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MASTER THESIS

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Abbreviations

CE	Circular Economy
BOP	Blowout Preventer
VOC	Volatile Organic Compound
OSPAR	Oslo / Paris convention (for the Protection of the Marine Environment of the North-East Atlantic)
CoP	Cessation of Production
AM	Asset Management
EoL	End of Life
BoL	Beginning of Life
MoL	Middle of Life
NRV	Net Recovery Value
O&G	Oil and Gas
GDPR	General Data Protection Regulation

Abstract

The CE has been fast erupting in terms of its relevance. It has tried to be implemented to achieve sustainable development and most importantly, reap economic benefits since it is reflected as attractive for business but it has not been implemented to its full potential.

Due to a lack of awareness and understanding of the impacts of CE, theoretical knowledge was gathered and it was necessary to do a literature review. A question-based survey was conducted as well; however, the survey findings were inconclusive as a result of insufficient participants.

As a case study, a further study was discussed on oil and gas asset decommissioning and how it is impacted by the CE. Considering the numerous years an oil and gas project could be running, the field production eventually ends after which the assets or equipment on the platform will have to be removed. A lot of materials are obtained in this phase of the oil and gas projects. An amount of the platform structures and equipment offshore are transported to onshore where a good amount is recycled, and the rest is being disposed of in landfills as scrubs. These practices are not environmentally and economically friendly and therefore the Circular Economy comes in to save the day by various methods such as refurbishment, reusing, remanufacturing and repurposing rather than abandoning the equipment or just recycling.

Another aspect of the thesis was mainly on developing a CE assessment tool. The CE assessment tool was built based on literature and theoretical knowledge gathered. It was focused on the decommissioning phase of the assets where the End of life(EoL) stage has been reached. Two study cases or examples were used to demonstrate the two functionalities of the CE assessment tool.Other functionalities of the tool were summarised as well.

Finally, a product development process framework in terms of the CE applied to equipment/product in their EoL phase was developed.It was developed on basis of a generic product development process consisting of six phases and based on CE concepts and theoretical knowledge.The objective of the framework is to be able to have a structured plan for when products are to be looped into the CE when they reach their EoL phase to extend their life.

Table of Contents

List of Tables

Table of figures

1 Introduction

A small amount of oil and gas is found near the earth's surface but the majority are found very deep underground on land and deep underwater in the seabed. The oil and gas industry has been around for several decades, taking offshore platforms, for example, there are over 6500 offshore oil and gas platforms spread across the Gulf of Mexico, Asia, Northeast Atlantic, North Sea, and the Middle East (Osmudsen & Tveteras, 2003). On these platforms, there is equipment such as drill pipes, blowout preventers, mud pumps, travelling blocks, rotating oil and gas equipment, motor (power source), shale shaker, mud tank, drill bits, etc. Many platforms and rigs are to reach their completion stage or have already reached where there will be the removal of all the equipment. The process of removal of the equipment and the platform is termed decommissioning and the process comes with some consequences that impact environmentally, economically, and socially. After decommissioning, a lot of the equipment becomes a potential source of the material. The image represents the number of platforms and tonnage of steel that can be obtained in various oil and gas platforms around the North sea.

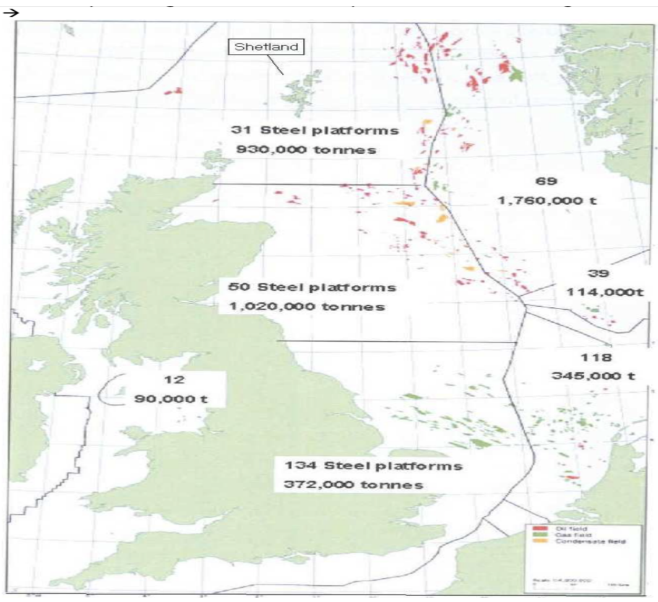


Figure 1.1: Image represents the number of platforms and tonnage of steel that can be obtained.

Source: Scottish Enterprise Energy Team, “Offshore Decommissioning: Opportunities for Scottish Based Businesses”, 2002, Pg14

1.1 Problem Statement

Decommissioning an offshore installation takes a long time and requires a lot of energy. Asset decommissioning has several impacts on the environment, according to an impact assessment done in the Rose field, decommissioning calls for energy consumption in both offshore and onshore which results in gaseous emissions such as Carbon dioxide (CO_2) Nitrogen Oxides (NO_x), Sulphur dioxide, SO_2 and VOC in the atmosphere which results in the formation of photochemical pollution in the presence of sunlight, comprising low-level ozone (Centrica Energy, 2015).

Depending on the mode of decommissioning, be it partial or complete removal of oil and gas assets, there are environmental as well as economically unfriendly consequences. A new report by Malgorzata Olesiewicz, an energy business analyst and Sam Gomersall, a commercial director discussed the potential value a CE could bring to the decommissioning market where there was a review that the industrial economic system has been solely based on the 'linear' throughput of materials, that is, essentially focusing on production but then considering a reverse of the process would have nothing valuable to retrieve and CE, on the other hand, emphasises on sustainable economic development by implementing the model "resource-product-regenerated resource" which is all about reducing the waste production. They also stated that many multinational businesses have endorsed the Circular Economy approach, however, the adaptation in the oil and gas sector has been limited. (Pixie Energy & Scottish Energy News, 2021). A good amount of the platform asset is recycled (Centrica Energy, 2015) which consumes more energy and reduces the value of equipment and that means new equipment must be purchased or manufactured for every new platform to be constructed. Reusing which is more lucrative for business and environmentally friendly is exempted and this brings about the question of how decommissioning different assets can be improved by implementing CE depending on how safe the equipment will be according to technical safety standards especially for oil and gas assets.

1.1.1 Aims and Objectives

- Literature Review
- Survey on CE in asset decommissioning in the oil and gas industry
- Formulating a CE assessment tool
- Application of the assessment tool to two cases to illustrate the two functionalities of CE assessment tool
- CE Product development process

1.1.2 Limitations

- CE Assessment is focused only on reuse, repurposing, recycling, remanufacturing and refurbishment since these strategies are the most relevant for the assessment needed.
- The CE loops or strategies discussed in this research are focused on the technological cycle of the CE, not on the biological cycle.
- Some of the data used to demonstrate the first functionality of the assessment tool in the *first study case*(i.e internal floating roof tank) were assumed by using the cost of a floating roof tank to estimate other costs such as disassembly cost, repair cost, etc since obtaining the specific costs had to be obtained directly from companies.

1.2 Thesis outline

Chapter 1: This chapter discusses the general overview of how the CE has been implemented so far in the oil and gas industry and makes a problem statement about how the CE can be implemented in the most effective way.

Chapter 2: A literature review on the impacts of the CE on asset management, technical safety and asset decommissioning.

Chapter 3: This chapter provides explanations of the main concepts of this thesis.

Chapter 4: Describes and gives results of a survey conducted on targeted companies in the oil and gas industry about the CE in asset decommissioning.

Chapter 5: Proposing and developing a CE assessment tool with two functionalities of the tool explained and implemented in two different case studies.

Chapter 6: Developing a product development framework for implementing CE to products/assets/equipment in the decommissioning phase purposely for life extension.

Chapter 7: Conclusion

Chapter 8: Projecting into the future on upgrades that can be made to the CE assessment tool to increase precision.

2 Literature review

An analytical literature review was conducted to research papers on the current progress and trends on the impact and relationship the Circular Economy has on technical safety, assessment management and decommissioning as a whole and with respect to the oil and gas industry. Scopus was chosen for the search since research is focused on the Engineering field. In order to put the information gathered into perspective, the first set of keywords was: “Circular Economy” AND “Asset Management”. 74 Search results were obtained and 15 were selected for review since they were in proper relation to the subject matter. The disposed ones were either focused on other theories that were not necessarily in strong link with CE and AM even though they were stated a few times in the papers. Upon reviewing a relevant paper, an issue came across (Hanski, 2020) which is highly relevant in the Architectural, Constructional, and Engineering sectors. In terms of AM, most equipment has been designed in a way that does not encourage the implementation of reuse/repurposing strategies due to certain barriers. Solutions such as modification of designs and manufacturing have been proposed to enable easy dismantling.

(Sanchez & et al., 2020; Haas & et al., 2019, Sanchez & et al, 2019) have a respectable number of citations making it vital in the subject of interest. The papers discussed how an adaptive reuse strategy from CE can increase the value of assets in use and increase their usability throughout their lifecycle. According to these papers, this approach is particularly designed for building components which makes it partially relevant to this thesis.

A number of papers with respect to the assessment model for the usability of CE strategies were written (Xing & et al., 2020; Charef, 2022; Abrishami & et al. 2021; Eshamaiel & et al., 2019). They have a decent number of citations which means a decent amount of interest in the topic direction. They elaborate on the use of Building Information Modelling (BIM) to produce the feasibility of a CE strategy applied to the lifecycle of an asset for the best outcome in terms of cost and lifetime. It is a high-level approach to producing a decision for the most suitable circularity approach. However, this tool/model is narrowed and only specific to building structures and materials. This is somewhat limited and hence cannot benefit other industries.

CE and AM integration essentially improve the lifetime of assets bringing about economic benefits according to three papers under review (Hanski, 2020; Acerbi, 2020; Järnefelt, 2019).

This stands as a vital point considering the positive impact CE has on AM and projecting into the future as well.

Another major paper that indirectly highlighted the impact of CE on AM and has a sizable number of papers that have referenced it, (Chiar, 2017). It was researched that it is possible to use old components as spare parts in a sustaining maintenance plan for assets to ensure the reliability and safety of industrial assets. It can be thought through that using CE can enhance maintenance efficiency on assets.

The second phase of the literature search was using the keywords: “Circular Economy” AND “Technical Safety”. Just 36 results were found; to expand my search horizon, a keyword combination of “Circular Economy” AND “Technical Safety” OR “Safety analysis” was used and 150 results were obtained however after careful screening, less than 4% were concerning the subject matter. This is to be understood that not much effort has been put into understanding safety with respect to CE.2 papers elaborated on how the designing of equipment has been influenced by the introduction of CE (that is, reusing, remanufacturing, etc.) to ensure a much safer and sustainable design of equipment (Bertoni, 2020; Wahab & et al., 2018). This suggests a critical point that needs to be considered in the designing phase of equipment if CE is to be implemented in the future.

A paper emphasised a recent trend that the recycling/reusing of some materials that may contain hazardous substances has not especially been focused on. However, new risk management strategies such as REAC(EU-OSHA, n.d), as mentioned in the paper, analyse hazardous substances through a transparent policy platform to make decisions as to whether certain materials should be authorised or restrictions must be placed on them to be reused/recycled. It is critical to carefully analyse the substances that could be included in materials to be looped through another lifecycle, however, it is not discussed in papers.

In the third phase of reviewing; the reviewing process used the search terms; “Circular Economy” AND “Decommissioning” to search within the article title, abstract and the content of the article itself.30 contributions were found and about 7 documents discussed the implementation of reuse and refurbishment of wind turbines and blade waste in the decommissioning process, 1 was focused on re-entering the market to sell old buildings focused on prefabricated buildings in terms of decommissioning,

5 of the documents focused on CE, especially reusing components of energy infrastructure where it was being investigated on how to make reusing much easier to implement by applying modularization of infrastructure parts and the rest focused on general decommissioning without

necessarily having a link with the circular economy. The search was narrowed down by introducing an additional phrase; “oil and gas”. This yielded 8 contributions and they were

scrutinised by reading the titles and abstracts of each one of them. To further specialise in the search, some criteria had to be met, that is, studies addressing:

(i) Decommissioning by implementing the CE concept and (ii) oil and gas industry.

It cut down to four contributions, (Fabio, 2021), (Dawson et al.,2020), (Wan,2018), (Francesca, 2017) and (Vincenzo et al., 2021),

(Fabio, 2021) was all about decommissioning and CE in the oil and gas industry however it based its analyses on comparing decommissioning and CE by different analytical methods such as multi-criteria analysis (MCA), and cost-benefit analysis (CBA), weighted life-cycle assessment (WLCA), and monetary life-cycle assessment (MLCA). The approach was about being able to decide between the CE and decommissioning but not necessarily incorporating the two concepts.

Another contribution was made in a conference paper on “A global push for circular economy projects ", (Dawson et al., 2020) which described how the CE could be incorporated into one aspect of the oil and gas industry, that is, exploration and production which is usually in the early phase of an oil and gas project. This omits decommissioning or how CE can be incorporated into decommissioning for the most part.

One more conference paper, (Wan, 2018) discussed different approaches to minimising decommissioning costs in the North Sea where one of the ways was to implement the principles of CE which brought about the finding, that value is increased by five to seven times if reuse of platform equipment is implemented over recycling. This was a good finding; however, no further investigation was done to find out the possibility and compatibility of implementing reusing on certain platform equipment since we cannot assume every platform equipment is suitable, compatible or safe to be reused.

An article on the reuse of oil and gas platforms, (Francesca, 2017). It was focused on reusing hydrocarbon platforms after their end of life to load and unload Liquified Natural Gas (LNG) onto ships taking into consideration Italian regulatory developments and technical knowledge to make it possible.

Another article, (Vincenzo et al., 2021), about the usefulness of a business model innovation (BMI) by accessing a conceptual tool, sustainable business model canvas (SBMC) which was implemented on an offshore platform decommissioning and incorporating the CE concept. With this approach, it rendered several multiuse approaches to the platforms during decommissioning. Even though the CE was implemented, there was no model to analyse and determine the suitability of each of the different CE loops applied to various equipment.

CE and Decommissioning have a lot of articles being focused on them individually, there are considerably few works of literature written when it comes to incorporating CE into decommissioning, especially when considering the oil and gas industry. This has deemed it necessary to analyse and select the most suitable of the various loops of CE for different equipment in diverse industries during the decommissioning phase.

3 Theoretical Background

In this section, the concept of CE will be discussed to have a better understanding of the impact it has on technical safety and asset management. Understanding decommissioning and how it is influenced by CE will also be discussed.

3.1 What is Circular Economy?

Circular Economy (CE) theory comes in to play a significant role by reducing the act of wasting the materials and equipment during decommissioning in a way as to be able to reduce the negative environmental impact and improve the economic value of the materials and equipment. The Circular Economy concept replicates the natural life cycle where nothing goes to waste but becomes a source of food for other living organisms. With this rationale, waste of materials is managed and the cost of production is less since the materials or equipment can be refurbished, reused, or recycled. Essentially, CE implies that materials or equipment have a life cycle with a beginning, middle, end, and back beginning repeating the cycle, therefore contributing less waste and can add value to their ecosystem.

As discussed earlier, CE is a continuous cycle with the primary aim to minimise waste, however, there are several different cycles that form different loops and together form a butterfly diagram because of the shape.

On the right-hand side is the biological cycle and on the left-hand side is the technical cycle. Overall, feedback is vital for the continuous process of any of the CE loops or cycles. Feedback is about making value out of materials that seem to have come from products that have been used up. Rather than having these materials or resources lost from the economy they can return safely and positively into the system and rebuild or restore natural capital. Considering the biological cycles, the feedback is biological materials such as food, clothing, etc. that can return to a natural system, but the focus here would be more on the technical cycle. It comprises 4 main loops.

- Recycling
- Remanufacturing/refurbishing
- Reuse/redistribute
- Maintenance/repair

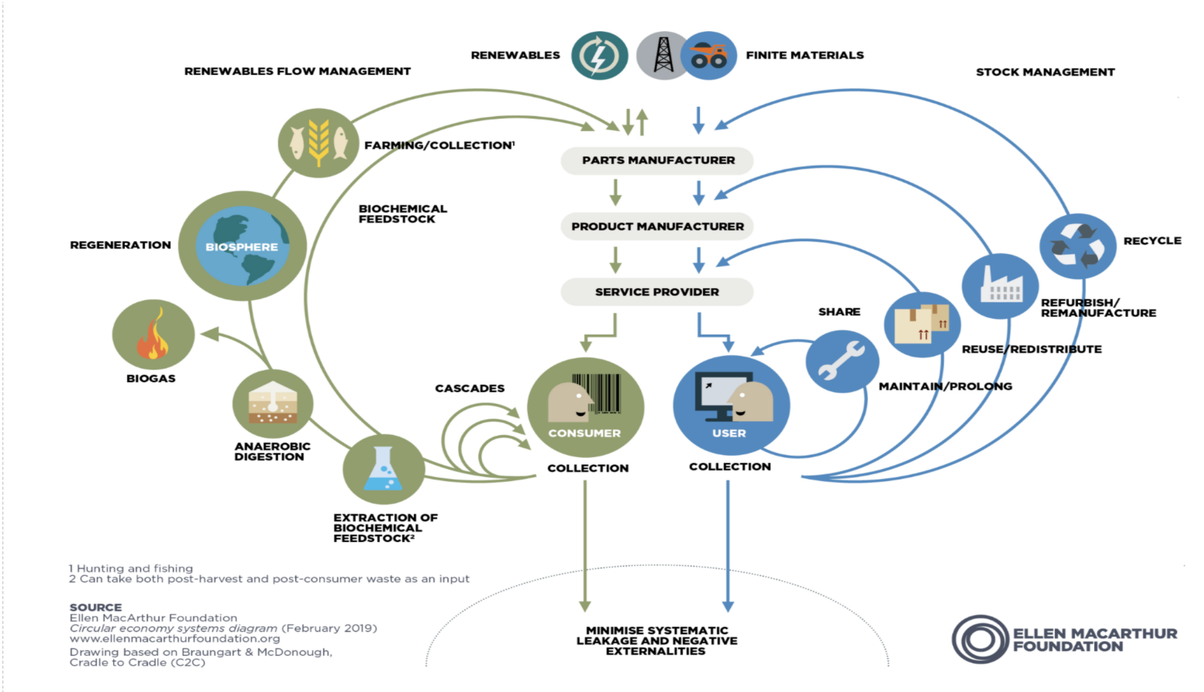


Figure 3.1 Butterfly diagram of Circular Economy

Source: Ellen MacArthur Foundation. (February 2019). Retrieved from https://ellenmacarthurfoundation.org/circular-economy-diagram

The *recycling* loop is the outermost loop. It is about taking the materials and passing them through the traditional recycling process, that is, taking waste materials and converting them into useful materials and objects (Wikipedia, 2022) however, this loop is also known as the "loop of last resort", (Ellen MacArthur Foundation, 2019). This is because even though recycling manages waste, taking a product or equipment and returning it to the materials that it was made of would reduce the value of the product and may even be expensive. On the other hand, the inner loops maintain the value of the product for better business and at the same time manage waste. There is the *remanufacturing/refurbish* loop. This is where a product, equipment, or its components are restored as new or even better than when it was new. The difference between refurbishment and remanufacturing is that remanufacturing is using discarded components of equipment or product to produce a new one and refurbishment is upgrading or updating an existing product or equipment. For example, oil and gas equipment such as BOP are refurbished to extend the life of the equipment (Surface Technology, 2022). Another inner loop is the *reuse/redistribute* loop. By definition, reuse is the act of using an item again for its original purpose (conventional reuse) or for a different function or purpose(repurposing), however, redistribution is when the equipment is given out to be reused by other entities (other individuals or companies)(Ellen MacArthur Foundation, 2022). This is a more familiar practice, a basic example is eBay, where people sell their old possessions and are used again by interested people on the market. There is not an adding of extra energy, labour, or materials in terms of returning the equipment or product to the economy. In reference to oil and gas equipment, a drill bit can be reused on another project depending on its condition rather than acquiring a new one where in this case, capital for the next project is minimised and no waste obtained. Another loop is the *maintenance/repair* loop where a piece of equipment is used intensively and could be maintained to be used for a prolonged period by repairing any damaged parts without having to take it through remanufacturing (Ellen Macarthur Foundation, 2019). According to CE principles illustrated by (Stahel. 2013), smaller loops (reuse, repair, remanufacturing(reconditioning)) are more profitable, efficient in the use of resources, and more cost-effective compared to the larger loop (recycling). It was also stated that “don’t repair what is not broken, don’t remanufacture what can be repaired, don’t recycle what can be remanufactured” (Stahel, 2013).

CE has been trying to be implemented in the oil and gas industry. A report produced by Green Alliance (Benton, 2015) from the UK in collaboration with the Scottish Council for Development and Industry in which they discussed many ways CE can be implanted in the oil and gas industry. One of the ways was to apply the recycling loop which is the last CE option is by improving the separation of high-quality metal alloys. Another option was to implement the reuse loop where the equipment is made known to be available to interested buyers at least a year beforehand for easy purchase. Another peculiar way that was discussed was to reuse pipelines to transport CO_2 instead of other gas, therefore, making pipelines useful again rather than removing them.This is considered as repurposing.

With all the assorted options available to implement the CE, it is very crucial to analyse its impact in terms of business feasibility, environmental compatibility, and technical safety.

3.2 What is decommissioning?

In the oil and gas sector, asset decommissioning is the process of ending offshore oil and gas operations ; usually, during decommissioning, the platform is completely removed, and the seafloor is returned to its unobstructed pre-lease condition. (Bull et al.,2019). It is the late-life stage where processes are carried out after the Cessation of Production (CoP). It is very energy and time-consuming as well as a risky and expensive process. According to Wood Mackenzie, decommissioning costs worldwide will be about 104.5 billion US dollars by 2030. (Khalidov et al.,2021)

Decommissioning has been around in the oil and gas industry for decades, however not until 1995, that it became popular whereby the concept was tried to be understood as well as the impact it has. Going back to 1991, Royal Shell tried to implement decommissioning on a North Sea oil tanker and storage loading in the Brent oilfield, Brent Spar, that was out of operation. There were two decommissioning approaches proposed by Royal Shell which were approved by the UK Department of Trade and industry but there was an extraordinarily strong opposing force coming from Greenpeace, an independent international campaigning organisation. It took 4 years to complete the Brent Spar decommissioning process, 1996-1999. Shell underestimated the process by assuming it was just a private process within the company without considering the existing national rules and regulations as well as international concerned organisations compared to previous times. (Shell Int., 2008) and led to a revision of the decommissioning method.

In 1998 UK, Norway and the Convention for Protection of the Marine Environment of the North-East Atlantic, OSPAR Convection together with the rest of Europe agreed on a fundamental decommissioning method for offshore platforms which was to dispose of equipment onshore (Pulsipher & Daniel IV, 2000). There was another agreement in conjunction with policies passed by the United Nations Law of the Sea (UNCLOS). This has been the most important law applicable in the North Sea,(Hamzah, 2003).

Another Organization to be stated, is the International Maritime Organization (IMO), a specialised agency of the United Nations. This organisation was responsible for setting standards and regulations for the safety, security and environmental performance of international shipping (IMO, 2014). With the laws applied, decommissioning was channelled to have offshore platforms completely removed and transported onshore for recycling, disposal, or reuse. However, it did not apply to every platform. (Osmudsen & Tveteras, 2003). Briefly, the decommissioning options on platforms are either a complete, partial removal or leave in place.

3.2.1 Decommissioning Process

As was stated earlier, decommissioning is an entire process in a stepwise manner. It varies depending on the location and laws within that region. We consider the North Sea here. The platform can be categorised into three different sections, that is, the pipelines, drill cuttings pile and the main platform installation. The platform itself comprises a topside that is placed on a concrete gravity base or a steel jacket. Part of the structure or the entire structure is transported onshore depending on the decommissioning option that was chosen. In a case where it is a partial removal option, the remaining structure in situ is left to fall apart over time for over 100 years. (Pors et al. 2011)

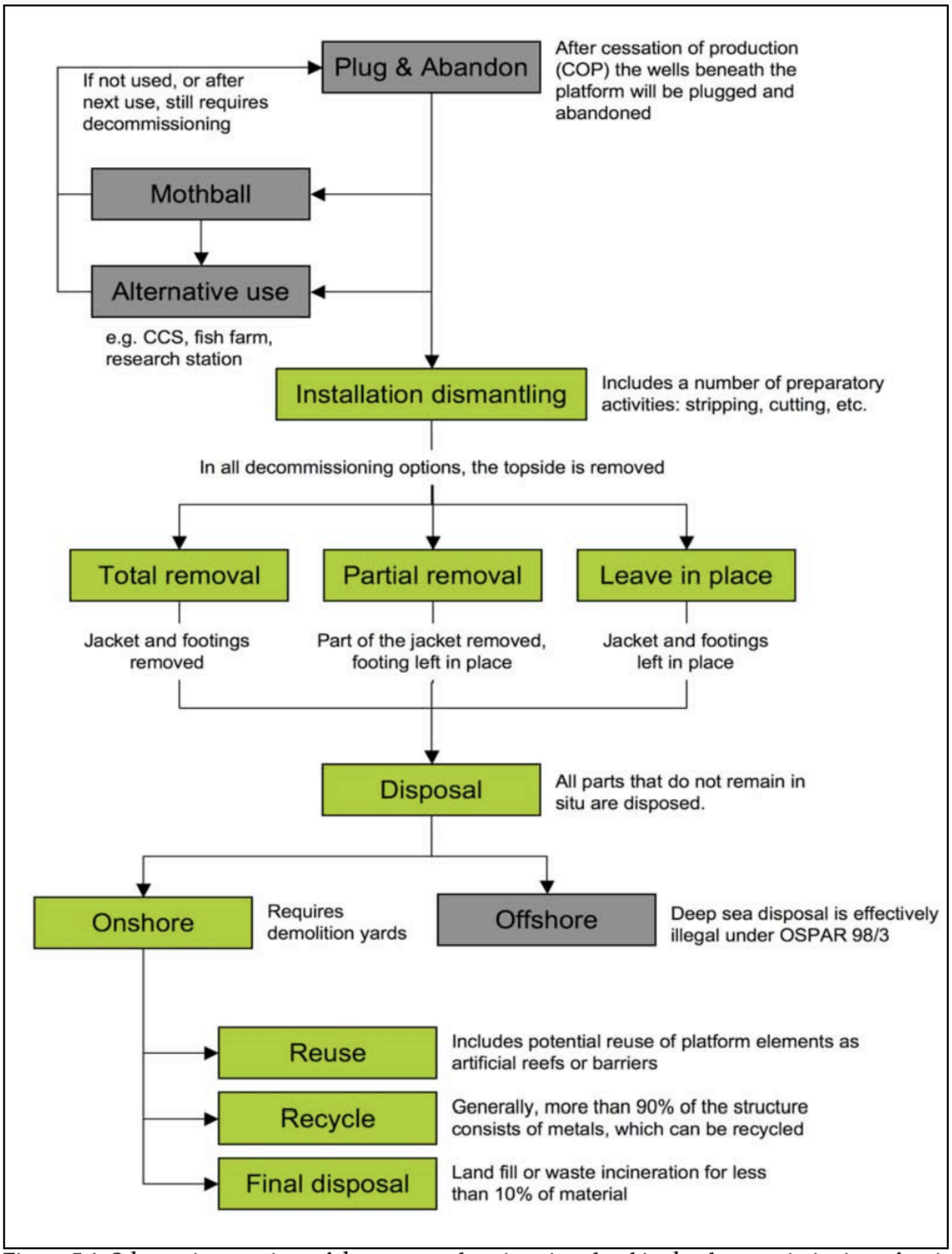


Figure 3.2: Overview of the decommissioning process with all three different options Source: IMSA Amsterdam, Sustainability and Innovation "Decommissioning of North Sea oil and gas facilities: An introductory assessment of potential impacts, costs and opportunities," 2011.

Most of the platform structure and equipment are recycled and the good part of the remainder is left to go to waste. This brings a lot of concerns as besides the negative environmental impact it has, it is not the best way to maximise profit. By applying the concept of lean thinking, waste can be minimised to increase profit margin (Luis, 2018).

3.3 Impact of CE on decommissioning of oil and gas assets

More work and research are done to refurbish and reuse equipment from both subsea and topside platforms. Recently, the circular economy is beginning to attract the oil and gas industry considering its potential benefits. It has been tried to be implemented in decommissioning of the platform equipment and other assets. Even though the oil and gas industry tries to implement the reuse/repurpose loop of CE, for example, according to Getech, in Malaysia, a jack-up oil rig was converted into a diving centre for marine aficionados (Getech, 2021), CE applied in the oil and gas industry is mostly implementing the recycling loop ,however there are efforts made to implement more of reuse and refurbishment over recycling when appropriate.

Surveys were conducted by a technology company for oil and gas operators. According to the assessment made between resellers and oil and gas operators, about 10-15% of models/equipment from the inventory could be reused sufficiently (Decom North Sea et al., 2015). The aim was to assess old oil and gas assets and equipment that can be reused or refurbished to their new state or even better. Besides reducing waste, this practice would help in reducing the use of new raw materials for the manufacturing of similar equipment which could be reused. (Zero waste Scotland et al., 2015). Decommissioning is a process where planning is required and by implementing CE, decommissioning planning can be more effective rather than following the traditional mode of decommissioning during the end of life. There are instances where re-purpose or reusing could be encouraging since it will contribute to the net-zero energy system or could be beneficial in other ways. By understanding the concept of Reuse/repurpose, operators or infrastructure owners would be able to make an informed decision as to whether to use the traditional decommissioning process or implement reuse/repurpose. (Oil & Gas Authority).

A strategy implementing CE (i.e., reuse/repurposing) in decommissioning planning is illustrated in the diagram below.

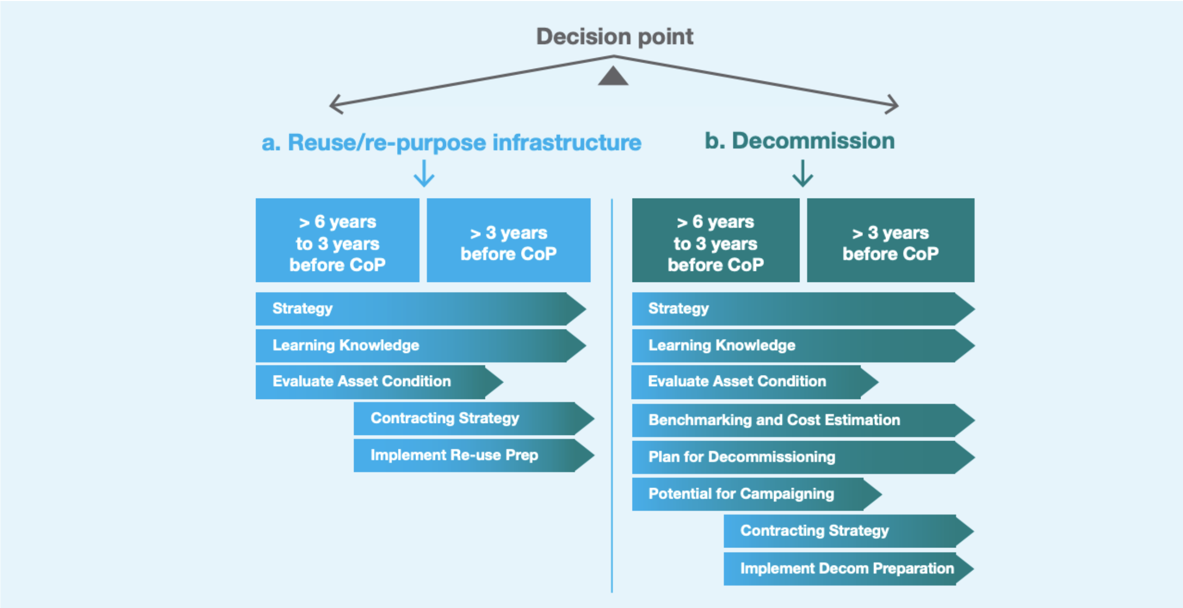


Figure 3.3: Decision three implementing reuse and repurpose strategy of CE into planning Decommissioning

Source: Oil & Gas Authority.2021." Decommissioning Strategy".

CE could be lucrative however there are major hindrances due to regulations, as stated above and addressed by Catherine Banet in a research paper on "Regulating the reuse and repurposing of oil and gas installations" (Banet, 2021), reuse/repurposing are limited by the regulations on offshore platforms, therefore, making it difficult to initiate**.**

Another interesting impact of CE is related to the supply and demand of the decommissioned equipment from the platform. In a series of interviews conducted according to a publication on "Reusing and Recycling Decommissioned Materials", there was attention drawn to the fact that there is little demand for the materials and equipment recovered from the offshore platforms for reuse since there could be a potential risk of failure and the supply side, it was gathered that the operators and the top tier contractor had little or no interest in the concept for reasons being that there is lack of confidence in the quality of materials retrieved from the platforms, especially for the steels retrieved since most of them do not meet the current European standards. However, there is a skilled supply chain working on innovative ways to make reusing and repurposing decommissioned materials attractive for the business market (Marques & et al., 2021)

3.4 Impact of the CE on technical safety.

The Safety of workers is as important as any vital factor in keeping a sustainable economy. With CE in mind, designing and manufacturing of equipment is encouraged to be readjusted to enable relatively easier reuse and recycling capability of equipment. However, this could turn out to be a potential risk to workers if safety is not seriously considered as equipment tend to be more dangerous when its designs are adjusted just to satisfy the environmental protection and economic success CE aims to achieve (such as using raw materials from recycling, developing a repair, the act of reuse, etc.). (Michel Héry & Marc Malenfer, 2020).

According to an article on the prospective study of CE, (Michel Héry & et al., 2019), the implementation of CE in terms of safety poses an elevated risk to workers when using a piece of equipment. However certain measures were considered to make equipment safer when implementing the different CE options.

According to the article, maintenance, which is one of the CE loops, is reflected by different organisations and comes with major consequences for the operators or workers. To make equipment safer, the suppliers must make sure the equipment is more resistant and suitable for frequent maintenance and repair operations and these requirements must be thought out in the design phase of the equipment. (Michel Héry & et al., 2019)

Another point made was that materials should be developed to be better compatible with life extension, reuse, and recycling. Factors such as unfavourable changes in the material composition during recycling or continuous reuse, some materials being prone to deterioration when in contact with different external conditions such as light, heat, etc. should be considered in the design phase of the equipment to avoid any failure (Michel Héry & et al., 2019).

Standards play a key role when it comes to safety. Standards are needed to ensure proper safety and reliability in conjunction with extending the life of components and equipment considering safety in CE (IEC, 2020)

CE can be considered a form of a green job as it falls under the general concept of green jobs which is understood as taking part in sustaining and preserving the environment (European Commission, 2012). As much as the introduction of CE technologies and strategies saves the environment, it brings about new hazards which call for new occupational safety and health (OSH) knowledge to tackle. (European Agency for Safety and Health at work,2022)

Projecting into the future, the rate at which the green economy is expected to expand might lead to the inadequacy of skilled workers to combat the new hazards that come with it, hence putting the health and safety of workers in that space at potential risk. Also, the health and safety of workers could be overlooked due to economic and political pressures. (European Agency for Safety and Health at work,2022)

3.5 Asset Management

An important aspect of understanding AM is understanding the asset life cycle. Every asset has a life cycle which can be categorised into four phases:
(Alba Keqa, 2016)

- Planning: This is the first stage of an asset, whereby realising the need and the potential of an asset to satisfy a particular requirement in the company or business is acknowledged
- Procurement/Acquisition: An asset is purchased or obtained in the most cost-effective way. It covers activities such as designing and procurement. The company compares and decides whether the asset should be procured or produced in-house.
- Operation and Maintenance: The Operation and Management stage is where the asset starts serving its purpose with effective maintenance to extend the life of the asset.
- Disposal: An asset reaches its end of useful life. This is when the asset deliverable is not meeting the standards required. At this stage, the asset could be dismantled piece by piece or clear of the data on it and either sold, repurposed, thrown away or recycled. (Comparesoft, 2021)

AM is defined as “the coordinated activities of an organisation to realise value from assets”, (ISO 55000, 2014).

It is mostly in relation to the operational phase of an asset with integrated methods to handle the assets over the entire life cycle, that is, from the beginning of life, middle of life to the end of life stage of the asset. (Federica Acerbi & et al., 2020). It is the responsibility of the management to make sure an asset's life cycle reaches its full potential to maximise its value and minimise the cost involved. (Reid Paquin, 2014).

Research on “Toward a resource-efficient built environment: a literature review and conceptual model”, (Xian & Ness, 2017), it was deduced that CE and AM have a common aim to optimise assets in the entire life cycle, however, there is a considerable difference between the two. According to the research paper, CE aims at the life extension of an asset when it reaches its EoL phase (by means of the different CE strategies) to maximise its efficiency whereas AM involves multiple criteria including an economic point of view and risk to produce a decision. Due to their difference, the approach acceptable from the AM perspective might not be acceptable from the CE perspective.

In terms of AM, CE can increase the efficiency of assets and asset components, and extend their lifetimes (Hanski & et al., 2016). CE also creates opportunities for assets that are old by implementing reusing or recycling and saves costs. (Hanski & et al., 2016)

Considering how CE impacts asset management, CE strategies are mostly implemented in the EoL and MoL phase of the asset. For example, in a theoretical framework in the article “Exploring Synergies Between Circular Economy and Asset Management”, (Federica Acerbi & et al., 2020) reuse, remanufacture and recycling were typical CE strategies that are implemented in AM and are mostly adopted in MoL and EoL of assets. Analysis was drawn that CE lacks industrial AM in the BoL stage. A conclusion was finally drawn that most research focuses more on the MoL of the asset thus implementing CE in that respect to extend the life of assets.

4 Methodology

4.1 Research methods

The case study research approach was used in this research where it was focused on the impact of the CE in asset decommission in the oil and gas industry.The reason for this approach was able to acquire specific and in-depth knowledge of the CE and influence or impact it has on asset decommissioning in the oil and gas industry.Secondary data was gathered through research papers, articles in a literature review and a survey was conducted to gather primary data in the oil and gas industry.

4.2 Survey

A survey was conducted to have a better feel of what employees in the oil and gas industry know about the CE also, to evaluate the impacts and barriers the CE has on the oil and gas industry, particularly in terms of asset decommissioning. The research results will provide information for developing CE awareness and even improving how CE strategies can be implemented for the best outcomes in terms of decommissioning of assets.
The targeted geographical area was Norway. To make the survey effective, a large range of oil and gas companies was the primary target.

- Equinor
- Akerbp
- Totalenergies
- Vår Energi
- PGNiG Upstream Norway AS
- Neptune Energy
- Wintershall
- OKEA Company
- SVAL Energi
- Repsol
- OMV

- Kuwait Foreign Petroleum Exploration Company (KUFPEC) Norway
- DNO Norge As
- ConocoPhillips Company
- Norske Shell
- Subsea 7 Norway As
- Technip Norge As
- Aker Solutions

4.2.1 Question Design

The questionnaire was designed with Kobotoolbox. It is composed of questions with predefined answers to pick one of them as an answer. For effective analysis, the questionnaire was designed to target *O&G operators* . The questionnaire consisted of 10 main questions. *"5R options"* a term that was used to represent the five CE alternatives, i.e reuse, repurpose, refurbishment, remanufacture and recycling in the questionnaire, for simplicity.(*Link to the complete questionaire:* https://ee.kobotoolbox.org/single/Q5RUqiQx)
Below is the set of questions that were asked to the targeted O&G operators:

- Do you have assets/equipment in your decommissioning plan that you are looking at applying to any of the 5R options? (a single choice question with two possible answers)

- Do you plan to develop/apply the 5R options to your assets/equipment or do you subcontract them? (A single choice question with three possible answers)

- How do you find applying the Circular Economy(i.e 5R options) to your decommissioning assets/equipment plan? (A single choice question with five possible answers)

- What are the major risks you encounter/foresee in your asset/equipment decommissioning? (Multiple choice question with six possible answers)

- You found that the most challenging aspect(s) to implement the 5R options for decommissioning assets and equipment is/are:(Multiple choice question with six possible answers)

- How much experience does your company have to implement the Circular Economy(i.e 5R options) to your assets/equipment in general? (Multiple choice question with four possible answers)

- How much experience does your company have to implement the Circular Economy(i.e 5R options) to your assets/equipment in asset decommissioning in particular? (Multiple choice question with four possible answers)

- What are your barriers/reasons for your difficulty to implement the Circular Economy(i.e 5R options) concept in decommissioning assets? (Multiple choice question with nine possible answers)

- What type of documentation do you have for applying the 5R options on assets/equipment at their end of life? (Single choice question with five possible answers)
- You reckon that the following will enable you to have a better overview of applying the Circular economy(i.e 5R options) to your decommissioned equipment/assets:(Multiple choice question with seven possible answers)

4.2.2 Questionnaire distribution

In order to ensure unbiased answers from employees, this questionnaire ensured the complete anonymity of participants.

The survey was executed from 1st May, 2022 to 13th May, 2022 13th. The questionnaires were supposed to be distributed via email, however due to GDPR regulations that was a challenge.With the help of Proactima company, another alternative to distribute questioned was devised by posting about the survey and the link to the questionnaire on their Linkedin platform as seen below:

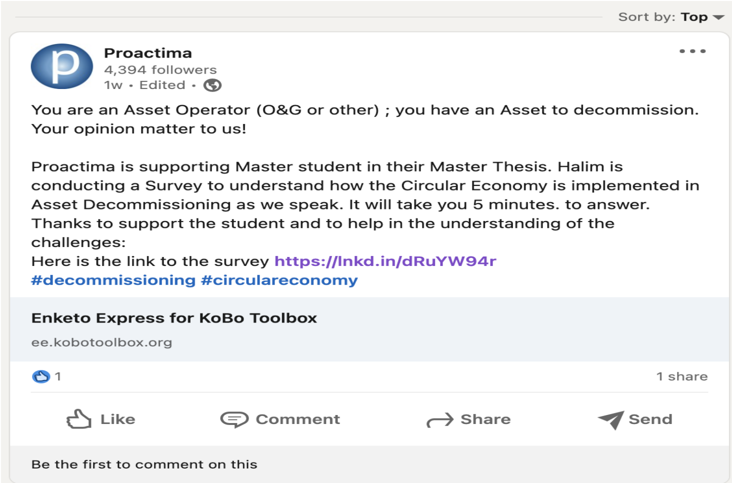


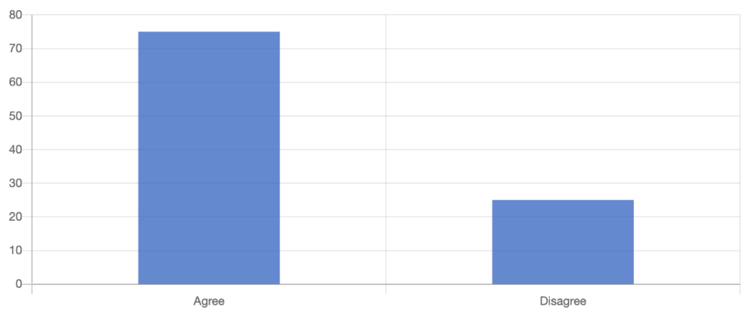
Figure 4.1: A screenshot of how questionnaire was distributed through Proactima Linkedin platform

4.3 Survey results and findings

The aim was to reach out to as many employees as possible in all the companies, however a total of only 4 responses were recorded and 3 agreed to participate in the survey whilst 1 disagreed

The purpose of this research project is part of a master thesis to understand the current state of the application of the Circular Economy to asset decommissioning in the oil and gas industry. This is a research project that is being conducted by Halim Tabsoba Iddrisu at the University of Stavanger with the support of Proactima. You are invited to participate in this research project because you are suitable for giving legitimate information to help in this research. Your participation in this research study is voluntary. You may choose not to participate. If you decide not to participate in this research survey, you may withdraw at any time. The procedure involves filling in an online survey that will take 5 to 10 minutes. Your responses will be confidential and we do not collect identifying information such as your name or IP address. We will do our best to keep your information confidential. All data is stored in a password protected electronic format. To help protect your confidentiality, the surveys will not contain information that will personally identify you. If you have any questions about the research study, please contact halim.tabsoba@gmail.com. ELECTRONIC CONSENT: Please select “Agree” if you agree to participate in the research study

TYPE: "SELECT_ONE". 4 out of 4 respondents answered this question. (0 were without data.)



Value	Frequency	Percentage
Agree	3	75
Disagree	1	25

Figure 4.2: Data representation of the entire survey

The expected sample size to make the survey statistically valid was about 80 participants, however, just 5% of the expected sample size was obtained.

Reliable conclusions could not be drawn since the number of participants is insignificant. As mentioned earlier, the reason for this challenge was due to the fact that GDPR is against sending direct emails to employees of all the companies listed. This caused a major limitation to directly having contact with employees in order for them to complete the questionnaire and that led to the second option where a post of an explanation of the survey and a link to the questionnaire was shared on the Proactima Linkedin page which resulted in a very low rate of response.

5 CE Assessment Tool

5.1 The functionality of the CE Assessment Tool

After understanding the different CE strategies/loops and knowing how the strategies interact with AM, technical safety and decommissioning, this chapter discusses two ways that CE assessment can be done on products or components. Two functionalities are to be focused on.The first functionality is to assess a product/equipment at its EoL phase and determine the best possible CE strategy to implement based on factors such as safety, economics, efficiency, etc. The second functionality is to compare two or more designs of a particular product/component/equipment to select the best one among them in terms of their circularities.
A CE assessment of equipment is important because it will enable engineers to think and analyse equipment from the right perspective when trying to apply CE in the most effective way.

5.1.1 First functionality

The CE assessment is formulated based on a multi-criteria method. It is implemented in a stepwise fashion according to the following steps:

- Step1: Assessment scoring of the possible CE Strategies that can be implemented based on a reverse-engineered design framework
- Step 2: Use of relevant indicators to narrow down the options (if possible)
- Step 3: Evaluating and ranking the CE strategies
- Step 4: In-depth analyses of the selected alternative to finalise a decision

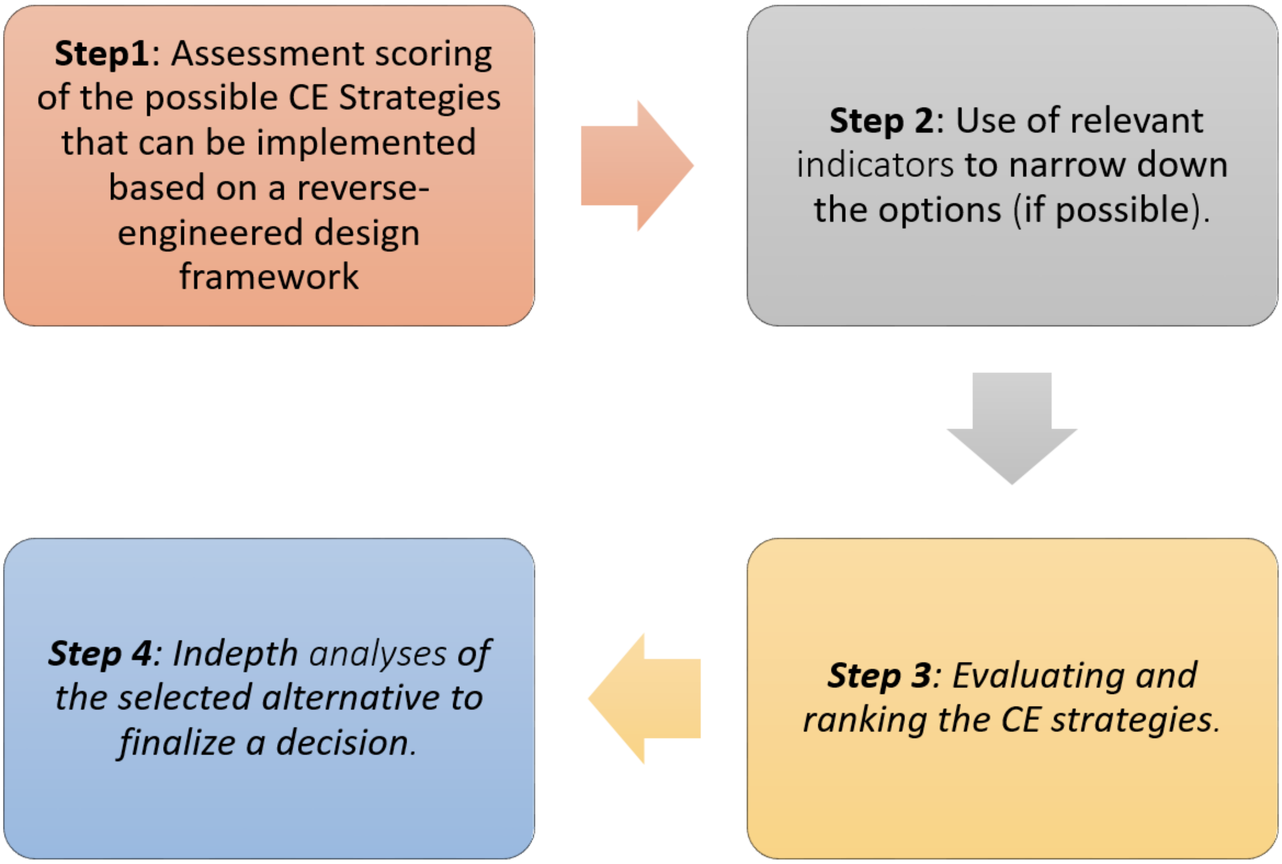


Figure 5.1: Summary of general steps of the CE assessment tool first functionality

The steps are explained and how they are implemented below:

Step 1: Assessment scoring the possible CE Strategies that can be implemented based on a reverse-engineered design framework

The first step of the assessment is based on an effective design framework. (Circle Economy, 2022). Before explaining the mode of operation of the framework, it is important to understand that it was developed for equipment in the design phase of its lifecycle. It is used as a guide in the manufacturing stage of a product/equipment. However, with respect to this thesis focus, the framework is reverse engineered since the way equipment or a product was designed has a major impact on the CE strategy suitable at EoL (Bertoni, 2020; Wahab & et al., 2018; Hanski, 2020) or to determine its circularity. Moreover, the same criteria need to be followed or satisfied both in the design phase and end of life phase(decommissioning). The framework is made up of levels and assessment factors which will be discussed below.

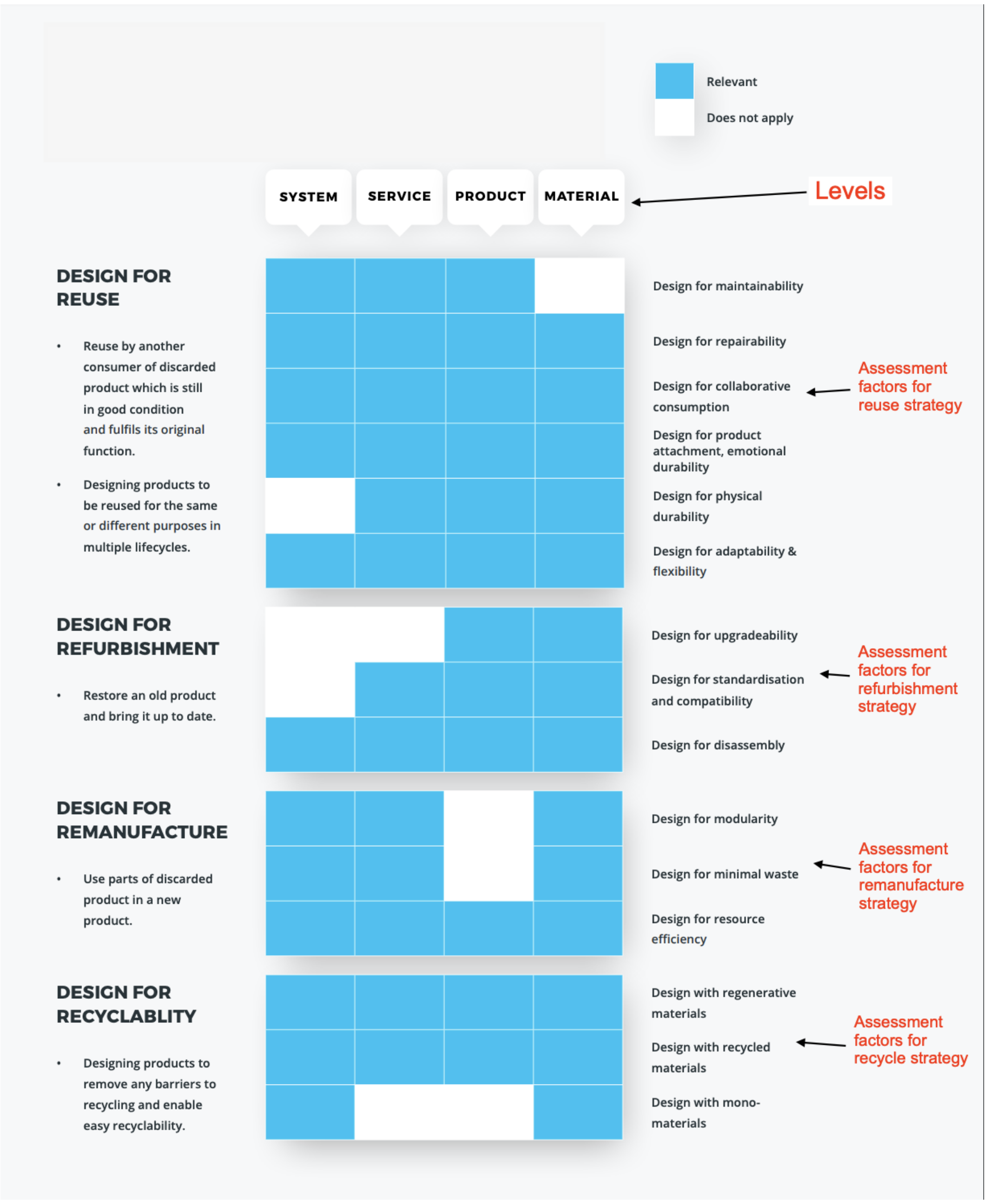


Figure 5.2: Assessment Framework to determine the best CE strategy to be applied to a piece of equipment or equipment component

Source: Circle Economy, (2008-2022).

Retrieved from:

https://www.circle-economy.com/resources/circular-product-design-framework

Levels

The CE framework is used to be able to assess different CE strategies at different buildup levels, beginning from the material level up to system level which is discussed in the following bullet points:

- Material level: Products/equipment comprise varied materials and components coming together as one unit. From the perspective of the aim of the assessment tool. This is about making assessment scoring based on the CE strategies on a material or component of a product/equipment. For example, assessing the reusability of the tyres of a vehicle that is out of use. The vehicle tyres are one component of the vehicle.

- Product level: Assessment of CE strategies to be implemented on a product/equipment as a unit. For example, evaluating the possibility to remanufacture a broken-down refrigerator unit.

- Service level: Assessing the applicability of a CE strategy on a combination of different equipment/products.

- System level: This is the highest level. Assessing an interconnected set of units of elements that come together for a single purpose.

According to how the framework has been built, the blue squares are implied as relevant assessment factors and therefore should be considered when making assessments whilst the white squares are implied as not relevant and therefore should not be considered when making assessments for a given level. The various levels are linked together, however, they are not interdependent. This means that a product or equipment can be assessed on the material, product, service, or system level independently. This thesis focuses only on the product and material level.

Assessment factors(sub-options)

The framework comprises a list of factors that are required to be assessed and given a score qualitatively for a CE strategy to be applied to an asset/equipment/product. These factors are then categorised into four groups of CE strategy options, namely:

- Design for reuse/repurpose
- Design for refurbishment
- Design for recyclability
- Design for remanufacture

Each group listed above has a set of criteria or assessment factors that are scored based on a qualitative analysis of a product/equipment.

To make scoring for each category (i.e., Design for remanufacture/Design for reuse/Design for refurbishment/Design for recycling), an average sum of the qualitative values for each category is taken.

$$\text{Scoring of a CE category } = \frac{(\text{Sum of the scales / scores of the used assesment factors for a given CE category})}{\text{Number of used assesment factors for a given category}}$$

It is important to note that an assessment factor that is not applicable to a product/equipment is given a scale of 0, hence excluded in calculating the average sum.

Below is an elaboration of the criteria or assessment factors under each CE strategy option:

- **Design for reuse/repurpose*:***

As seen in the framework, this group or category is focused on the reuse of equipment, that is, using a product by the same or different consumer again considering being used for the same purpose or different purpose (repurpose) in the next lifecycle. Below are the assessment factors to consider when evaluating equipment that is designed for reuse.

-*Design for maintainability*: This is about assessing the product/equipment to understand how easy it is to maintain it. From an engineering perspective and knowledge about the equipment, determining factors listed below can be considered:

- How high the cost of maintenance is.
-The amount of energy and effort required to maintain the equipment
-How often maintenance is required.
-Has it got the ability for life extension?

It is scaled as: 5-very easy, 4-easy, 3- fairly easy, 2- difficult and 1- exceedingly difficult

-*Design for repairability*: This is the extent to which the equipment can be repaired, that is, easy or difficult is to repair. Determining factors that may be considered for guidance when making a score for "Design for repairability" are:

-Availability of specialists to repair the product/equipment
-Availability of broken parts

It is scaled as: 5-very easy, 4-easy, 3- fairly easy, 2- difficult and 1- exceedingly difficult

-*Design for collaborative consumption*: For a better understanding of this criteria, the term 'collaborative consumption" must be understood. It can be described as "a well-established field of study about an economic approach concerning the shared use of a good or service by a group", (IGI Global. 2022). This simply means more than one user for a single piece of equipment. An assessment should be made to find out whether a piece of equipment or component was designed for multiple users. That is, being able to be used by more than one user comfortably without significant failure. There can be determining factor(s) to serve as a guide when making a score such as:

-How risky is it to be used by multiple users

It is scaled as: 5-very possible, 4-possible, 3- fairly possible, 2- almost impossible and 1- impossible

-*Design for product attachment and emotional durability*: Equipment can be considered for reuse if there is a form of attachment of its user to it. For example, a vehicle can be considered for reuse if there is some form of sentimental value to the vehicle. This is about how much the user of the equipment likes to keep the product/equipment.

It is scaled as: 5-very attached, 4-attached, 3- mildly attached, 2- not that attached and 1- not attached

- *Design for physical durability*: Assessing the product if it has been designed with high resistance to wear and tear after a long yet useful life (Circle Lab, 2022). Some determining factors that could aid in deciding are as follows:

-How long it has been used without a major breakdown
-Has it got only a few parts that need repair?

It is scaled as: 5-very high durability, 4-above average durability, 3- average durability, 2- below average durability and 5- not durable

-*Design for adaptability & flexibility*: A way to assess equipment's adaptability is to judge whether it is designed to adapt to change including being able to be upgradable or modified as time and technology advances. (Inman & et. al 2007). The flexibility of a piece of equipment determines whether a piece of equipment has more ability than is required of it in terms of its functions, performance, and accuracy (Berlac & et. al, 2014) or not. This is to determine whether the equipment can easily be modified or upgraded to be able to be used again. This criterium is particularly considered for repurposing an asset/equipment. Determining factors that may be considered in giving a score are as follows:

-Can product /equipment be used under different conditions without failure?

-Are there too many changes to be made to the equipment for it to be used for another purpose?

It is scaled as:

5- highly adaptable and flexible

4- Above average adaptability and flexibility

3- Averagely adaptable and flexible

2- below average adaptability and flexibility

1- not adaptable and flexible

- **Design for refurbishment**:

This category contains a set of criteria that are scored for a piece of old equipment or a component based on its capability to be restored and updated. Below are the assessment factors to consider:

-*Design for upgradeability*: This is an assessment of the capability of the equipment to be improved in its functionality. There should be an investigation into the availability of opportunities for an upgrade of the equipment or component. Determining factor(s) that can be considered:
-Availability of companies specialised in upgrades
It is scaled as: 5-very easy, 4-easy, 3- fairly easy, 2- difficult and 1- exceedingly difficult

-*Design for standardisation and compatibility*: Standardisation is the act of creating uniformity across manufacturing materials and processes (Circular Economy Practitioner guide, 2018). For a product to have the capability to be refurbished, there should be available products with parts that can fit into the product under assessment. Way(s) to make this assessment is to consider:

-Availability of parts to make upgrades

It is scaled as: 5-very easy, 4-easy, 3- fairly easy, 2- difficult and 1- exceedingly difficult

-*Design for disassembly*: This assessment is to determine how easily the parts of a product or component can be separated. Determining factors to help make a score are:
-Availability of tools to disassemble parts

-Assessing whether the component or equipment has been built with easily removable parts or components

It is scaled as: 5-very easy to disassemble

4-easy to disassemble

3- fairly easy to disassemble

2- difficult to disassemble

1- exceedingly difficult

- **Design for remanufacture**:

This category is based on assessing the capability of remanufacturing a piece of equipment or component, that is, using the parts of an unwanted product/equipment to produce another one. Below are assessment factors to consider:

-*Design for modularity*:" Modularity refers to the use of common units to create product variants", (Kusiak, 1998). This means that a product can be built with a number of different modules or components rather than built as one homogeneous unit. Based on this assessment factor, determining the possibility of remanufacturing is by judging the extent to which the product/equipment has been built into subcomponents. In this way, modules or subcomponents of the discarded product under assessment can be taken to reproduce a new product/equipment. Determining factors to make a scoring:
-The extent to which the equipment or product was built into subcomponents
-the extent of removable and fixable parts

It is scaled as:

5- high modularity

4-above average modularity

3- average modularity

2- below average

1- homogeneous buildup (little or no modularity)

-*Design for minimal waste*: This is to determine the extent to which waste will be produced when the parts of the discarded product/equipment under assessment are to be used to remanufacture a new product based on how it was designed. If a lot of waste is produced by the end of producing a new product, then remanufacturing will not be a suitable strategy. Determining factor(s) to consider:

-the extent of use of all the parts and materials of the equipment/product in producing another one.

It is scaled as:

5- Minimum waste produced (< 20% of the product/equipment is not usable for remanufacturing)

4-below average waste produced (20%-49% of the product/equipment is not usable for remanufacturing)

3-average waste produced (50% of the product/equipment is not usable for remanufacturing)

2 -more than average waste produced (50%-70% of the product/equipment is not usable for remanufacturing)

1-maximum waste produced (>70% of the product/equipment is not usable for remanufacturing)

-*Design for resource efficiency*: Here, the equipment under assessment must have low consumption of resources (water, energy, materials, etc.) when in use to be compatible for remanufacturing into a new product. For instance, a discarded refrigerator with high electricity consumption cannot be suitable to be remanufactured.

It is scaled as:

5- high resource efficiency (Consumes a very satisfactory minimum amount of resource to function)

4- above-average resource efficiency (Consumes a fairly low amount of resource to perform its function)

3- average resource efficiency (Consumes a fairly high amount of resource but acceptable to perform its function)

2- below average resource efficiency (Consumes a high amount of resource to perform its function)

1- low resource efficiency (Consumes extremely high amount of resource to perform it function)

According to the framework," Design for modularity" and "Design for minimal waste" assessment factors are not relevant criteria at the product level but for the purpose of higher accuracy of the framework based on how it is used in this thesis, both assessment factors (Design for modularity and Design for minimal waste) are considered at the product level as well.

- **Design for recyclability:**

This category of the framework is about assessing equipment or components of equipment to determine how easy it is to be recycled without any barriers. Below are assessment factors to make a qualitative scoring:

-*Design with regenerative materials*: This assessment factor is to determine how much of the product under assessment is made up of regenerative materials such as bio-based, reusable, non-toxic materials, etc. The product (equipment/component) is suitable for recycling if it has most of its parts made up of regenerative materials.

It is scaled as:

5- > 80% of the product/equipment is made up of regenerative materials
4- 51%-80% of the product/equipment is made up of regenerative materials
3- 50% of the product/equipment is made up of regenerative materials
2- 20%-49% of the product/equipment is made up of regenerative materials
1- < 20% of the product/equipment is made up of regenerative materials

-*Design with recycled materials*: A product produced/ manufactured using recycled materials should suggest that it can be recycled again. The more recycled materials used to produce the product the better.

It is scaled as:

5 - > 80% of the product/equipment is made up of recycled materials

4- 51%-80% of the product/equipment is made up of recycled materials

3- 50% of the product/equipment is made up of recycled materials

2- 20%-49% of the product/equipment is made up of recycled materials

1- < 20% of the product/equipment is made up of recycled materials

-*Design with mono materials*: A Product or component that is made of a single material is easier to recycle. For a product to be recyclable make sure most of it is made of a single material type.

It is scaled:

5 - > 80% of the product/equipment/component is made up of a single material type

4- 51%-80% of the product/equipment/component is made up of a single material type

3- 50% of the product/equipment/component is made up of a single material type

2- 20%-49% of the product/equipment/component is made up of a single material type

1- < 20% of the product/equipment/component is made up of a single material type

(See Appendix for excel file containing the complete assessment scoring tool)

Step 2: Select relevant indicators to narrow down the options (if possible)

As elaborated in the theoretical background, CE has a significant impact on technical safety, AM as well as decommissioning(EoL). They can be categorised into environmental, social impacts, and economic impacts and measured or evaluated to come up with a decision on which strategy has the least negative impact. (Alamerew & Brissaud, 2019). Depending on the CE strategy, a number of predefined indicators for evaluation are selected (Bufardi et al., 2007). According to Alamerew & Brissaud, based on the categorised impacts, the indicators can be as follows:

Economic Indicators:(I1):

Net Recoverable Value (NRV)

Net Recoverable Value (NRV) = CE Economic Value - Disassembly cost

Disassembly cost = (Labour to disassemble product × Labour rate) +Tooling costs + Material costs + Overhead costs

Labour to disassemble product = total number of human resources(or labour force) x total number of hours

Repair to reuse value = Value of component - Repair cost - Miscellaneous cost

Refurbishment value = Value of component - Refurbishment cost - Miscellaneous cost

Remanufacture value = Value of component - Remanufacture cost -Miscellaneous cost

Recycling value = Value of Component – Recycling Cost – Miscellaneous cost

Miscellaneous cost = Extra expenses

Where:

CE Economic Value = Repair to reuse value or Refurbishment value or Remanufacture value or Recycling value

The aim here is to consider the maximum net recoverable value possible.

(See Appendix for an excel file with complete NRV calculation steps)

Environmental Indicators (I2):

There are three indicators that can be considered considering the environmental impact.

(i) End of Life Impact on the Environment (EOLI)

CE impact on the environment at the EoL phase of a product can be computed with the aid of an eco-indicator proposed by Product Ecology Consultants, (Ministry of housing, 2000). They have a broad database of common materials and processes and the extent to which they impact the environment. It is dimensionless; however, it is expressed as eco-indicator points (pts) and milli-indicator points(mPt) where mPt= pt x 10^-3. The value of pt or mPt can either be negative, positive or 0. Where positive values represent adverse impacts, negative values represent the beneficial impact and 0 stands for neutral. There is no standardised process for making these impact calculations for remanufacturing and refurbishment processes (Erik, 2012) hence we can assume a neutral impact. According to Khoo & et al., (Khoo & et al., 2001), the computation of the EoL impact on the Environment can be computed as:

$$\mathrm{EOLI} = \sum_{i=1}^{N_T} (\mathrm{IE_i}\ \mathrm{W_i})$$

Where:

N_T: total number of materials in the product

IE_i: end of life impact of material i

W_i: weight of material i (kg)

$$\sum_{i=1}^{N_T} (\mathrm{IE_i}\ \mathrm{W_i}) = \text{end of life impact of component i}$$

n: number of materials in component i

(ii) CO_2 emissions

CO_2 emissions are considered and measured in Kg or any other conversions depending on the data available. The aim here is to have minimum CO2 emissions.

(iii) SO_2 emissions

SO_2 emissions are considered and measured in Kg or any other conversions depending on the data available. The aim here is to have minimum SO2 emissions.

Safety indicators (I3):

These indicators are purposely for safety:

(i) For scaling the exposure of workers to any form of harmful substances or materials throughout the process of the CE strategy. The aim here is to have minimum exposure of workers to harmful materials.

Qualitative Scale of exposure:

1-very low or No exposure, 2-Low exposure, 3-Average exposure, 4-High exposure and 5-Maximum exposure or even death

(ii) Assessing the availability of Safety Standards for the safe use of the equipment

Below is a summary of all indicators explained. However, more indicators can be added by the decision-maker for suitability.

“component” used in the expressions represents components or equipment under assessment

	Indicators	Unit	Aim
Economic (I1)	Net Recoverable Value (NRV)	NOK	Maximum
Environmental (I2)	EOLI	Pt or mPt	Minimum
	CO_2 emissions	Maximum, Average or Minimum	Minimum
	SO_2 emissions	Maximum, Average or Minimum	Minimum
Safety (I3)	Workers Exposure to Harmful Materials	1,2,3,4,5	1
	Available Safety Standard	Yes or No	Yes

Table 5.1: Representation of Indicators to assess the available CE strategy options based on 3 main impacts.

Step 3: Evaluating and ranking the CE strategies

In this step, the selected CE options are critically evaluated and ranked based on the selected indicators and scores in the last two steps to select the most appropriate alternative. For example, there are two CE alternatives under assessment for the equipment, (i.e., Alt 1 and Alt2). By ranking the CE alternatives based on the indicators and score, Alt2 seems the most appropriate option compared to Alt1. Hence Alt 2 is selected as the most suitable CE strategy for the equipment.

Step 4: In-depth analysis of the selected alternative to finalise a decision

After finally selecting the most appropriate CE strategy option based on the analysis done by the decision maker, it is important to understand there may be problems and consequences of the alternative that may arise as there is no perfect solution. According to (Alamerew & Brissaud, 2019). There is a checklist as seen in the table below that can be run through to understand the possible consequences and problems that could be faced by the choice made. After making an in-depth analysis, if there are unbearable consequences then the next option in the ranked list of CE alternatives will be chosen and then it is run through an in-depth analysis. This process is repeated down the list until a satisfactory choice is made.

It is important to note that not all the factors listed in the table below will be applicable to every CE strategy chosen for a product under a final assessment. That means, depending on the product and the CE strategy chosen for assessment, only appropriate factors in the table below should be considered.

Category	List of key factors
Ecological (Environmental)	*Human health (HH)
	*Ecosystem Quality (EQ)
	*Resources (R)
Legislation	***Compliance with legislation**/ EU legislation/WEEE
	*Compliance with new legislation
Market	***Customer demand (Market demand)**
	*Competitive pressure
Social	*Additional job creation
	***Level of customer satisfaction**
	*Consumer perception
	*Safe working environment
	*Customer relations
Business	***Return core volume**
	***Consumption model**
	*Degree of damage
	*Return rate (Timing of product return)
Economic	***Financial cost of operating product recovery business**
	*Quality requirement of recovered product
	*Resell price
	*Possible obsolescence of an assembly
Technical	*** Technical state (EoL condition of returned products)**
	*Advancement in technology
	*Availability of recovery facilities
	*Presence/Removability of Hazardous content
	* Processibility
	*Separability of materials

Table 5.2: Table of further factors to conclude with a single appropriate CE strategy or a circularity design

Source: https://link.springer.com/article/10.1007/s13243-018-0064-8/tables/5

5.1.2 Second Functionality

As discussed earlier, another important way the CE assessment tool can be used is by applying it to two or more designs of the same equipment/product to select one with the best circularity options. Circularity in this context refers to how well a piece of equipment or product can adapt to the CE concept with the overall aim of minimising waste (Nicolaus, 2021). The procedure to apply the tool in this manner is the same as the steps explained in Section 5.1. However, a few changes were made. Firstly, the assessment framework has additional assessment criteria to apply, that is," Safety" and "Knowledge" which will be discussed further in "Step 1a" below. Secondly, Step 2 is excluded. Thirdly, in Step 3, two or more designs of a product/equipment that are under assessment are compared to select the best design in terms of their circularity. In step 4, there is an in-depth analysis of the best-selected equipment design based on factors/criteria in Table 5.2 to find out and understand the problems or shortcomings of the selected equipment design. For simplicity and better understanding, below is a summary of the steps:

- Step 1a: Assessment scoring of the possible CE strategies that can be implemented based on a reverse-engineered design framework for each equipment design
- Step 2a: Evaluating and comparing the products or pieces of equipment in terms of their circularity (or CE alternatives)
- Step 3a: In-depth analysis of the best equipment design selected to finalise a decision

Step 1a: Assessment scoring of the possible CE strategies that can be implemented based on a reverse-engineered design framework for each equipment design

The framework discussed in section 5.1.1 is used to assess the circularity of the different designs of a product/equipment, based on the CE alternatives in the framework (figure 5.1) and making a scoring. In addition, two more assessment criteria are introduced:

- Safety: Refers to the exposure of workers or users to any form of harmful substances or materials for each assessment factor. The aim here is to have minimum exposure of workers or users to harmful materials.

It is scaled as:

1-very low or No exposure, 2-Low exposure, 3-Average exposure, 4-High exposure and 5-Maximum exposure or even death

- Knowledge: This refers to the amount of knowledge a decision-maker has on a particular assessment. That is, knowledge uncertainty of an assessment.; the extent of certainty for a given assessment factor in the framework example, a washable facemask may be designed for maintainability since it can be washed and reused repeatedly, however, there is high uncertainty about the number of times it can be washed and reused safely.

It is scaled as:

5- High certainty (Strongly knowing enough information on the assessment factor)
4- above average certainty (knowing enough information but little uncertainty)
3- average certainty (50/50 information on the assessment factor)
2- below average (a considerable amount of uncertainty knowledge)
1- uncertain (fully no knowledge of certainty on an assessment factor)

For example, assessing the CE alternatives that can be implemented on three different car models (Toyota Camry, Toyota Corolla, and Toyota Yaris).

At this point, there are three different scores namely, *Circularity score, Safety score* and *Knowledge score*. An average of each score is calculated (not applicable assessments with 0 score is excluded in calculating the average) and then finally, a "*Total average circularity score*" is calculated by taking an average of the 3 average scores as seen below.

Total average Circularity Score for reuse/repurpose/refurbishment/remanufacturing/ recyclability= (Circularity Score + Safety Score + Knowledge Score)/3
(See Appendix for excel file containing the complete assessment scoring tool)

Step 2a: Evaluating and comparing the products or pieces of equipment in terms of their circularity (or CE alternatives)

Based on the scoring of each equipment, they are compared against each other. Different modes and methods such as graphs and spider diagrams can be used to help in making comparisons

Step 3a: In-depth analysis of the best equipment design selected to finalise a decision

After finally selecting the most appropriate design among different designs of a product. There is a checklist as seen in Table 5.2 that is used to assess and detect possible drawbacks and consequences that could be faced for the selected design. If the consequences and drawbacks detected are accommodative, then the selected choice in step 2 is maintained. However, if the possible drawbacks are critical, then the next best design is selected and assessed in Table 5.2. This procedure is repeated until a suitable choice is selected.

It is important to note that not all the factors listed in Table 5.2 will be applicable to every design/product under a final assessment. That means, depending on the product under assessment, only appropriate factors in Table 5.2 should be considered

5.2 Study Case

There are two case studies that are discussed to show how the two functionalities of the CE assessment tool can be used. The first case study is to show how the first functionality of the tool is implemented and the second case study shows how the second functionality of the tool is implemented.

5.2.1 First study case

A study of a crude oil storage tank that has reached EoL is done to implement the CE assessment tool in order to show how the first functionality of the CE assessment tool is implemented. Various approaches can be taken that have their own consequences environmentally, economically, and safety-wise. In this case, a specific type of crude oil storage tank is an internal floating roof tank. It is mainly used in the storage of crude oil.

Figure 5.3: Internal floating roof tank

Source:

http://www.largestoragetank.com/storage-tank/Oil-Storage-Tank/Internal-Floating-Roof-Tank.html

Step 1: Assessment scoring of the possible CE strategies that can be implemented based on a reverse-engineered design framework

In this step, there is an assessment of the design of the internal floating tank in terms of remanufacturing, refurbishment, reusing, repurposing, and recycling by using the assessment framework discussed in section 5.1.1. The internal floating roof tank based on how it was designed is given scoring for each CE category(strategy) in the framework. The floating roof tank is a whole product or equipment itself hence the *product level* assessment in the framework is implemented. The scorings of the equipment are recyclability, 5, remanufacturing,1.5, refurbishment,4.3, repurpose,4.75 and reuse 4.6. As seen below (See Appendix for an excel file with complete scorings of the internal floating roof tank) :

Internal Floating roof tank -Product Level Scoring

Design for Reuse

Assessment Factors	Score/Scale	Comments
Design for repairability	5	**There are known specialist to repair a floating roof tank**
Design for collaborative consumption	0	**Not applicable since the sole purpose of a floating roof tank is to store crude oil**
Design for product attachment and emotional durabilty	0	**Sentimental value is not so much relevent for a Floating roof tank**
Design for physical durability	5	**It is designed to be used for a good number of years**
Design for maintenability	4	It may require regular maintenance routines for life extension
Scale/Score sum	14	
Score for Design for Reuse	4.6	

Design for Repurpose

Assessment Factors	Score/Scale	Comments
Design for repairability	5	**There are no known specialist to repair FFP3 mask or availablity of broken parts**
Design for collaborative consumption	0	**Impossible to be used by more than one person due to health safety reasons**
Design for product attachment and emotional durabilty	0	**Sentimental value is not so much relevent for a FFP3 mask**
Design for physical durability	5	**Can be used for a long time without damage but not advisable for health safety reasons**
Design for adaptability & flexibility	5	It can be used for storing other liquid based fluids without any known problems so far
Design for maintenability	4	It may require regular maintenance routines for life extension
Scale/Score sum	19	
Score for Design for Repurpose	4.75	

Design for Refurbishment

Assessment Factors	Score/Scale	Comments
Design for upgradeability	5	**It is possible for upgrades.There are companies specialised in tank upgrades and imporvement.**
Design for standardization and compatibility	5	**There is availabilty of the parts to make upgrades**
Design for disassembly	3	**Easy to disassembly the floating roof from the tank.However,furtheer disassembling of tank is a challenge**
Scale/Score sum	13	
Score for Design for Refurbisment	4.3	

Design for Remanufacture

Assessment Factors	Score/Scale	Comments
Design for modularity	2	Has few fixable/removable parts
Design for minimal waste	1	Assuming inner walls of tank is heavily corroded,the tank itself will be of no use except the floating roof
Design for resource efficiency	0	**Not applicable since no resource is requied for its function**
Scale/Score sum	3	
Score for Design for Remanufacture	1.5	

Design for Recyclability

Assessment Factors	Score/Scale	Comments
Design with regenerative material	5	**Over 80% of the equipment is made of steel which is a reusable and non-toxic material**
Design with recycled materials	5	**Over 80% of the equipment is made of steel which is a recycled material**
Scale/Score sum	10	
Score for Recylability	5	

Table 5.3: Scoring assessment for an internal floating roof tank

Step 2: Use of relevant indicators to narrow down the options (if possible):
In this step, the CE strategies are further assessed and evaluated using selected indicators. Depending on the decision maker any number of indicators can be selected. In this case, the following indicators are selected:

Economic Indicator(I1): Net recoverable value
Environmental Indicators(I2): CO_2 emissions.
Safety Indicators(I3): Workers' Exposure to Harmful Materials; Available Safety Standards

Step 3: Evaluating and ranking the CE strategies

This step is about the evaluation of the CE options based on the selected indicators and then ranking them based on the indicators and the scoring in step 1. The net recoverable value (NRV) is the economic indicator and is calculated by subtracting the cost required to process the CE strategy and any other expenses from the cost at which the equipment was obtained. In this case, according to a number of suppliers in a Chinese marketplace(Made-in-China, 2018), the highest price a floating roof tank could cost is $68000 which is about 600000 NOK bulk figure. Based on the cost of the internal floating roof tank, assumed estimates were made for the repair cost, refurbishment cost, recycling cost, miscellaneous cost and disassembly Cost hypothetically as seen in the calculations
NRV of the internal roof tank in terms of:

- Repurpose =
  Value of internal floating roof tank -Repair Cost- Miscellaneous cost - Disassembly Cost =
  600000 - 100000 - 20000 - 50000 = 430000 NOK
- Reuse =
  Value of internal floating roof tank -Repair Cost- Miscellaneous cost - Disassembly Cost =
  600000 - 100000 - 2 000 - 50000 = 430000 NOK
- Refurbishment =
  Value of internal floating roof tank -Refurbishment Cost- Miscellaneous cost - Disassembly Cost = 600000 - 200000 - 50000 - 100000 = 250000 NOK

- Recycling =
  Value of internal floating roof tank -Recycling Cost- Miscellaneous cost - Disassembly Cost =
  600000 - 200000 - 50000 - 20000 = 330000 NOK

Remanufacture alternative is not considered for further assessment since it had a very low score of 1.5 in the assessment scoring compared to the rest of the alternatives that had a score above 4.

	Value of Internal Floating roof tank (NOK)	Repair Cost (operating cost, energy consumption, workforce cost, etc)	Refurbishment Cost (operating cost, energy consumption, workforce cost, etc)	Recycling Cost (i.e operating cost, energy consumption, workforce cost, etc.)	Miscellaneous cost	Disassembly Cost	NRV
Repurpose	600 000	100 000	N/A	N/A	20 000	50 000	430000
Reuse	600 000	100 000	N/A	N/A	20 000	50 000	430000
Refurbishment	600 000	N/A	200 000	N/A	50 000	100 000	250000
Recycling	600 000	N/A	N/A	200 000	50 000	20 000	330000

Table 5.4: Evaluation of the selected CE alternatives based on the Economic Indicator

Evaluation of the environmental impact is based on CO_2. It is assumed that there are minimum CO_2 emissions from the reuse, repurpose and recycling alternatives while there is an average CO_2 emission from the refurbishment alternative. However, specific data on the amount of CO_2 emissions may be necessary to give distinct differences among the CE alternatives.

In evaluation based on safety, the exposure of the workers to hazardous materials as well as the availability of safety standards is considered as seen in the table below.

	Available Safety Standard	Exposure to Hazardous Materials
Reuse	YES	1
Repurpose	YES	1
Recycling	N/A	4
Refurbishment	YES	2

Table 5.5: Evaluation of the selected CE alternatives based on the Safety indicators

Rank	CE Alternatives	Economic (NRV)	Environmental (CO_2 emissions)	Safety		Scoring from step 1
				Available Safety Standard	Exposure to Hazardous Materials	
1	Reuse	430000	Minimum	Yes	1	4.6
2	Repurpose	430000	Minimum	No	1	4.75
3	Refurbishment	250000	Average	Yes	2	4.3
4	Recycling	330000	Minimum	N/A	4	5

Table 5.6: Ranking the selected CE alternatives based on all the indicators and assessment scoring

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In respect to the case study, reusing, repurposing and recycling have the best economic value and scoring over refurbishment, yet recycling is ranked the worst option. This is because recycling may have a high NRV and the best scoring but then a recycling process reduces the value of any equipment or component drastically since it is broken down to fundamental materials, therefore, it is always regarded as an “option of last resort” as mentioned earlier. Reuse is the best option, this is because, apart from having the best economic value, it does not expose employees to any hazardous material, moreover, there are available safety standards unlike repurposing since using a floating roof tank for another purpose could be quite a new idea.

Step 4: In-depth analysis of the selected alternative to finalise a decision

Before reuse can be taken as the final decision or the best CE option for the study case. Further extensive factors must be considered to understand and assess the challenges that might come with reusing the equipment. From Table 5.2, some of the criteria can be checked. Every single criterion may not be relevant to our study case; In this case study, it is assumed the internal floating roof tank is going to be sold as a reusable product, therefore customer demand is put into consideration and the resell price on the market as well to make sure it doesn’t go against the net recoverable value which has been estimated. If the information gathered after making the inquiries is unsatisfactory, then repurposing could be considered as the next option in line and then it is assessed in the same fashion using Table 5.2

5.2.2 Second study case

This section is to demonstrate the second functionality of the assessment tool. An assessment of three different types of face masks for coronavirus prevention is done to determine the best design amongst them with respect to their circularity using the CE assessment tool implemented. The face masks under assessment are:

- Filtering facepiece mask(FFP)
- Surgical mask
- Washable face mask

Figure 5.4: Washable mask

Source: https://www.nytimes.com/wirecutter/reviews/best-cloth-face-masks/

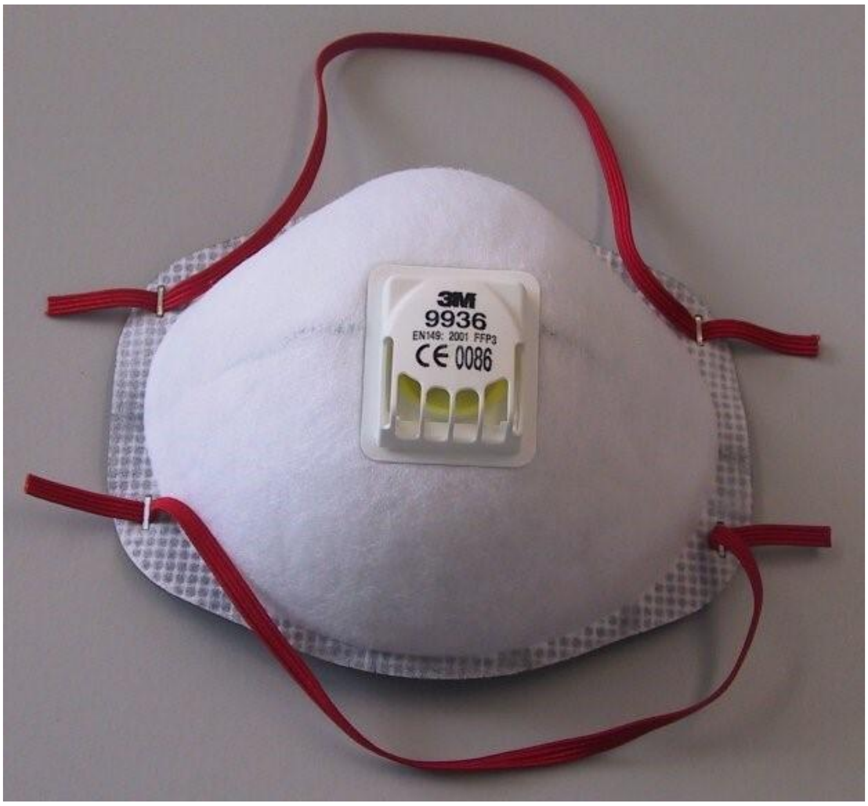

Figure 5.5: Filtering facepiece mask (FFP)

Source: Wikipedia

Figure 5.6: Surgical mask

Source: Wikipedia

Step 1a: Assessing the possible CE Strategies that can be implemented based on a reverse-engineered design framework (assessment framework)

Based on the CE alternatives/ categories, the three face masks are assessed and scored on the product level of the framework. The excel spreadsheet shows how scores are distributed.(See Appendix for an excel file with complete scorings of the 3 different masks in terms of the "second functionality" of the assessment tool)

PRODUCT Level Scoring for Surgical mask using the second tool functionality

Max Score is 5

Design for Reuse

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comment
Design for repairability	1	It is exceedingly difficult to rapair a surgical mask.No particular specialist for that	0	Not applicable	0	Not applicable
Design for collaborative consumption	1	Impossible to be used by more than one person due to health reasons	1	Highly risky due to transferraable diseases	0	Not applicable
Design for product attachment and emotional durabilty	0	Sentimental value is not so much relevent for a surgical mask	0	Not applicable	0	Not applicable
Design for physical durability	1	Gets damaged very easily . It has a shortlife span	0	Not applicable since it is not designed for physical durability	0	Not applicable
Design for maintenability	1	It is not maintenable since it has no ablilty for life extension.Limited shelf life	0	Not applicable	0	Not applicable
Total Scores	4		1		0	

Circualarity Score for Design for reuse	1
Safety Score for Design for reuse	1
Knowledge Score for Design for reuse	0

Total average Circularity Score for reuse= 0.67

Design for Repurpose

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for repairability	1	It is exceedingly difficult to rapair a surgical mask.No particular specialist for that.	0	Not applicable	0	Not applicable
Design for collaborative consumption	1	Impossible to be used by more than one person due to health reasons	1	Highly risky due to transferraable diseases	0	Not applicable
Design for product attachment and emotional durabilty	0	Sentimental value is not so much relevent for a surgical mask	0	Not appplicable	0	Not applicable
Design for physical durability	1	Gets damaged very easily . It has a shortlife span	0	Not applicable	0	Not applicable
Design for adaptability & flexibility	1	Cannot be used under different condtions except its main purpose, for health reasons	0	Not applicable	0	Not applicable
Design for maintenability	1	It is not maintenable since it has no ablilty for life extension	0	Not applicable	0	Not applicable
Total Scores	1		1		0	

Circualarity Score for Desgin for repurpose	1
Safety Score for Design for repurpose	1
Knowledge Score for Design for repurpose	0

Total average Circularity Score for repurpose= 0.67

Design for Refurbishment

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for upgradeability	1	There are no known industries for upgrading used surgical masks	0	not applicable	0	Not applicable
Design for standardization and compatibility	1	Has no available parts for upgrades	0	not applicable	0	Not applicable
Design for disassembly	3	Easy to dissamble with physical strength,however, it was not disigned for that	2	No potential risk to dissamble a surgical mask but not necessary	0	Not applicable
Total Scores	5		2		0	

Circualarity Score for Design for refurbishment	1.67
Safety Score for Deisgn for refurbishment	2
Knowledge Score for Design for refurbishment	0

Total average Circularity Score for refurbishment= 1.22

Design for Remanufacture

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for modularity	1	Has no removable parts and was not built into subcomponents	0	Not applicable	0	Not applicable
Design for minimal waste	1	Has no usefulness after being used once	0	Not applicable	0	Not applicable
Design for resource efficiency	0	Not applicable since no resource is requied for its function	0	Not applicable	0	Not applicable
Total Scores	2		0		0	

Circualarity Score for Design for remanufacture	1
Safety Score for Design for remanufacture	0
Knowledge Score for Design for remanufacture	0

Total average Circularity Score for remanufacture= 0.33

Design for Recyclability

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design with regenerative material	5	Over 80% of mask is made of polypropylene which is a reusable	3	Safe if precautionary measures are taken by workers	0	Not applicable
Design with recycled materials	5	Over 80% of mask is made of a recycled materials	2	not so safe.some recycled materials could contain harmful sustances dangerous to users	0	Not applicable
Total Scores	10		5		0	

Circualarity Score for Design for recyclability	5
Safety Score for Design for recyclability	2.5
Knowledge Score for Design for recyclability	0

Total average Circularity Score for recyclability= 2.50

Table 5.7: Scoring assessment for a surgical mask

PRODUCT Level Scoring for a washable mask using the second tool functionality

Max Score is 5

Design for Reuse

Assessment Factors	Circularity S	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comment
Design for repairability	3	There is a possibility to fix it on your own	5	No risks, very safe	2	No particularly known method specially to repair mask
Design for collaborative consumption	1	Impossible to be used by more than one person due to health reasons	1	Highly risky due to transferraable diseases	0	Not applicable
Design for product attachment and emotional durab	0	Sentimental value is not so much relevent for a surgical mask	0	not applicable	0	Not applicable
Design for physical durability	4	Made of fabric that can last for a satisfactory amount of time	3	Might become unsafe to use continously after using for a long time	1	Uncertain how long fabric will last without posing health dangers to user
Design for maintenability	5	It is washable making it able to be used for an extended period of time	3	Might become unsafe to use continously after using for a long time	1	Uncertain how many washes is still safe to keep using mask
Total scores	13		12		4	

Circualarity Score for Design for Reuse	3.25
Safety Score for Design for Design for Reuse	3
Knowledge Score for Design for Reuse	1.3

Total average Circularity Score for reuse= 2.5

Design for Repurpose

Assessment Factors	Circularity S	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for repairability	3	There is a possibility to fix it on your own	5	No risks, very safe	2	No particular known method specially to repair ask
Design for collaborative consumption	1	Impossible to be used by more than one person due to health reasons	1	Highly risky due to transferraable diseases	0	Not applicable
Design for product attachment and emotional durab	0	Sentimental value is not so much relevent for a surgical mask	0	Not applicable	0	Not applicable
Design for physical durability	4	Made of fabric that can last for a satisfactory amount of time	3	Might become unsafe to use continously after using for a long time	1	Uncertain how long fabric will last without posing health dangers to user
Design for adaptability & flexibility	5	It has excellent flexibility feature.eg.used for protection from inhalation of dust	5	very Safe	4	There is a least one known way on how the mask can be repuposed(Dust proctector)
Design for maintenability	5	It is washable making it able to be used for an extended period of time	3	Might become unsafe to use continously after using for a long time	1	Uncertain how many washes is still safe to keep using mask
Total scores	18		17		8	

Circualrity Score for Design for Repurpose	3.6
Safety Score for Design for Repurpsoe	2.83
Knowledge Score for Design for Repurpose	2

Total average Circularity Score for repurpose= 2.81

Design for Refurbishment

Assessment Factors	ircularity Scr	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for upgradeability	2	Upgrades could be possible.However, there are no known industries for that	0	not applicable	1	Uncertain on how upgrades how upgrades can be done
Design for standardization and compatibility	1	Has no available parts for upgrades	0	not applicable	0	Not applicable
Design for disassembly	1	The disign of a washable mask does not make it to disassemble	0	not applicable	0	Not applicable
Total scores	4		0		1	

Circualrity Score for Design for Refurbishment	1.3
Safety Score for Design for Refubishment	0
Knowledge Score for Design for Refurbishment	1

Total average Circularity Score for refurbishment= 0.77

Design for Remanufacture

Assessment Factors	Circularity S	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for modularity	1	Has no removable parts and was not built into subcomponents	0	Not applicable	0	Not applicable
Design for minimal waste	3	Usuablity of the entire material to produce a new one is possible.Not encouragable, healthwise	1	Not safe, risky healthwise	0	Not applicable
Design for resource efficiency	0	Not applicable since no resource is requied for its function	0	Not applicable	0	Not applicable
Total Scores	4		1		0	

Circualrity Score for Design for Remanufacture	2
Safety Score for Design for Remanufacture	1
Knowledge Score for Design for Remanufacture	0

Total average Circularity Score for remanufacture= 1

Design for Recyclability

Assessment Factors	ircularity Scr	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design with regenerative material	5	Over 80% of mask is made of fabric which is a reusable	3	Safe but not 100% safe.Resuing fabric may pose danger	0	Not applicable
Design with recycled materials	5	Over 80% of mask is made of a recycled materials	2	Not so safe.some recycled materials could contain harmful sustances dangerous to users	0	Not applicable
Total scores	10		5		0	

Circualrity Score for Design for Recyclability	5
Safety Score for Design for Recyclability	2.5
Knowledge Score for Design for Recyclability	0

Total average Circularity Score for recyclability= 2.5

Table 5.8: Scoring assessment for a washable mask

PRODUCT Level Scoring for a FF3 mask using the second tool functionality

Max Score is 5

Design for Reuse

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comment
Design for repairability	1	There are no known specialist to repair FFP3 mask or availablity of broken parts	0	Not applicable	0	Not applicable
Design for collaborative consumption	1	Impossible to be used by more than one person due to health safety reasons	1	Highly risky due to transferraable diseases	0	Not applicable
Design for product attachment and emotional durabilty	0	Sentimental value is not so much relevent for a FFP3 mask	0	Not applicable	0	Not applicable
Design for physical durability	3	Can be used for a long time without damage but not advisable for health safety reasons	1	Risk of Infection	0	Not applicable
Design for maintenability	3	Can be decontaminated and used again for an extended period	3	Only safe to use for a limited time period	1	Uncertain on the number of times it can be deomininated and used safely
Total Scores	8		1.67		1	

Circularity Score for Design for Reuse	2
Safety Score for Design for Reuse	1.67
Knowledge Score for Design for Reuse	1

Total average Circularity Score for reuse= 1.6

Design for Repurpose

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for repairability	1	There are no known specialist to repair FFP3 mask or availablity of broken parts	0	Not applicable	0	Not applicable
Design for collaborative consumption	1	Impossible to be used by more than one person due to health safety reasons	1	Highly risky due to transferraable diseases	0	Not applicable
Design for product attachment and emotional durabilty	0	Sentimental value is not so much relevent for a FFP3 mask	0	Not applicable	0	Not applicable
Design for physical durability	3	Can be used for a long time without damage but not advisable for health safety reasons	1	Risk of Infection	0	Not applicable
Design for adaptability & flexibility	4	Can be used as a general respiratory protection equipment.	3	safe, depending on the environent t is being used	4	There are other known ways the mask can be used besides covid protection
Design for maintenability	5	Can be decontaminated and used again for an extended period	3	Only safe to use for a limited time period	1	Uncertain on the number of times it can be deomininated and used safely
Total Scores	14		8		5	

Circularity Score Design for Repurpose	2.8
Safety Score for Design for Repurpose	2
Knowledge Score for Design for Repurpose	2.5

Total average Circularity Score for repurpose= 2.4

Design for Refurbishment

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for upgradeability	2	maybe possible.However, there are no known procedures for upgrades	0	Not applicable	1	Unknown procedures on upgrading mask
Design for standardization and compatibility	1	Has no available parts for upgrades	0	Not applicable	0	Not applicable
Design for disassembly	1	Not desined to be disassembled	0	Not applicable	0	Not applicable
Total Scores	4		0		1	

Circularity Score Design for Refurbishment	1.3
Safety Score for Design for Refurbishment	0
Knowledge Score for Design for Refurbishment	1

Total average Circularity Score for refurbishment= 0.8

Design for Remanufacture

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design for modularity	1	Has no removable parts and was not built into subcomponents	0	Not applicable	0	Not applicable
Design for minimal waste	1	The mask was designed to be disposed after use	0	Not applicable	0	Not applicable
Design for resource efficiency	0	Not applicable since no resource is requied for its function	0	Not applicable	0	Not applicable
Total Scores	2		0		0	

Circularity Score Design for Refurbishment	1.3
Safety Score for Design for Refurbishment	0
Knowledge Score for Design for Refurbishment	0

Total average Circularity Score for remanufacture= 0.4

Design for Recyclability

Assessment Factors	Circularity Score	Comments	Safety Score	Safety Comments	Knowledge Score	Knowledge Comments
Design with regenerative material	5	Over 80% of mask is made of polypylene which is a reusable	3	Safe but not 100% safe.Resuing polypylene may pose danger	0	Not applicable
Design with recycled materials	5	Over 80% of mask is made of a recycled materials	2	Not so safe.some recycled materials could contain harmful sustances dangerous to users	0	Not applicable
Total Scores	10		5		0	

Circularity Score Design for Recyclability	5
Safety Score for Design for Recylability	2.5
Knowledge Score for Design for Recyclability	0

Total average Circularity Score for recyclability= 2.5

Table 5.9: Scoring assessment for FFP3 mask

Step 2a: Evaluating and comparing the products or pieces of equipment in terms of their circularity (or CE alternatives)

In terms of how the three types of masks were scored, they are put side by side to compare their circularities as seen in the table below.

	Total average circularity Score				
	Design for Reuse	Design for Repurpose	Design for Refurbishment	Design for Remanufacture	Design for Recyclability
Surgical Mask	0.67	0.67	1.22	0.33	2.50
Washable Mask	2.5	2.81	0.77	1	2.50
FFP3 Mask	1.6	2.4	0.8	0.4	2.50

Table 5.10: A table representing the circularity scoring for all the 3 types of face masks

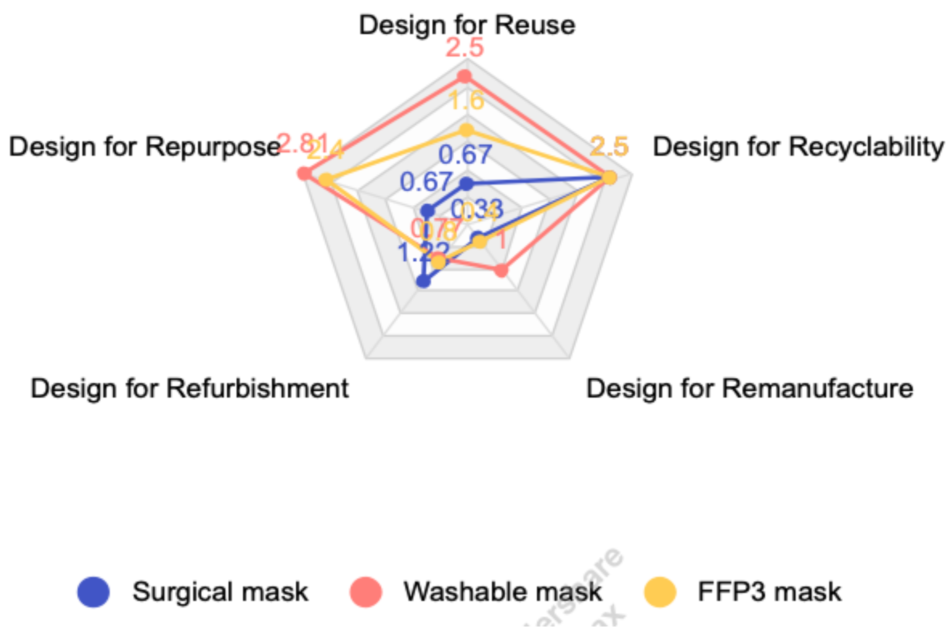

Figure 5.7: Spider diagram showing the Circularity of the 3 types of masks

Evaluating and comparing the scoring of the three different mask designs using a spider diagram (Figure 5.7), it can be seen clearly that the washable mask has the best circularity design in the sense that it scored 2.5 of total average circularity for reuse which was the highest compared to FFP3 mask which scored 1.6 and surgical mask which scored 0.67. The scores consider the extent of knowledge available (there was relatively more certainty of knowledge for assessment compared to the other two face masks) for assessment as well as the amount of safety. Apart from the washable mask having the highest score for the highest circularity loop (design for reuse), it has the highest score for most of the other circularities (Design for repurposing, recyclability, remanufacture) i.e., it has the highest scores for almost all the CE categories in the framework compared to the surgical mask and the FFP3 mask. The second-best design is the FFP3 mask and the last is the surgical mask since it has the lowest scoring on average for each CE category in the framework.

Step 3a: In-depth analysis of the best equipment design selected to finalise a decision

The washable mask is the most suitable choice. However, that does not make it the perfect choice of design on the planet. There would certainly be a few drawbacks and it is important to identify them. The main aim of this step is to make a final in-depth assessment of the washable face mask using Table 5.2. The washable facemask may face a competitive market as there are so many facemask options available for consumers so this could be a major drawback, however, good marketing and promoting the economic benefits of using a washable mask can combat the challenge. Another drawback that could be faced is the consumer perception of reusing a single mask repeatedly. This might be a turn-off for some consumers. It can be solved by giving out medical proof of how safe it is to reuse a washable mask without sharing. The risk of exposure of employees when dealing with the recycling of washable masks is due to the possibility of the presence of COVID-19 in some of the masks. This drawback can be solved by intensive disinfection of masks as the first step to recycling them. Possible consequences and drawbacks have been detected. However, there are possible solutions to rectify them. Hence, a washable mask is confirmed as the most circular design of a facemask.

Summary of the assessment tool and its functionalities:

- Step1/Step 1a,
    - Fig 5.2 is an assessment framework that can be used to evaluate the circularity level(i.e the most suitable CE strategy) for a business model, a system, a service, a product, or material.
    - Circularity level can be defined as follows: the longer (duration, number of circular loops such as reuse, repurpose, remanufacture, etc.) a product can keep its value, the higher the circularity level
    - In fig 5.2, 5 CE strategy options or loops or categories are *design for reuse, repurpose, refurbishment, remanufacture, recyclability* and each of the CE strategy options have sub-options called **assessment factors** (i.e., design for maintainability, etc.)
    - The tool allows decision-makers to score each **CE option or Circularity level**
        - **Each Circularity level or CE option and sub-options** (assessment factors) are scored using the Likert scale (e.g very easy to repair, easy to repair, difficult to repair, exceedingly difficult to repair, not applicable for this product design, etc) with corresponding qualitative values from 1 to 5 where 1 is minimum and 5 is the maximum.
        - **A comment is added to justify the scoring**.
        - To help you **to score and make a comment,** a definition of the sub-option (assessment factors) is given. For instance, “very easy” for repairability is characterised by a repair method in place, well-proven, available on the market, etc.

For the “second functionality” of the tool, additionally:

- Like in risk assessment, each sub-option(assessment factor) has semi qualitative scoring **on Knowledge** (knowledge/uncertainty related to the circularity level scoring) and an average score is taken for each of the circularity levels
- A semi-quantitative **safety** scoring of the sub-options(assessment factors) and the average is taken for each circularity level.

    - The scoring can be prepared by a consultant, then a workshop is called to validate the scoring and the argument for time effectiveness
- Step 2,
    - Not included in the “second functionality”
    - When step 1 uses a semi-quantitative approach, step 2 uses Indicators that are additional quantitative economic, environmental KPI like C02 emission, water consumption and risk assessments for each CE option for further detailed assessments.
- Step 2a,
    - Not included in the “first functionality”
    - Based on the scoring of each piece of equipment/product in step 1a they are compared against each other. Different modes and methods such as graphs and spider diagrams can be used to help in making comparisons
    -
- Step 3 is a combination of step 1 and step 2 evaluation and discussing the best option for a piece of equipment or product when it has reached EOL.
- Step 4/step 3a,
    - Other factors (social, economic, regulation, etc.) could influence finding from the model from step 1\step 1a, 2 and 3.
    - Step 4 provides a more holistic (high-level) evaluation to finalise a decision.

More functions/uses of the tool:

- There are potentially 4 scenarios where the step 1 assessment and in general the tool can be used
    - Scenario 1: Compare in terms of circularity of different designs of the same product, system, or service (second functionality of the tool). Recommendations based on client strategy/ need can be made. So it is particularly useful when you create a new design for a product and evaluate its circularity.
    - Scenario 2: A product in (EoL) that has no design for circularity. You use the “first functionality” to define the circularity level and the best

option to recirculate the product/equipment based on the sub-options(assessment factors)

- Scenario 3: Use of Proactima database and any old product from the scenario 2 assessment as an input to a new design to make it circular as per company strategy.
- Finally, the model can be used to reassess how improvements in a Design of a product can be made.

In this chapter, the CE Assessment Tool generated was built mainly on carefully selected literature considering the impact CE has on technical safety and asset management at the EoL of a product or asset. Qualitative scoring was implemented based on the design of the asset/products with the help of a framework. Indicators were formulated by categorising the CE impacts in terms of an economic, environmental and safety point of view.

6 Product development process of products at their end of life stage in terms of CE

In an enterprise or company that deals with manufacturing, it is important to follow a structured process. The endgame for implementing the CE into asset management and decommissioning is to extend the life of assets and maintain their value for as long as possible. An intellectual and systematic process named the *Product development process* which serves as a pathway to plan and execute the CE concept would be necessary. It is necessary to ensure quality, effective planning, and coordination in the development process of remanufactured, refurbished, or reused products.

A product development process is a sequence of activities that an enterprise employs to conceive, design and commercialise a product (Ulrich & Eppinger, 2016). The product generic development process comprises 6 main phases: *Planning, Concept Development, System-Level Design, Detail Design, Testing and Refinement, and Production Ramp-up.*

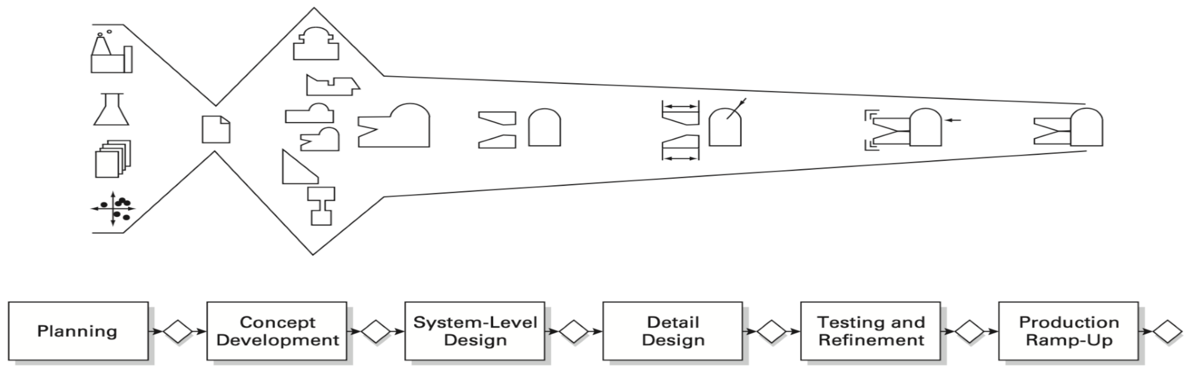

Figure 6.1: The 6 phases of the product development process

The relevant objectives and guidelines to be followed in the 6 phases of CE product development in their end of life are discussed below:

6.1 Planning phase

This is the first phase of the product development process. For products that are in use or have already reached their EoL phase and are due for decommissioning, in the light of the CE, the main objective and plan here are to find the best way to render products for an extended value period. Depending on the organisation/company, the outcome of the development process could be commercialising by putting products up on the market for sale or to be used by the company itself to save money. The outcome of this phase is to clarify the mission of the project, which in this case is to find the best CE options to implement on the products that have reached their end of life via considering a list of factors including the market available for such products.

At this stage, the information gathered is unstructured. The **project manager and product manager** may be responsible for deciding the possible result of a product that has reached its EoL, in the planning phase, also, technical expertise such as **mechanical** and **industrial engineers** are invited to determine the technical possibilities of decisions made. (Diaz et al., 2021). This is the technical feasibility of the CE options.

Policy analysis, market analysis, and consumer surveys are necessary as the available market demand for a particular product under review is identified based on its circularity status (i.e available markets for the reusable, refurbished, and remanufactured products). For example, the market available for used generators to be reused should be identified and other alternative markets for refurbished or remanufactured generators. **Market/business analysts** and **communicators** shall be responsible for this process. External support to produce a clarified motif may be necessary through holding workshops and even professional consultation.

6.2 Concept Development phase

The specific customer needs are supposed to be known in this phase. Before a product/equipment is to be put into the loop of the CE, the most preferred option by the customers for the equipment under assessment must be investigated and arranged in order of relevance. For example, when already used washing machines are to be sent back to the market for sale, it must be investigated whether reused, refurbished, or remanufactured washing machines are the most preferred and it is communicated to the development team. The **development team** at this point takes the most needed or most preferred CE options for that product and converts that into technicalities that may be involved to make it possible. The list of the most preferred CE options by customers is analysed and the inapplicable ones due to the product/equipment design and other factors are eliminated, leaving the most promising option(s) by the **design engineers.** An important analysis is the understanding of the cost involved in implementing the laid-out CE options.

The cost involved such as manufacturing cost and development cost when implementing each CE option for a given product or equipment is evaluated through cost-benefit analysis by **project engineers** (Roseke, 2019). For instance, estimating the cost to reuse a generator, the cost to refurbish the same generator and the cost to remanufacture the same generator are compared. The cost involved is considered an investment and the expected return value is crucial. Below is an image illustration to depict a very simplified version of a cost-benefit analysis.

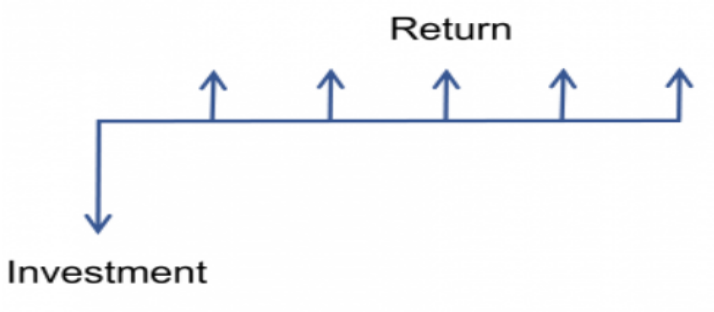

Figure 6.2: Depiction of cost-benefit analysis

The larger the cost involved, the higher value of the return is expected; this is why reusing equipment/product is mostly suggested if it is a feasible approach since little or no cost is involved yet a significant value of the product can be salvaged. Applying the *CE assessment tool first functionality* proposed in chapter 5 could be used for the analysis.

The market potential of one or more of the CE options for the product is assessed by the **market analyst**. If the customers' response is not encouraging, then the development process may consider termination or some improvements must be made.

If remanufacturing or refurbishment is the selected CE option to be implemented, a structured schedule to complete the project that includes a strategy is relevant in order to be time effective and identify the resources needed in the development process.

In order to build a strong conclusion on the selected CE options that can be applicable to the product, further analysis such as understanding the product performance analysis(i.e number of activities, rate of usage or other relevant data) by the **product manager** may deem necessary.

Major outcomes from this phase such as the most customer preferred CE option(s) for the product, the technicalities of the selected CE option(s), an assessment made on the CE option(s) for the product, development schedule and budget are expected after which a contract agreement can be signed between the development team and the senior management.

To summarise:

- Customers' most needed or preferred CE option for a product: reused, remanufactured, or refurbished product.
- Converting the most preferred choices of customers into technicalities: materials, architecture, design, cost, etc.
- Technicalities are analysed, assessed and the unfeasible CE options or alternatives are eliminated.
- The market potential of the promising CE options selected for the product is analysed
- Development is made and an agreement between the development team and the senior management may be necessary

6.3 System-level design phase

According to definition, this is the phase where the product's design, architecture and overall structure are considered when developing a product, (Ulrich & Eppinger, 2016). In terms of CE, for equipment/product in use or has reached its end of life (EoL) with the interest to extend its life, the design, structure, and components of the equipment/product are considered as well. This is where available suppliers for components must be researched, especially when it comes to remanufacturing or refurbishing the product. The architecture of a product is assessed which includes determining how difficult it is to dismantle. Again, remanufacturing or refurbishing may be options to consider eliminating if dismantling is an issue after assessment.

The employees in this phase are like those in the concept development phase but weigh more on the technical employees. The CE options obtained from the previous phase are analysed again but with more information such as risk analysis and safety. The team may need to structure their thinking towards the goal of investing less and at the same time being profitable.

For instance, assuming an engine block is in the process of being looped into the CE and the most feasible options are to remanufacture (i.e take out broken parts and replace them with new ones) or refurbish it(i.e make upgrades to adapt to new car models). To measure down the number of CE options that can be implemented on the engine block, team members could ask questions like:

- How would the architecture of the product impact their ability to upgrade it?
- How would the architecture of the product impact their ability to replace/or fix broken parts?
- What would be the specific cost implications to remanufacture compared to refurbishing the engine block?
- How would the design of the engine block impact their ability to complete remanufacturing compared to refurbishing in the shortest possible time?
- How would the architecture and design of the product affect their capability to manage the development process?

With more quantitative information gathered about the product, weighted decision matrix (Salustri, 2020) and index metrics (MSCI, 2020) are used to make decisions to cut down the CE options to be implemented.

Computer aid application and Building Information Modelling might be necessary, especially in remanufacturing or refurbishing if adjustments must be made to the model or to collect quantitative data.

6.4 Detail design phase

This is the phase of the product development process where detailed specifications of materials, geometry and available standard parts are gathered to produce a document called a *control document* for a product, (Ulrich & Eppinger, 2016). It is expected that every product will come with a control document. Detailed engineering and production specifications in order to implement CE options (remanufacturing or refurbishing) are highlighted. This process may not be necessary for a product that is suitable to be reused.

The **production engineer** (Gessinger, 2009) assesses the physical characteristics further such as material type, dimensions and one or two attributes that might have to serve as trade-offs to ensure the quality level potential of the product. The environmental impact of production (remanufacturing or refurbishing) is considered. Setting a kind of prototype for testing its quality and performance is necessary. For instance, if a respectable number of generators are brought-in to be put through the loop of CE and the agreed CE options to be implemented so far are remanufacturing, refurbishing, and reusing. It is important to test the performance of CE options by creating a prototype of each, that is, a prototype testing for a refurbished generator, a prototype testing for a remanufactured generator and a prototype testing for a reused generator. This is necessary since remanufacturing or refurbishing may involve the replacement of parts (materials, engines, cables, electronics, etc) that may have been produced in different departments or even different companies.

6.5 Testing and refinement phase

The testing and refinement phase is about evaluating the durability and reliability of the product with the implemented CE options selected so far. As discussed earlier, circularity has a hierarchy, that is, CE alternatives are arranged in terms of importance. Reuse/repurpose is the most important and the first to consider implementing if possible whilst recycling should be the option/alternative of last resort.

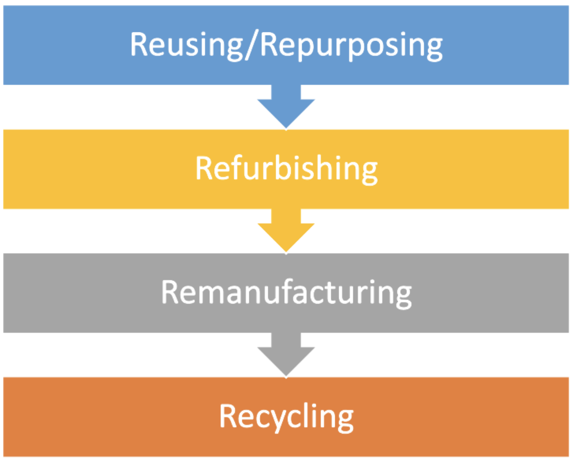

Figure 6.3: CE hierarchy in terms of relevance

In the previous phase, the performance of the product when each of the CE options is implemented is tested, however, their performances are not compared. In this phase, the performance and reliability of the product are compared in terms of the CE options implemented on them in the order of the circularity hierarchy. An acceptable performance and reliability together with a high level in the CE hierarchy become the most suitable CE choice to be implemented on the product.

For example, due to the condition of a set of turbine blades, the most suitable CE alternatives after evaluations through the previous phases are reuse and refurbishment. In terms of circularity hierarchy, reusing of the turbines should be tested first for their reliability and performance and be considered as the first option to be implemented on the turbine blades. Refurbished turbine blades should only be considered if it has a drastically better performance and more reliability compared to the reused turbine blades when tested. **Production and operational employees** are usually responsible for testing and operations (Diaz et al., 2021).

6.6 Production ramp-up phase

This is the last phase, the CE alternative to be implemented is finalised and the workforce is trained to apply it to the product especially when the CE alternative to be implemented is either remanufacturing or refurbishment. Not so much manufacturing has to be done if the product was good enough to be reused/repurposed. If possible, the products produced are sent to interested customers to identify any remaining issues. At some point, products can finally be put on the market.

6.7 Framework

According to the product development phases explained above, below is a framework that summarises how an enterprise can implement CE to product(s) to render it an extended value period.

CE product development process (phases)						
	Planning and initialization	**Concept feasibility and development**	**Initial designing**	**Final designing with details**	**Product testing and verification**	**Improvements and final implementation**
Primary goal	1. Declare mission: find the best CE options to implement on a product that has reached its end of life via considering a list of factors including the market available for such products)	1. Specific customer needs(most preferred CE option for a product/equipment) 2. Development schedule	To cut down the CE options: 1. Product's design, architecture and overall structure assessment 2. Identifying availability of suppliers of product/equipment parts	1. Gathering detailed specifications of materials, geometry and available standard parts 2. Ensure product/equipment quality	1. Selecting the most reliable CE option to be finally implemented on the product/equipme nt	1. Finalising the best CE option to be implemented. 2. Producing or applying the finalised CE option on products/equipment

Marketing	Market surveys	Evaluation of the market potential of the selected CE option for a product				-Finalise pricing
Tools		Circular Economy assessment tool	-Weighted decision matrix -Index metrics -Computer aid application Building Information Modelling	-Prototype testing	-Prototype testing	
Core Employees involved	-Market analysts -Mechanical engineer -Project manager	-Design Engineer -Project engineer -Market analysts	-Design engineer -Project engineer	-Production engineer	-Production engineers	-Production engineers
Engineering	-Technical possibilities of decisions made from market demand/survey	-Engineering analysis (eg.possibility of failure).	- Design/structure assessment(eg. difficulty to dismantle)	-Gathering knowledge of materials, dimensions and other detailed specifications of the equipment/product		

Manufacturing			-Determining replaceable/fixable parts	-Assessing physical characteristics (material type dimensions, etc) and making adjustments to ensure potential of a quality remanufactured or refurbished product -Making a prototype to test to ensure quality	-Comparing the CE prototypes of a product/equipment in terms of performance	-Detecting any issues that might need improvements or changes

Table 6.1: Product development process framework in terms of CE applied to equipment/product in their EoL phase

7 Conclusion

This thesis aimed to come up with ways to improve the implementation of a CE in asset decommissioning when it comes to the oil and gas industry. Based on the objective, the various issues that hinder the progress of the CE in asset decommissioning in the oil and gas industry were identified as this should be a starting point to improvement. According to research, factors such as regulations, risk(technical and health risk) and the lack of circularity design of equipment were some of the hindering factors and the modification of designs of products/equipment could alleviate the issue.Companies in the oil and gas sector practice mostly practice only recycling in the decommissioning and the majority are not even interested for various reasons. More improvements can be done in ways and means of implementing the CE such as regulations adjustments, making it attractive to these companies. A survey which was conducted to confirm the research findings was inconclusive due to insufficient participants as it was a challenge to reach out to individual employees through email due to GDPR regulations.

With the aim of improving the applicability of the CE in decommissioning of oil and gas assets, a tool was developed. The tool has been developed with two main functionalities. The first functionality which is referred to as "first functionality" and aims at assessing equipment/products in their EoL phase to determine the most suitable CE strategy to implement rather than just straight-out disposing or recycling when decommissioning. A case study which gives an illustration of a use case of the "first functionality" was an assessment of an internal floating roof tank to determine the most suitable CE option (i.e recycling, remanufacturing, refurbishing, repurposing or reusing). The second functionality of the tool, which is referred to as "second functionality" is to assess and select the best design amongst two or more designs of a product/equipment that has the best circularity. This functionality possesses a potential utility when deciding on selecting the best product among the rest in terms of circularity. A case study was elaborated in determining the best COVID-19 face mask among three face masks in terms of their circularity. Aside from the discussed functionalities, extra functionalities of the tool were stated.

A CE inclined framework for a product development process was developed for implementing CE loops to asset/product/equipment in their EoL. It was based on the 6 main phases in a generic product development process, namely: planning phase, concept development phase, system-level design phase, detail design phase, testing and refinement phase and production ramp-up phase. The development of this framework is essential for service companies or enterprises to have a structured plan when trying to implement CE on products/equipment.

8 Future Prospects

- Further precision can be enabled in the CE assessment tool in future studies by involving the input of expertise(cost analysis, safety analysis and other technicalities). This could increase the number of indicators for analysis and make them more defined. In advanced terms, a database of equipment and assets can be generated with data collected from various factories and industries which can be used to build a software program for quicker and more efficient analysis.

- A secondary CE assessment tool developed using the Analytic Hierarchy Process (AHP) method can be considered for a future study.AHP is popular and mostly known for solving multicriteria problems to come up with a final decision. Comparing results of CE assessment and the tool built with AHP and coming up with a more reliable and robust decision could be possible in future studies.

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Appendix

Supplementary Excel files

1. Description: The link below is an Excel file that is part of the CE assessment tool discussed in Chapter 5

   https://1drv.ms/x/s!AkNiV0s_OJHajxUMdTnPt2Fa112N?e=Vm52Vn

The Excel file comprises of :

- A spreadsheet/tool called “**Material level(1st Func.)**” which is used to score products/equipment qualitatively at the material or component level when using the “first functionality” of the assessment tool described in the thesis.

- A spreadsheet/tool called “**Product level(1st Func.)**” which is used to score products/equipment qualitatively at the product level when using the “first functionality” of the assessment tool described in the thesis.

- A spreadsheet/tool called “**Material level(2nd Func.)**” which is used to score products/equipment qualitatively at the material level when using the “second functionality” of the assessment tool described in the thesis.

- A spreadsheet/tool called “**Product level(2nd Func.)**” which is used to score products/equipment qualitatively at the product level when using the “second functionality” of the assessment tool described in the thesis.

- 3 spreadsheets called “**Surgical mask**”, “**FFP mask**” and “**Washable mask**”.They illustrate how the CE assessment scoring is done when the “second functionality” of the assessment tool is applied to three face masks; surgical mask, FFP mask and washable mask”.

- A spreadsheet called “**Float roof tank**”. It illustrates how the CE assessment scoring is done when the “first functionality” of the assessment tool is applied to an internal floating roof tank.

2. Description: The link below is an Excel spreadsheet that is used to calculate the Net Recoverable Factor(NRV) of product/asset/equipment if it is to be used as an indicator in Step 2 of the first functionality of CE assessment tool.

   https://1drv.ms/x/s!AkNiV0s_OJHajxet9QnHhuLLem7K?e=1hy8yq