N2	O2	K1	K1	K1	K1	K1	K1	K1	K1	K1	K1	K1
L	L/M												N2	O2	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1

	N	O	P	Q	R	S	T	U	V	W	X	Y
M	N2	O2	M2	M2	M2	M2	M2	M2	M2	M1	M1	M1
N	N3	N3	N3	N3	N2	N3	N3	N3	N3	N1	N3	N3
O	O4	O4	O4	O4	O4	O4	O4	O4	O4	O3	O3	O3
P	P/Q	P/R	P/S	P2	P2	P2	P2	P2	P2	P2	P2	P2
Q	Q/R	Q/S	Q2	Q2	Q2	Q2	Q2	Q2	Q2	Q2	Q2	Q2
R	S2	R4	R4	R4	R/Q	R2	R2					
S	S3	S3	S3	W2	S2	Y1						
T	T/U	V1	W4	S3	Y4							
U	V1	W4	S3	Y4								
V	W4	S3	Y3									
W	W2	W2										
X	X3											

Table 33 below shows the results of the value matrix; all functions are weighted based on their scores. The raw scores can be used directly in the evaluation phase. However, for convenience and in order to convert the scores into weights on a scale (1 to 10), Flanagan (1989) suggested using the following formula:

$$W=10R/M(n-1) \dots\dots\dots Eq (14)$$

Where M is the maximum value for each criterion (4 in this example) and n is the number of criteria (25 in this example).

So, for example, to calculate the weight for function E, the equation will be as follows:

$$W = 10R / 4 (25-1) = 0.1041R,$$

Thus, the weight for criterion E will be $38 \times 0.1041 = 3.96$

Table 33 weighted functions

Function	Score	Weight
F	96	10
C	78	8.12
I	76	7.91
O	69	7.2
N	56	5.83
G	41	4.27
E	38	3.96
W	30	3.12
R	30	3.12
M	29	3.02
D	28	2.91
J	27	2.81
L	26	2.70

K	25	2.60
S	25	2.60
P	24	2.5
Q	24	2.5
Y	24	2.5
V	10	1.04
X	10	1.04
B	5	0.52
T	5	0.52
U	5	0.52
A	3	0.31
H	2	0.21

8.3.3.4 *Creative phase (workshop two)*

As mentioned in chapter 3, during this phase the value team tries to develop a list of applicable alternatives that will be judged in the next phase (evaluation phase). It is important to note here that all suggested alternatives are applicable; however, there is only one optimum solution. Therefore, the objective of the next phase is to narrow the alternatives and select the optimum solution. Consequently, the value team brainstormed the alternatives, and after a long discussion, the following alternatives were suggested:

- Steel grating 38mm thickness, as per the offshore requirements and standards. This material is considered as the tradition material.
- Glass reinforced plastic (GRP) phenolic type, 38mm thickness, heavy duty (high specification).
- Glass reinforced plastic (GRP) phenolic type, 38mm thickness, normal type.
- Glass reinforced plastic (GRP) Vinylester type, with 38mm thickness.
- Aluminum grating.

8.3.3.5 Evaluation phase (workshop two)

The objectives of this phase are to evaluate and analyse the generated alternatives from the previous phase in order to rank them for further investigation. Listing the advantages versus the disadvantages for each alternative can help the value team to judge between the alternatives. Following this, the evaluation matrix will be applied to rank the alternatives (refer to chapter 3 for more details). The advantages versus disadvantages are shown in table 34 below.

Table 34 Advantages Vs disadvantage for the alternatives

Criteria	Alternatives				
	Steel grating	GRP (phenolic resin) high specification	GRP (polyester resin)	GRP (vinylester resin)	Aluminium
Conformance to standards and codes	Yes, meets all specifications and codes.	Yes, meets all specifications and codes.	Partially, some issues related to the fire retardant tests.	Partially, some issues related to the fire retardant tests.	Partially
Mechanical properties	Excellent, ultimate tensile strength from 370 to 700 MN/M2. However, it can deform under impact.	Excellent, tensile strength from 60 to 1250 MN/M2 based on the fabrication process. High strength to weight ratio. High impact resistance (does not deform under impact).	Very good, tensile strength from 60 to 1250 MN/M2 based on the fabrication process. High strength to weight ratio. Polyester resin in general is weaker than phenolic and vinylester.	Very good, tensile strength from 60 to 1250 MN/M2 based on the fabrication process. High strength to weight ratio. Vinylester resin in general is weaker than phenolic, but better than polyester.	Good, but weaker in general compared to the other. More elastic than steel and GRP. Easily deforms under impact.
Corrosion resistance	Low corrosion resistance, subject to oxidation.	Excellent corrosion resistance.	Excellent corrosion resistance.	Excellent corrosion resistance.	Low corrosion resistance, subject to galvanic corrosion.
Fire resistance.	Excellent	Excellent, passes ASTM-E84 and US Coast Guard rating.	Good, passes only ASTM-E84.	Good, passes only ASTM-E84.	Poor, low melting temperature compared to the other.

Chemical resistance	Excellent	Excellent	Good	Very good	Good
Flammability and toxicity	Excellent	Excellent, no flammability and toxicity, in accordance with the UL94-97 test for flammability of plastic materials.	There is some concern in terms of flammability.	There is some concern in terms of flammability.	There is a concern.
Corrosion control and inspection.	Requires constant inspection to capture any corrosion at the early stage.	Maintenance free.	Maintenance free.	Maintenance free.	Regular maintenance is required, as well as painting.
Electrical properties (conductivity).	Conducts electricity.	Excellent, not conductive.	Excellent, not conductive.	Excellent, not conductive.	Conducts electricity.
Offshore welding	Sometimes welding is required.	No welding is required.	No welding is required.	No welding is required.	No welding is required
Installation and removal	Hot work is required (cut with torches). Special installation equipment required. Hence, there are safety concerns.	Easy installation and removal. Cold work.	Easy installation and removal. Cold work.	Easy installation and removal. Cold work.	Complex, mechanical joining is required. Sometimes soldering.
Prefabrication process	Pre-fabrication is required onshore, otherwise in case of field adjusted, hot work will be required. Hence	Can be field adjusted (offshore) without hot works, easy erection and installation.	Can be field adjusted (offshore) without hot works, easy erection and installation.	Can be field adjusted (offshore) without hot works, easy erection and installation.	Pre-fabrication onshore is required, otherwise offshore adjustment is complex.

	safety concerns.				
Offshore installation hours	High offshore installation hours.	Low offshore installation hours.	Low offshore installation hours.	Low offshore installation hours.	High offshore installation hours.
Durability and reliability	Good	Excellent	Excellent	Good	Poor
Heat and thermal resistance	Thermal conductivity and thermal coefficient of expansion are very high.	Thermal conductivity is very low.	Thermal conductivity is very low.	Thermal conductivity is very low.	Thermal conductivity and thermal coefficient of expansion are high.
Design life	8 to 12 years (because of the corrosive environment offshore).	Depending on GRP vendor and supplier, it could last for 40 years.	Depending on GRP vendor and supplier, it could last for 40 years.	Depending on GRP vendor and supplier, it could last for 40 years.	No offshore study is available.
Weight	Heavy compared to the others.	Very lightweight (about 70% less than steel and 30% less than aluminium).	Very lightweight (about 70% less than steel and 30% less than aluminium).	Very lightweight (about 70% less than steel and 30% less than aluminium).	Lightweight (about 30% less than steel).
Reused and recyclable Content	Excellent	Partially	Partially	Partially	Very good
Availability in local market or region	Available	Available	Available	Available	Needs to be imported.
Safe and easy to use	Low slip resistance. Safety and health concerns.	High slip resistance.	High slip resistance.	High slip resistance.	Low slip resistance. Safety and health concerns.

Coating and protection method	Requires constant inspection.	Maintenance free	Maintenance free	Maintenance free	Requires constant inspection.
-------------------------------	-------------------------------	------------------	------------------	------------------	-------------------------------

Note: 1. The above information was generated based on participant's work experience, previous projects, vendor and supplier catalogs. 2. The specification of the GRP gratings varies from one fabricator to another based on the fabrication process, amount of fiber glass, amount and type of plastic resin, and chemical formulations required to give strength, corrosion and chemical resistance and fire retardance. The above judgment is based on some products from local suppliers.

In terms of the energy consumption and CO₂ emissions throughout a material's life cycle, this information can be attained from books or software related to material's life cycle, however, the most accurate data can be acquired from the manufacturer. DeckSafe Solution (2013) compared steel, aluminum and GRP gratings in terms of the environmental impacts; the comparison was based on the production of 100 sq.ft. Moreover, DeckSafe Solution (2013) stated that GRP produced 54% less green house gas than steel and used 56% less energy in production than steel. In addition, GRP can be recycled and returned to a powder state so it can be used in future GRP. A summary of the impacts has been presented below in table 35.

Table 35 Energy consumption and CO₂ emission for the alternatives

Environmental Impacts	Steel	Aluminium	GRP Grating 38mm
Cumulative energy consumption (embodied energy + manufacturing) (Mj.eq)	11,949.76	Range from (7,475.7-26,219.3) based on the percentage of recycled materials. If it is virgin aluminium, then it will be 26,219.3.	5,219.3
Co₂ equivalent, (Kg Co₂.eq)	612.65	Range from (459.7–1,826.1) based on the percentage of recycled materials. If it is virgin aluminium, then it will be 1,826.1	282.35

Based on tables 34 and 35, the participants in the workshop will be ready for the next step of the evaluation phase (generating the evaluation matrix) in order to rank the alternatives.

In the evaluation matrix shown in table 36, each material (alternatives) is scored on a range from 1 to 5 according to the level to which material satisfies the criteria. Therefore, in table 36 for criterion I (resist corrosion and erosion) – from the workshop and based on the discussion undertaken by the value team – the steel grating was given a score of 3, in terms of corrosion resistance compared to 5 for GRP Phenolic grating. The evaluation is based on the advantages and disadvantages of each material presented in table 34.

Therefore, this score for steel grating (3) will be multiplied by the weight for criteria I, which is 7.91 from table 36, to give the final result, which is 23.73 for steel grating, and so on until all materials are scored against each criterion. The overall score for each material will be computed by adding all scores for that material against each criterion; materials with a high score will rank highest as shown in table 36.

Table 36 Evaluation matrix

Criteria	Weight	Steel Grating		Aluminum Grating		GRP Vinylester		GRP Polyester		GRP Phenolic heavy duty	
		Scale 1 to 5	Score	Scale 1 to 5	Score	Scale 1 to 5	Score	Scale 1 to 5	Score	Scale 1 to 5	Score
Criterion A	0.31	3	0.93	2	0.62	5	1.55	5	1.55	5	1.55
Criterion B	0.52	3	1.56	2	1.04	5	2.6	5	2.6	5	2.6
Criterion C	8.12	5	40.6	2	16.24	2	16.24	2	16.24	4	32.48
Criterion D	2.91	3	8.73	3	8.73	5	14.55	5	14.55	5	14.55
Criterion E	3.96	3	11.88	3	11.88	5	19.8	5	19.8	5	19.8
Criterion F	10	5	50	2	20	3	30	2	20	5	50
Criterion G	4.27	5	21.35	2	8.54	3	12.81	2	8.54	5	21.35
Criterion H	0.21	1	0.21	2	0.42	5	1.05	5	1.05	5	1.05
Criterion I	7.91	3	23.73	3	23.73	5	39.55	5	39.55	5	39.55
Criterion J	2.81	3	8.43	3	8.43	5	14.05	5	14.05	5	14.05
Criterion K	2.6	4	10.4	2	5.2	5	13	5	13	5	13
Criterion L	2.7	4	10.8	2	5.4	5	13.5	5	13.5	5	13.5
Criterion M	3.02	5	15.1	2	6.04	3	9.06	3	9.06	5	15.1
Criterion N	5.83	4	23.32	3	17.49	5	29.15	5	29.15	5	29.15
Criterion O	7.2	5	36	1	7.2	2	14.4	2	14.4	4	28.8
Criterion P	2.5	4	10	3	7.5	5	12.5	5	12.5	5	12.5
Criterion Q	2.5	4	10	3	7.5	5	12.5	5	12.5	5	12.5
Criterion R	3.12	3	9.36	2	6.24	5	15.6	5	15.6	5	15.6
Criterion S	2.6	3	7.8	4	10.4	5	13	5	13	5	13
Criterion T	0.52	5	2.6	3	1.56	3	1.56	3	1.56	3	1.56
Criterion U	0.52	5	2.6	3	1.56	3	1.56	3	1.56	3	1.56
Criterion V	1.04	5	5.2	4	4.16	4	4.16	4	4.16	4	4.16
Criterion W	3.12	4	12.48	3	9.36	5	15.6	5	15.6	5	15.6

Criterion X	1.04	4	4.16	3	3.12	5	5.2	5	5.2	5	5.2
Criterion Y	2.5	3	7.5	2	5	5	12.5	5	12.5	5	12.5
Total score		334.74		197.36		325.49		311.22		390.71	
Rank		2		5		3		4		1	

8.3.3.6 Recommendations

From the above table (36), GRP phenolic and steel gratings are ranked first and second respectively. Therefore, the other alternatives are rejected and only the first and second alternatives are taken to the next stage of the framework for further investigation.

8.3.4 Stage three of the framework

In chapter three, the importance of the life cycle costing concept is highlighted specially when this technique is used at the early stage of project. The objective of this stage is to evaluate the selected alternatives from economic point of view.

8.3.4.1 Cost data of the selected alternatives

The following data (refer to table 37) have been gathered from similar and previous works on constructed offshore projects and also based on past experience. Initial costs of the alternatives have been collected from local suppliers in Qatar.

Table 37 Cost breakdown for the alternatives

Based on an area of 100 m2					
A	Capital Cost		Steel 38mm	GRP Phenolic 38mm	Notes and explanation
	1	Engineering and design	250 hours x 100 USD = 25,000 USD	150 hours x 100 USD = 15,000 USD	Include: demolition drawings of old grating, installation drawings of new grating, and prefabrication drawings for the steel grating. GRP gratings do not require prefabrication drawings. Approximately one engineering hour costs 100 USD.
	2	Materials cost	182 x 100m2 = 18,200 USD	245 X 100 m2 = 24,500 USD	Steel Gratings cost 182 USD/m2. GRP gratings cost 245 USD/m2
	3	Prefabrication cost	Assume 40% of the materials cost = 0.4 X 18,200 = 7,280 USD	Not required	It is very costly to modify the steel grating panels offshore to fit in the final location. To reduce the cost, the gratings panels are usually modified and adjusted onshore based on the shop drawings. The prefabrication cost can often be estimated from 30 to 50 % of the materials cost based on the complexity of the project. GRP gratings can be cut to fit offshore with simple tools.
	4	Offshore removal and installation cost	100m2 x 6 hours x 60 USD = 36,000 USD	100m2 x 6 hour x 60 USD = 36,000 USD	It has been estimated that 1m2 of steel gratings require 6 hours for removing the old gratings and installing the new gratings. For GRP, we know it is much easier to remove and Install GRP gratings than steel, however, because the GRP gratings are cut to fit offshore; hence we will consider this the same as steel gratings. The offshore hour rate is estimated to be 60 USD.
B	Maintenance and replacement cost		Replacement cost is required between 6 and 12 years, sensitivity analysis should be applied. The cost of the replacement will be similar to the capital cost	Lifetime of the GRP is 40 years	GRP gratings are maintenance free; the lifetime of the GRP gratings based on the manufacturer is 40 years. In contrast, the steel gratings are subject to corrosion; based on experience and previous work the lifetime of the steel gratings is from 6 to 12 years in offshore environment. Replacement cost includes removal of the old gratings panel and installation of the new panels costs.

8.3.4.2 Assumptions and basis of the analysis

The following assumptions have been considered in order to perform the analysis of the life cycle costing.

- The offshore platform is designed for a service life of 25 years.
- The bank interest rate in Qatar is 3% yearly, and inflation rate is about 1%.

Cash flow diagrams (figures 43 and 44) for both alternatives will be as follows:

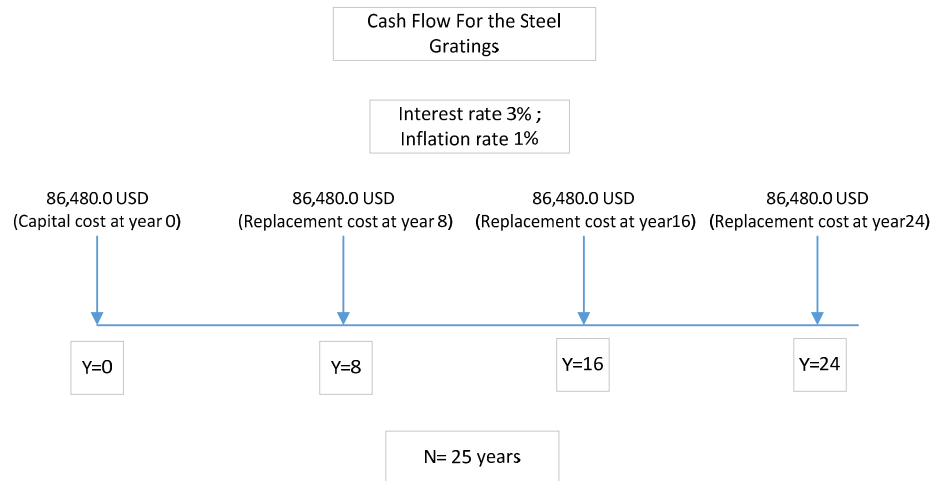


Figure 43 Cash flow diagram for steel grating

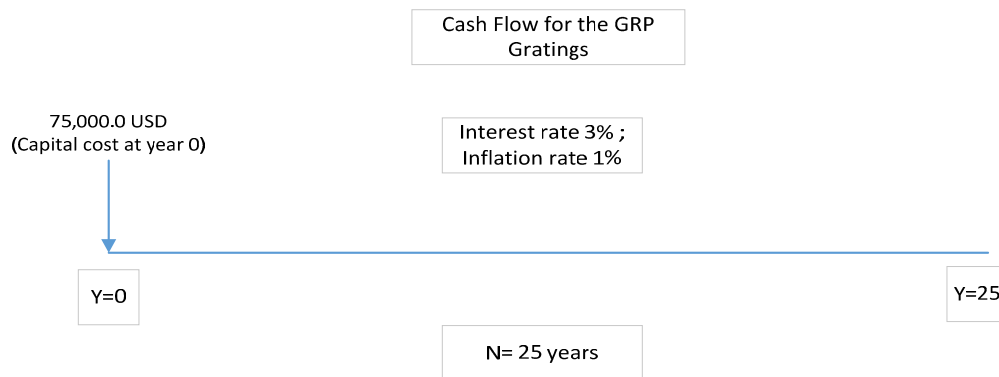


Figure 44 Cash flow diagram for GRP grating

8.3.4.3 *Life cycle costing analysis*

- **Steel gratings**

Based on the cash flow diagram of the steel grating:

- Capital cost of the steel grating is = $25,000 + 18,200 + 7,280 + 36,000 = 86,480$ USD.
- Replacement cost = capital cost (will be applied every 8 years).

Calculations:

Based on the equations presented in chapter 4, and the following inputs: $n = 25$ year; interest = 3% and inflation 1%.

The adjusted interest rate after the inflation will be 0.0403

First step (find NPV of the cash flow):

NPV of the cash flow by using economic equations as described in chapter 3 = $86,480 + 63,044.45 + 45,959.80 + 33,504.97 = \mathbf{228,989.23}$ USD.

Second Step (convert NPV into EUAW):

The EUAW as per economic equations described in chapter 4 = $14,704.57$ USD yearly.

- **GRP phenolic gratings**

Based on the cash flow diagram of the GRP phenolic grating:

- In this case of the GRP grating, capital cost = NPV, since there is no future cost is shown in the cash flow diagram.

Calculations:

Based on the equations presented in chapter 3, and the following inputs: $n = 25$ year; interest = 3% and inflation 1%.

The adjusted interest rate after the inflation will be (0.0403)

First step (find NPV)

Capital cost = NPV = 15,000 + 24,500 + 36,000 = 75,500 USD

Second step (convert NPV into EUAW)

The EUAW as per economic equation described in chapter 3 = **4,848.24 USD yearly** .

Conclusion

Although the difference in the capital cost between the two materials is minor (capital cost of the steel is 86,480 USD and the capital cost of the GRP is 75,500 USD); however, the saving in terms of life cycle costing from using GRP will be $(14704.57 - 4848,24) / (4848.24) * 100 = 203.3\%$.

Figures 45 and 46 show the EUAW for both steel and GRP gratings. More investigation will be carried out in the sensitivity analysis.

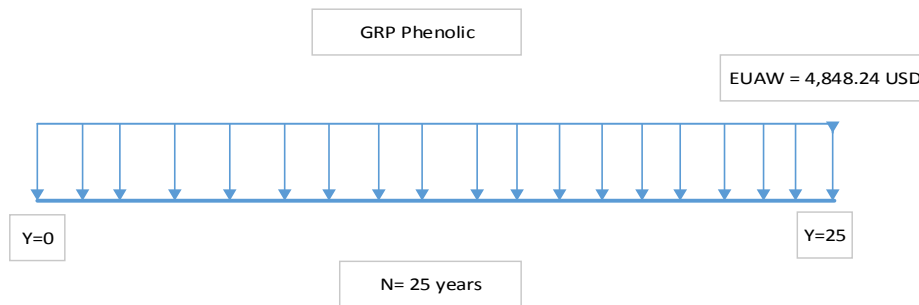


Figure 45 EUAW for GRP grating

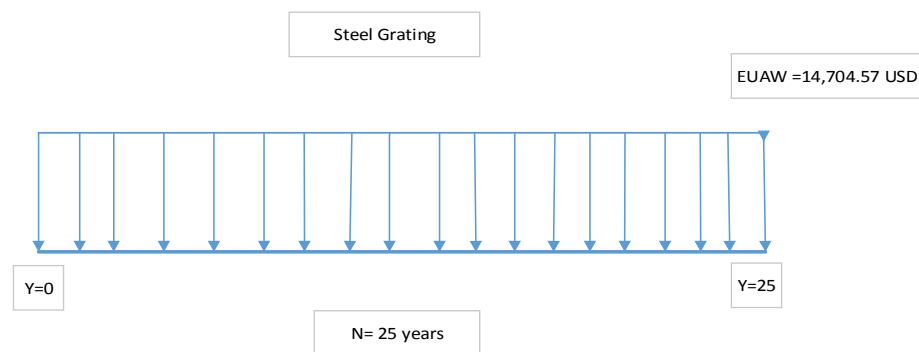


Figure 46 EUAW for steel grating

8.3.4.4 Sensitivity Analysis

In this section, we will study the impact of a change in value by considering two scenarios. The **first scenario** is “what is the impact on the result if the initial cost of the GRP materials increases by 50%”; the **second scenario** is “what is the impact on the result if the design life service is less than 25 years, also considering 50% increase in the materials cost of the GRP”.

First scenario

If the materials of the GRP grating increases by 50%, then:

$$\text{Capital cost} = \text{NPV} = 15,000 + 1.5 (24,500) + 36,000 = 87,750.0 \text{ USD}$$

Therefore: EUAW = **5,634.87 USD** < **14,704.57 USD** which is still lower than EUAW for steel grating.

Second scenario

In the second scenario, we will change the service life of the platform by applying the LCC analysis at each year from year 1 to year 25 to highlight the impact.

Figure 47 below shows the total life cycle costing of GRP grating versus steel grating for each year of the service life of the platform, considering 50% increase in GRP materials. The results show that LCC for steel gratings is lower in case of the project life is less than 8 years; however, for any project with service life above 8 years, GRP is still the best option.

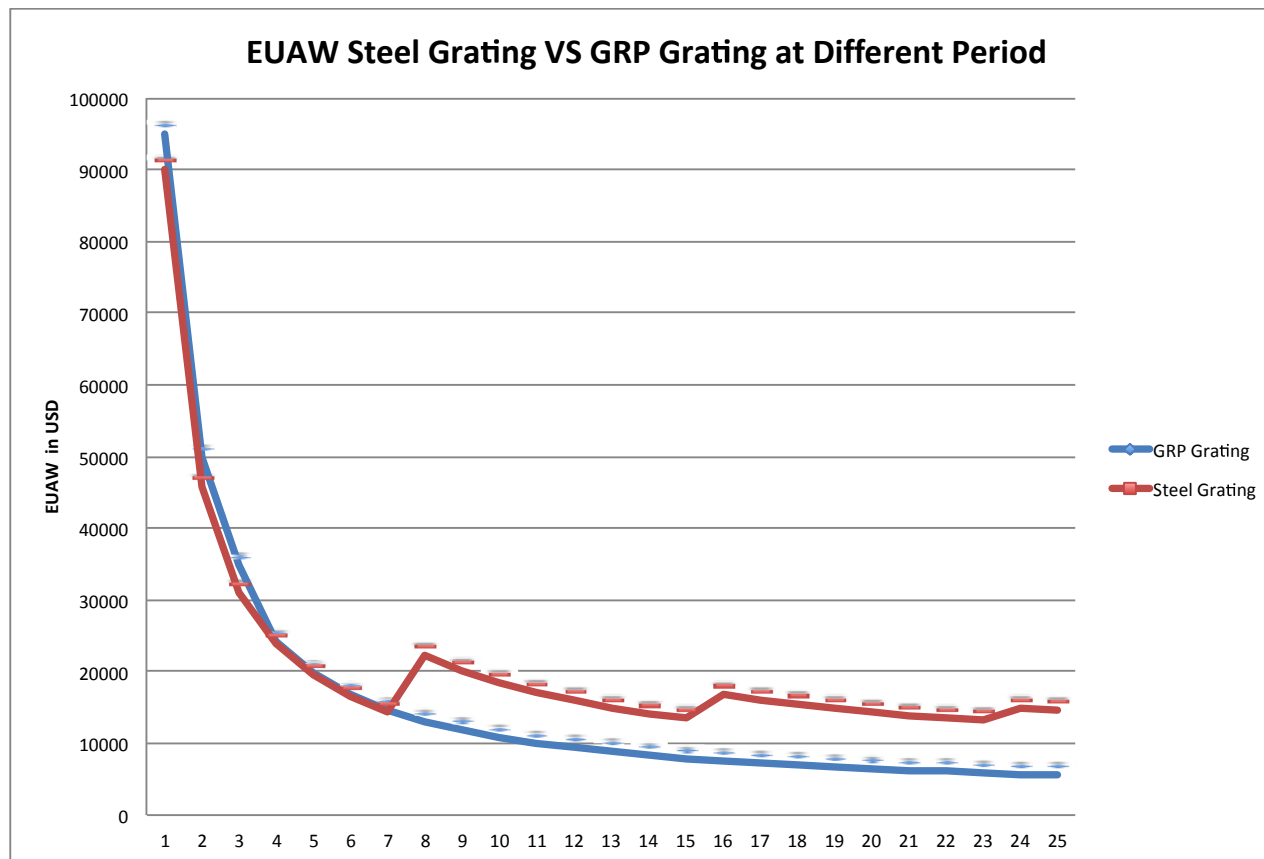


Figure 47 LCC analysis (EUAW) at different period of time

Final Recommendation

GRP Phenolic gratings will be selected for the following reasons: (1) lower life cycle costing; (2) less energy consumption and gas emission through materials life cycles (table 35); (3) very lightweight compared to steel (70% less than steel); (4) recyclable contents; and (5) free of maintenance and monitoring job (design life between 30 to 40 years with no replacement).

8.4 Framework Evaluation (Scoring Approach)

Participants from the first semi-structured interviews (during data collection, see chapter 4) were selected to study the proposed framework and provide feedback and evaluation of some assessment criteria, as will be shown later. The evaluation was carried out by using semi-structured interviews (face to face) (refer to appendix C). Sample size, interviewees profile and the assessment criteria were discussed in the methodology chapter in section 4.10.3.

8.4.1 Analysis and discussion of the closed ended questions

Results from the assessment of the framework are shown in table 38 and figures 48 and 49 below. The overall results indicate positive assessment of the developed framework as most of the criteria used to evaluate the framework has a mean score of 4.0 and above. The highest mean score of 4.875 out of 5 was received for the criteria “***systematic and well structured***”. However, the lowest mean score of 3.875 out of 5 was received for the criteria “***framework efficiency***”. In general, this is not a bad score as it produces an average score of about 4, however, the result is not surprising as not all the validators have been used or tested the framework yet.

It is observed from table 38 that the validators have given the framework in terms of “***clear and easy to understand***”, a mean score of 4.250 which is above the average; 75% of the validators have scored as “excellent” as shown in figure 48. Similarly, the measure

of “*systematic and well structured*” was rated as the highest attribute; 87.5 % of the respondents rated this attribute as “excellent” with a mean score of 4.875. The attribute “*easy to use without complicated software*” was evaluated with a mean score of 4.25. From these three attributes, it can be seen that the proposed framework is clear and easy to understand for the end users; it is an easily used tool without complicated calculation or software.

The “*comprehensiveness*” attribute of the framework is also assessed; the comprehensiveness means that the components of the framework are complete and include all the necessary items to perform the required function as intended. 87.50% of respondents rated this attribute as “above the average” with mean score of 4.125 (refer to table 38 and figures 48 and 49).

In terms of “*applicability*”, “*practicability*” and being “*appropriate for offshore construction projects*”, 62.5% and 75% of the validators rated the applicability and practicability as “above average”, with a mean score of 4.375 and 4.00 respectively. 87.5% consider that the framework is an appropriate tool for offshore topside projects, as this is rated above average with a mean score of 4.125. This means the end users are certain of the ability of the framework to benefit practical application.

In terms of capturing new knowledge and providing new opportunities to learn new concepts and apply new techniques for end users, the validators were asked to evaluate whether the framework “*helps to understand new concepts such as life cycle costing and sustainability*”. High mean scores (4.625 and 4.50) were received for the life cycle costing concept and sustainability, where 62.5% and 50% of the validators rated life cycle costing and sustainability as “excellent” respectively.

Table 38 Means score of assessment criteria

Criteria	Frequency (Scores)					Mean
	1	2	3	4	5	
	Poor	Below Average	Moderate	Above Average	Excellent	
Clear and easy to understand	0	0	0	6	2	4.250
Systematic and well structured	0	0	0	1	7	4.875
Comprehensiveness (includes all aspects of sustainability and engineering)	0	0	0	7	1	4.125
Framework applicability	0	0	0	5	3	4.375
Framework efficiency	0	0	3	3	2	3.875
Framework practicability	0	0	1	6	1	4.00
Appropriate to the construction projects for offshore topside facilities	0	0	0	7	1	4.125
Helps to understand the concept of sustainability	0	0	0	4	4	4.50
Helps to understand the concept of life cycle costing and its application	0	0	0	3	5	4.625
Easy to use without complicated software	0	0	1	4	3	4.250

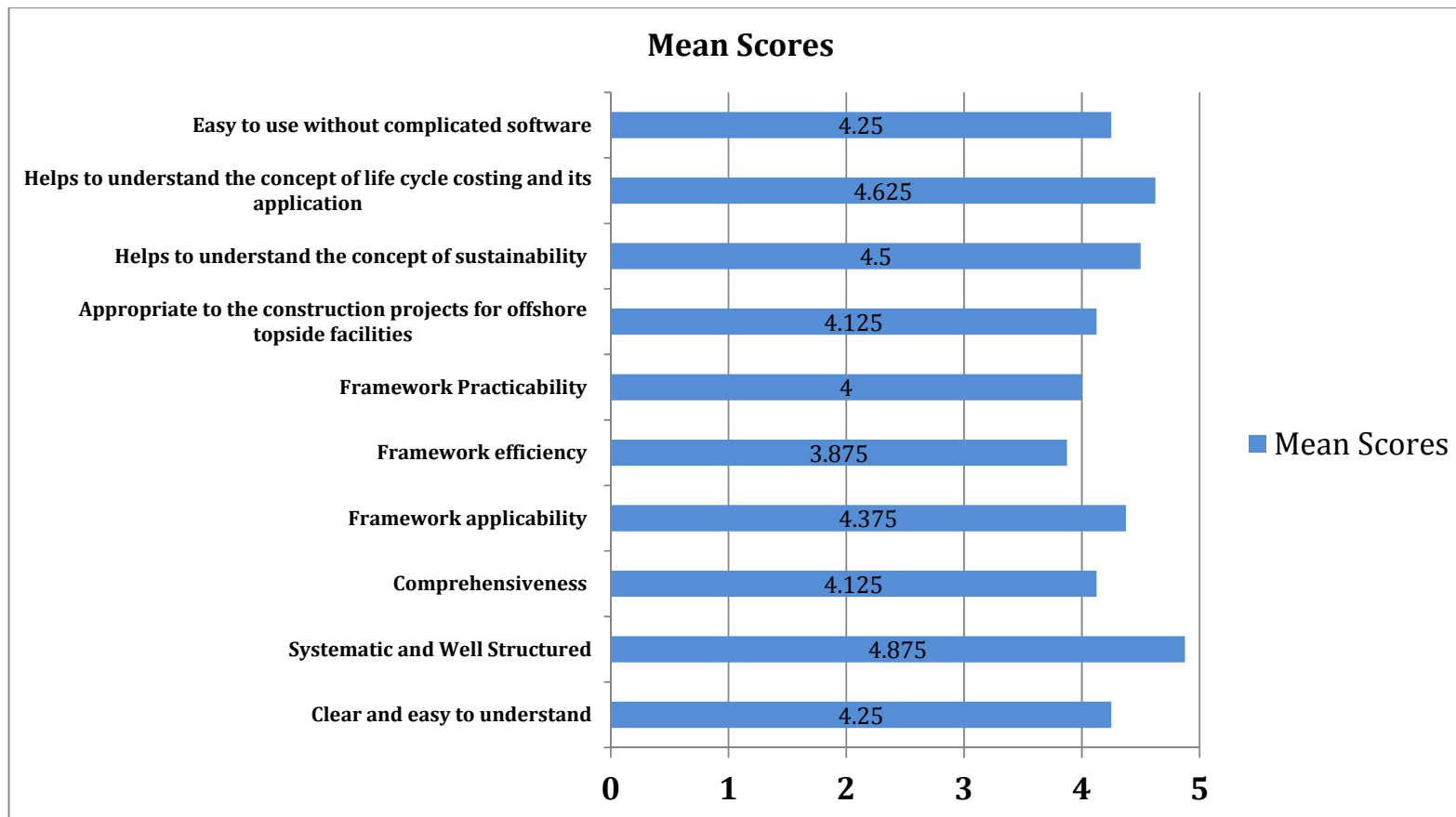


Figure 48 Means score of assessment criteria

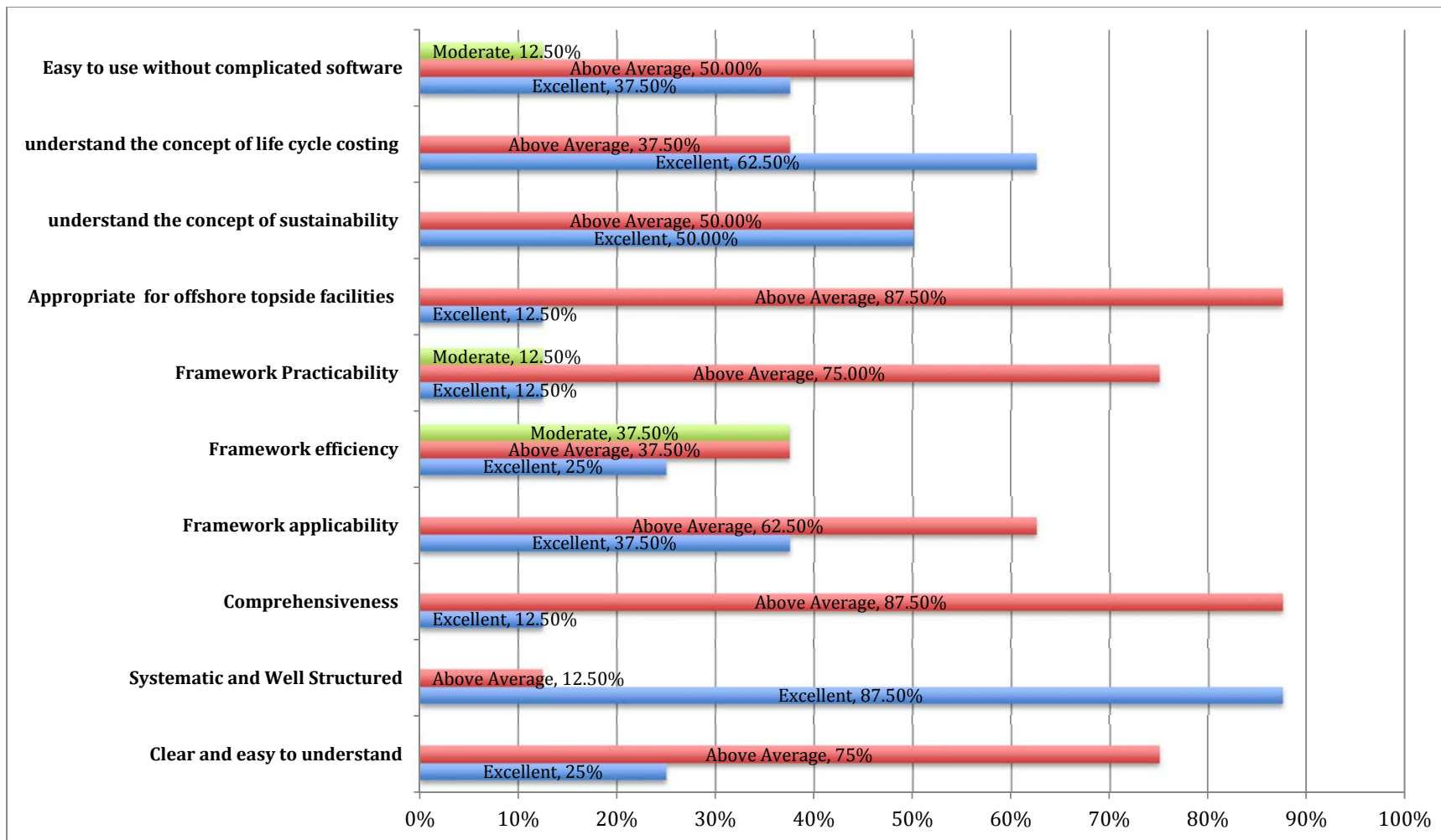


Figure 49 Percentage for each criterion

8.4.2 Analysis and discussion of the open ended questions

In this part, the interviewees/validators were asked to provide their opinions about the potential weaknesses, limitations and strengths of the framework, as well as providing any comments or suggestions that might help in implementing the developed framework. The following questions were discussed:

Mention and provide any possible area of strengths/advantages of the framework?

The validators highlighted the following strong points of the proposed framework:

- The framework will provide a good opportunity for end users to avoid mistakes during projects in terms of the selection of materials based on the life cycle costing.
- It will help the end users in decision-making and problem solving based on scientific knowledge.
- It will help in reducing the operating cost and keeping higher quality in the selection of materials.
- It is useful for considering the sustainability dimensions (which never been used) such as embodied energy and CO₂ released and their impacts on the environment.
- It helps in ranking alternatives and is easy to use without complicated calculation.
- It is a very good idea to implement the framework at the conceptual stage and before the design takes place.

Life cycle costing and value engineering techniques are unfamiliar to most designers; this is a good opportunity to learn such techniques.

Mention the weaknesses/limitations if they exist of the proposed framework?

No points were raised in this regard.

Mention any suggestions or recommendations?

There were no particular comments on the framework itself. However, some of the suggestions were to hold several workshops in the company to teach the stakeholder how to perform the value engineering methodology, as well as life cycle costing calculations.

8.5 External Validity (Generalisability)

Rosnow and Rosenthal (2013, p.116), citing VandenBos, suggested that external validity can be defined as “the extent to which the results of research or testing can be generalised beyond the sample that generated the results to other individuals or situations”. Zikmund (2003, p.273) stated that external validity is the ability of the researcher to generalise the results of an experiment to the external environment, for example, to other business offices or markets.

The proposed framework can be used for any project related to offshore topside facilities, and it can be used globally (internationally) in the oil and gas sector for the following reasons:

1. The strategy of sample selection, as described in section 4.8.4, has considered a sample selected from an international oil operator; this operator has operation activities in more than 10 international sites in four continents. Most of the experts who participated in the semi-structured interviews have developed international experience in three different sites globally during their job rotation. Hence, this provides valid international data.
2. Similarly, the international consultancy office has 112 offices in 42 countries; most of the engineers have international experience.
3. The case application performed during the framework validation approved the applicability and practicability of the framework with real data, which can be used worldwide in the offshore industry.

8.6 Summary

One of the major output of this research is the awareness of using value engineering and life cycle costing techniques between the participants and within organisation. Change management process is very important tool to create plan for the required business outcome as well as to make sure that all employees are receiving the awareness and the training in order to change successfully. Change management practice is being performed within the organization (my employer); value engineering and life cycle costing techniques were selected as part of the required change in order to implement these concept in future projects. This chapter presented the validation and evaluation process adopted for sustainable framework. The validation and evaluation were carried out by using two main approaches; face validity approach by involving the end users and scoring model approach which included a semi-structured interviews. The results show that the framework is valid, applicable and effective for offshore topside projects. The next chapter concludes this study and provide recommendations for best practice and for future study.

Chapter 9

Conclusions, Recommendations and Limitation

9.1 Introduction

The aim of this research was to build a sustainable design framework for offshore oil and gas platforms, and specifically for topside facilities. This framework should be used at the early stage of any project; it considers the sustainability dimensions (environmental, social and economic), as well as engineering and technical aspects, in order to reduce environmental and social impacts and provide lower life cycle costing for any project. The research has achieved the main goal by following the research methodology outlined in chapter 4. The development of the framework and its validation has been discussed in the previous two chapters (7 and 8). The research showed that there is a significant requirement for such a framework for the oil and gas industry; it proved that the proposed framework is practicable and efficient for both brown field and green field projects in the offshore industry. This chapter presents the main findings of the research and how the aims and objectives of this study were achieved. In addition, the limitations of the work and recommendations for future study are discussed.

9.2 Achievements of the Aims and Objectives

As mentioned at the beginning of this thesis, in chapter one, this study sought to achieve six main objectives. The following explains how the research design and process adopted the aims and objectives of this study.

Achievement of objective one: identifying the environmental and social impacts of topside facilities for offshore platforms.

The research began with a review of the literature on the construction of offshore platforms, phases of development plans in offshore projects and the importance of the FEED stage (conceptual stage) in designing and selecting proper materials that will

influence the cost. In addition, sustainability in construction, requirements of green design, the importance of life cycle costing and value engineering as evaluation techniques was highlighted. These subjects were described and discussed in chapters 2 and 3. The topside facility system of offshore platforms was first explained in chapter 3 in order to understand the components of offshore platforms and how they operate. Following this, the environmental impacts of topside facilities was discussed in detail. Five main areas were identified that negatively contribute to the environment; these are: discharging into the marine (water pollution); air emissions (air pollution); noise pollution (impact on marine life and offshore workers); oil and chemical spills due to accidental or normal operation activities; and solid and liquid waste from offshore operation and activities. In terms of social impacts, two main areas were highlighted in detail: offshore process safety and occupational health and safety. Recommendations as to how to mitigate environmental and social impacts were also mentioned and discussed in chapter 3.

Achievement of objective two: identifying and exploring the influential factors/criteria that affect materials selection and the sustainable design of topside projects for offshore fixed platforms from the sustainability perspective (environmental, social, economic and engineering).

In order to identify the criteria that affect the sustainable design of offshore projects, it was very important to study and explore the impacts of offshore topside facilities on environments, offshore assets and workers, as explained in the previous objective. Moreover, identifying the criteria required exploring the offshore materials requirements in terms of design, materials selection, corrosion and inspection and monitoring strategies, requirements for eco materials and green design; these topics are covered in chapters 2 and 3. Therefore, the literature in chapters 2 and 3 was analysed using the thematic approaches presented in chapter 5. Four main themes were identified: environmental, social, economic and engineering aspects. 77 identified criterions were extracted and grouped into 7 subgroups under four main themes: 12 criterions were identified and distributed into two subgroups under the environmental category; 13

criteria were identified and distributed into two subgroups under the social category; 43 criteria were identified and distributed into two subgroups under the engineering and technical category; and finally life cycle costing components (9 criteria) were identified to represent the economic category.

Achievement of objective three: proving and validating the identified criteria by consulting offshore experts through semi-structured interviews, and rating the identified criteria based on their importance.

This objective was implemented by designing and conducting semi-structured interviews based on the identified factors from the previous objective. The semi-structured interviews (chapter 6) comprised two components: open ended and closed ended questions. In the closed ended part, the participants were asked to rate the derived factors based on their importance on a Likert scale from 1 to 5, where 5 is the most important and 1 is the least important. In the open ended parts, participants were asked several questions about what they thought about the sustainability of the offshore industry, the environmental and social impacts of topside facilities, the materials selection procedure, project evaluation techniques and concepts such as value engineering, life cycle costing and time value of money. In addition, they were asked to provide their thoughts on the proposed framework in terms of the components that should be considered during its development. At the end, the interviewees were asked to add any additional criteria or factors that had not been mentioned or covered by the literature review, as well as being asked to provide any additional comments and suggestions.

Analysis of the closed ended part was carried out by using the relative importance index; the results show that all the 77 derived factors are highly important with a minimum RII value of 0.640. All criteria were rated as “extremely important” or “very important” and no criterion was rated as less than very important. This means that, for the offshore experts, all the criteria were considered to be very important in terms of sustainability. Thematic and narrative analysis were carried out to analyse the open ended part; the most important findings from this part were that participants still consider more effort to be

necessary to achieve environmental and social sustainability in offshore topside facilities. Most of the interviewees had not experienced any sustainable framework and they highlighted the significant need for such a framework; life cycle costing and value engineering techniques are completely ignored and not considered during most designs and as such they encouraged the implementation of these techniques in the proposed framework.

Achievement of objective four: developing a value-based framework for sustainable design and materials selection in the offshore industry from a sustainability point of view.

The literature review and the findings from the semi-structured interviews both suggested that there is currently no sustainable framework available for offshore topside projects. The proposed framework was developed to address this need considering the following: findings from literature reviews; 77 derived criteria from the literature reviews (chapter 5); findings from semi-structured interviews (chapter 6); and work experience in the offshore industry as a project engineer. The framework consists of three stages: (1) environmental and social evaluation; (2) evaluation of the materials and equipment; and (3) life cycle costing evaluation. Each of these stages was broken down into sub-processes and activities, as presented in chapter 7.

Achievement of objective five: validating the framework in terms of applicability through a case application (face validity).

The proposed framework was validated in two steps. The first step, which represents objective five, involved end users in determining the framework validity (face validity), as explained in chapter 8. Case application was performed to check the applicability and workability with real data and to check the framework's logic and structure. The case application considered a real problem in offshore projects in terms of materials selection. The framework demonstrated its effectiveness and practicability in solving such problems.

Achievement of objective six: evaluating the framework by conducting semi-structured interviews (scoring model approach).

The second part of the validation process involved evaluating the framework; semi-structured interviews were used and these comprised two components: open ended and closed ended questions. In the closed ended part, a scoring model approach was used by asking the participants to evaluate the framework in terms of certain assessment criteria by using a scale of 1 to 5, where 1 is poor and 5 is excellent. The evaluation process showed that the developed framework has a high level of acceptance for all assessment criteria; hence the framework is valid and credible (refer to chapter 8). In the open ended part, the interviewees were asked to provide their opinions on any potential weaknesses, limitations and the strengths of the framework, as well as providing any comments or suggestions that might help in implementing the developed framework. The interviewees gave positive feedback with no potential weaknesses reported. Therefore, the framework is able to serve its intended purpose of guiding end users (stakeholders) to achieve sustainability.

9.3 Originality and Contribution to Knowledge

This research includes a critical review of the literature on the offshore oil and gas industry in general, with a focus on the topside of fixed platform. The literature demonstrates that the existing literature does not provide the offshore practitioners with a sound decision making system to be used for selecting one among various sustainable materials for offshore topside projects during conceptual stage. This research is contributed to knowledge by tackling the negative impacts of topside facility systems of offshore platform in terms of sustainability by providing sound sustainable framework that can be used during the conceptual stage of project. This research also attempts to fill the gap in the existing knowledge about the topside of offshore platform by contributing to the following:

1. This thesis is one of very few academic works to focus on the construction side of offshore oil and gas platforms and topside facilities projects, drawing an extensive theoretical picture of the construction process of offshore platforms, as described in chapter 2. Moreover, this study identifies the impacts of topside facilities on the environment, as well as addressing the social impacts in terms of health and safety. The study can be used as a reference for other researches on the same subject and themes.
2. Exploring and developing the elements affecting sustainable design for offshore platforms, the extensive literature reviews were used to extract and explore factors. 77 factors were identified and distributed into four main groups, which represent the aspects of sustainability (social, environmental, economic and engineering); the criteria and factors were proven and validated by experts from the offshore industry. Therefore, these criteria can be used as a basis for engineering design in the oil and gas sector.
3. This research will make a valuable contribution to sustainability in the offshore industry through the development of a sustainable design framework for offshore topside projects; the proposed framework is a value-based framework considering both value engineering and life cycle costing concepts.
4. This is the first framework to have considered all sustainability aspects (in fixed platform offshore topside facilities) and provided an effective tool for the decision maker at the conceptual stage. Other researches have either focused on energy or environmental aspects of operations in the oil and gas sector, or on subsea systems such as pipelines.
5. The framework will provide a practical tool for selecting and evaluating the proper materials or systems for offshore topside facilities projects, considering the environmental, social, economic and engineering criteria. The case application

during the validation process, as described in chapter 8, outlined how the framework works.

6. This framework is unlike the existing methods that measure how sustainable the project is, or how the project is contributing to sustainable development. The proposed framework in this study is a design tool that can be applied at the design stage of the project by implementing and considering sustainability aspects. Moreover, this tool (framework) is easy to use and easy to interpret and it can be utilised effectively by the designer, drafter and engineer, avoiding any complex calculations or software.

9.4 Limitations of the Research

This research has a number of restraints and limitations as follows:

1. The study is limited to the topside facility projects of fixed offshore oil and gas platforms; pipelines and drilling activities are excluded from this research.
2. There was no specific existing framework for offshore topside facility projects that could be used as a basis for this study.
3. Due to the nature of offshore projects, some interviewees felt awkward about providing more details due to the limited time they had. Moreover, one hour costs 150 USD as engineering rate.

9.5 Recommendations for Practice

Based on the findings and results of this study, the following recommendations are highlighted in order to improve and complement the existing policies and strategies in the offshore oil and gas industry.

9.5.1 Recommendations to improve engineering design in offshore topside projects

Improving engineering design and cost effective decision making will require end user commitment from the conceptual stage of projects. Accordingly, the recommendations are as follows:

- The policies and standards for offshore oil and gas platforms should encourage the use of both value engineering and life cycle costing concepts at the conceptual stage (most of the existing procedures, standards and policies lack these concepts).
- Cost estimation in offshore projects is generally done based on the initial cost and future cost is ignored. Consequently, there is a higher OPEX cost. Therefore life cycle costing considering maintenance and replacement costs should be considered.
- Welding offshore is a major concern; to enhance safety and mitigate the health impact on offshore workers, as well as reducing the high installation cost due to welding requirements, the policies and standards should encourage practitioners to avoid welding offshore as much as possible. A bolting design should be implementing instead.
- In offshore projects, installation cost contributes significantly to the total cost of the project. In many of the projects, the installation cost exceeds 50% of the total cost due to offshore welding and safety requirements. Therefore, all structural frames should be prefabricated onshore, considering easy assembly and disassembly; the design should consider minimum offshore joint connections for easy and safe installation.

9.5.2 Recommendations to mitigate environmental and social impacts from topside facilities

In order to achieve the sustainability of offshore topside projects by mitigating environmental pollution and maintaining process safety and occupational health for offshore workers, this study has suggested integrating several studies and strategies at the

conceptual stage. The writer would like to highlight the importance of implementation of these strategies at the early stage of any project:

- The majority of water pollution comes from produced water from oil processing. A produced water treatment study is therefore important to address the options to prevent or mitigate discharging it into the sea.
- The greatest source of air pollution is gas flaring from topside facilities. Air emission studies should be considered to address the impact of the emission gases on the environment and offshore workers. Moreover, gas flaring needs more attention from oil operators, local and international authorities, in order to address this problem and suggest new alternatives and solutions; zero emissions should be the target for governments and authorities.
- It is important to provide a solid and liquid waste management plan for all new brown field projects, as well as for routine jobs. This will ensure that pollution is reduced to the barest minimum.
- The safety of topside processes and operations is a major concern offshore. Hazard identification related to personnel health, the environment, offshore assets and operations should be carried out for each project at the conceptual stage. Studies such as HAZID, HAZOP, installation procedure and mechanical handling studies should be performed at early stage of any project.
- Corrosion control and a monitoring strategy is important for any offshore organisation to predict and prevent structural failure due to corrosion.
- A fire and explosion design strategy should be considered for each new project to protect offshore assets, as well as personnel offshore.
- In order to reduce exposure of offshore workers to hazardous and radioactive materials and equipment, procedures for controlling hazardous materials should always be considered.

- Procedures and policy should be available for noise control. Equipment selection guidance in terms of noise creation should be given more attention to reduce the impact on offshore workers.

9.6 Recommendations for Further Research

Most of the projects in the oil and gas sector are long-term projects; offshore platforms are designed to run for 25 to 30 years, and in fact many last for longer than that. In chapter 2, the main stages of the field development were described: (1) exploration and feasibility; (2) engineering and construction; (3) operation and production; and (4) decommissioning. As explained, the framework proposed in this study was designed to be used in the conceptual phase of the engineering and construction stage. However, project evaluation during the exploration and feasibility study is also very important to determine whether the project is profitable and worth pursuing. During this stage, the financial model and analysis are prepared quickly with limited data; the major problem is that the forecasting and cost estimation implemented in the financial or economic analysis model is not accurate due to the uniqueness and complicated nature of offshore oil and gas projects. Determining CAPEX and OPEX costs is always uncertain; the construction of a topside platform lasts for 3 to 4 years for the entire topside module to be built and shipped to the offshore site, and during this period many variables are subject to change in terms of the cost of products, materials and equipment due to, for example, inflation. Therefore, one of the most important aspects of forecasting and cost estimation is determining an accurate cash flow (revenue and cost). Hirschey and Bentzen (2016) mentioned that forecast error in large and complex projects can be extensive; they note the example of the Alaska pipeline, where many oil companies forecast that it would cost around 700 million Dollars to build, but the actual cost at the end was about 7 billion Dollars (10 times the original estimation). Similarly, the author has experienced a green field project, for which the conceptual and engineering design took place in 2004 and the project was installed and completed by 2009. The final cost was 60 to 70% above the forecast budget; one reason for this was the dramatic inflation in the price of steel between 2005 and 2008.

Therefore, forecasting and cost estimation needs to be improved and, as the OPEX and CAPEX costs are part of the financial and economic analysis of any oil and gas project, it is suggested that the proposed framework in this study can be used as an integral part of the financial model and economic analysis in order to improve the forecasting and cost estimation, especially the cost related to the CAPEX and OPEX components.

The findings of the study also showed that future cost is often completely ignored during the engineering and design phase; this is one of the reasons that OPEX cost is usually vast and unexpected. Reasons for not using concepts of life cycle costing and value engineering in oil and gas should be investigated.

Water and air pollution produced from topside facilities are major concerns due to their impact on environments and health issues. Research into the environmental and social impacts of offshore topside facilities requires more effort by both offshore operators and agency regulators in order to eliminate the negative impacts, instead of mitigating them; developing air monitoring and produced water treatment systems could be further investigated with this in mind. The same impacts of topside facilities of offshore platforms, as described in chapter 3, are produced by the onshore facilities for oil and gas. Therefore, a similar framework could be developed for onshore oil and gas facilities and the framework could be improved to include petrochemical projects and downstream sectors such as refinery projects. Gas flaring from both offshore and onshore facilities are a waste of energy sources, so researches into how to use the associated gas instead of burning it should be conducted. Finally, the proposed framework could be used as a basis for future research for both upstream and downstream sectors in the oil and gas industry in terms of sustainable design and environmental management systems.

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