# LCA for Offshore Installations Decommissioning: Environmental Impact Assessment

by

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Dissertation submitted in partial fulfillment of
the requirements for the
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# FINAL YEAR PROJECT DISSERTATION

# LCA for Offshore Installations Decommissioning: Environmental Impact Assessment

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# CERTIFICATION OF APPROVAL

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Civil Engineering Programme
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BACHELOR OF ENGINEERING (HONS)
(CIVIL ENGINEERING)

Approved by,

___________________________________
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UNIVERSITI TEKNOLOGI PETRONAS
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August 2013

# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

___amy_________________________
AMY NGU PEI JIA

# ABSTRACT

In the upcoming years, many offshore oil and gas installations around the world will be decommissioned as they approach the end of their economic production lives. Offshore installations decommissioning brings along environmental impacts. However, there is minimal published information on environmental impact assessment of offshore decommissioning. Life-cycle assessment (LCA) is preferable to be used as it provides quantitative and structured comparisons between decommissioning options, while addressing environmental impacts simultaneously. The main objective of this study is to determine and to quantify the environmental impacts associated with decommissioning of an offshore platform in North Sea using LCA tools, process LCA and Economic Input Output(EIO-LCA). Two offshore decommissioning options are studied; complete removal and partial removal. The environmental impacts of offshore decommissioning concerned in this study are total energy consumption and gaseous emissions ($CO_2$, $SO_2$ and $NO_x$). For this research, data from an estimation of the energy consumption and gaseous emission for decommissioning of an offshore platform in North Sea is used as input data for LCA analysis. Cost data for decommissioning is obtained from a published report on decommissioning insights and EIO model is constructed using online model. Results from both process LCA and EIO-LCA prove that partial removal is a better decommissioning option over complete removal in terms of energy consumption and gaseous emissions. The findings from this research provide a relative comparison between complete and partial removal that shall help the owners of platform to decide suitable decommissioning option. For future LCA analysis, it is recommended to have a complete set of detailed and up-to-date data to produce a more comprehensive results.

**Keywords: Offshore decommissioning; environmental impacts; life-cycle assessment; process LCA; EIO-LCA**

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# ABBREVIATIONS AND NOMENCLATURES

| | |
|---|---|
| $CO_2$ | Carbon dioxide |
| EIO | Economic Input Output |
| EPA | US Environmental Protection Agency |
| IMO | International Maritime Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| ISO | International Standardization Organization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| $NO_x$ | Nitrogen oxides |
| OSPAR | Convention of the Protection of the Marine Environment of the North East Atlantic |
| SETAC | Society of Environmental Toxicology and Chemistry |
| $SO_2$ | Sulphur dioxide |
| T | Metric Tonne |

# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND

In the coming years, offshore decommissioning activity will increase as a number of existing installations approach their end of production lives and thus, the platform owners now faces the challenging task of decommissioning offshore installations. According to Oil & Gas UK (2012), 40 platforms and 360 wells located in North Sea are going to be decommissioned in 2012 to 2017. The decommissioning of offshore installations has always been debated regarding the issues of the environment impacts. One of the major environmental impacts associated with offshore decommissioning is harmful gaseous emissions, especially carbon dioxide emission which is the main culprit for global warming (OGP Discussion Paper, 1996). For example, carbon dioxide released from decommissioning works of an offshore platform in North Sea was estimated to be around 90000t, which is about the same as carbon dioxide emissions from the electricity use of 14000 homes for one year in United States (European Union, 2013). Carbon dioxide produced will remain in the atmosphere for 100 to 200 years, absorb the heat energy and result in global warming (European Union, 2013). Thus, it is very important to assess and to quantify the environmental impacts associated with offshore installations decommissioning.

LCA tools, process LCA and EIO-LCA are used to quantify the environment impacts in this study. One of the advantages of process LCA is that a particular decommissioning activity, which contributes the most to total energy consumptions or gaseous emission, can be determined and recommendations could be made to reduce the environmental impacts. On the other hand, EIO-LCA eliminates two major issue of the process LCA, which are defined boundaries and circularity effects. This method also includes the direct and indirect energy costs that gives an overview for the environmental impacts of offshore installations decommissioning. By analyzing results from both methods, the results obtained will be reliable and more representative.

## 1.2 PROBLEM STATEMENT

Decommissioning of offshore installations definitely will bring impacts to the environment. The waste substances produced, gaseous emission, noise pollutions and vibrations from the decommissioning works are good examples for the environment impacts of offshore decommissioning (Gibson, 2002). With the increased awareness on environmental issues, it is very important to ensure that decommissioning activities would not bring drastic damages or harms to the environment or to check whether gaseous emissions are within the limit set by the authorities.

Currently, there is minimal published information on environmental impacts assessment associated with offshore installations decommissioning and framework to assess and to quantify the environmental impacts. LCA is preferable to be used as it could provide quantitative and structured comparisons between decommissioning options, while addressing the environmental impact simultaneously. In addition, the decommissioning activity that is the major contributor for total energy consumption and gaseous emissions could be identified by using LCA analysis. Recommendations could be proposed to minimize the environmental impacts of that particular decommissioning activity. For this study, the author aims to produce a comprehensive LCA analysis to determine and to quantify the environmental impacts of decommissioning of an offshore platform in North Sea.

## 1.3 OBJECTIVE OF STUDY

The objectives of this study are:

i) To determine the volume and type of waste materials in offshore installations decommissioning for complete removal and partial removal of an offshore platform in North Sea
ii) To quantify the environmental impacts of decommissioning of an offshore platform in North Sea using LCA tools, process LCA and EIO-LCA
iii) To compare the environmental impacts of complete removal and partial removal of an offshore platform in North Sea
iv) To propose for measures to address environmental and other concerns that arise in connection with the offshore installations decommissioning

## 1.4 SCOPE OF STUDY

This study will cover two decommissioning options, that are complete removal and partial removal of an offshore platform in North Sea. In addition, the environment impacts concerned in this study are total energy consumptions and gaseous emissions($CO_2$, $SO_2$ and $NO_x$). Heather Platform was selected as a case study in this project. Data for the estimation of the energy consumption and gaseous emissions associated with decommissioning of Heather Platform obtained from a published paper was used as input data for the LCA analysis. For EIO-LCA, cost data was obtained from a published report and a model was constructed based on the online EIO model (Green Design Institute).

For this study, the decommissioning of drill cutting piles and pipelines were not being considered due to technical complexity and safety concerns. The scope will cover the environment impacts resulted from temporary steelwork, marine vessel utilization, platform running, helicopters, platform materials recycling, platform materials left at sea and platform facility dismantling that consists of topsides and jacket removal that will be further elaborated in the later part of this report.

## 1.5 RELEVANCY AND FEASIBILITY OF THE PROJECT

Decommissioning is closely related to oil and gas industry in Malaysia as stated previously that many of 280 jacket platforms located off the coast of Malaysia are approaching the end of their useful lives (Na, Wan Abdullah Zawawi, Liew, & Abdul Razak, 2012). Hence, the offshore decommissioning activity will be increasing in the near future in Malaysia. The author aims to produce a basic framework for future assessment of environmental impacts of offshore decommissioning activities in Malaysia based on the case study on decommissioning of an offshore platform in North Sea.

The project is feasible within the scope, time frame and budget given. The scope and main objectives had been clearly defined and narrowed, so that the author managed to complete the study within the time frame. LCA analysis for both complete and partial removal could be completed within the time frame with the defined boundaries and scope.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter presents the literature review on offshore installations decommissioning, particularly on the decommissioning laws and regulations, decommissioning costs and decommissioning process. Besides that, this chapter also presents the literature review on life-cycle assessment, outlines the LCA framework and compares the advantages and limitations of process LCA and EIO-LCA. The last part of this chapter contains the case study, Heather platform's descriptions, respective decommissioning costs and decommissioning plan developed by the researchers.

## 2.2 DECOMMISSIONING OF OFFSHORE INSTALLATIONS

In the global context of oil and gas industry, decommissioning is nothing new and it became a concern after the 1995 Brent Spar controversy. During 1991 to 1993, Shell investigated several disposal options and decided to dump the oil platform, which was weighed around 14500t at the Atlantic Ocean (Shell International Limited, 2008). This deep sea disposal plan was actually approved by the UK government. However, Greenpeace opposed this deep sea dumping method. On 30 April 1995, the activists occupied the platform and called for boycott of shell petrol stations (Shell International Limited, 2008). Due to public pressure, Shell finally agreed to dismantle and recycle the platform onshore.

Decommissioning refers to the dismantling, decontamination and removal of process equipment and facility structures (Ruivo & Morroka, 2001). When production of oil or gas from a field becomes uneconomical that the well is too costly to be maintained or low production volume, a decision may be made by the relevant regulatory agencies in conjunction with the platform operator to cease production, abandon the field and decommission the platform. Most of the experience to date comes from the relatively shallow water of the Gulf of Mexico. Around 1000 offshore structures had been removed from the Gulf of Mexico (Evans, 2008). Around 280 jacket platforms are located off the coast of Malaysia. Many of these are approaching the end of their production lives (Na, Wan Abdullah Zawawi, Liew, & Abdul Razak, 2012). The decommissioning activities in Malaysia are forecasted to be increased in the near future. Hence, it is important to have a basic framework to assess the offshore decommissioning activities in Malaysia, particularly regarding the environmental impact assessment as environmental issues are a big concern around the globe now due to arising of global warming and ocean pollutions.

### 2.2.1 DECOMMISSIONING LAWS AND REGULATIONS

The first international removal standard was found in the 1958 Geneva Convention on the Continental Shelf, in which the Article 5 states that any installations which are abandoned or disused must be entirely removed (Hamzah, 2003). This Convention outlines clearly obligations of states regarding to their responsibilities and duties on the continental shelf.

1982 UN Law of the Sea Convention (UNCLOS) covers most legal aspects of ocean space and its uses. Article 60.3 of UNCLOS states any installations or structures which are abandoned or disused shall be removed to protect marine environment and ensure safety of navigation and fishing (Hamzah, 2003).

In addition, International Maritime Organization (IMO) had developed a guidelines for offshore decommissioning in 1989, named “Guidelines and Standards of the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone” (Hoyle & Griffin, 1989). The guidelines stated that all abandoned or disused installations and structures standing in less than 75m of water and weighing less than 4000t in air, excluding the deck and superstructure, should be entirely removed. Furthermore, all abandoned or disused installations and structures, which were installed on or after January 1998 standing in less than 100m of water and weighing less than 4000t in air, excluding the deck and superstructure, should be entirely removed. In the case where entire removal is not technically feasible or would involve extreme cost or an unacceptable risk to personnel or the marine environment, the coastal state may determine that the installations need not be entirely removed. For partial removal, an unobstructed water column sufficient to ensure safety of navigation, but not lesser than 55m should be provided above any parts remaining on the seabed (Hoyle & Griffin, 1989).

In 1993, a new regional convention, the Convention of the Protection of the Marine Environment of the North East Atlantic (OSPAR Convention) was formed. In OSPAR Decision 98/3, all steel installations with a jacket weight of less than 10000t must be completely removed for reuse, recycling or final disposal on land, while for steel structures with jacket weight more than 10000t, it is possible to consider for remaining the footings in place and for concrete installations, it is possible to left them in place wholly or partially (Department of Energy and Climate Change, 2011). Pipelines are not covered by OSPAR Decision 98/3 and there are no international guidelines on the decommissioning of disused pipelines.

### 2.2.2 DECOMMISSIONING COSTS

Decommissioning is a very costly process. For instance, it costs Shell sixty million pounds sterling to decommission the Brent Spar in 1995 (Hamzah, 2003) and a study has conservatively estimated that it will cost PETRONAS around eight billion Malaysian Ringgit to remove about two hundred plus offshore installations in Malaysia (PETRONAS, 1997).

Oil & Gas UK (2012) forecasted the total cost of decommissioning for existing and sanctioned infrastructure to be 28.7 billion sterling pound (2011 money) from 2012 onwards. Information on numbers of wells, pipelines, removal tonnages and onshore dismantling volumes had been gathered directly from the decommissioning operators. Operators were asked to quantify physical decommissioning activities. Significant cost is predicted during the suspension live phase of a decommissioning project that the majority of which is operational costs related with the running facilities when the decommissioning takes place (Oil & Gas UK, 2012).

One fifth of the total expenditure is accounted for the topsides, jacket and subsea installations removal. Total of 170000t is expected to be removed between 2012 and 2017 that would cost around £800 million (Oil & Gas UK, 2012). In addition, total of 162000t of material is expected to be returned onshore for dismantling and processing between 2012 and 2017 (Oil & Gas UK, 2012). The demand for related services from the supply chain, for example heavy lift companies and disposal yards, will increase starting from 2015. The forecast expenditure presented in the chart below is a simple collection of expenditure provided by operators in the decommissioning survey responses and Oil & Gas UK has not applied any additional treatment to the figures submitted by operators.

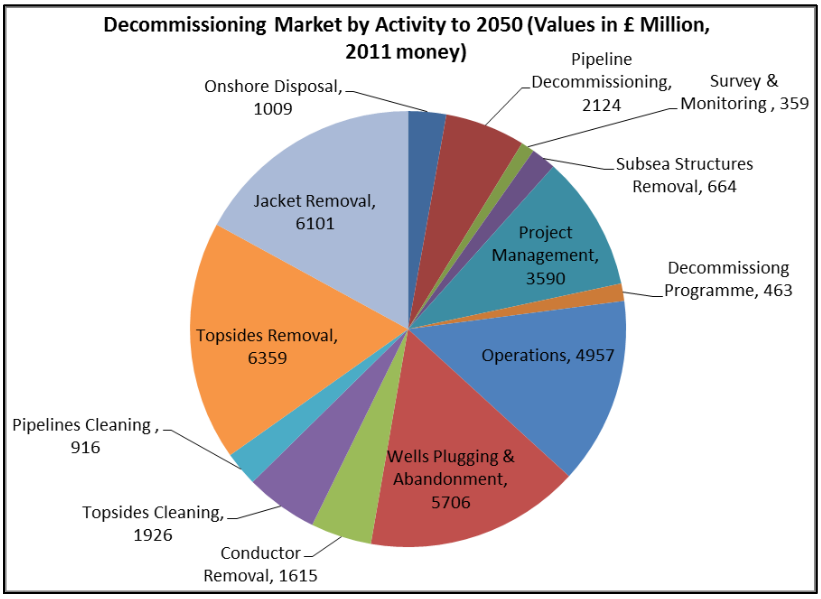
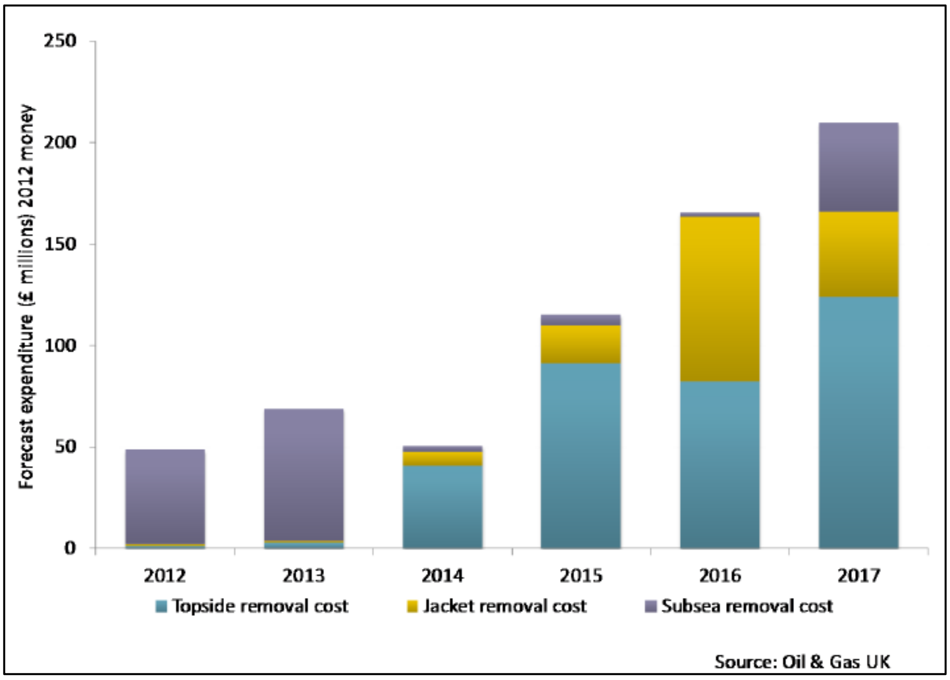


Figure 1: Decommissioning market by activity to 2050 (Oil & Gas UK, 2012). (Values in the chart are shown in (2011 money) million sterling pound.)

From the chart above, it can be seen that the topsides removal, jacket removal and the plugging and abandonment of wells are the three most cost intensive aspects of decommissioning, account for over half of total decommissioning costs.



Source: Oil & Gas UK

Figure 2: Forecast expenditure for removal activities in the central and northern North Sea 2012-2017 (Oil & Gas UK, 2012).

Based on Oil & Gas UK (2012), the average topside module in the decommissioning survey in the central and northern North Sea weighs 1710t and costs £4200 per tonne to remove, while jackets cost £3100 per tonne to remove on average. It must be reminded that actual removal costs per tonne are dependent on a wide variety of factors such as location, weather, previous experience, age of installation and varies with each installations.

### 2.2.3 DECOMMISSIONING PROCESS

Two main decommissioning options are studied in this paper, that are complete removal and partial removal. The complete removal means the structure to be entirely removed by lifting either in one piece or in sections depend on the size of the jacket and the capacity of the lift vessel (Anthony, Ronalds, & Fakas, 2000), while the partial removal, which is allowed under IMO guidelines for large structures, means the jacket to be cut to the required depth, not less than 55m for safe navigation and leaving the bottom portion on the seabed. It happens under certain circumstances due to safety or technical complexity. For instance, it is considered not safe to remove completely a steel jacket with weight more than 10000t or with large concrete installations.

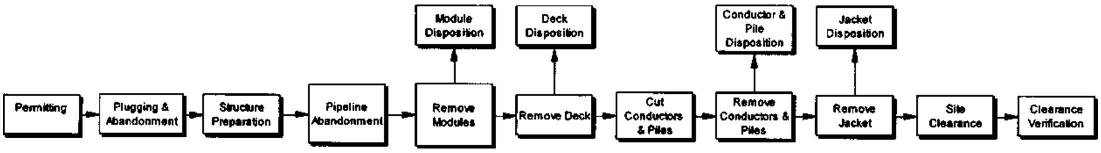


Figure 3: Primary activities for decommissioning processes (Kaiser, Pulsipher, & Bryd, 2003).

Decommissioning process can be divided into stages as shown in Figure 2 above. After project engineering and cost assessment, federal and state regulatory permits for well plugging and abandonment. Wells are plugged and the facility is prepared for removal. Examples for structure preparation for decommissioning are flushing and cleaning process components. Then, the pipelines are pigged or flushed, detached from the structure and capped. They are normally leave in-situ with the ends buried 1m below the mudline. Later, modules are separated from the deck, lifted and transported onshore. The deck is then cut and removed onshore and followed with the cutting of conductors and pulling of piles. The jacket will be either transported by heavy lift vessels, towed onshore or leave in situ as for reefing. After the structure has been removed, the site is cleared with a trawling vessel or divers with side scan sonar. Site clearance is then verified with a trawler. Normally, the operator has 60 days to verify clearance starting from the moment the structure has been removed (Kaiser, Pulsipher, & Bryd, 2003).

## 2.3 LIFE-CYCLE ASSESSMENT

In this modern days, public environmental awareness increases and industries or businesses are assessing how their activities would affect the environment. Society becomes concerned for depletion of natural resources and arouse of environment issues. Some manufacturers start to produce greener products or use green energy to increase the companies' public image. The environmental impacts of products or processes have become a hot issue that the companies are investigating ways to minimize their environment effects and adopting LCA to assess their products.

Life cycle assessment is a "cradle to grave" approach for assessing industrial systems. It begins with the extraction of raw materials from Earth to manufacture a product and ends when all materials are returned to the Earth (Curran, 2006). According to Consoli et al (1993), life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy, materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment. The assessment includes the entire life-cycle of the product, process or activity, encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, use/re-use/maintenance, recycling and final disposal (Consoli, 1993). LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, provides a wide ranging view of the environmental aspects and a more accurate picture of the true environmental trade-offs in product and process selection.

In the 1960s and 1970s, life cycle assessment were used to calculate total energy consumption and predict future supplies of raw materials or resources. For some cases, they were combined with economic input-output models and became hybrid LCA to estimate environment emissions and economic costs over their life cycle . In the early 1990s, LCA was being used for external purposes like marketing. Then, the focus of LCA was shifted back to environmental optimization as LCA provides quantitative and structured comparison between alternatives or options to identify the preferred solution, while addressing environmental concerns simultaneously (Leontief, Input-output economics, 1996).

### 2.3.1 LCA FRAMEWORK

The use of LCA could assist in the development planning of offshore decommissioning by indicating those activities where possible optimization with respect to energy consumptions and reduction of gaseous emissions can be achieved.

An internationally harmonized and standardized approach is given in the International Standardization Organization Standards (ISO) (Poremski & Jochen, 1998):

- 14040 Basic principles of life cycle assessment
- 14041 Goal and scope definition and life cycle inventory
- 14042 Life cycle impact assessment
- 14043 Life cycle interpretation

ISO standard 14040 includes the principles and framework for LCA, providing an overview of the practice and its applications and limitations. Typical LCA framework consists of goal and scope definition, inventory analysis, impact assessment and interpretation as shown in the figure below.

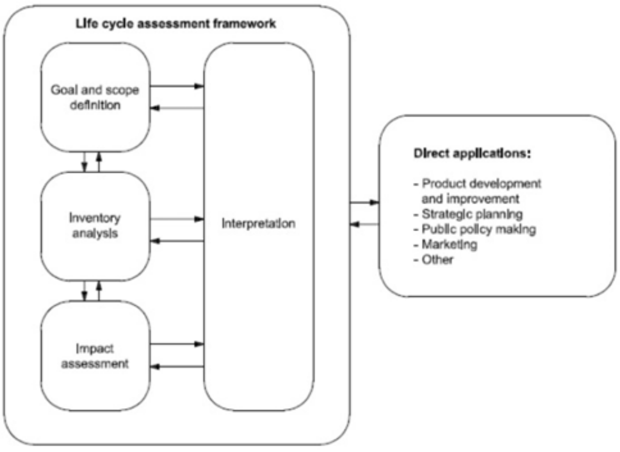


Figure 4: Life cycle assessment framework (Consoli, 1993).

Goal and scope definition is the first phase of LCA that defines the purpose of study, sets boundaries and establishes functional unit. Goal and scope of study must be clearly specified to set stages for the entire LCA analysis in order to identify procedures, impact categories, data requirements and assumptions or limitations. Some of the important terms related to this stage are product system, functional unit, system boundaries and data requirements. A product system consists of a set of unit processes that consume energy resources and release waste materials into the environment, while a functional unit means a quantitative reference to which inputs and outputs are related. System boundaries are based on the scope of study and the quality of inventory data depends on the boundaries set. Data requirements means the level of detail and specific data required (Curran, 2006).

The second stage of LCA is life cycle inventory (LCI), where the data are collected to quantify inputs and outputs of the system. Data collected includes energy or raw resources input and wastes released into the environment as the output. Total amount of energy consumption and gaseous emissions would be calculated and be presented either in tabular or graphic form.

The third stage of LCA is life cycle impact assessment (LCIA), where the quantified inputs and outputs are assessed to identify their environmental significance. The objective of this stage is to transform the inventory results into consequences. LCIA combines several LCI inventory results into single impact category (Curran, 2006). For example, LCIA combines emissions of $NO_x$ and $SO_2$ into one impact category, acidification.

The final stage is the life cycle interpretation where the findings from LCI and LCIA are being further interpreted and recommendations could be proposed.

There are different methods for LCA. Process LCA is the most popular method for conducting life cycle assessment and is often referred as the SETAC-EPA method as they have biggest role in LCA development (Joshi, 2000). There are three tools existing in the current market, GaBi, Ecoinvent and Umberto that can be used to conduct process LCA. These tools obtain data from previous researches on the environmental impact of materials and processes that are then strung together by the user to form a system.

The another method is EIO-LCA. EIO-LCA utilizes economic input-output tables and industry–level environmental data to construct a database of environmental impacts per dollar sold by an industry (Green Design Institute, 2010). The boundary problem of process LCA is solved because the EIO table captures the interrelations of all economic sectors.

### 2.3.2 PROCESS LCA VERSUS EIO METHOD

As stated previously, LCA tools used in this paper are process LCA and EIO-LCA. Process LCA itemizes the inputs (energy resources) and the outputs (emissions and wastes released to the environment) for each step over the entire life cycle, while EIO-LCA estimates the energy resources required and the environment emissions resulting from the whole process and link it with monetary transactions (Consoli, 1993). Both methods have their respective strength and limitations. By using process LCA, the decommissioning activities, which have the greatest contributions to the total energy consumption and gaseous emissions, could be identified and measures could be proposed to minimize the environment impacts.

On the other hand, EIO-LCA eliminates the two major issues of process LCA, defined boundaries and circularity effects. As the transactions and emissions of all industry sectors among all the other industry sectors are included, the boundary for EIO model is very broad and inclusive. Since the EIO model includes the self-sector transaction, the circularity effects are included in the analysis (Green Design Institute, 2010). For example, the EIO model used in this study, which was taken from www.eiolca.net, includes even energy consumed by iron ore mining as the pig iron is needed in the steel recycling process, which proved that EIO-LCA has a broad boundary and includes circularity effects as it is not included in the process LCA and being considered as one of the circularity effects for recycling process.

## 2.4 DECOMMISSIONING OF HEATHER PLATFORM

Decommissioning of offshore installations will definitely have impacts on marine life and the environment. Atmospheric emission, waste materials produced, noise pollutions, physical presence of vessels for decommissioning and vibrations produced will have effects on the marine life and the environment. For this study, the environment impacts concerned were the total energy consumption and gaseous emissions ($CO_2$, $SO_2$ and $NO_x$). Heather Platform was selected as a case study.

### 2.4.1 HEATHER PLATFORM DESCRIPTIONS

Heather Platform was operated by Unocal Britain Limited and located in Block 2/5 in the U.K. Sector of the North Sea, 145km east of the Shetland Islands. Oil was discovered in the Heather Field in December 1973 and first oil was exported from the platform in October 1978. Since 1978, in excess of 110 million barrels of oil and condensate have been produced from the field, with a peak average daily production of 36000 barrels per day being reached in 1982 (Morel, 2002).

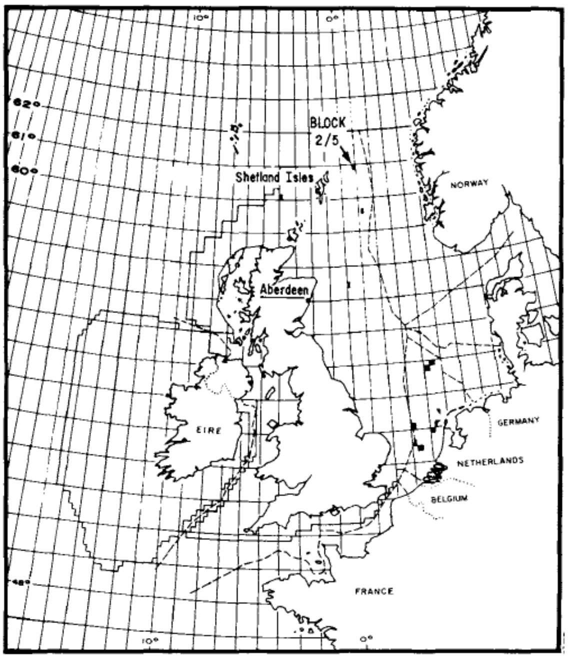


Figure 5: Location of Heather Platform at Block 2/5 in North Sea (Morel, 2002).

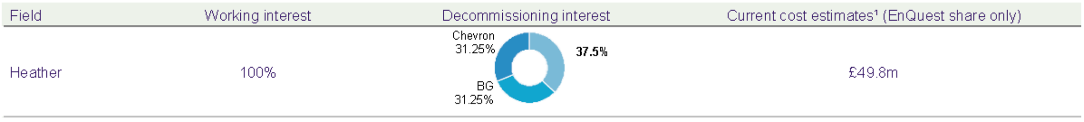
The field has been developed with single combined drilling, production and quarters platform standing in 143m of water. The platform has a maximum height of 236m and consists of modular topsides sitting on top of deck support frame supported by steel jacket substructure piled to the seafloor (Side, Kerr, & Gamblin, 1997).

The topsides consists of drilling, production, utility and quarters modules and two flare boom. The topside facilities were prefabricated onshore and consisted of a relatively large number of lift units based on the lifting capability of the lift vessels available in the mid 1970’s. There are three main deck levels, covering nearly 10000m$^2$, which contain all the equipment necessary for upstream operations together with numerous ancillary utility systems. The platform contains a skid mounted enclosed drilling derrick, two flare booms with each 52m long and two diesel powered pedestal cranes. The total dry weight of the topside is estimated at 12300t (Side, Kerr, & Gamblin, 1997).

The jacket is an eight leg, tubular space frame and steel structure supported by six piles connected to each of the four corner legs. The legs have a 1:10.824 batter in the transverse direction and vertical in the longitudinal direction. The jacket with the piles and grout within the pile sleeves to the mudline is estimated to weigh 17000t. It can accommodate forty-three of twenty six inches diameter well conductors, which are laterally supported through slots provided in the conductor guide framing and its weight is estimated to be 4300t. Marine growth on the jacket is estimated to weigh 2000t (Side, Kerr, & Gamblin, 1997).

Figure 6: Heather Platform (Auger, 2008).

The Heather Field development has always been a marginal operation, but tight cost control, focused management and fitness for purpose operating culture has enabled the platform operation to remain economically viable (Hustoft & Gamblin, 1995). Production from the field over much of its life has been marginally economic as revenue and operating costs are finely balanced. In 1991, the Heather field experienced low production volume. The field redevelopment commenced in 2008 and had a recovery factor of 27% in the end of 2009 with expected field life extended to 2029 (EnQuest, 2010). Lundin Petroleum acquired a 100% stake from DNO in February 2004 with the acquisition of DNO Britain (EnQuest, 2010). Decommissioning costs for Heather field is then shared with former owners, Chevron and BG with current owner, EnQuest's liability limited to 37.5% of the total decommissioning costs. According to EnQuest (2010), the estimated total decommissioning costs for Heather platform in 2010 is £132.8 million.



| Field | Working interest | Decommissioning interest | Current cost estimates¹ (EnQuest share only) |
|---|---|---|---|
| Heather | 100% | Chevron 31.25%<br>37.5%<br>BG 31.25% | £49.8m |

Figure 7: EnQuest's share on total decommissioning costs estimated in 2010 (EnQuest, 2010).

### 2.4.2 DECOMMISSIONING PLAN FOR HEATHER PLATFORM

Extensive engineering studies covering a wide range of options for decommissioning, removal and disposal of the Heather Platform facilities had been completed by Hustoft R. and Gamblin R. (1995). Issues such as legislation, environmental concerns, impact on sea users including fishing, technology available, platform characteristics, cost, safety and risk management have to be considered. Both technical and non-technical issues are important to determine the final platform decommissioning scheme.

A set of decommissioning program constraints were established by the researchers, consists of compliance with current legislation and applicable national and international guidelines, prohibition of deep sea disposal, minimization of underwater cutting and lifting activities, reduction of personnel risk exposure and other considerations (Hustoft & Gamblin, 1995). There are significant cost differences between different decommissioning options and emphasis on planning stage would ensure a cost effective decommissioning. In order to ensure the owners will not be exposed to unacceptable risk of undesired events and future residual liability or to prevent any delay that increase the total costs, the decommissioning program must be properly planned, engineered and executed.

The researchers considered three decommissioning options, full removal, partial removal and alternative use of the facilities. Full removal scheme involves the use of extensive heavy construction type diving exposure and complex underwater rigging operations. The operational complexity, risk exposure, safety concerns and costs of full removal is many times folded compared with partial removal that removes and disposes the facilities until a minimum clear water depth of 55m is left. Partial removal is operationally simpler, significantly cheaper and safer than complete removal. However, all navigation and fishing charts must be marked accordingly and regular inspection is required. Reuse of the platform is not practical as the facilities are based on 1970’s technology (Hustoft & Gamblin, 1995). Refurbishing and upgrading works would be expensive and uneconomic.

The decommissioning process was broke down into several phrases as shown in the figure below.

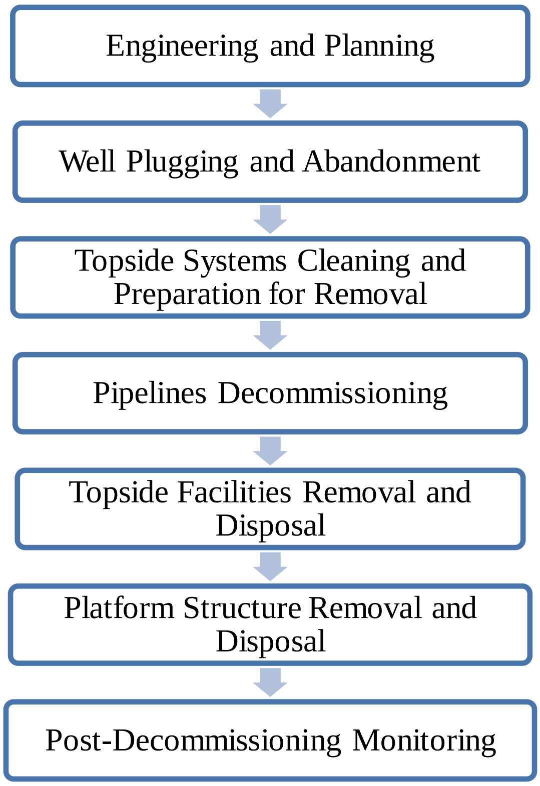


Figure 8: Decommissioning stages of Heather Platform (Hustoft & Gamblin, 1995).

The first decommissioning activity offshore is well plugging and abandonment. The Heather well abandonment scheme has been developed based on initiation abandonment of water injection and low productivity wells while retaining high productivity wells, that is simultaneous production and well abandonment (Hustoft & Gamblin, 1995). Based on the published research work by Hustoft and Gamblin (1995), a total of 41 wells is required to be abandoned on the platform. The well plugging and abandonment operation has been separated into two phases. Phrase one is preparatory work and placement of the required cement plugs. Phase two is the cutting and pulling of casing and tubing 150m below the mudline and followed with the cutting and removal of conductor strings to a depth consistent with the jacket removal scheme (Hustoft & Gamblin, 1995).

Next is the topside system cleaning and preparation. Shut in of the last production well, isolation, hydrocarbon freeing and inert of all systems will be carried out to prepare for topside removal. This step requires personnel’s specialized knowledge of the platform systems to reduce hazards and ensure a cost effective decommissioning. The initial cleaning process includes nitrogen purge and seawater flush throughout all systems, which will generate large volumes of waste seawater contained with hydrocarbon residual. The waste seawater will be treated before discharge into sea and residues will be injected into a disposal well that will be the last well to be abandoned. The cleanliness is governed by environmental requirements and if a higher degree of cleaning is required, methods such as low and high pressure hydro jetting, steam cleaning, detergent flush, hot detergent flush and acidizing could be carried out (Hustoft & Gamblin, 1995).

The Heather field is served by two pipelines, a 16” oil export pipeline protected with a 1 $^{1}/_{8}$” concrete coating installed in 1976 and a 6” epoxy coated gas import pipeline installed in 1985 (Hustoft & Gamblin, 1995). The researchers recommended to leave the pipeline in situ based on environmental, operational, safety and residual liability considerations.

For the topside removal, there are two methods, removal by heavy lift vessel that is a reverse operation to installation or piecesmall removal that involves the dismantling of the modules offshore, broken down to sizes to suit platform based cranes and loaded to be disposed onshore. The Heather topsides module weights are relatively low compared with recently installed platforms (Hustoft & Gamblin, 1995). If without the deck support frame, the topside modules could be removed by lifting in a reverse installation order. As discussed by Hustoft and Gamblin (1995), the final choice of topside removal method, either by module lifting, piecesmall or a combination will be left as a commercial decision to be made following bidding of the work.

After the topside removal, the next challenging task is jacket removal. The jacket will be either partially removed down to 55m below sea level or totally below the mudline. The jacket is recommended to be cut into sections of manageable size and weight to be lifted and transported onshore. The researchers estimated the number of lifts for partial removal of jacket approximately to be one and eight lifts for complete removal. The use of a semi-submersible crane vessels is required to lift the large jacket sections.

Drill cutting piles are present within or around most of the first generation fixed platforms (Hustoft & Gamblin, 1995). They reflect the drilling history and drill mud used. Drill cuttings removal is costly, hazardous, technical complexity and causes environment issues. For instance, if the drill cutting piles are not removed accordingly, the oil residue from the drilling muds and heavy metals may be released to the sea. Hence, it is considered the best to leave these drill cutting in situ as recommended by Hustoft and Gamblin (1995).

For the post-decommissioning survey, the IMO guidelines states that the owners must provide notification of any remaining materials on the sea bed to mark nautical charts and regular monitoring and maintenance to be carried out.

## 2.5 SUMMARY

This chapter has presented literature review on offshore decommissioning, mostly on international laws and regulations, costs and activities involved in decommissioning process. This chapter also presented literature review on life-cycle assessment, outlined the LCA framework and compared both process LCA and EIO-LCA for their strength and limitations. In addition, in the last part of this chapter, the author presented the literature review on the case study, Heather platform on its descriptions, estimated decommissioning costs and detailed decommissioning plan developed by the researchers. In the next chapter, the author will present on the methodology used in this study, mainly on research methodology, project activities, key milestone, Gantt chart, tools required and LCA methodology.

# CHAPTER 3

# METHODOLOGY

## 3.1 INTRODUCTION

The main objective of this chapter is to describe the methodology used for this study. In Chapter One of this report, the main problem and objectives were outlined and will be elaborated further in this chapter. This chapter starts with research methodology used and project activities involved. Furthermore, this chapter also presents key milestone, Gantt chart and tools required. The last part of this chapter elaborates the detailed breakdown of LCA methodology used in this study. The project activities involved are clearly presented in Figure 11. This figure shows steps of the author in achieving the objectives of this research.

### 3.1.2 RESEARCH PROBLEM

Offshore installations decommissioning would definitely bring along environmental impacts and with increased public awareness on environmental issues, it is very important to assess and quantify the environmental impacts associated with offshore decommissioning. However, there is minimal information and framework published to assess the environmental impacts of offshore decommissioning. LCA analysis is used as it provides quantitative and structural comparison between different decommissioning options. Therefore, the goal of this research is to develop a basic framework to assess environmental impacts associated with offshore decommissioning.

### 3.1.3 RESEARCH OBJECTIVES

The objectives of this study are:

a) *To determine the volume and type of waste materials in offshore installations decommissioning for complete removal and partial removal of an offshore platform in North Sea*

   Heather Platform, which is located in the U.K sector of North Sea, was selected as a case study. The volume and type of waste materials released during offshore decommissioning are identified. The main concern for waste materials produced are harmful gaseous emissions ($CO_2$, $SO_2$ and $NO_x$). The data was obtained from a published paper on estimation of energy consumption and gaseous emissions associated with decommissioning of Heather Platform.

b) *To quantify the environmental impacts of offshore decommissioning of a platform in North Sea using LCA tools, process based method and EIO method*

   For this objective, LCA tools are used to quantify the environmental impacts of Heather Platform decommissioning. The detailed LCA methodology would be further explained in this chapter.

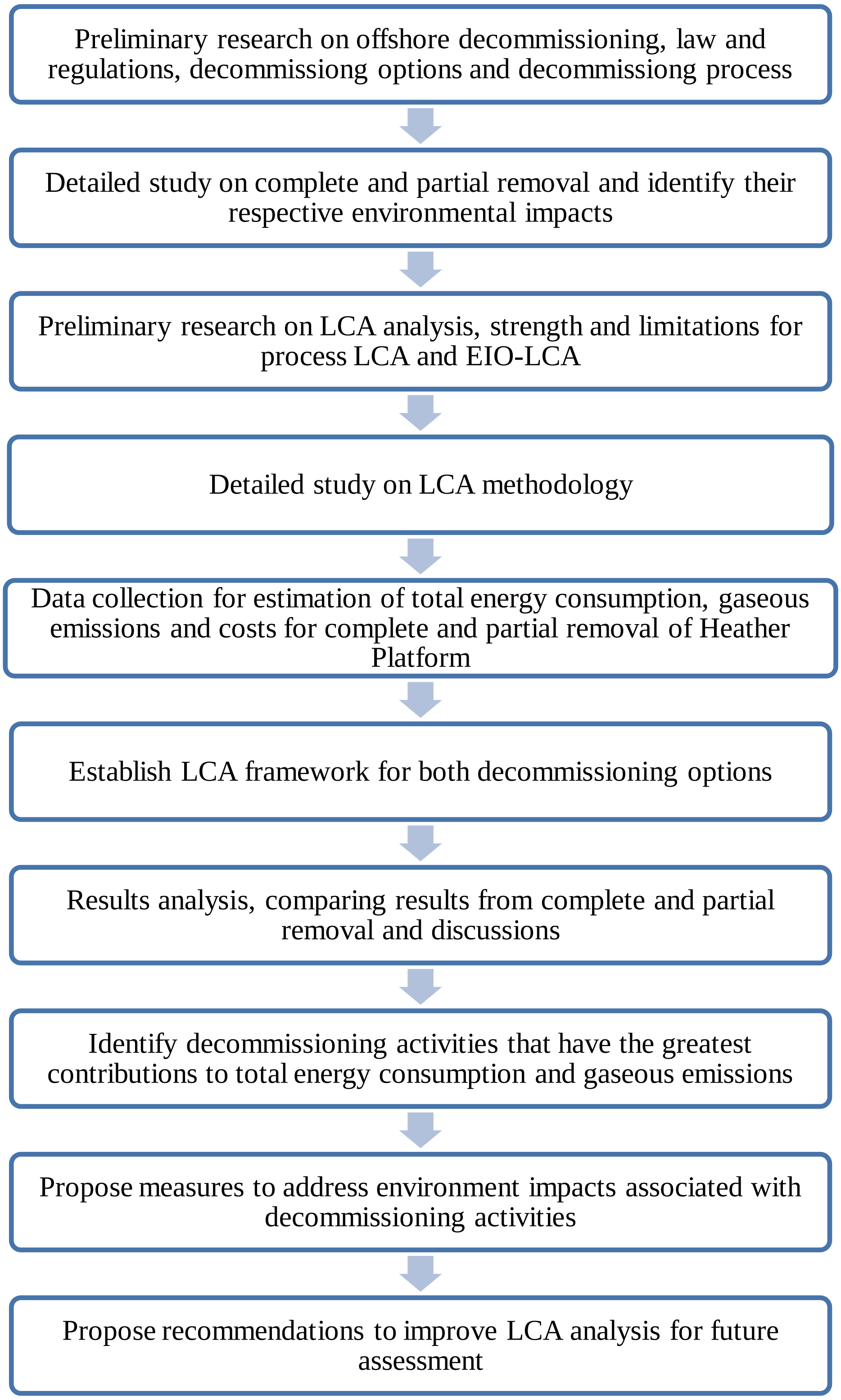
c) *To compare the environmental impacts of complete removal and partial removal of an offshore platform in North Sea*

   In order to address this objective, results obtained from process LCA and EIO-LCA would be further interpreted in the next chapter to compare the complete and partial removal of Heather Platform.

d) *To propose for measures and instruments to address environmental and other concerns that arise in connection with the decommissioning of offshore installations*

   For this objective, based on the results from process LCA, the decommissioning activity which is the major contributor for energy consumption and gaseous emissions could be identified and measures or recommendations would be proposed in the following chapter to reduce the environmental impacts.

## 3.2 RESEARCH METHODOLOGY



Preliminary research on offshore decommissioning, law and regulations, decommissiong options and decommissiong process

Detailed study on complete and partial removal and identify their respective environmental impacts

Preliminary research on LCA analysis, strength and limitations for process LCA and EIO-LCA

Detailed study on LCA methodology

Data collection for estimation of total energy consumption, gaseous emissions and costs for complete and partial removal of Heather Platform

Establish LCA framework for both decommissioning options

Results analysis, comparing results from complete and partial removal and discussions

Identify decommissioning activities that have the greatest contributions to total energy consumption and gaseous emissions

Propose measures to address environment impacts associated with decommissioning activities

Propose recommendations to improve LCA analysis for future assessment

Figure 9: Research methodology used in this study.

### 3.3 PROJECT ACTIVITIES

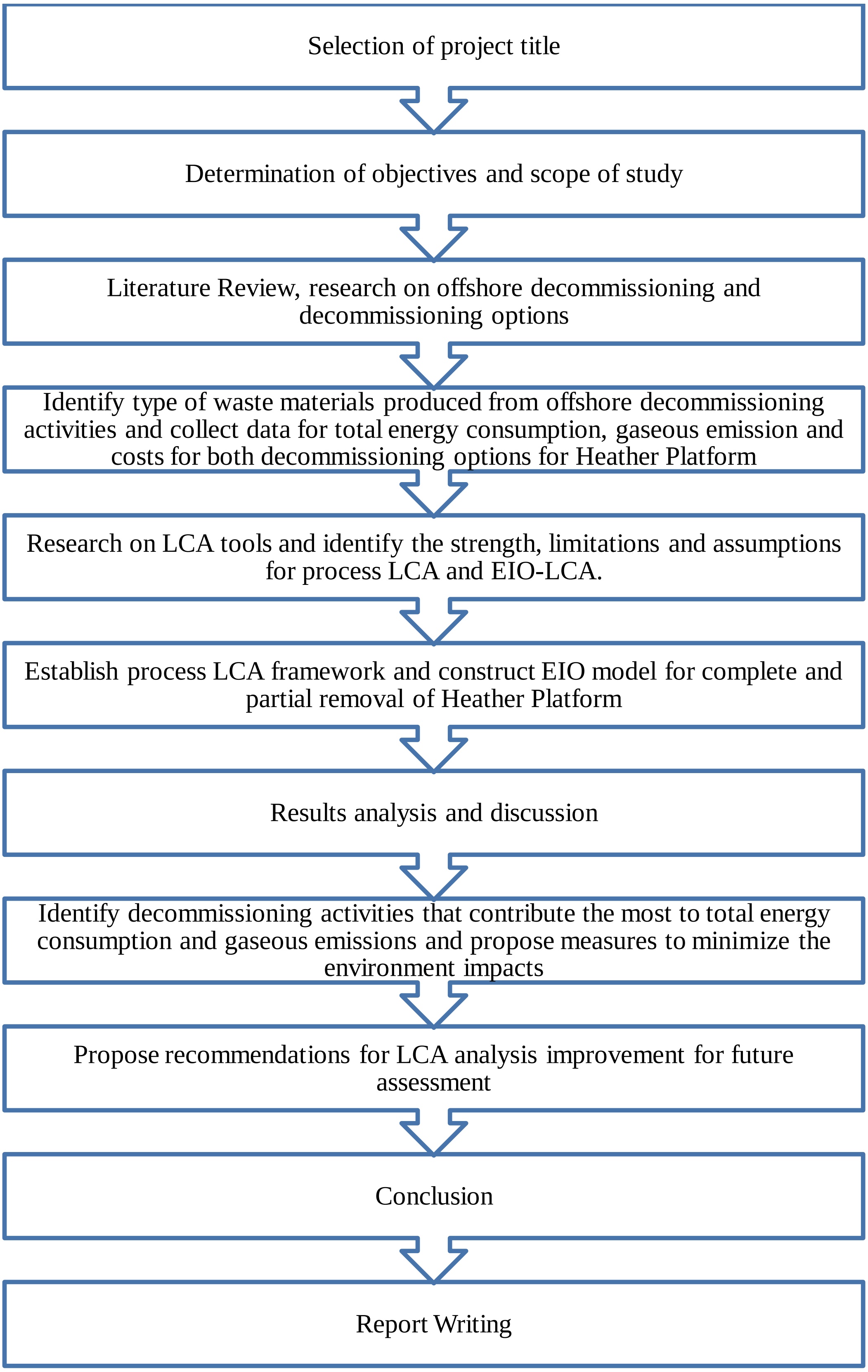
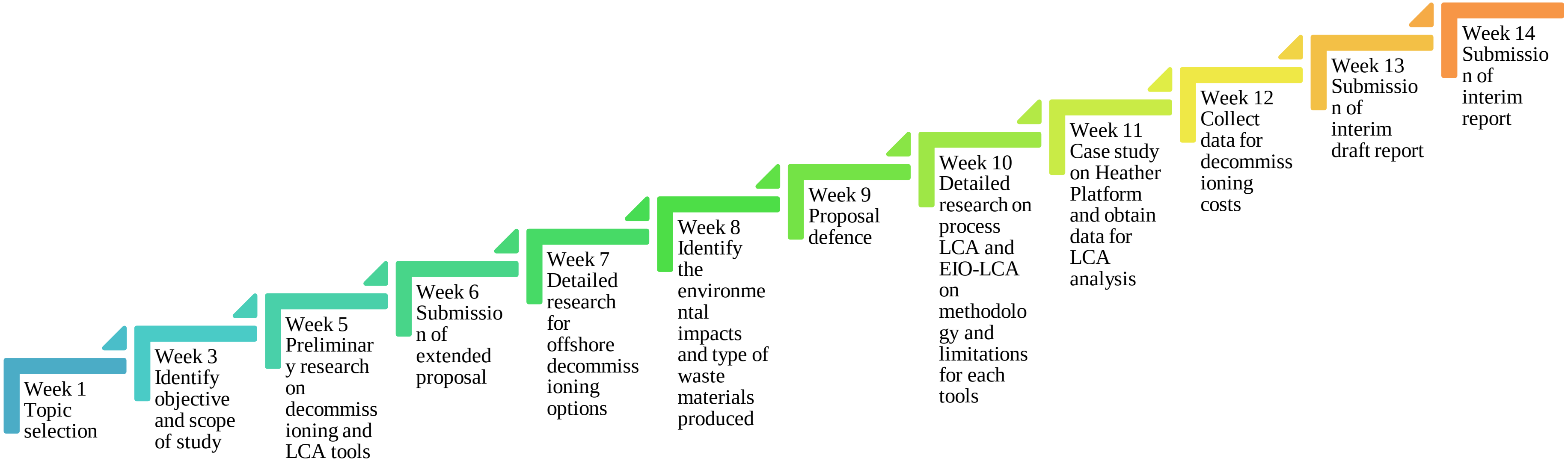


Figure 10: Project activities involved in this study.

## 3.4 KEY MILESTONE

The planned schedules for Final Year Project I are as follows:



The planned schedule for Final Year Project II are as follows:

- Week 1 Conduct process LCA analysis for complete removal option
- Week 2 Conduct process LCA analysis for partial removal option
- Week 3 Research on EIO-LCA online models and their limitations
- Week 5 Construct EIO model for complete removal option
- Week 6 Construct EIO model for partial removal option
- Week 7 Analyze results obtained and discussion
- Week 8 Submission of progress report
- Week 9 Propose recommendations to minimize the environmental impacts of offshore decommissioning
- Week 10 Propose for improvement of LCA analysis for future assessment
- Week 11 Pre-Sedex
- Week 12 Submission of draft report
- Week 13 Submission of technical paper and dissertation
- Week 14 Oral presentation
- Week 15 Submission of hard bound dissertation

## 3.5 GANTT CHART

| | | FYP I | | | | | | | | | | | | | | FYP II | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Detail / Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | Selection of project title | 🟦 | 🟦 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | Determination of problem statement, objective and scope of study | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | Research on decommissioning options, procedures, regulations and identify type of waste materials produced and the environment impacts | | | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | Submission of extended proposal | | | | | | 🟦 | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | Research on LCA tools for their respective strength and limitations | | | | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | |
| 6 | Proposal defence | | | | | | | | | 🟦 | | | | | | | | | | | | | | | | | | | | |
| 7 | Research on procedures to conduct process LCA and online models of EIO | | | | | | | | | | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | |
| 8 | Submission of interim draft report | | | | | | | | | | | | | 🟦 | | | | | | | | | | | | | | | | |
| 9 | Submission of interim report | | | | | | | | | | | | | | 🟦 | | | | | | | | | | | | | | | |
| 10 | Conduct process LCA for complete and partial removal | | | | | | | | | | | | | | | 🟩 | 🟩 | | | | | | | | | | | | | |
| 11 | Research on online EIO models and their assumptions or limitations | | | | | | | | | | | | | | | | | 🟩 | 🟩 | | | | | | | | | | | |
| 12 | Conduct EIO analysis for complete and partial removal | | | | | | | | | | | | | | | | | | | 🟩 | 🟩 | | | | | | | | | |
| 13 | Life cycle interpretion and discussions | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | |
| 14 | Submission of progress report | | | | | | | | | | | | | | | | | | | | | | 🟦 | | | | | | | |
| 15 | Propose recommendations or measures to address environment impacts | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | |
| 16 | Propose recommendations for LCA improvement | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | |
| 17 | Pre-Sedex | | | | | | | | | | | | | | | | | | | | | | | | | 🟦 | | | | |
| 18 | Submission of draft report | | | | | | | | | | | | | | | | | | | | | | | | | | 🟦 | | | |
| 19 | Submission of technical report and dissertation | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟦 | | |
| 20 | Oral presentation | | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟦 | |
| 21 | Submission of hardbound dissertation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟦 |

🟦 Administrative requirement

🟩 Milestone

## 3.6 TOOLS REQUIRED

**Software used**

- Laptop pre-installed with Windows, Microsoft Office and Adobe Reader
- Online EIO models from www.eiolca.net

## 3.7 LCA METHODOLOGY

LCA methodology used in this study consists of four stages based on the ISO standard as described previously in the literature review.

### 3.7.1 ASSUMPTIONS FOR LCA ANALYSIS

It must be clear that the author had set some assumptions and limitations for this study due to limited available data. The data used for process LCA were retrieved from a research work that was published in 1997. Due to limited detailed data for environmental impacts, particularly gaseous emissions associated with offshore installations decommissioning, the author had to utilize the data available. However, the author had checked unit conversion factors used in the published work (Side, Kerr, & Gamblin, 1997) with recent published rate (Department of Energy & Climate Change, 2013) and confirmed that the differences will be not significant. For example, carbon dioxide emission due to usage of aviation fuel would differ only by 5% with the recent emission factor based on (European Union, 2013). The percent of variation due to unit conversion for gaseous emission stays below 10%.

Besides that, the author discovered that the emission factor for carbon dioxide during steel production in year 1990 was 0.12 and remained the same factor in year 2011 based on European Environment Agency (2011). This further proved that data published by Side, Kerr & Gamblin (1997) is still applicable and valid since the emission factors remained the same or varies within the range of 10%.

Furthermore, this published paper was cited by few authors in the recent years too. Please refer to the Appendices for the unit conversion factors and constants for energy consumption and gaseous emissions related to onshore and scrap vessel haulage round trip distance, marine vessels, engine and helicopter usage, recycling process and fuel consumption during decommissioning process used in process LCA and their respective references.

According to Side, Kerr & Gamblin (1997), they obtained quantification of energy consumption associated with platform facilities dismantling based on unit fuel consumptions per tonne dismantled from the demolition contractors based on their decommissioning experience. Data variables, especially gaseous emissions are particularly sensitive to combustion chamber conditions and vary according to engine age, maintenance and vessels loading.

For EIO-LCA, as all data incorporated into the EIO-LCA model was compiled from surveys and forms submitted by industries to governments for national statistical purposes, there are uncertainties in sampling, incomplete data or estimates. The data associated with the model is based on US 2002 Benchmark Model that has 428 sectors involved. Although the data related with the EIO model is based on the year of 2002, the author checked the model documentation and discovered that Green Design Institute revised the model with latest economic-input-output coefficients in 2009. Hence, the results would be valid.

This method is a linear model that the result of a $1000 change in demand or level of economic activity will be 10 times the result of a $100 change in demand (Green Design Institute, 2010). Most of the EIO models represent producer price that has boundaries of “cradle to gate”. It is the price a producer receives for goods and services with taxes and minus subsidies or the cost of buying all the materials, running facilities and workers’ wage. The purchaser price, which has boundaries of “cradle to consumer”, includes the producer price with the transportation costs of shipping product to sale and profit margin. For this project, as the recovered platform materials are returned onshore for recycling, the purchaser price model is chosen. By using the EIO model, the author could estimate the total energy consumption and gaseous emissions associated with decommissioning of Heather Platform.

### 3.7.2 STAGE 1: GOAL AND SCOPE DEFINITION

Based on the ISO standard, the goal of the LCA has to be stated firmly with the reasons, field of application and groups involved. For this assessment, the goal is the same with the objectives of this study, that were to identify type and volume of waste materials produced, to quantify the environment impacts and to propose measures or other concerns related to offshore installations decommissioning.

The scope of this study was limited to two decommissioning options, complete removal and partial removal that is removal of jacket for 55m below the sea level. Heather Platform was selected as the functional unit or case study for this project. The following boundaries had been made to ensure no energy is being counted twice and consistency in data evaluation (Side, Kerr, & Gamblin, 1997).

Indirect energy costs of plant and equipment not altered by decommissioning process are ignored.

- For example, energy used to construct the crane barge used in decommissioning process are igored.

Trivial energy costs are ignored.

- Energy costs of sandblasting steel in the recyling process are included in the analysis, but not the energy used to transport sand used for the sandblasting process.

All renewable energy sources and materials are treated as cost free goods.

All non-renewable materials that are recycled are treated as substitutes for the basic raw materials that would be used in the decommissioning process.

- Pig iron is needed in recycling of steel and it is assumed that the steel scrap recycled substitutes directly for the pig iron.

Figure 11: Defined boundaries for consistency in data evaluation.

### 3.7.2 STAGE 2: LIFE CYCLE INVENTORY

Life cycle inventory analysis involves data collection and calculation to quantify relevant inputs and outputs of the system (Poremski & Jochen, 1998). For offshore decommissioning, the input was the energy consumption, while the outputs were gaseous emissions. Four inventory parameters, that are Carbon Dioxide ($CO_2$), Sulfur Dioxide ($SO_2$), Nitrogen Oxides ($NO_x$) and Equivalent Carbon Dioxide emissions were chosen due to their significant amount of emission associated with offshore installations decommissioning.

The LCI method used in this project were process LCA and EIO-LCA. For process LCA, the data were obtained from the published paper by Side, Kerr & Gamblin (1997) for estimation of energy consumption and gaseous emissions associated with decommissioning of Heather Platform.

For the ease of data evaluation in process LCA, the decommissioning activities were then divided into seven discrete aspects, consists of:

| | |
|---|---|
| Temporary steelwork | Manufacture, haulage, fabrication, dismantling and recycling of temporary steelwork such as grillages, seafastenings, lifting aids and structural strengthening. |
| Platform facility dismantling | Recovered platform materials, fuel consumption for transportation of materials for recycling and all materials resulting from the dismantling operations. |
| Marine vessel utilization | Product of vessel utilization and corresponding fuel consumption. |
| Platform running | Product of platform running and corresponding fuel consumption throughout the decommissioning operations on the platform. |
| Helicopters | Estimated helicopter flying manhours and fuel consumption. |
| Platform materials recycling | Product of recycling materials. |
| Platform materials left at sea | Product of material left in-situ (For partial removal option). |

For EIO-LCA, the author collected the cost data from a report, Decommissioning Insights published by Oil & Gas UK in 2012. The author could estimate the total costs for decommissioning the Heather Platform, which is located in the northern North Sea. In a decommissioning survey in the northern North Sea, it costs £4200 per tonne to remove the topside module and £3100 per tonne to remove the jacket on average (Oil & Gas UK, 2012). However, these are estimated numbers and the actual removal costs per tonne depend on a wide variety of factors, like weather, age of offshore installations, inflation, location and previous experience of decommissioning.

According to the Side, Kerr & Gamblin (1997), the topside of the Heather platform weighted around 12300t, which will cost £51.66 million to be removed, while the jacket, which weighted around 23300t including well conductors and marine growth, will cost £72. 23 million. The total decommissioning costs for complete removal was estimated around £123.89 million (194.63 million US Dollar).

For partial removal, the jacket is cut at 55m below the seabed and the remaining jacket is considered to be leave in-situ. As estimated by Hustoft and Gamblin (1995), 55m of jacket below the sea level weighs around 20% of the total jacket weight. The author estimated that cost to remove 20% of the total jacket weight plus the weight of well conductors, but not the marine growth to be around £23.87 million and the total decommissioning cost for partial removal around £75.53 million (118.66 million US Dollar), which is lesser than complete removal option.

As the cost data was in British Pound Sterling, the author converted it to US Dollar to be used in EIO model on 17 June 2013. Although the currency rate fluctuates every day, it would not affect much the results as the fluctuation rate is insignificant compared with the huge amount of decommissioning costs.

Then, an online EIO model was constructed from www.eiolca.net assuming the amount of economic activity is one million US Dollars under the sector for support activities for oil and gas operations that includes performing support activities on a contract or fee basic for oil and gas operations, excluding site preparation and related construction activities. Services included in this sector are exploration (except geophysical surveying and mapping), excavating slush pits and cellars, well surveying, running, cutting and pulling casings, tubes and rods, cementing wells, shooting wells, perforating well casings, acidizing and chemically treating wells, cleaning out, bailing and swabbing wells.

### 3.7.3 STAGE 3: LIFE CYCLE IMPACT ASSESSMENT

Life cycle impact assessment involves the evaluation of the significance of potential environmental impacts based on the results from the previous stage. Inventory data were classified to their respective impact categories followed with the modeling of the data within impact categories and finally prioritizing and weighting the impact categories. For this LCA, the impact categories applicable are global warming ($CO_2$ and Equivalent $CO_2$) and acidification ($SO_2$ and $NO_x$).

### 3.7.4 STAGE 4: LIFE CYCLE INTERPRETATION

Life cycle interpretation is where the findings from the inventory analysis and impact assessment will be analyzed and concluded. During the final stage of this study, the decommissioning activities, which contribute the greatest for total energy consumption and gaseous emissions, would be identified. The better decommissioning option would be suggested based on the results and measures or recommendations related with offshore decommissioning would be proposed. For future LCA assessment, the author would propose several recommendations for process LCA and EIO-LCA with concerns regarding limited data in the end of this study.

## 3.8 SUMMARY

This chapter has presented the methodology used in this research. Research methodology and project activities involved were elaborated on the earlier of this chapter. In addition, this chapter also outlined key milestone, Gantt chart and tools required. Detailed steps to establish LCA framework including assumptions and boundaries made were explained in the last part of this chapter. In the next chapter, results from process LCA and EIO-LCA will be presented in the form of tables and graphs. The results will be further discussed and recommendations on offshore decommissioning and LCA analysis will be proposed in the following chapter.

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 INTRODUCTION

In this chapter, the results from process LCA and EIO-LCA are presented in the tables and graphs. The results are then further discussed and interpreted in this chapter. In the last part of this chapter, the author proposes few measures to reduce environmental impacts associated with offshore decommissioning and recommendations on improvement of LCA analysis.

## 4.2 RESULTS AND DISCUSSION

Data for process LCA was obtained from a published work by Side, Kerr & Gamblin (1997) on the estimation of energy consumption and gaseous emissions associated with the decommissioning of Heather Platform. The detailed unit conversion and constants used for fuel consumption and gaseous emissions are attached in the Appendices. Total energy consumption and gaseous emissions ($CO_2$, $NO_x$, $SO_2$ and Equiv. $CO_2$) for complete and partial removal were divided in to seven decommissioning aspects for the ease of evaluation. The detailed results from each decommissioning aspects are shown in the table in the Appendices. Table below showing the results from process LCA, indicating total energy consumption and gaseous emissions for both complete and partial removal of Heather Platform.

| Variable | Complete Removal | Partial Removal | % Difference Between Complete and Partial Removal |
|---|---|---|---|
| Energy Consumption (GJ) | 939479 | 881309 | 6.19 |
| NOx Emissions (Kg) | 624318 | 411470 | 34.09 |
| $SO_2$ Emissions (Kg) | 631674 | 452688 | 28.34 |
| $CO_2$ Emissions (Kg) | 65149362 | 71709855 | -10.07 |
| Equivalent $CO_2$ Emissions (Kg) | 26301329 | 19812430 | 24.67 |
| Overall $CO_2$ Emissions (Kg) | 91450691 | 91522286 | -0.08 |

Table 1: Percentage difference between complete and partial removal of Heather Platform in energy consumption and gaseous emissions.

From the table, we can conclude that complete removal option consumes more energy (6.19% more), emits more $NO_x$ (34.09% more), $SO_2$ (28.34% more) and Equivalent $CO_2$ (24.67% more) than partial removal.

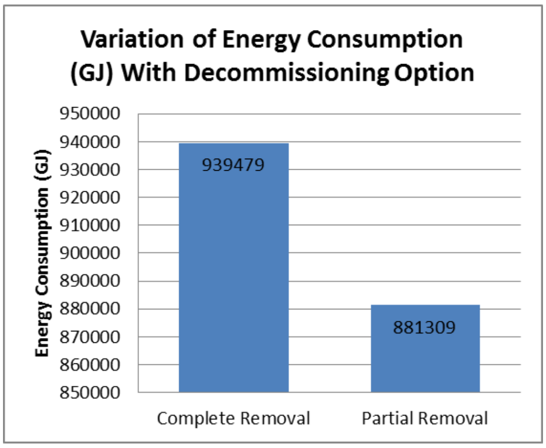


Figure 12: Comparison of energy consumption between complete and partial removal of Heather Platform.

Based on the figure above, it showed that complete removal consumes more energy (6.19% more) than partial removal due to energy used to remove the jacket completely, transport and recycle the steel jacket.

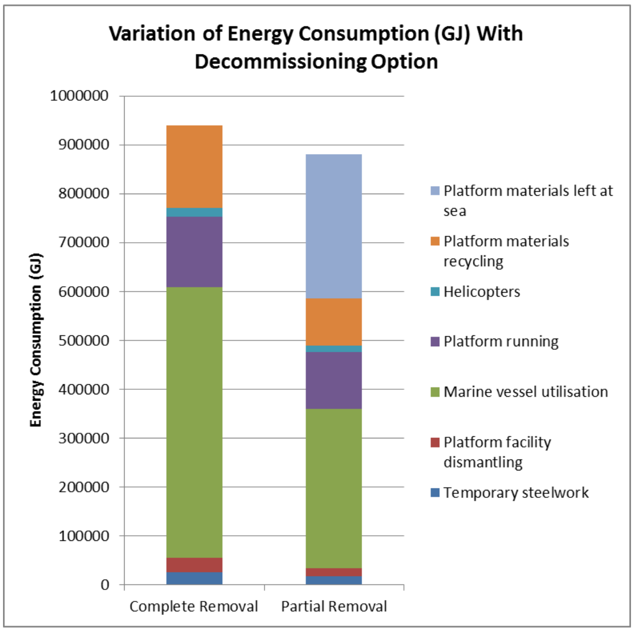


Figure 13: Breakdown of energy consumption with respective decommissioning activities for complete and partial removal of Heather Platform.

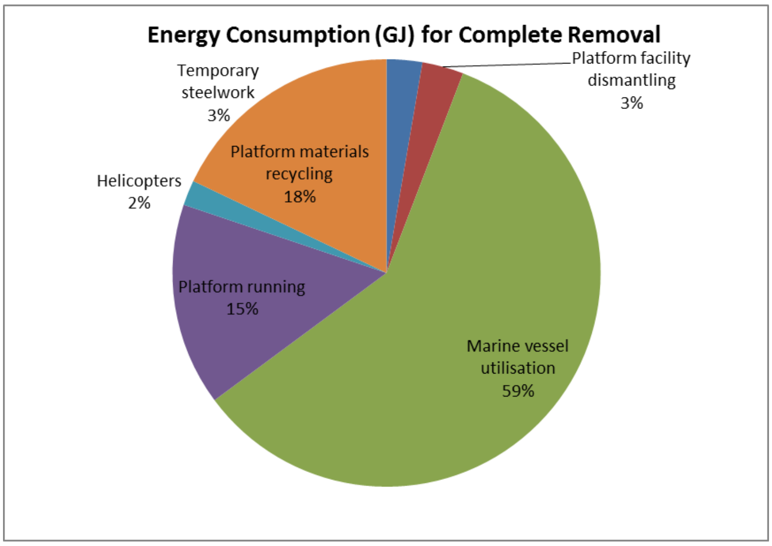


Figure 14: Energy consumption for complete removal of Heather Platform.

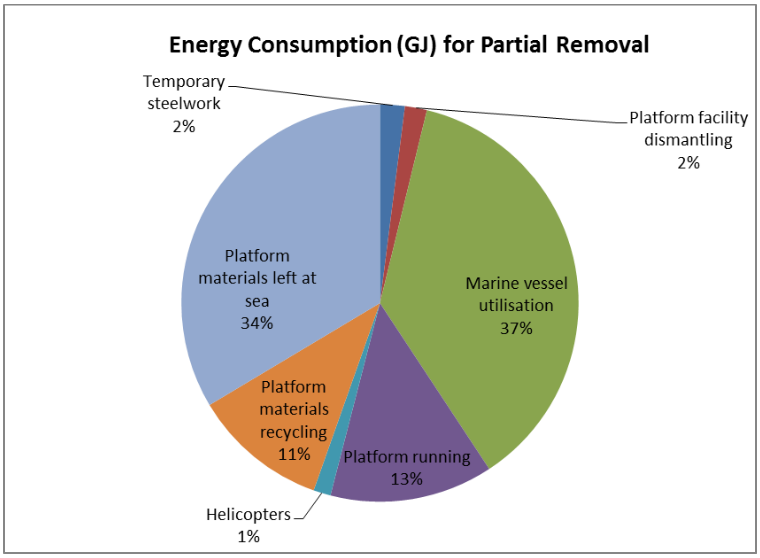


Figure 15: Energy consumption for partial removal of Heather Platform.

From the figures above, it showed that marine vessel utilization (59%), platform material recycling (18%) and platform running (15%) are the three largest energy consumption activity for complete removal. For partial removal, they are marine vessel utilization (37%), platform material left at sea (34%), platform running (13%) and platform material recycling (11%). For platform material left at sea, it indicates the energy wasted due to the recyclable material, the steel jacket left in the sea bed. To conclude, the three most energy consuming decommissioning activity are marine vessel utilization, platform running and platform material recycling.

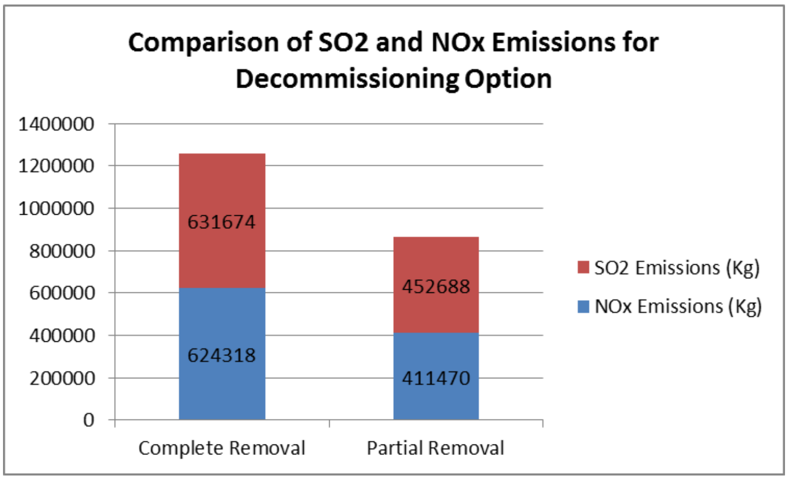


Figure 16: Comparison of $SO_2$ and NOx emissions for complete and partial removal of Heather Platform.

The $SO_2$ and $NO_x$ are the main culprits for acid rain that is dangerous to human's health and bring detriments to agriculture and building properties. Form the figure above, complete removal releases more $SO_2$ (28.34% more) and $NO_x$ (34.09% more) than partial removal due to greater usage of marine vessel to transport the steel jacket that is being removed completely onshore for recycling.

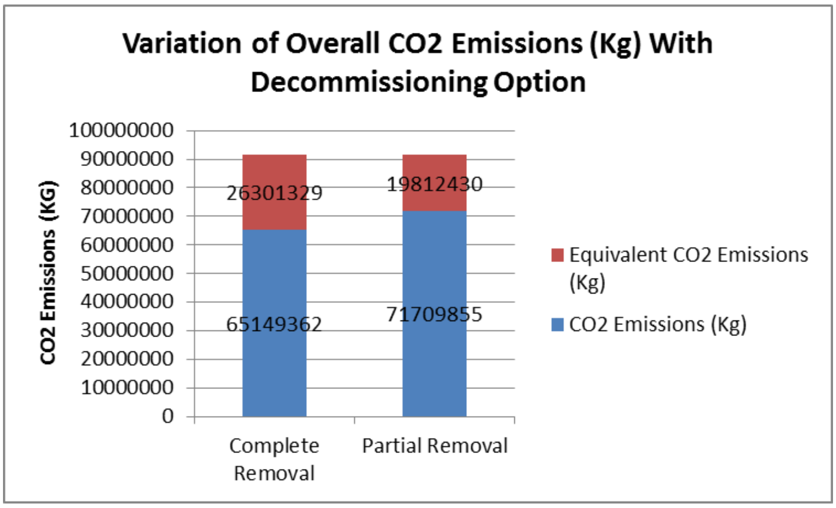


Figure 17: Comparison of overall $CO_2$ emissions for complete and partial removal.

The $CO_2$ and Equivalent $CO_2$ emissions are the main factor for global warming that resulting in the rise of sea level and heat waves. From the figure above, it is evident that the overall $CO_2$ emissions are about the same for both decommissioning option (0.08% difference). However, it is clear that complete removal produces more

(24.67% more) equivalent $CO_2$ when compared with partial removal. The greater amount of equivalent $CO_2$ is because of the greater amount of fuel used by marine vessel to transport the removed steel jacket completely onshore and more materials for recycling.

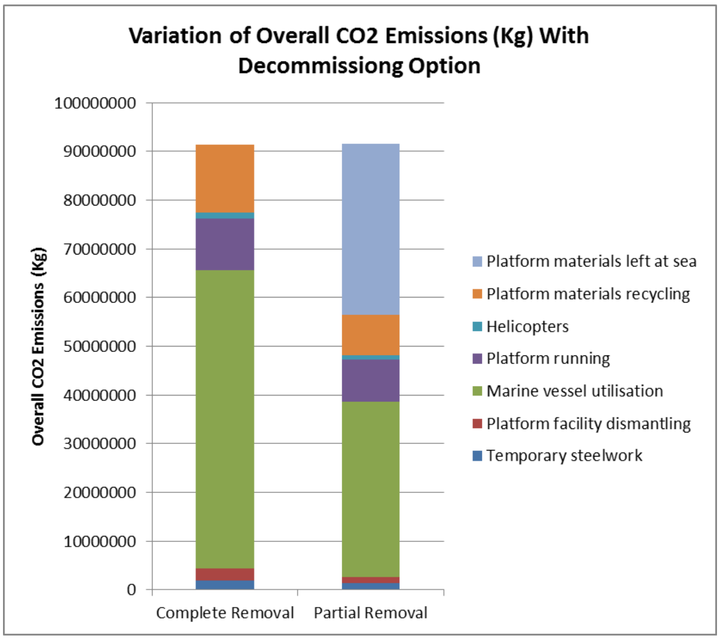


Figure 18: Breakdown of overall $CO_2$ emissions for respective decommissioning aspects for both complete and partial removal of Heather Platform.

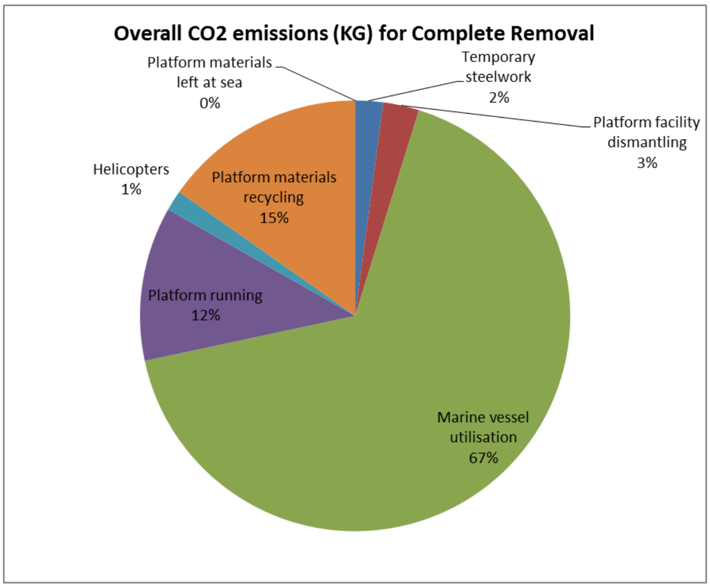


Figure 19: Overall $CO_2$ emissions for complete removal of Heather Platform.

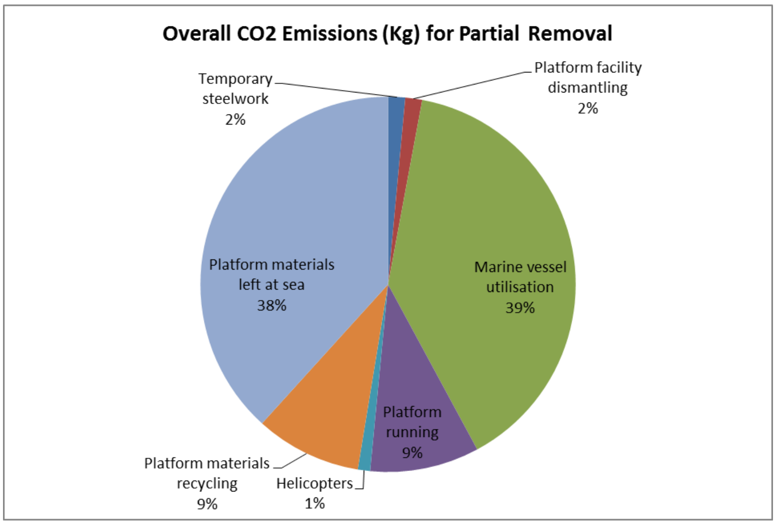


Figure 20: Overall $CO_2$ emissions for partial removal of Heather Platform.

From the figures above, we can observe that for complete removal, three greatest contributors for $CO_2$ emissions are marine vessel utilization (67%), platform material recycling (15%) and platform running (12%). For partial removal, they are marine vessel utilization (39%), platform material left at sea (38%), platform material recycling (9%) and platform running (9%). For platform material left at sea, the overall $CO_2$ emission is because of the steel jacket left in the sea bed. From the results, we can conclude that major factors for $CO_2$ emission are recycling process, fuel consumption by marine vessel utilization and platform running.

Based on the results for process LCA, it is evident that the marine vessel utilization is the major factor for $NO_x$ and $SO_2$ emissions, while recycling process, fuel consumption by marine vessel and during platform running are the major contributors for $CO_2$ emission. Furthermore, the three decommissioning activities that contribute the most to the energy consumption were identified to be marine vessel utilization, platform running and platform materials recycling. It can be concluded that marine vessel utilization is the main factor to minimize the environmental impacts of offshore decommissioning as marine vessels consume a great amount of fuel (energy) and release a large amount of harmful gases, especially $NO_x$ and $SO_2$.

The results from process LCA also proved that in terms of energy consumption and gaseous emissions, partial removal is the best decommissioning option as it consumes lesser energy and produces lesser gaseous emissions. The complete removal option that recovers the greatest amount of platform steel for recycling purposes, shows no environmental benefit over the partial removal from the view of energy consumption and gaseous emissions. Instead, it brings more damages to the environment than partial removal due to greater amount emissions of acidifying gases $NO_x$ and $SO_2$.

On the other hand, EIO model used by the author represents purchaser price for support activities for oil and gas operations. By using cost data by Oil & Gas UK (2012), the author calculated the total energy consumption and gaseous emissions by referring to the standard unit model for total amount of economic activity of one million US Dollar. The total energy consumption and gaseous emissions for the standard unit model are attached in the Appendices.

| Variable | Total Energy Consumption (GJ) | Nox Emissions (Kg) | SO2 Emissions (Kg) | Overall CO2 Emissions (Kg) |
|---|---|---|---|---|
| Standard unit (1 million USD) | 7790 | 6330 | 1890 | 650000 |
| Complete Removal (194.63 million USD) | 1516167.7 | 1232008 | 367850.7 | 126509500 |
| Partial Removal (118.66 million USD) | 924361.4 | 751117.8 | 224267.4 | 77129000 |

Table 2: Total energy consumption and gaseous emissions for complete and partial removal of Heather Platform.

From the results obtained from EIO model, it is clear that complete removal option uses more energy (39.03% more) and releases more harmful gases. Referring to the results from process LCA and EIO-LCA, it can conclude that complete removal shows no environment benefits over partial removal in terms of energy consumption and gaseous emissions. Partial removal is recommended for offshore installation decommissioning as long as the scheme is approved by local authorities and international regulations.

Similar studies had been conducted previously on LCA of high rise structure, comparing reinforced concrete and steel for the construction of Embassyview Condominium using process LCA (Ishak, 2012)and EIO-LCA (Adham, 2012). Although they were using different LCA method, both reported that the same results that the steel is more environmental friendly than reinforced concrete. This further proved that no matter which LCA methods employed, the final results on the better alternative would be the same. As in this study, both methods proved that partial removal is a better decommissioning option than complete removal in terms of energy consumptions and gaseous emissions.

## 4.3 RECOMMENDATIONS

### 4.3.1 RECOMMENDATIONS ON MARINE VESSEL UTILIZATION

As marine vessels utilization was identified to be the greatest contributor for the environmental impacts of offshore decommissioning in terms of energy consumption and gaseous emissions (especially $NO_x$ and $SO_2$), few suggestions on increasing the efficiency of marine vessels that lead to reduction of environmental impacts are proposed. IMO has adopted mandatory technical and operational energy efficiency measures which will significantly reduce the amount of $CO_2$ emissions from vessels. More researches shall be done to investigate measures to reduce gaseous emissions from marine vessels by increasing the efficiency of the vessels.

Based on the report by The International Council on Clean Transportation (2011), one of the important components of a ship’s efficiency is propeller. It generates thrust for the ship and a damaged propeller will generate additional friction that reduce overall efficiency. Propeller upgrading involves replacing the damaged properller or optimizing the pitch of controllable pitch properllers. In addition, propeller shall be cleaned and polished regulary to reduce frictional loss.

Marine vessels used shall be designed with modified hull form to help in reduction of propulsion resistance with modified propeller to enhance the propulsion efficiency. Hull cleaning shall be carried out regularly to remove marine growth between dry-dockings to reduce frictional resistance and increase energy efficiency. In addition, the researchers suggested to increase the deadweight capacity by increasing the hull size and promote the use of renewable energy, such as wind engines to generate thrust to provide some propulsion (McCollum, Gould, & Greene, 2009).

According to Winebrake (2008), reducing fuel sulfur content is essential to reduce sulfur dioxide emissions from marine vessels. Cleaner fuels shall be introduced to marine sector to control harmful emissions. As the fuel consumption and gaseous emissions of marine vessels are highly sensitive to combustion chamber conditions, engine age and maintenance, vessels loading and weather conditions, the author would suggest the decommissioning operators to plan marine vessel utilization before their operations, like location of standby and vessel loadings to avoid any wastage. The decommissioning operators should check the weather forecast daily and ensure the operation days are in good weather. Weather routing shall be adopted by vessels’ operator to determine the most fuel-efficient route by considering currents and real time sea conditions (Hustoft & Gamblin, 1995). Besides that, it is important to maintain the engine of vessels in good conditions as the aged or faulty one will consume more fuel and emit greater amount of gaseous.

### 4.3.2 RECOMMENDATIONS ON OFFSHORE DECOMMISSIONING

In order to reduce environmental impacts of offshore decommissioning, the planning stage for decommissioning shall be longer and properly managed to minimize the safety risks, reduce cost and ensure that the owners are not exposed to undesired events or any future residual liability. The decommissioning program must be compliance with current legislation and international guidelines, onshore disposal of materials prohibited from disposal at sea, removal of any materials which could generate debris that may migrate from the disposal site, minimization of underwater cutting and lifting activities and reduction of personnel risk exposure throughout the process (Hustoft & Gamblin, 1995).

The platform must be adequately prepared before platform facilities removal to reduce the risk of debris movement and future maintenance. Besides that, for topside removal, it is suggested to implement piecesmall removal rather than reverse installation using an HLV as the piecesmall method is technically feasible and more cost effective (Hustoft & Gamblin, 1995). Further investigation and researches shall be done on mechanical or explosive underwater cutting to minimize the environmental impacts associated with offshore decommissioning (Side, Kerr, & Gamblin, 1997). Pipelines and drill cutting piles are recommended to be leave in situ as improper or inadequate caution in removing those materials would reduce harmful materials, for example, heavy metal into the sea bed (Hustoft & Gamblin, 1995). Post decommissioning survey must be done immediately after the completion of decommissioning program as debris or residual may move with current (Salem Y. Lakhal, 2008).

Lately, rigs-to-reefs concept had been introduced and applied by several operators for the offshore installations decommissioning. The jacket is cut to required depth and toppled in place or towed to specific location to be leave in the sea bed as artificial reef (Na, Wan Abdullah Zawawi, Liew, & Abdul Razak, 2012). This alternative reduces costs and gaseous emissions due to reduction of marine vessel utilization and fuel consumption. It is more environmental friendly as the jacket provides habitat for marine life and protect them from illegal bottom trawlers. However, this option is still consider new to the decommissioning industry around the globe. More researches need to be done to investigate the benefits, side effects, possibilities and developments of rigs-to-reefs.

### 4.3.3 RECOMMENDATIONS ON LIFE-CYCLE ASSESSMENT

For future life cycle assessment, it is recommended to have more life cycle stages to be included into the whole process. Moreover, it is suggested to have complete set of detailed and relevant data on costs, energy consumption and gaseous emissions for offshore installations decommissioning. Data availability is always a barrier to conduct LCA analysis. Poor data would limit the validity of the results. For future assessment, the researchers must understand the type of data required and collect reliable, relevant and detailed data. If complete set of reliable and relevant data is available, the sensitivity and uncertainty analyses could be carried out at the end of assessment. Then, the important variables could be identified and the results could be verified.

During the first stage of assessment, the objectives of the study and scope or boundaries must be clearly set. Assumptions and methodology shall be consistent and documented to ensure consistency and transparency. LCA is still not popular in some of the countries. Many potential users are still not exposed to LCA and its benefits to improve their companies' operations. Awareness shall be spread and more LCA works or researches shall be published to promote the use of LCA.

## 4.4 SUMMARY

This chapter has presented the results from process LCA and EIO-LCA and the results were further discussed and elaborated. Besides that, the decommissioning activity, which is the major contributor for energy consumption and gaseous emissions was identified in this chapter. The author has proposed several measures to reduce environmental impacts and few recommendations to improve future LCA analysis. The following chapter will contain conclusions of this research and recommendations proposed by the author.

# CHAPTER 5
# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 INTRODUCTION

This chapter presents conclusions of this research that includes recap of problem statement, objectives, LCA limitations and assumptions, methodology and results from process LCA and EIO-LCA. The later part of this chapter presents measures and recommendations proposed by the author to reduce environmental impacts of offshore decommissioning and improvements on LCA analysis.

## 5.2 CONCLUSIONS

Decommissioning of offshore installations has always been an issue for the international oil industry. Since the number of platforms approaching the end of their production lives keep on increasing, it was forecasted that the decommissioning activities will increase in the years to come. Offshore installations decommissioning brings along environmental impacts that arise the concern of the society. There is minimal published works on environmental impact assessment for offshore decommissioning and framework to quantify the environmental impacts. By using LCA analysis, the decommissioning activity, which is the major contributor for total energy consumption and gaseous emissions could be identified. The main objective of this study was to determine and quantify the environmental impacts associated with offshore installations decommissioning using LCA tools, process LCA and EIO-LCA. The scope of this study was limited to two offshore decommissioning options, complete removal and partial removal. The environmental impacts focused in this study were total energy consumption and gaseous emissions ($CO_2$, $SO_2$ and $NO_x$).

For this research, Heather Platform was selected as a case study. An estimation of total energy consumption and gaseous emission associated with decommissioning of Heather Platform obtained from a published work was used as input data in performing the LCA analysis. For EIO-LCA, the cost data was obtained from a report published by Oil & Gas UK and EIO model was constructed based on the EIO mode available online.

Based on the detailed results from process LCA, the decommissioning activities, which contribute the greatest value for energy consumption and gaseous emissions, are marine vessel utilization, platform material recycling and platform running. Marine vessel utilization was found out to be the main contributor for energy consumption and gaseous emissions.

Furthermore, results from both process LCA and EIO-LCA proved that complete removal shows no environment benefits over partial removal in terms of energy consumption and gaseous emissions. Partial removal is more preferable for offshore installations decommissioning as long as this option is permitted by local authorities and international regulations.

In conclusion, all the objectives of this study were achieved that the environment impacts associated with offshore decommissioning were identified, quantified and assessed using LCA tools and both complete removal and partial removal of Heather Platform were compared in the previous chapter. Furthermore, several recommendations were proposed to reduce the environmental impacts and improve LCA analysis. The results obtained provides relative comparison for the energy consumption and gaseous emissions associated with complete and partial removal of offshore installations that shall help the platform owners to decide the appropriate decommissioning option. The findings from this research could serve as a basic framework for future LCA analysis to assess the environmental impacts of offshore decommissioning in Malaysia.

## 5.3 RECOMMENDATIONS

In order to minimize the environmental impacts associated with marine vessels utilization, the operators shall plan and manage the usage of vessels properly beforehand, ensure the operation days are in good weather, practice weather routing, increase the efficiency of vessels by performing propeller upgrading and hull cleaning.

Moreover, it is recommended to have longer and well managed planning stage to develop decommissioning scheme to reduce cost, safety risk, future residual liability and minimize environmental impacts of offshore decommissioning. The platform must be well prepared and cleaned before removal stage. For topsides removal, it is suggested to use piecesmall method rather than reverse installation using heavy lift vessels to reduce costs and safety risk of personnel.

Besides that, for life cycle assessment, it is recommended to have complete set of detailed and up-to-date data so that the results would be reliable. Sensitivity and uncertainties analysis could be done if a whole set of detailed data is available.

## 5.4 SUMMARY

This chapter has presented conclusion including recaps from previous chapters. This research examined the environmental impacts of offshore installations decommissioning; identified the problems and defined main objectives for this study; assessed and quantified the environmental impacts of decommissioning of Heather Platform using LCA tools, process LCA and EIO-LCA; compared both complete and partial removal options; discussed the results and lastly proposed recommendations to address environmental issues. Besides that, the author had proposed few recommendations for future LCA analysis in the last part of this chapter. The findings from this paper could serve as a basic framework to be used in the near future to assess the environmental impacts associated with offshore decommissioning activity in Malaysia.

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# APPENDICES

| | |
|---|---|
| Temporary Steelwork (Tonne) | Topsides Temporary Steel Used |
| | Jacket Temporary Steel Used |
| Topsides Piecesmall Dismantling Offshore (Tonne) | Structural Steel |
| | Quarters Timber / GRP (Tonne) |
| | Pipework |
| | Equipment |
| | Electrical and Instrumentation |
| | Paint and Galvanised Coatings |
| Topsides Modular Dismantling Onshore (Tonne) | Structural Steel |
| | Quarters Timber / GRP (Tonne) |
| | Pipework |
| | Equipment |
| | Electrical and Instrumentation |
| | Paint and Galvanised Coatings |
| Jacket Dsimantling Onshore (Tonne) | Steel |
| | Non-ferrous Materials (Aluminium) |
| | Other (Cement, Timber, Coating, Etc.) |
| | Marine Growth |
| Conductor Dismantling Onshore (Tonne) | Steel |
| | Other (Cement Grout) (To Landfil) |
| All Dismantling (Tonne) | Total Steel |
| | Total All Non-ferrous Material |
| | Total Others Incl. Marine Growth (To Landfill) |
| | Grand Total |
| Materials Left At Sea (Tonne) | **Topsides** |
| | Structural Steel |
| | Quarters Timber / GRP (Tonne) |
| | Pipework |
| | Equipment |
| | Electrical and Instrumentation |
| | Paint and Galvanised Coatings |
| | **Jacket** |
| | Steel |
| | Non-ferrous Materials (Aluminium) |
| | Other (Cement, Timber, Coatings, Etc.) |
| | Marine Growth |
| | **Conductors** |
| | Steel |
| | Cement Grout |
| Platform Running (Days) | Well Plugging & Abandonment (Pre-Production Shutdown) |
| | Well Plugging & Abandonment (Post-Production Shutdown) |
| | Topsides Decommissioning (Post-Well Abandonment) |
| | Topsides Removal |
| Miscellaneous | Crew Change (Helicopter Flying Manhours) |
| | Scuttled Transport Barge Weight (Tonne) |

Table showing input data variables used in evaluation of total energy consumption and gaseous emissions.

| Conversion | Unit Conversion Factor | | Source / Reference |
|---|---|---|---|
| Steel Plate and Shape From Ore | Energy Consumption | 19 GJ/t | Ogivile (1992), Iron and Steel Institute (1990), Philip et al (1995) |
| | $SO_2$ emissions | 2 kg/t | |
| | NOx emissions | 1.5 kg/t | |
| | Equivalent CO2 | 60 kg/t | |
| | CO2 emission | 2200 kg/t | |
| Steel Plate and Shape From Scrap | Energy Consumption | 5 GJ/t | Ogivile (1992), Iron and Steel Institute (1990), Philip et al (1995) |
| | $SO_2$ emissions | 1.4 kg/t | |
| | NOx emissions | 1.0 kg/t | |
| | Equivalent CO2 | 40 kg/t | |
| | CO2 emission | 360 kg/t | |
| Aluminium Plate and Shape From Ore | Energy Consumption | 154 GJ/t | Ogivile (1992), Aluminium Federation (1995), Abrahamson (1992), Cook (1995), IPCC (1995) |
| | $SO_2$ emissions | 249 kg/t | |
| | NOx emissions | 98 kg/t | |
| | Equivalent CO2 | 16160 kg/t | |
| | CO2 emission | 1400 kg/t | |
| Aluminium Plate and Shape From Scrap | Energy Consumption | 9.5 GJ/t | Ogivile (1992), Aluminium Federation (1995) |
| | $SO_2$ emissions | 7.1 kg/t | |
| | NOx emissions | 2.5 kg/t | |
| | Equivalent CO2 | 100 kg/t | |
| | CO2 emission | 55 kg/t | |
| Non-ferrous (Cu) From Ore | Energy Consumption | 140 GJ/t | Ogivile (1992), IMI Refineries (1995), US Bureau of Mines (1990) |
| | $SO_2$ emissions | 4 kg/t | |
| | NOx emissions | 4 kg/t | |
| | Equivalent CO2 | 160 kg/t | |
| | CO2 emission | 8000 kg/t | |
| Non-ferrous (Cu) From Scrap | Energy Consumption | 32 GJ/t | Ogivile (1992), IMI Refineries (1995) |
| | $SO_2$ emissions | 1.5 kg/t | |
| | NOx emissions | 1.5 kg/t | |
| | Equivalent CO2 | 60 kg/t | |
| | CO2 emission | 4000 kg/t | |
| Engine Diesel | Calorific Value | 45.4 GJ/t | Munday and Farrar (1989), Brown and Root (1993) |
| | $SO_2$ emissions | 5 kg/t | |
| | NOx emissions | 5.8 kg/t | |
| | Equivalent CO2 | 238 kg/t | |
| | CO2 emission | 3100 kg/t | |
| Marine Diesel | Calorific Value | 45.4 GJ/t | Munday and Farrar (1989), Bouscaren (1990), Van Der Most (1990), Alexandersson (1990), Melhus (1990) |
| | $SO_2$ emissions | 45 kg/t | |
| | NOx emissions | 45 kg/t | |
| | Equivalent CO2 | 1905 kg/t | |
| | CO2 emission | 3100 kg/t | |
| Propane | Calorific Value | 50 GJ/t | Munday and Farrar (1989) |
| | $SO_2$ emissions | 0 kg/t | |
| | NOx emissions | 3 kg/t | |
| | Equivalent CO2 | 120 kg/t | |
| | CO2 emission | 3007 kg/t | |
| Aviation Fuel | Calorific Value | 46.5 GJ/t | Munday and Farrar (1989) |
| | $SO_2$ emissions | 8 kg/t | |
| | NOx emissions | 20 kg/t | |
| | Equivalent CO2 | 800 kg/t | |
| | CO2 emission | 2840 kg/t | |

Table showing the unit conversion factors for energy consumption and gaseous emissions for recycling process, engine usage, propane and aviation fuel usage used in process LCA and their respective references.

| Haulage Constants And Factors | Value |
|---|---|
| **Onshore Haulage Roundtrip Distance (Miles)** | |
| Steelmile to fabrication site | 500 |
| Onshore dismantling site to landfill | 100 |
| Onshore dismantling site to scrap vessel loading site | 20 |
| Scrap vessel unloading site to smelter | 10 |
| Piecesmall landfill to landfill | 100 |
| Piecesmall landfill to scrap vessel loading site | 20 |
| **Onshore Haulage Factors** | |
| Average truck fuel consumption (M/Ltr) | 1.8 |
| Average truck load (Tonne) | 20 |
| Additional percentage fuel consumption allowance for loading and offloading (%) | 10 |
| **Scrap Vessel Roundtrip Distance (Miles)** | |
| Onhire site to offhire site | 800 |
| **Scrap Vessel Haulage Factor** | |
| Average vessel fuel consumption (Tonne MDO/Mile) | 0.035 |
| Maximun cargo capacity (Tonne) | 5000 |
| Additional percentage fuel consumption allowance for loading and offloading (%) | 20 |

Table showing onshore and scrap vessel haulage round trip distances, fuel consumptions and payloads for process LCA.

| **Decommissioning phase** | Average Daily Fuel Consumption (Tonne DO/Day) |
|---|---|
| Well plugging & abandonment (Pre-production shutdown) | 17.4 |
| Well plugging & abandonment (Post-production shutdown) | 17.4 |
| Topsides decommissioning (Post-well abandonment) | 7.2 |
| Topsides removal | 7.2 |

Table showing the average daily fuel consumption for platform operation during decommissioning phases considering the platform minimum facility would be in operation for process LCA.

| Unit Conversion Factors (Fabrication and Dismantling) | Propane Consumption (Kg/Tonne) | Diesel Consumption (Ltr/Tonne) |
|---|---|---|
| **Temporary Steelwork** | | |
| Fabrication | 0.5 | 5 |
| Dismantling | 2.4 | 11 |
| **Topsides Piecesmall Dismantling Offshore** | | |
| Structural steel | 2.4 | 14.5 |
| Quarter timber/GRP | 0 | 14.5 |
| Pipework | 2.4 | 14.5 |
| Equipment | 0.6 | 14.5 |
| Electrical and instrumentation | 0 | 14.5 |
| **Topsides Modular Dismantling Onshore** | | |
| Structural steel | 2.4 | 11 |
| Quarter timber/GRP | 0 | 11 |
| Pipework | 2.4 | 11 |
| Equipment | 0.6 | 11 |
| Electrical and instrumentation | 0 | 11 |
| **Jacket Dismantling Onshore** | | |
| Steel | 2.4 | 11 |
| Non-ferrous materials | 0 | 11 |
| Marine growth | 0 | 11 |
| Other materials | 0 | 11 |
| **Conductor Dismantling Onshore** | | |
| Steel | 2.4 | 11 |
| Cement grout | 0 | 11 |

Table showing fuel consumption conversion factors for propane and diesel fuel consumption during fabrication and dismantling works both onshore and offshore for process LCA.

| | |
|---|---|
| Helicopter Fuel Consumption | 37 Ltrs Jet A-1 Fuel/Passenger Flying Hour |

Table showing helicopter fuel consumption factor for process LCA.

| Vessel | Average Daily Fuel Consumption By Location (Tonne MDO/Day) | | | |
|---|---|---|---|---|
| | In Port | In Transit | Working | W.O.W. |
| Diving suport vessel (Jacket) | 3 | 20 | 10 | 10 |
| Heavy lift vessel (Topsides) | 20 | 60 | 35 | 35 |
| Anchor handling tug for HLV | 2 | 10 | 10 | 10 |
| Semi-submersible crane vessel (Jacket) | 50 | 100 | 50 | 50 |
| Anchor handling tug for SSCV | 2 | 10 | 10 | 10 |
| Multi-support vessel (Topsides) | 2 | 20 | 25 | 25 |
| Multi-support vessel (Jacket) | 2 | 26 | 25 | 25 |
| Cargo barge tug (Topsides) | 2 | 10 | 10 | 10 |
| Cargo barge tug (Jacket) | 2 | 10 | 10 | 10 |
| Launch barge tug (Topsides) | 2 | 15 | 15 | 15 |
| Launch barge tug (Jacket) | 2 | 15 | 15 | 15 |
| Special tug (Jacket) | 3 | 22 | 15 | 15 |
| Flotel (Topsides) | 10 | 40 | 20 | 20 |
| Safety boat | 1 | 8 | 4 | 4 |
| Supply boat | 2 | 10 | 5 | 5 |

Table showing average daily fuel consumption by a range of marine vessel used for four locations of in post, in transit, working at site and waiting the weather at site during decommissioning process for process LCA.

| Variable | Decommissioning Aspect | Complete Removal | Partial Removal |
|---|---|---|---|
| Energy Consumption (GJ) | Temporary steelwork | 25286 | 17739 |
| | Platform facility dismantling | 29395 | 15790 |
| | Marine vessel utilisation | 554561 | 325382 |
| | Platform running | 143963 | 117105 |
| | Helicopters | 17893 | 12388 |
| | Platform materials recycling | 168380 | 97035 |
| | Platform materials left at sea | 0 | 295870 |
| | **All Decommissioning Aspects** | **939479** | **881309** |
| NOx Emissions (Kg) | Temporary steelwork | 5276 | 3707 |
| | Platform facility dismantling | 11641 | 6331 |
| | Marine vessel utilisation | 549675 | 322515 |
| | Platform running | 18392 | 14961 |
| | Helicopters | 7696 | 5328 |
| | Platform materials recycling | 31638 | 17243 |
| | Platform materials left at sea | 0 | 41385 |
| | **All Decommissioning Aspects** | **624318** | **411470** |
| $SO_2$ Emissions (Kg) | Temporary steelwork | 6608 | 4641 |
| | Platform facility dismantling | 11145 | 6070 |
| | Marine vessel utilisation | 549675 | 322515 |
| | Platform running | 15855 | 12897 |
| | Helicopters | 3078 | 2131 |
| | Platform materials recycling | 45313 | 24404 |
| | Platform materials left at sea | 0 | 80030 |
| | **All Decommissioning Aspects** | **631674** | **452688** |
| $CO_2$ Emissions (Kg) | Temporary steelwork | 1703231 | 1194887 |
| | Platform facility dismantling | 1979619 | 1064222 |
| | Marine vessel utilisation | 37866500 | 22217700 |
| | Platform running | 9830100 | 7996140 |
| | Helicopters | 1092832 | 756576 |
| | Platform materials recycling | 12677080 | 7672330 |
| | Platform materials left at sea | 0 | 30808000 |
| | **All Decommissioning Aspects** | **65149362** | **71709855** |
| Equivalent $CO_2$ Emissions (Kg) | Temporary steelwork | 214139 | 150488 |
| | Platform facility dismantling | 489557 | 266270 |
| | Marine vessel utilisation | 23269575 | 13653135 |
| | Platform running | 754698 | 613897 |
| | Helicopters | 307840 | 213120 |
| | Platform materials recycling | 1265520 | 689720 |
| | Platform materials left at sea | 0 | 4225800 |
| | **All Decommissioning Aspects** | **26301329** | **19812430** |
| Overall $CO_2$ Emissions (Kg) | Temporary steelwork | 1917370 | 1345376 |
| | Platform facility dismantling | 2469176 | 1330492 |
| | Marine vessel utilisation | 61136075 | 35870835 |
| | Platform running | 10584798 | 8610037 |
| | Helicopters | 1400672 | 969696 |
| | Platform materials recycling | 13942600 | 8362050 |
| | Platform materials left at sea | 0 | 35033800 |
| | **All Decommissioning Aspects** | **91450691** | **91522286** |

Table showing energy consumption and gaseous emissions for each decommissioning aspects for both complete and partial removal.

| | **Sector** | **Total Energy TJ** |
|---|---|---|
| | *Total for all sectors* | *7.79* |
| 213112 | Support activities for oil and gas operations | 2.11 |
| 221100 | Power generation and supply | 1.46 |
| 331110 | Iron and steel mills | 0.785 |
| 211000 | Oil and gas extraction | 0.493 |
| 327310 | Cement manufacturing | 0.412 |
| 324110 | Petroleum refineries | 0.259 |
| 484000 | Truck transportation | 0.211 |
| 325190 | Other basic organic chemical manufacturing | 0.172 |
| 322130 | Paperboard Mills | 0.135 |
| 486000 | Pipeline transportation | 0.113 |

Table showing total energy consumption (TJ) for EIO standard model.

| | **Sector** | **NOx t** | **SO2 t** |
|---|---|---|---|
| | *Total for all sectors* | *6.33* | *1.89* |
| 213112 | Support activities for oil and gas operations | 5.03 | 0.886 |
| 331110 | Iron and steel mills | 0.050 | 0.038 |
| 532400 | Commercial and industrial machinery and equipment rental and leasing | 0.005 | 0.002 |
| 211000 | Oil and gas extraction | 0.152 | 0.010 |
| 327310 | Cement manufacturing | 0.196 | 0.144 |
| 221200 | Natural gas distribution | 0.006 | 0.002 |
| 484000 | Truck transportation | 0.136 | 0.003 |
| 331200 | Iron, steel pipe and tube manufacturing from purchased steel | 0.007 | 0.005 |
| 33131A | Alumina refining and primary aluminum production | 0.002 | 0.015 |
| 333920 | Material handling equipment manufacturing | 0.011 | 0.000 |

Table showing $NO_x$ and $SO_2$ emissions (Tonne) for the EIO standard model.

| | **Sector** | **Glob Warm kg CO2e** |
|---|---|---|
| | *Total for all sectors* | *650000* |
| 213112 | Support activities for oil and gas operations | 139000 |
| 221100 | Power generation and supply | 120000 |
| 211000 | Oil and gas extraction | 82300 |
| 327310 | Cement manufacturing | 71200 |
| 331110 | Iron and steel mills | 67700 |
| 484000 | Truck transportation | 15500 |
| 324110 | Petroleum refineries | 15500 |
| 212100 | Coal mining | 12500 |
| 325120 | Industrial gas manufacturing | 10400 |
| 486000 | Pipeline transportation | 9410 |

Table showing overall $CO_2$ emissions (Kg) for the EIO standard model.