Circular performance of project equipment

The material circularity and economic value of project equipment on a project, product, and company level

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MARINE CONTRACTORS

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The confidential information in the appendix is redacted in this version.

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Preface

Before I conducted this master's thesis, my understanding of the circular economy concept was rather limited. Nevertheless, I was convinced that I wanted to spend my research time to contribute to sustainability. Now, a year later, through collaboration with Delft University of Technology and offshore company Heerema Marine Contractors (HMC), my knowledge of the circular economy has been built. After a rather theoretical study, I am happy to continue working on the circular economy by putting my experience into practice at HMC.

This research paper aims to create a better understanding of how to tackle the circular economy concept for project-based organizations. It focuses on the measurement of the circular economy performance of project equipment, to reduce resource use and waste. Next to this, it shows the relation between the circular economy performance in terms of mass and economic value, as well as the benefits the circular economy can have on a company's financial results.

Although this graduation thesis was a personal endurance task, I would not have been able to do it without the help of others. First and foremost, I would like to thank my girlfriend Noah Moeys for her patience at home, who gave me space to be grumpy so often. My eldest aunt for being my coach and mental support, pushing me forward through the last months. From HMC, I want to thank Arjan Buijsse for his enthusiastic support, Meike Kolthof for her motivating drive, Joris Treurniet for his dedicated time and passion for steel, Liselotte Wisman for being my circular buddy, the other Sustainabuddys for doing such important work, Jeroen Kriek and Ewout Bastian for their critical eyes, and all other people who made time for me. Lastly, I would like to thank Jeroen Pruyn from Delft University of Technology for supervising me and especially for giving me the freedom to tailor the process to my individual needs.

T.O. Rodermond
Utrecht, January 2024

Abstract

The global awareness of the environmental and economic advantages of the circular economy (CE) concept has grown significantly. In order to implement this concept into company practices, a vital starting point is the adoption of a measurement framework. In the past years, the evolution of CE metrics resulted in maturity and practical applicability. However, no method exists able to quantify CE performance specific to a project-based organization. The Material Circularity Indicator (MCI) is one of the most ambiguous methods, which captures circularity with mass as the measurement unit. Alternatively, the Material Circularity Indicator based on economic value (MCI') is developed as a solution for the reliance of the MCI on mass flow, by using cost-based economic value as the measurement unit. However, existing economic value indicators — as accounts for the MCI' — are criticized for not including all significant and relevant life cycle cost factors. To solve these implications, both methods are adapted to indicate the CE performance on the levels of interest for a project-based organization: the project, product, and company level. To work from level to level, a bottom-up approach is taken, aggregating using a weighted sum. Additionally, the MCI' is enhanced by including more life cycle cost factors. The results show that the enhanced MCI' gives a more accurate estimate of cost-based economic value. Furthermore, the aggregation from the project level to the product and company level, gives valuable insights into the CE performance of project-based organizations.

Contents

1 Introduction

In 1972, Meadows et al. (1972) warned about the environmental consequences of the current unsustainable economic growth model, enabling a 28.6 billion tonnes of global material consumption annually. Fifty years later, in 2019, the 100 billion tonne limit was surpassed, with a worldwide projection of 167 billion tonnes per year in 2060 (Organisation for Economic Co-operation and Development [OECD], 2019). As a consequence, resource extraction and processing was responsible for half of global greenhouse-gas (GHG) emissions and over 90% of biodiversity loss and water stress in 2019 (Oberle et al., 2019). The emissions are projected to increase to 50 Gt of the total 75 Gt of GHG emissions in 2060 (OECD, 2019). To stop the ever increasing environmental impact of resource extraction and processing, a way to change our habits is needed.

To tackle this issue, the concept of a circular economy (CE) can provide useful support. This is because a CE requires less raw materials, generates less waste, and results in fewer emissions and pollution (European Parliament Research Service [EPRS], n.d.). The transition to a CE is acknowledged as a unique opportunity to make our economy more sustainable, competitive, and resilient, as it creates decent and green jobs, improves security and strategic dependencies of supply, boosts innovation, contributes to climate neutrality, and preserves biodiversity and ecosystems (European Commission [EC], 2023). Since governments find the concept promising, some use CE targets to limit resource use and the generation of waste. The Dutch government, for instance, has set a goal to use 50% fewer primary materials by 2030, with the ultimate target of a waste free economy by 2050 (Government of The Netherlands, n.d.). The question that then remains is how these targets can be met, to thus support the transition to a CE.

To assist governments, companies, and individuals in changing to a CE, an adequate measurement framework is necessary. The question how to quantify, define the benefits, and to identify opportunities in CE strategies, experienced growth in interest and methodological debate (Walker et al., 2018). This is because CE initiatives can only be guaranteed when there is an appropriate evaluation framework for monitoring progress toward a CE (Saidani et al., 2019). Although various methods arose from the research conducted over the past few years, further room for improvement remains.

This research was initiated by an offshore contractor, to measure and improve their CE performance. To find out why this is important for them, Section 1.1 will elaborate the problem the contractor encounters. In Section 1.2, the CE concept is described, to understand how it can help to solve the problem. Finally, a research definition is drawn, consisting of the research questions and scope.

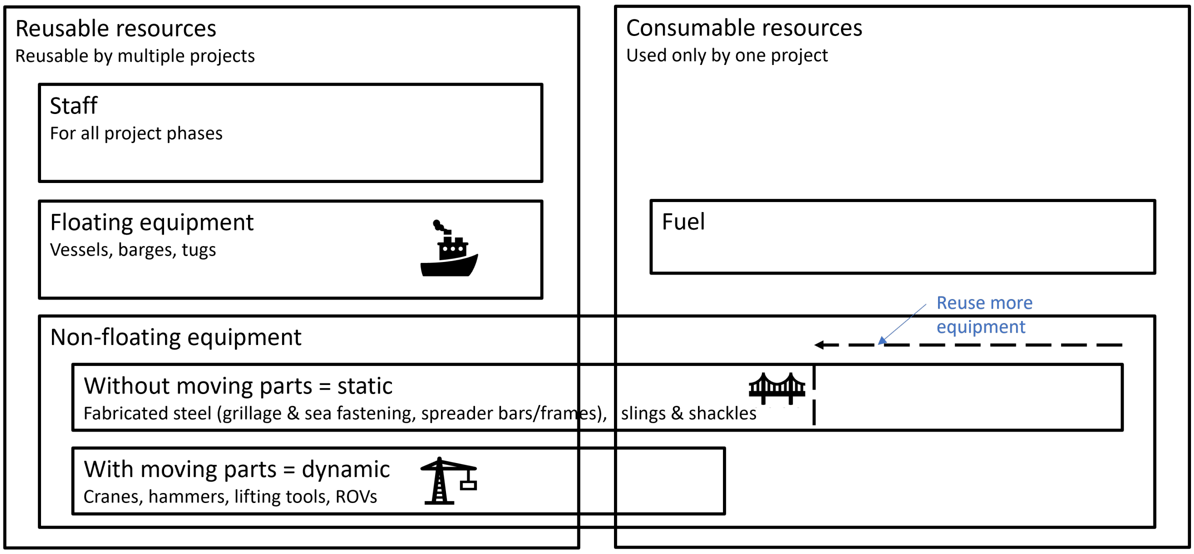
1.1. Problem description

The offshore industry is a resource intensive industry which could benefit from the CE concept. Within this industry, one of the key players is the offshore contractor, responsible for the transport, installation, and removal (TIR) of offshore structures. Such structures are, for instance, oil or gas platforms, wind turbines, or offshore transformer platforms. The activities of an offshore contractor are considerably resource intensive, as large amounts of materials and people are required to execute the job.

For its TIR projects, the contractor uses various types of project resources, such as staff, equipment, and fuel (see Figure 1.1). This research focuses on project equipment because a lot of equipment is used as *consumable*, meaning it is used only once. This consumable resource could, however, be used in multiple projects, and that is when the CE concept can be of use.

Figure 1.1

Offshore transport, installation, and removal resources



Offshore equipment can be divided into floating equipment — such as vessels, cargo barges, and tugs — and non-floating equipment — such as transport frames, hammers, and lifting tools. The floating equipment is most often designed for a lifetime of 25 years or more, whereas non-floating equipment often has a much shorter lifetime. The latter type of equipment thus requires a more frequent resource extraction and processing, favoring a CE approach. Amongst the non-floating equipment, fabricated steel — consisting of transport frames, spreader bars and beams, and lift points — tends to be fabricated by the offshore TIR contractor itself. This provides the contractor with the control over the design, manufacturing, and end-of-life (EoL) decisions. For other equipment purchased from subcontractors, a higher degree of cooperation is required to embed the CE into the value chain.

Another key reason why resources are managed in an unsustainable manner is that the TIR contractor works on a project-by-project basis. This makes the company a so-called *project-oriented* organization (Gemünden et al., 2018), and the equipment used for the projects is defined as *project equipment*. As the complete project cycle is the main revenue-generating activity for such organizations (Gemünden et al., 2018), this creates a strong focus on the project level, resulting in the project budget being one of the most important decision drivers. Related to resource use, the project level refuses to take a whole life cycle approach, which is necessary for less exhaustive resource use.

To find out how the idea of a CE can reduce resource extraction and processing for project equipment, the concept and requirements of a measuring method are reviewed in the following sections. In this research, a case study on offshore project equipment is performed. However, the findings of this research are valuable for any organization making use of project equipment, and aiming to reduce resource depletion caused by equipment production.

1.2. The circular economy concept

To identify how the concept of a CE can be used to reduce primary resource use and waste in the life cycle of project equipment, the CE concept is analyzed in section 1.2.1. As part of the principle, the process and effect side of CE are reviewed in Sections 1.2.2 and 1.2.3 respectively.

1.2.1. Definition of the circular economy

Kirchherr et al. (2017) made a thorough analysis of over one hundred definitions of the CE. The study found that scholars have a different opinion about its true definition, which leads to confusion about the required aspects of a CE. The effect of this diversity scatters through when implementing the CE concept, for instance, when developing a framework to measure its performance. Apparently, various definitions exist, and the definition is likely to change as we are in a so-called "validity challenge period" (Blomsma and Brennan, 2017, p. 610; inspired by Hirsch and Levin, 1999). One general definition which states the elements of a circular economy necessary to be included (Kirchherr et al., 2017):

> We defined CE within our iterative developed coding framework as an economic system that replaces the end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers.

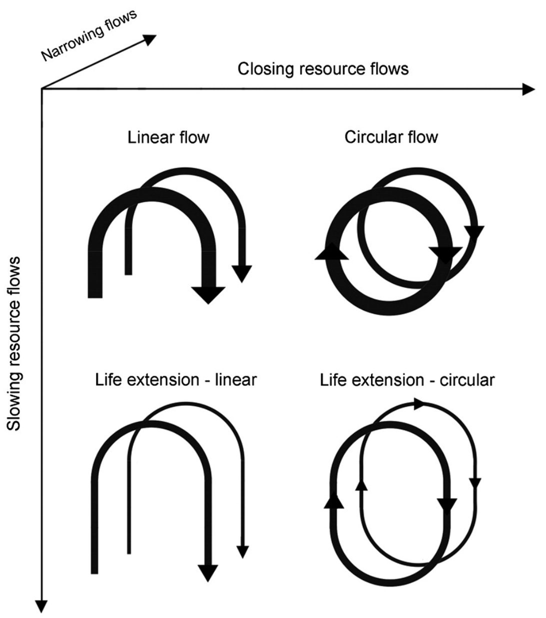
Some have argued that a single definition is unachievable (Korhonen et al., 2018). Therefore, Moraga et al. (2019) proposes to define the CE in *sensu stricto* (in a narrow or strict sense) and *sensu lato* (in the broad sense). This proposal aligns with a cause and effect split made by other authors, for instance, process and effect (PBL Netherlands Environmental Assessment Agency [PBL], 2017a), or intrinsic and impact (Saidani et al., 2019). In this research, the division of the CE sensu stricto and sensu lato, will be used.

The CE sensu stricto, is characterized by three aspects: closing and slowing (Bocken et al., 2016; Moraga et al., 2019), and narrowing resource flows (Bocken et al., 2016). As seen in Figure 1.2a (Bocken et al., 2016). Closing happens when the resource flow between post-use and production is closed, resulting in a circular flow of resources', meaning the linear flows of waste are turned into secondary resources. This way, so-called resource loops (R-loops) are formed. Slowing resource flows, happens through the design of long-life goods and product-life extension (i.e. service loops to extend a product's life, for instance through repair), therefore, the utilization period of products is extended and/or intensified, resulting in a slowdown of the flow of resources'. Narrowing refers to targeting a resource loop (as discussed in Section 1.2.2) which require fewer resources.

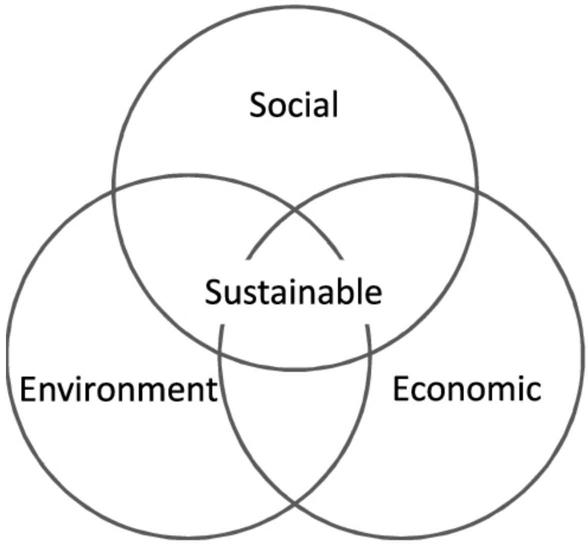
The CE sensu lato, refers to the effect of a circular economy in terms of sustainable development. The sustainable development is widely adopted as the three-pillar concept, consisting of a social, economic and environmental part. Which has multiple visual representations, such as the Venn Diagram (see Figure 1.2b), where sustainability lays at the intersection of the three pillars. In this research, the idea of an interrelation of the three pillars of sustainable development is adopted, however, not each pillar is included in the measurement framework.

Figure 1.2

The circular economy sensu stricto / intrinsic and sensu lato / impact



(a) *Sensu stricto: closing, slowing, and narrowing resource flows (Bocken et al., 2016)*



(b) *Sensu lato: Venn Diagram of social, economic and environment (Purvis et al., 2018)*

1.2.2. Circular economy sensu stricto

In the previous section, the definition of a CE is explained. Because various definitions exist, and are likely to change, a split between the CE sensu stricto and sensu lato is deemed appropriate. In this section, the sensu stricto side is described in greater detail, by covering its aspects. This starts by, shortly, describing the definition of circularity, as this term arises in multiple references. Followed by the resource loops which can be taken in a CE. Lastly, the levels in a CE, as applicable to the problem are discussed.

Circularity

Circularity is the progress of the process of a CE (PBL, 2017a), described by the slowing, closing, and narrowing of resource flows. As can be seen in Figure 1.2, improvement along any of the three axes leads to a reduction in resources used. Therefore, circularity is also called material circularity resource efficiency. If resource use is decreased, one speaks of increased circularity or higher resource efficiency. However, if the circularity increases, whether this origins from closing, slowing, or narrowing resource flows, may not be clear directly.

Resource loops

As in the general definition given in Section 1.2.1, the CE consists of various resource loops (R-loops). These R-loops have different representations in various models, which all build on the Ladder van Lansink waste hierarchy. It started with the 3R-model, which may refer to 'reduce', 'reuse', 'recycle, but can also refer to 'remanufacture', 'reduce', 'recover', and even 'revenue. As the CE is an evolving — not yet strictly defined — concept, scholars tend to use their own thought (Reike et al., 2018). This evolved in approaches starting from a 3R-model, adding R's, to the 9R-model (including R0 Refuse) of PBL (see Figure 1.3). This model is widely used as the most inclusive (Reike et al., 2018) and nuanced (Kirchherr et al., 2017) model. It consists of various CE-strategies, which target certain R-loops.

PBL (2017a) studied the innovation in product chains. They build on the efforts to assess circularity on a national level by the European Environment Agency (European Environment Agency, 2016). The authors define circularity as resource efficiency. As such, increased efficiency occurs when resources are kept in the economy for a longer period of time, preferably maintaining quality. This is achieved by targeting higher CE-strategies, as seen in Figure 1.3. As a rule of thumb, more circularity results in reduced consumption of primary resources, and has reduced environmental effects (PBL, 2017b). However, it is advised to examine side effects of improved circularity, which might have a negative effect on resource consumption and the environment.

R0 - Refuse

When targeting the 'zero-th' strategy, the use of raw materials is prevented by not producing the product at all. Not having the product can be simply accepted as is or an alternative product can be found. Although this strategy does not cover the circulation of resources, it is included as it does abandon product use entirely. Which, in turn, reduces resource use.

R1 - Rethink

This circular stage was added by PBL (2017a) to the nine levels of circularity from Cramer (2014). Rethinking targets the business models which promote sharing or other initiatives which cause more extensive product use. In the context of offshore wind installation, the concept of resource sharing was studied and proven successful in intensifying use (Beinke et al., 2017). When sharing, the performance is based on resource use instead of possession, which creates new opportunities and challenges in logistics (Beinke et al., 2017; Freitag et al., 2016). Similar to R0, this strategy does not include resource circulation, but the prevention of resource use.

R2 - Reduce

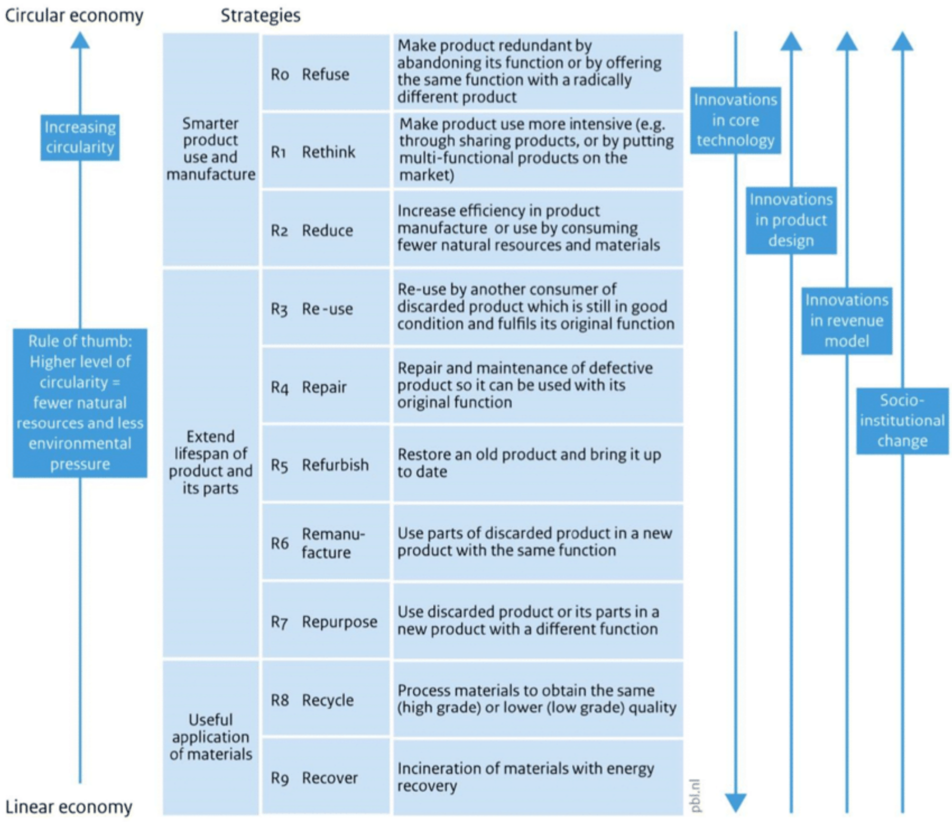
This R-loops specifically involves improving resource efficiency by reducing the use of primary materials in the life cycle. This can be at first production at the original equipment manufacturer, or at any product modification step in the life span.

R3 - Reuse

This strategy aims to extend the product lifespan by reuse by another user. Within a project-based company, reuse can apply to a different project within the firm or the product can be used again outside of the firm. Closely related to this strategy, are the business models associated with R1 - Rethink, such as second-hand or sharing. The idea of reuse is that the product lifespan is extended without testing and modifying the product. Therefore, no additional materials have to be used for the product. Reuse does, however, require additional resources for

Figure 1.3

9R framework (PBL, 2017a; adapted from Cramer, 2014 and Vermeulen et al., 2014)



the distribution of the product between users, and storage of the equipment as a whole. This requires less administration compared to components.

R4 - Repair
Extending the lifespan often requires repair and maintenance of the product. For maintaining the product, spare parts and refill options are often required, which involves the need for extra primary materials. As followed from an LCA (Kong et al., 2022), the maintenance can have significant environmental impact, in the case of heavy duty equipment (construction material lift/mover). This specifically accounts for equipment with moving parts, such as engines or fluids, as they require extensive maintenance.

R5 - Refurbish
Refurbishment is defined as the restoration of a product to bring it up to date. This can be by updating the software or hardware, to bring the product to a certain, pre-determined, quality standard (De Lage Landen Group [DLL], 2018). The desired quality may be somewhat lower than a comparable new product, but the warranty of the product will be extended by refurbishment compared to direct reuse. This may include inspection and certification of the product.

R6 - Remanufacture
For remanufacturing, a product is taken apart and rebuilt with used and new parts. This can include technological upgrades of both hardware and software. The product will have a like new or better quality, modification costs are relatively high and the product will gain its original warranty terms. As the logistics occur for components, this requires extensive administration and handling.

R7 - Repurpose
In this case the product or its parts are used in new product with a different function.

R8 - Recycle
A product is recycled when the materials are processed to a same (high grade) or lower (low grade) quality. As the product is dismantled and used as secondary materials, this step requires high amounts of energy.

R9 - Recover
The ultimate, and least favourable, step of the circular economy is when incinerating materials for energy recovery. The step outside of the circular economy would be to landfill the product or materials.

Circular economy levels

The CE acts on different implementation levels, see Figure 1.4 (Circular Regions, n.d.). As described by Saidani et al. (2019), it operates at the micro (products, companies, consumers), meso (eco-industrial parks) and macro level (city, region, nation, and beyond). Some include a nano level as well, which covers the material level (Shevchenko et al., 2022). Whereas others include materials in the micro level (Saidani et al., 2019). In the light of a project-based organization, the consumers are replaced by the project. This is because, in essence, the project is the consumer (or user) of the project equipment.

To understand what the aspects of such measurement method should be, the organizational structure should be understood. The offshore TIR operations are addressed on a project-by-project basis, which makes the offshore TIR contractor a so-called *project-oriented* organization. The complete project cycle is the main revenue-generating activity for such organization. A project-oriented, organization, can be distinguished in three levels of managing projects: 1) the management of single projects, 2) the management of project landscapes (project portfolio management), and 3) the leadership of the project-oriented organization (Gemünden et al., 2018). As these levels form the structure of such organization, these should also be represented when evaluating the performance of the organization. To match with the CE levels in Figure 1.4, the consumer is replaced by the project, with the three levels of interest remaining as: project, product, and company.

Each of these levels gives a different perspective on material flow. In Figure 1.5, the circular and virgin through the boundaries of the various levels is shown, with curved and straight arrows, respectively. It is shown that products — project equipment in this study — can be used by multiple projects. These projects can, thereby, be seen as the consumers or users of the equipment. The projects use multiple pieces of equipment, with corresponding material flow to produce or modify the equipment. At the company level, one can look at a combination of projects or a combination of equipment to determine overall material flow. Some material may recirculate within the company boundary, whereas all virgin material origins from outside the company. The different levels, represent a different perspective on material flow, thus on the CE.

1.2.3. Circular economy sensu lato

As explained in Section 1.2.1, a CE sensu lato, refers to the effect of a CE in terms of sustainable development, consisting of the three pillars: social, economic and environmental. As a rule of thumb, the higher the circularity, the better for sustainable development (Geissdoerfer et al., 2017), specifically resulting in lower environmental

Figure 1.4

Circular economy levels (Circular Regions, n.d.)

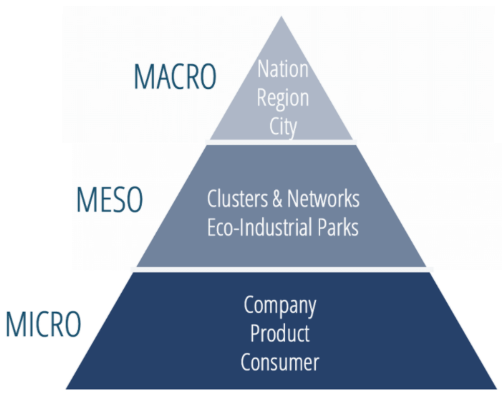
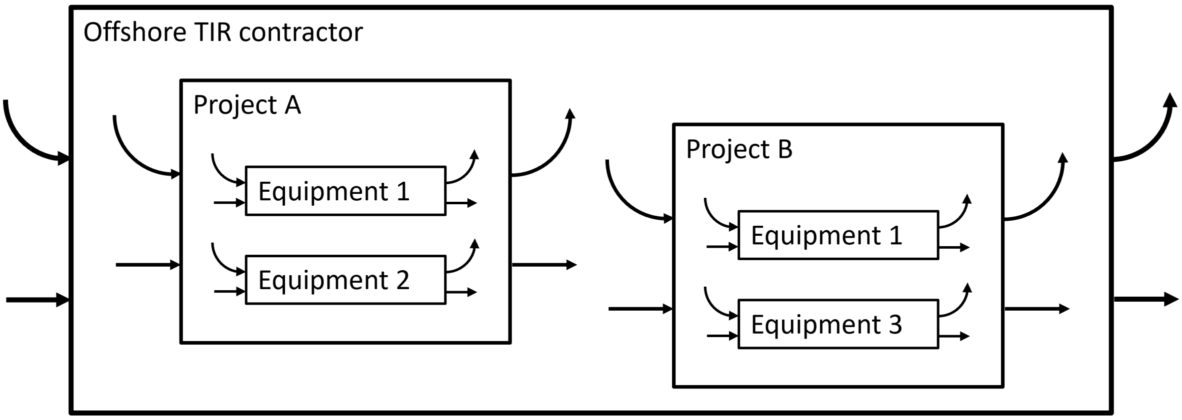


Figure 1.5

Material flow of project equipment at the micro levels: project, product, and company



Note. Straight and curved arrows indicate linear and circular material flow respectively.

impact (PBL, 2017a). However, this is not always the case, as, for instance, increased circularity in one product chain, may lead to reduced circularity in another (PBL, 2017a). Additionally, Andersen (2007) points out that next to the benefits of a CE, the costs of circular systems should be balanced to avoid negative value created. To make sure both the CE sensu stricto and sensu lato are improved, it is, therefore, advised to measure both sides (PBL, 2017a; European Environment Agency, 2016).

When measuring the effects of a circular economy, all three pillars of sustainability should be included. However, as will be discussed in Section 2.1, no such measurement framework exists to include all three aspects. As mentioned by Corona et al. (Corona et al., 2019), a circular — in contrast to a linear economy — supports sustainable development by decoupling economic growth from resource use (Corona et al., 2019). As the CE is part of an economic system, the economic effects are important to analyze. Especially to show the project-oriented organization the benefit on economic effects of a CE-approach of project equipment, the decision is made to only cover the economic part of sustainability.

1.3. Research definition

To summarize, an offshore contractor is interested in measuring its CE performance, to identify how the concept can be used to reduce its resource use. As indicated by various authors (PBL, 2017a; Geissdoerfer et al., 2017), it is advised to measure the CE sensu stricto and sensu lato. Therefore, a metric has to be found to express the CE in terms of material circularity and sustainable development. As the metric has to be used by a project-oriented organization, the CE performance has to be expressed at three levels: the project, product, and company level. As seen in Section 2.1, no metric exists to express all three pillars of sustainable development, therefore, the decision is made in Section 1.2.3 to only include the economic effects. As the problem, and aspects of the CE concept, are now better understood, the study continues by defining the research questions in the next section.

1.3.1. Research questions

To find the right answers to the problem depicted, the following research questions are established:

A How can the material circularity of circular material flows be determined on a project level?
B How can the economic effects of circular material flows be determined on a project level?
C How to translate the circular economy performance on a project level to a product and company level?
D How do the material circularity and economic value performance compare for the case of offshore project equipment?

Together, the answers to these questions will support in answering the main research question:

How to measure the material circularity and cost-based economic value of circular material flows from project equipment on a project, product, and company level?

These questions will be covered in various sections of this research paper. In Chapter 2, research sub-question A is covered, where useful metrics are identified and a material circularity metric is chosen. In the following chapter, the chosen economic value metric is modified to suit a project-oriented organization. In Chapter 4, the CE performance on the project level is translated to the product and company level, to answer research sub-question C. The last research sub-question is covered in Chapter 5, where is case study is performed. To limit the research scope, next section will describe the boundaries of the study.

1.3.2. Scope

To limit the research to focus on the important parts, and prevent it from continued growth, a scope is defined. This is based on the following. The main research question is specific to multiple elements, thereby, bounding the research scope. These are: the included parts of a CE in measuring its performance, the targeted type of industry and resource, and the various organizational levels. Next to this, the conducted research needs to be limited in extent, corresponding with the graduation research period.

The CE performance is limited to the material circularity (CE sensu stricto) and economic part of sustainability (CE sensu lato), thereby, excluding the social and environmental part of sustainability. In the following chapters, a metric is found which is suitable for the project-oriented organization. Here, the scope of the performance indicators is further defined.

This research focuses on equipment used by a project-oriented organization. A case study is performed on offshore equipment, which is used to test the CE metric for project equipment. The decision is made to only include the offshore equipment without moving parts, or *static* equipment, in the study. Although the case study is focused on only one project-oriented organization and a limited number of equipment, the methodology is applicable to any such organization and project equipment. However, other companies in- or outside the offshore industry, may have a different setup affecting the applicability of the method.

This research enables the evaluation of CE performance on the project, product, and company level. As such, the scope is limited to the product boundary at the lower level and the company boundary at the highest level. Thereby, the method does not cover part or component level at the lower side, and does not analyze the entire supply chain at the higher side.

2
Material circularity at the project level

To continue the quest for measuring the circular economy performance of project equipment, in this chapter the material circularity will be covered at the project level. Thereby answering the first research sub question: *How can the material circularity of circular material flows be determined on a project level?* First, in Section 2.1, the methods to measure the circular economy are discussed, to eventually choose a method which is suitable to solve the problem of this research. In the second and last section, a metric covering the material circularity is adjusted to the project level.

2.1. Methods to measure the circular economy

As noted at the start of this chapter, the advantages of the CE can only be guaranteed if there is an appropriate evaluation framework for monitoring its developments (Walker et al., 2018; Saidani et al., 2019). The framework is useful for business stakeholders, supported by the old idiom: "What gets measured gets managed." (Linder et al., 2017) Therefore, in the following sections, first the most appropriate CE measurement frameworks are found. Based on its limitations, and the necessity for enhancing the adopted framework(s), a proposal is made for adjustments.

2.1.1. Circular economy indicators

Starting with a definition, the measurement framework to be found is often referred to as an indicator, as it indicates the state or level of what is measured. Related to the CE, these are called CE-indicators, or short circular economy indicators (c-indicators). To find a framework which is most suitable for the problem described in this chapter, a comparison between the indicators is useful. Such comparison is presented in a taxonomy by many authors (Elia et al., 2017; Pauliuk, 2018; Parchomenko et al., 2019; Saidani et al., 2019; Janik and Ryszko, 2019). Saidani et al. (2019), classified 55 sets of c-indicators, including a reflection on previous indicator comparisons (Elia et al., 2017; Pauliuk, 2018). The c-indicators are defined by 10 categories, as seen in Figure 2.1 (Saidani et al., 2019). The categories classify the indicators into a need-based taxonomy (Saidani et al., 2019), specifying the usage of the each indicator.

This taxonomy is used to guide in deciding which c-indicators to use. It has to be noted, however, that the comparisons are dated and in the meantime new c-indicators are (being) developed. Due this rapid evolution, the literature is consulted to find newly emerged indicators.

Figure 2.1

Categories for the proposed taxonomy of circular economy indicators (Saidani et al., 2019)

Categories *(criteria)*	#1 - **Levels** *(micro, meso, macro)* #6 - **Transversality** *(generic, sector-specific)*	#2 - **Loops** *(maintain, reuse/ reman, recycle)* #7 - **Dimension** *(single, multiple)*	#3 - **Performance** *(intrinsic, impacts)* #8 - **Units** *(quantitative, qualitative)*	#4 - **Perspective** *(actual, potential)* #9 - **Format** *(e.g. web-based tool, Excel, formulas)*	#5 - **Usages** (e.g. *improvement, benchmarking, communication)* #10 - **Sources** *(academics, companies, agencies)*

#1 - Levels

As discussed in section 1.2.2, circularity can be measured at a micro, meso, or macro level. These relate to the circularity of a product (or material or component), consumer, company or service (micro); an industry, eco-park or a value chain (meso); and a city, province, region, or nation (macro) (Kirchherr et al., 2017). To indicate the circular economy performance (ce-performance) of project equipment, the micro level perspectives of a consumer, product, and company, should be included. With respect to the case for project equipment, these perspectives refer to the project, equipment, and contractor, respectively. Each of these perspectives, or layers, should be measured and indicated, as they represent a different side of the story. The ce-performance of the project, shows the result of the decisions made by the project. Namely, a project can decide whether to purchase a new piece of equipment, to rent one externally, or to use one from the company its stock. The way projects deal with the project equipment, combined with how the equipment is managed (e.g. maintained or repaired) apart from the projects, results in the overall product perspective. In essence, the product, or equipment, level is a combination of the project (as user) level. To evaluate the company level, a combination of the projects or of the equipment can be made. The difference is that the former shows how the projects perform, and the latter how the products perform.

To conclude, the c-indicators should act on the micro level, and enable a distinction between the sub levels of project, equipment, and contractor. From the 55 sets of c-indicators in the taxonomy of Saidani et al. (2019), 20 act on the micro level. The c-indicators at the micro level are included further on in Section 2.1.3, when selecting an appropriate metric based on the criteria of the taxonomy.

#2 - Loops

The focus of a circularity indicator can be on various resource loops, as explained in Section 1.2.2. A higher level of circularity is reached for lower R-values (R0, R1, etc.), which generally require fewer natural resources and result in less environmental pressure (PBL, 2017a). This refers to as the 'narrowing of resource loops', as one of the three main parts of circularity (see Figure 1.2a). Therefore, it is important for an indicator to distinguish resource loops (Wilts et al., 2016).

#3 - Performance

The performance category is divided in intrinsic, or sensu stricto, and impacts, or sensu lato. The sensu stricto performance covers the circulation of resources, indicated by resource efficiency or material circularity, which relates to the progress of the process. Circularity is often indicated as the ratio of recirculated material over total material used. As displayed in Figure 1.2a, the process of improving the circularity includes the closing, slowing, and narrowing of resource loops. Most c-indicators do indeed include the closing and narrowing of resource loops, which leads to higher circularity. However, only few consider the slowing of resource loops, for instance, indicated by 'longevity' or 'utility'. As a CE aims to reduce resource use and reduces waste (Government of The Netherlands, n.d.; EPRS, n.d.), these factors should be part of the indicator. Various c-indicators only include the material feedstock in the analysis, as such, excluding the waste generated.

The sustainability performance of CE practices is covered in the sensu lato side. As explained in Section 1.2.3, sustainability includes a social, economic, and environmental side; but only the economic aspect will be covered in this research. From the taxonomy, the only c-indicators capable of describing the economic effects are: PCM, CC, and Output Balance Sheet (IOBS). Next to those, the Material Circularity Indicator based on economic value (MCI') also includes the economic value.

As mentioned in section 1.2.1, it is advised to look at the CE sensu stricto and sensu lato (PBL, 2017a; European Environment Agency, 2016), as more material circularity not always means more sustainability (PBL, 2017a; Geissdoerfer et al., 2017). Comparing the level of material circularity with the economic effects, clarifies how the CE can be used to create financial benefits for a company. Adopting the CE induces changes to company practices, which can be justified by indicating the material circularity and economic effects. The only c-indicators capable of describing both the circularity and economic effects, are the CC and IOBS. The downside of the CC, is that the economic value captured only represents a post-use indication of economic value. Neglecting the pre-use benefit of costs saved. As the circularity indicator does indeed combine pre- and post-use, a comparison between the two is in-equal.

Based on this section, the c-indicators should cover the CE sensu stricto and sensu lato. As part of the sensu stricto side, the closing, slowing, and narrowing of resource flows should be included. Next to this, the material circularity indicated, should cover both the resource use as the waste generated. The CE sensu lato is covered solely by economic effects. Although the decision is made to only include the economic facet of sustainability, the indicator should allow for implementing environmental and/or social effects in the future. This scalability allows for enhancement instead of replacement, favoring a structured progress of the CE concept.

#4 - Perspective

The CE can be measured in a retrospective or prospective manner, describing actual and potential performance respectively. As the current status of the CE-performance of project equipment has to be understood first, the initial step is to describe the actual situation. The remaining c-indicators capable of this, are the PCM, Material Circularity Indicator (MCI), Building Circularity Indicator (BCI), and IOBS. Based on the current status, an evaluation is made where to put the focus for further development. After this, a prospective approach is required in the development of project equipment.

#5 - Usages

As indicating the CE-performance of project equipment is a new topic, it is beneficial as general information and benchmarking. This will form the basis for internal and external communication, and eventually decision-making.

#6 - Transversality

The c-indicators can be either generic or sector-specific. As project equipment is used by various sectors, a generic setup is required. Due to the generic setup of most c-indicators, the frameworks are often specifically suitable to consumer goods. As industrial goods are different than industrial goods (Rink and Swan, 1979), as applies to project equipment, it is important to justify that the chosen framework suits these type of products.

#7 - Dimension

Some c-indicators result in only one indication, whereas other provide more detailed results with multiple indicators. For the guidance of experts such as designers and engineers a higher degree is favorable (Saidani et al., 2017a; Saidani et al., 2017b), in contradiction to one indicator for managerial decision-making (Linder et al., 2017). There are also indicators, which combine indicators into a so-called *composite indicator*, which is defined as (United Nations Economic Commission for Europe [UNECE], 2017):

> A composite indicator is formed when individual indicators are compiled into a single index, on the basis of an underlying model of the multi-dimensional concept that is being measured.

A framework describing the CE sensu stricto and sensu lato in one indicator, would combine parts of the CE which are different by principle. Therefore, at least the sensu stricto and lato should be indicated separately. Next to this, based on the experiences gained in this research, it is identified that for users it is highly important to understand what the indicator is composed of. If the indicators composes of a collection of measurements, which is the case for composite indicators or indices, it is increasingly difficult to grasp its composition. This will stall the understanding and ultimately the benefits of using the indicator.

#8 - Units

The units in which the indication is given vary per indicator. Most give a quantitative indication as a fraction of circularity, money, mass, energy, emission or time. Some give a qualitative result either as suitable pathways for improved circularity or as fulfilling certification criteria yes or no. Whether an indicator is able to quantitative or qualitative result, depends on the input information. For a quantitative indicator this is often based on material flow data, such as provided by a bill of materials. As the indicator will be used to evaluate a variety of products, such indicator is most appropriate. Using the bill of materials can make it possible to evaluate a large amount of products, without having to retrieve input data for every product separately.

#9 - Format

If an indicator is used directly, it is favorable to have a web-based or Excel tool. However, as this research proposes modifications to an existing indicator, the formulas from these tools will be used. These will be translated in a new environment.

#10 - Source

Companies and agencies generally do not open source the information, which makes it hard to use their tools. Therefore, sources from academics are most beneficial. This is the reason why the IOBS indicator is not usable, because the methodology is not open sourced.

2.1.2. Translation principle between micro sub levels

To use the same indicator for product, project, and company circularity, a way of aggregating bottom-up or disaggregating top-down should be considered. When aggregating the circularity indication of multiple products into a group of products, presenting one overall circularity measure, there are two important aspects: the weighting and the aggregation principle. The most used application is the weighted sum (Becker, 2016), where the weight per indicated (w_i) and sum ($\sum$) as aggregation principle are included:

$$y_j = \sum_{i=1}^{d} w_i x_{ji}, j = 1, 2, \cdots, n \tag{2.1}$$

where:

y_j = Aggregated result [any];
w_i = Weight factor [-];
x_{ji} = Indicator or metric [any].

If the weights summed up equal one, one speaks of a weighted average. The weighted average is also used in the MCI, where the material circularity of multiple products can be aggregated to the company level (Ellen MacArthur Foundation et al. [EMF et al.], 2019). The weight, or normalizing factor, for the weighed average can be selected as preferred, which can, for instance, be the product mass, the sales revenue, or raw material cost (EMF et al., 2019; Saidani et al., 2017a). This principle can also be used to start at a lower level, by taking the MCI of components and aggregate them into a product. Or to work towards higher levels, for instance, from project to product to company.

To allow for a theoretically robust manner of aggregating the circularity of multiple items, an appropriate weight unit should be selected. The aggregation principle in MCI was considered of 'medium' quality, due to the dimension consisting of a single circularity value, difficulty in weighing different cycle types, and aggregation only possible for specific reference products within similar product groups (Linder et al., 2017). Jiang et al., 2022 note that the MCI is too dependent on mass as the aggregation principle, not considering relative value scarcity of different materials (Linder et al., 2017). A kilogram of gold and a kilogram of sand cannot be aggregated solely based on mass, considering there relative scarcity value (Coenen et al., 2021).

To make sure that the aggregation of an indicator is not only based on mass, another approach has to be found. Linder et al. (2017) used economic value as a unit to measure circularity, and used the same unit to aggregate the circularity of components into a product. Tashkeel et al. (2021) compared the mass-based MCI weighed by mass and recycling cost, and concluded that the aggregated outcome would be the same. Jiang et al. (2022) combines both approaches by replacing the unit of mass in the MCI by the economic value from Linder et al., 2017, but did not evaluate the aggregation of multiple products. One of the suggestions for future research is to evaluate the MCI against other weight factors (Linder et al., 2017, Jiang et al., 2022).

Based on the suggestions of these academia, this research will continue studying the aggregation principles and weight factors. This is done by splitting the material circularity on the sensu stricto side of the CE, from economic value on the sensu lato side. As will be discussed in Section 2.2, the material circularity has unit mass and the aggregation weight factor is also mass. In Chapter 3, the MCI' methodology is used (Jiang et al., 2022), with economic value as unit of the indicator and weight factor. Jiang et al. (2022) studied the relation between the mass-based MCI with economic value-based MCI' for buildings, but did not study the aggregation behavior.

2.1.3. Selection of circular economy indicators

Based on the taxonomy of Saidani et al. (Saidani et al., 2019) described in Section 2.1.1, and the translation principle discussed in Section 2.1.2, a suitable CE indicator is selected. In Table 2.2, the decision based on the taxonomy is visualized, by grading each category from good (green) to bad (red). In the right-most column of the table, the criteria influencing the result are given.

From the first criterion, the CE levels, an indicator including solely the material level is missing the higher product level. On the other hand, a positive aspect of an indicator is to both include the product level, as well as the company level. The CE levels interrelate, with corresponding translation principles (see Section 2.1.2) varying per indicator. For indicators including only one level, a translation principle is missing, which is an important aspect of finding a suitable indicator describing the three levels: project, product, and company. However, a solution for the lack of a translation method, is to incorporate the translation principle from another indicator.

The second criterion, the R-loops, is of great influence for selecting an appropriate indicator. The indicators only including describing the R3 reuse or R8 recycling loops from the 9R framework (see Figure 1.3), are not

Figure 2.2

Selection of a circular economy indicator for project equipment

c-indicators	#1 - Levels	#2 - Loops	#3 - Performance	#4 - Perspective	#5 - Usages	#6 - Transversality	#7 - Dimension	#8 - Units	#9 - Format	#10 - Sources	Result
RRs	Material	R8	Stricto	Retro	I	G	Multi	Quanti (%)	f	A	#2
EoL-RRs	Material	R8	Stricto	Retro	I, L	G	Multi	Quanti (%)	f	A	#2
CEPI	Material	R8	Lato (env.)	Retro	D	G	Single	Quanti (ratio)	f	A	#2
RPI	Material	R3	Stricto	Pro	D, C, L	G	Single	Quanti (%, ratio)	c-tool	A	#2
Ris	Material, product	R8	Stricto	Retro	I, C, L	G	Single	Quanti (%)	c-tool	A	#2
CEIP	Product	R1, R3, R6, R8	Stricto	Pro	I, C, L	G	Single	Quanti (score)	Xls	A	#4
CET	Product	R1, R3, R6, R8	Stricto	Pro	I, C, L	G	Multi	Semi-quanti (cat.)	w-tool	A	#4, #8
CPI	Product	R1, R3, R6, R8	Stricto	Pro	I, D, C, L	G	Single	Quanti (%)	Xls	A	#4
PCM	Product	R3, R6, R8	Lato (econ.)	Retro	D, C	G	Single	Quanti (%)	f	A	#2
CEI	Product	R8	Lato (econ.)	Retro	D	S	Single	Quanti (%, ratio)	f	A	#2
CI	Product	R8	Stricto, lato (env.)	Retro	I, C	G	Multi	Quanti (%)	f	A	#2
CLC	Product	R1, R3, R6, R8	Stricto	Pro	C	S	Single	Quanti (score)	c-tool	Co	#4, #6
CP	Product	R1, R3, R6, R8	Stricto	Pro	D	G	N/A	Quali (cat.)	w-tool	O	#4, #8
CC	Product	R3, R6, R8	Stricto, lato (econ.)	Pro	I, D	G	Multi	Quanti (%)	w-tool	O	#2, #4, #9
MCI	Material, product, company	R1, R3, R6, R8	Stricto	Retro	C, L	G	Single	Quanti (%)	Xls	Co	#5, #9, #10
BCI	Material, product, company	R1, R3, R6, R8	Stricto	Retro	I, D, C, L	S	Multi	Quanti (%)	Xls	A	#6
IOBS	Product, company	R1, R3, R6, R8	Stricto, lato (econ.)	Retro	I	G	Multi	Quanti (%)	c-tool	Co	#9, #10
C2C	Product, company	R3, R6	Stricto, lato (env., soc.)	Retro	I, C	G	Single	Quali (standard)	f	Co	#2, #8
EVR	Product, company	R8	Lato (econ., env.)	Retro	I, C	G	Single	Quanti (score)	f	A	#2
RDI	Product	R1, R3, R6, R8	Stricto	Pro	I, D, C	G	Single	Quanti (time)	f	A	#4, #8
MCI'	Material, product	R1, R3, R6, R8	Lato (econ.)	Retro	C, L	G (S)	Single	Quanti (%)	f	A	#1, #6

Note. Selection is based on micro level indicators and categories from taxonomy of Saidani et al. (2019). Colors show grading from good (green), to medium (orange), to bad (red). Indicators are abbreviated in order of appearance as (see sources in Table A.1): Recycling Rates (RRs), End-of-Life Recycling Rates (EoL-RRs), Circular Economy Performance Indicator (CEPI), Reuse Potential Indicator (RPI), Recycling Indices (RIs), Circular Economy Indicator Prototype (CEIP), Circular Economy Toolkit (CET), Circular Potential Indicator (CPI), Product-level Circularity Metric (PCM), Circular Economy Index (CEI), Circularity Index (CI), Closed Loop Calculator (CLC), Circular Pathfinder (CP), Circularity Calculator (CC), Material Circularity Indicator (MCI), Building Circularity Indicator (BCI), Output Balance Sheet (IOBS), Material Reutilization Part (C2C), Eco-efficient Value Ratio (EVR), Resource Duration Indicator (RDI), and Material Circularity Indicator based on economic value (MCI'). MCI' not originally part of taxonomy. resource loops corresponding to 9R framework of PBL (2017a), as: rethink (R1), reuse (R3), remanufacture (R6), recycle (R8). Performance referring to circular economy sensu stricto (process) and sensu lato (effect), which the latter consists of the three pillars of sustainability: environment (env.), economy (econ.), and social (soc.). Perspective corresponding to retro- and prospective. Usage corresponding to: information (I), decision making (D), communication (C), and learning (L). Format corresponding to formulas (f), computation tool (c-tool), and web-based tool (w-tool). Sources corresponding to academics (A), companies (Co), and organizations (O).

covering sufficient R-loops, thus are excluded. Which are the Recycling Rates, End-of-Life Recycling Rates, Circular Economy Performance Indicator, Reuse Potential Indicator, Recycling Indices for the CE, Circular Economy Index, Circularity Index, and Eco-efficient Value Ratio. Next to this, indicators not including R8 recycling, are missing a vital part of material recovery. This excludes the Material Reutilization Part. On the positive side, indicators including R-loops from R1 rethink to R8 recycling, are covering the CE in great extent. Specific for the taxonomy, R1 rethink includes "maintain or prolong", which corresponds to the slowing as an important part of the CE sensu stricto (Bocken et al., 2016; Moraga et al., 2019). From these, the Product-level Circularity Metric (PCM) and Circularity Calculator (CC) lack in addressing the slowing of R-loops by maintaining or prolonging the product (Saidani et al., 2019).

The #3 - performance, covering the CE sensu stricto and sensu lato, shows that only two indicators are capable of describing the CE sensu stricto and economic effects of sustainability. Which are the CC and Output Balance Sheet (IOBS). These indicators are preferred, as this would mean only one indicator can be used. The indicators including only one part of the CE, are marked orange, as two indicators could be combined to indeed describe both parts.

For the fourth category, the indicator should have a retrospective approach, based on actual data. Therefore, the remaining prospective indicators which are excluded, are the Circular Economy Indicator Prototype, Circular Economy Toolkit, Circularity Potential Indicator, Closed Loop Calculator, and Circular Pathfinder. However, some prospective indicators can be used with actual data, which enlarges the applicability. The CC is identified as being capable of this. Although the indicator is used to set a benchmark based on actual data, the influencing parameters should be clear to understand the drivers for improvement. The format (#9 - Format) can support this, by providing formulas instead of a tool with hidden computations.

The #5 - usages, is a category of lower influence, as most indicators can be used for multiple purposes. The indicators which at least have information usage, such as progress tracking, or benchmarking, are most preferred. Indicators only used for decision-making are excluded, as they have a too prospective approach.

The transversality of the indicator should be generic, so it can be used for project equipment. No specific indicator exists, tailor made to project resources. Specific indicators are, therefore, excluded, such as the Building Circularity Indicator (BCI) which is specific to the building sector.

The seventh category covers the dimension of the indicator, which can be either single or multi dimensional. As discussed, the indicator should be capable of describing the mass-based material circularity and economic value, for which as multi-dimensional indicator is required. However, single dimensional indicators could be combined to produce a multi-dimensional approach.

Regarding the #8 - units, the indicator should be of quantitative nature. A qualitative indicator does not provide a scalable way for implementing a large collection of products. The indicators with qualitative or semi-quantitative units were already excluded based on former categories.

The format of the indicator is important, as it supports usability, scalability, and understanding of the driving parameters. Web-based tools have the downside of not able to be incorporated in a company its in-house software, which reduces the usability and scalability. However, for the remaining CC, which is a web-based tool, the formulas are presented in a supporting document (de Pauw et al., 2022). Therefore, this tool could potentially be reproduced with some efforts. Various computational tools, web-based tools, and Excel sheets, can have the downside of not providing insights in the driving parameters, so this is something to bear in mind.

The #10 - source can also have similar issues as for the format of the indicator. A high-quality indicator is created by academics, as these are peered by the academics. However, some academic indicator can have lower applicability for companies. Indicators created by companies can have the downside to not be open source, which could induce subscription fees. The IOBS is excluded, as the indicator was not provided, even after contact with the designated company.

As a result of the criteria of the taxonomy, four potentially useful micro level indicator remain: the PCM, the CC, the Material Circularity Indicator (MCI), and the Material Circularity Indicator based on economic value (MCI'). The obvious choice would be the CC, as this is the only one of these indicators including the CE sensu stricto and economic part of sustainability. However, after thorough testing the CC is excluded because of two points: the pre- and post-use flows are connected, and the slowing of resource flows is not included (Saidani et al., 2019). The former aspect means that the inflow of materials into the product, is attached to the outflow of materials. This would mean that each product use cycle is the same. However, in the life cycle of a product, the composition of reused and virgin materials changes per use cycle. The other aspect is that the indicator does not include the factor time, which should be there to slow the use of resource. Therefore, by not paying sufficient attention to the use phase, the indicator is not usable.

Now, the remaining indicators cover either one side of the CE sensu stricto and sensu lato. This means that two indicators have to be combined, to cover both sides. As the MCI is the only remaining indicator covering the CE sensu stricto, this indicator is selected for describing the material circularity. The MCI does cover the slowing of resources, by including a utility factor, which is a strong element of the indicator. Supporting the MCI, the decision is made to select the MCI' for measuring the economic value. The reason for this is that the composition of both indicators are the same, which allows for a fair comparison between the two units. On the other hand, the PCM fails in describing the slowing of resources (Saidani et al., 2019), which is indeed included in the MCI' by the same utility factor as in the MCI.

To conclude, the taxonomy resulted in selecting the MCI and MCI' to be used in parallel. Where the MCI describes the CE sensu stricto, and the MCI' sensu lato with economic value as the unit. In the following section, the MCI is described and related to the project equipment at the project level.

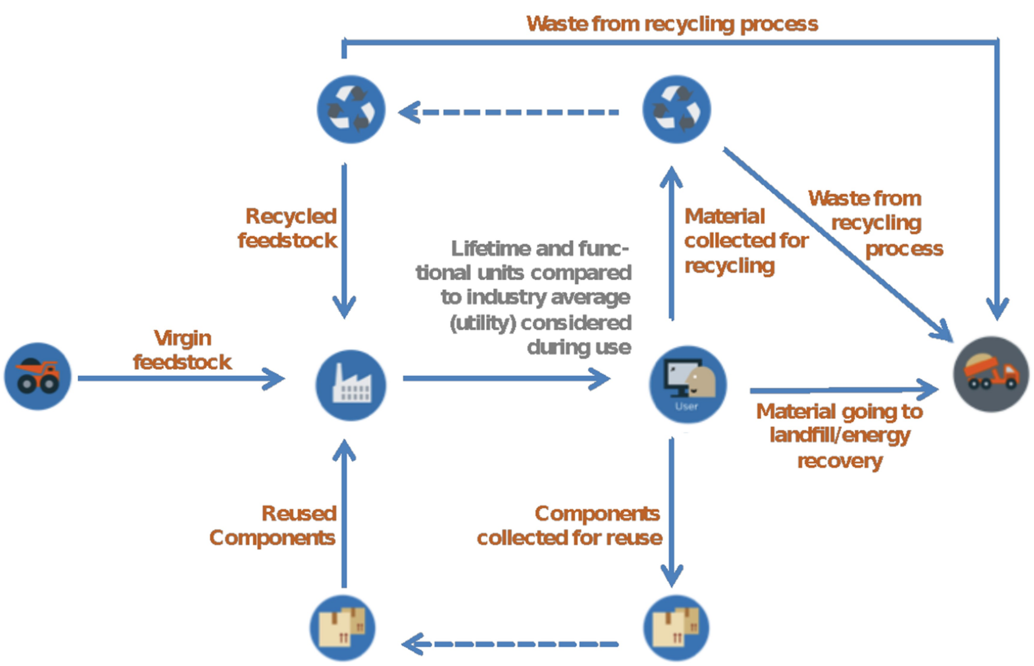
2.2. Selected method to measure material circularity

As described in previous section, the MCI is the chosen indicator for the sensu stricto side of CE. The main reasons for using this indicator is that the indicator includes both the pre- as post-use phases of a product, the slowing of R-loops is included by a utility factor, and the setup is similar to the MCI'. The latter reason is important, as it allows for a fair comparison between the CE sensu stricto and lato. As opposed to the only usable indicator describing both sides of the CE, the CC, where the circularity indicator and economic indicator have a different composition.

In this section, the methodology for computing the MCI is set out, as adapted from EMF et al. (2019). As the focus in this chapter is on the project level, the MCI is computed for one use cycle (project as user). This may also be a modification step not designated to a project, for instance, occurring at planned maintenance. The MCI represents one product, or piece of project equipment, from feedstock to post-use recovery (see Figure 2.3). In the last stage of this section, the MCI of multiple pieces of project equipment are combined, to represent the project level. Later, in Chapter 4, it is shown how the higher levels of product and company are determined.

Figure 2.3

Diagrammatic representation of material flows in the Material Circularity Indicator (EMF et al., 2019)



2.2.1. Material Circularity Indicator

The MCI of one product on the project level, is computed as (EMF et al., 2019):

$$MCI = \max\left[0, 1 - LFI \cdot F(X)\right] \tag{2.2}$$

where:

MCI = Material Circularity Indicator [-];
LFI = Linear Flow Index [-];
$F(X)$ = Utility factor built as a function of the utility X of a product [-];
X = Utility of a product [vary].

Here, the MCI is bound between 0 and 1, to indicate no and full material circularity, respectively. In the equation, the starting point is full material circularity, of which a linear flow factor is subtracted. The LFI is multiplied by factor $F(X)$, a function of utility X. The introduction of the utility is there to include the 'slowing' of resource loops into the equation, as explained in Section 1.2.1.

However, the MCI only represents one project use cycle is considered, ignoring the use of a utility factor for the following reason. As is further explained in Section 4.1.4, the decision is made to derive the utility based on lifetime and allocation rate. The project duration is set to a fixed value, thus the lifetime only changes when equipment is allocated to projects. The allocation rate — i.e. the number of times a piece of equipment is allocated to a project — obviously, only changes for multiple projects. Therefore, in the single project use the utility is not included. The utility factor is, indeed, included when describing the product or company level, covered in Chapter 4. To not include utility into Equation 2.2, $F(X) = 1$. Additionally, by definition $LFI \leq 1$, which leads to the MCI adjusted to:

$$MCI = 1 - LFI \tag{2.3}$$

2.2.2. Linear Flow Index

Now, the sole component of the MCI has to be computed, the LFI. The LFI measures the proportion of material flowing in a linear fashion. The linear — as opposed to the circular — material, is sourced as virgin feedstock and ends up as unrecoverable waste. The combination of this is divided by the total amount of material flow, resulting in Equation 2.4 (EMF et al., 2019).

$$LFI = \frac{V + W}{2M + (W_F - W_C)/2} \tag{2.4}$$

where:

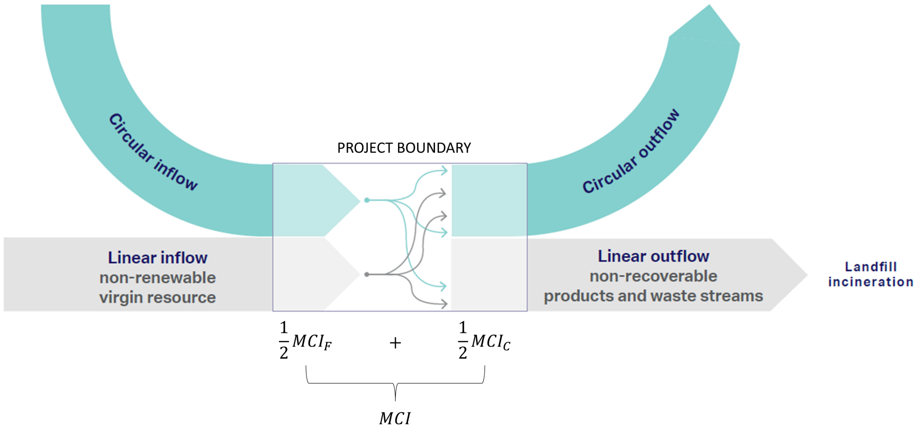
V = Material that is not from reuse, recycling [kg];
W = Mass of unrecoverable waste associated with a product [kg];
M = Mass of a product [kg];
W_F = Mass of unrecoverable waste generated when producing recycled feedstock for a product [kg];
W_C = Mass of unrecoverable waste generated in the process of recycling parts of a product [kg];

Specific to the methodology of the MCI, the feedstock and waste are combined in the LFI. To combine the in- and outflow, the product mass is taken twice in the denominator. This way, the inflow of virgin feedstock and the outflow of unrecoverable waste is taken as a weighted average. For a project, the total mass of inflow and outflow is the same, leading to a 50/50 approach (see Figure 2.4). For a company, on the other hand, the outflow of materials may be less than the inflow if the level of stock is rising. In this case, this should be corrected by taking the weighted sum. The idea of combining the in- and outflow into an index, is to give both material flows importance in the material circularity. An LFI of 0, leading to an MCI of 1, can thus only be achieved when there is no virgin feedstock nor unrecoverable waste.

When introducing a new indicator to users and other stakeholders (company internal or external), it is highly important to clarify how it is composed. The Linear Flow Index is composed of a material feedstock part and a material outflow part (recovery and unrecoverable waste), which makes it a composite indicator (see Section 2.1.1, *#7 Dimension*). Although it can be convenient to create a composite indicator to limit the number of indicators, for instance for managerial purposes (Linder et al., 2017), a higher degree of intelligibility is more suitable for experts — e.g. designers or engineers (Saidani et al., 2017a; Saidani et al., 2017b). To show the

Figure 2.4

Illustration of material flows in Material Circularity Indicator (adapted from World Business Council for Sustainable Development [WBCSD], 2022)



Note. With Material Circularity Indicator of inflow (MCI_F), outflow (MCI_C), and 50/50 shared total (MCI).

individual influences of both indicators on the index, they can be described separately (see Figure 2.4). The fraction of linear feedstock over total material inflow, and waste over total material outflow, are expressed as:

$$LFI_F = \frac{V}{M + (W_F - W_C)/4} \tag{2.5}$$

$$LFI_C = \frac{W}{M + (W_F - W_C)/4} \tag{2.6}$$

where:

LFI_F = Linear Flow Index of inflow [-];
LFI_C = Linear Flow Index of outflow [-].

This split allows for a weighted average (50/50 influence) of the LFI_F and LFI_C, to form the LFI. That is:

$$LFI_F + LFI_C = \frac{1}{2} \cdot \frac{V}{M + (W_F - W_C)/4} + \frac{1}{2} \cdot \frac{W}{M + (W_F - W_C)/4} = \frac{V + W}{2M + (W_F - W_C)/2} = LFI \tag{2.7}$$

To make sure the LFI_F only describes the material feedstock, and LFI_C the recovery, the waste generated in the recycling processes pre- and post-use are neglected. Generally, the amount of waste from these processes is relatively small compared to other material flows, as found in the case study. This leads to the following equations:

$$LFI_F(W_F = W_C = 0) = \frac{V}{M} \tag{2.8}$$

$$LFI_C(W_F = W_C = 0) = \frac{W}{M} \tag{2.9}$$

To indicate the separate parts of the MCI, the circular fractions of the in- and outflow are:

$$MCI_F = 1 - LFI_F \tag{2.10}$$

$$MCI_C = 1 - LFI_C \tag{2.11}$$

where:

MCI_F = Material Circularity Indicator of inflow [-];
MCI_C = Material Circularity Indicator of outflow [-].

2.2.3. Virgin feedstock

The pre-use phase, includes the design and manufacturing of the product. In the manufacturing a certain amount of virgin and circular feedstock is used, as seen in Figure 2.3. The circular feedstock can come from recycled source, or reuse of parts or components. As opposed to the original methodology, these are used in absolute values.

$$V = M - F_U - F_R \tag{2.12}$$

where:

F_U = Mass of a products feedstock from reused sources [kg];
F_C = Mass of a products feedstock from recycled sources [kg].

2.2.4. Unrecoverable waste

The post-use phase describes the recovery of materials from a product, and the unrecoverable waste generated when this is not pursued. The direct waste generated for unrecoverable materials is calculated by taking the total amount subtracted by recovered material:

$$W_0 = M - C_U - C_R \tag{2.13}$$

where:

W_0 = Mass of unrecoverable waste going to landfill or energy recovery [kg];
C_U = Mass of product going to component reuse [kg];
C_R = Mass of product going to recycling [kg].

In the MCI methodology, only three post-use resource flows are present, which represent multiple resource flows in the 9R framework. Here, reused material C_U is a combination of the resource flows R3 Reuse to R7 Repurpose from the 9R framework (see Figure 1.3). The recycling flow C_R is equal to R8 Recycle from the 9R framework, and the unrecoverable waste W_0 includes R9 Recover of the incineration of materials with energy recovery, as well as material to landfill outside of the 9R framework. Combining material flows has the implication that no clear distinction is made between the narrowness of the flows. On the other hand, it is a choice which simplifies computations. To still be able to justify outcomes by the resource loop taken, the resource loops from the 9R framework are indicated for each product.

Project equipment has the important feature that it is kept in stock before being used again, which changes the perspective of the MCI. Namely, it changes the MCI from having a retrospective to a prospective perspective. Originally, the MCI has an effective or retrospective perspective (see Section 2.1.1, #4 Perspective), meaning that it is fed by actual or historical data. Based on a case study in this research, on a past project (see Chapter 5), this perspective holds. However, in this section, the different post-use material flows have to be defined, to calculate the unrecoverable waste generated. When a piece of equipment is stored after being demobilized from a project, the intention is to reuse it either partially or completely. Because of this, the material which is stored is considered as material for reuse C_U. However, this is potentially true, and gives the MCI a prospective perspective.

Apart from the waste generated directly in the post-use phase, there is also secondary waste generated in the pre- and post-use material processes. Waste generated in the post-use recycling process is expressed by Equation 2.14. Where E_C indicates the efficiency of the recycling process of the material post-use. In a closed loop system, as is the case for steel recycling (1.2.2), E_C equals the efficiency of recycled feedstock (E_F).

$$W_C = (1 - E_C)C_R \tag{2.14}$$

where:

W_C = Mass of waste generated in the post-use recycling process [kg];
E_C = Efficiency of post-use recycling process [kg].

Waste generated in the pre-use/feedstock recycling process (EMF et al., 2019) is expressed by Equation 2.15. Here, the efficiency of the recycled feedstock (E_F) indicates the amount of material that is wasted in the recycling process. For an increasing number of material types, this recycling efficiency is known. For other material types, this number can be set to 1 or an estimation can be used.

$$W_F = \frac{(1-E_F)F_R}{E_F} \tag{2.15}$$

where:

W_F = Mass of waste generated in the pre-use recycling process [kg];
E_F = Efficiency of pre-use recycling process [kg].

In the MCI (EMF et al., 2019), only the waste generated in the recycling process is included. This was already identified by the authors of the MCI as one of the limitations of the method. To also include waste generated in the production process of creating reused feedstock, Equation 2.15 can be expanded. For simplicity reasons, however, these are not introduced, so remain a limitation to the model.

As the post-use phase of one product, enters the pre-use phase of the next product, it is important not to count the waste twice. To follow the procedure of the MCI, a 50/50 approach is taken for waste generated by recycling and reusing materials. Now, the waste generated in processing used materials pre-use (W_F) and post-use (W_C), is added to the waste to energy recovery and landfill (W_0).

$$W = W_0 + \frac{W_F + W_C}{2} \tag{2.16}$$

2.2.5. Aggregation principle to project level

To find the material circularity of the entire project, there are two ways. In the first approach, a weighted sum of the products is taken, as discussed in Section 2.1.2. In the second approach, all material flows are combined to calculate the project MCI. This approach would theoretically create one product — or piece of equipment — from the combination of products.

Aggregation by a weighted average

Taking the weighted sum of the products to form the project level is:

$$MCI_j = \sum_i w_i \cdot MCI_i \tag{2.17}$$

where:

j = Project index [#];
MCI_j = Material Circularity Indicator of project j [-];
i = Product — or piece of equipment — index [#];
w_i = Weight factor of product i [-];
MCI_i = Material Circularity Indicator of product i [-].

The weight factor can be chosen as preferred. To make sure that the first and second approach lead to the same results, the weight factor is determined as follows. First, the aforementioned equation is decomposed, using Equation 2.3 and 2.4:

$$MCI_j = \sum_i w_i \cdot MCI_i = \sum_i w_i \cdot (1 - LFI_i) \tag{2.18}$$

of which:

$$LFI_i = \frac{V_i + W_i}{2M_i + (W_{F,i} - W_{C,i})/2} \tag{2.19}$$

where:

LFI_i = Linear Flow Index of product i [-];
V_i = Material used for making product i that is not from reuse, recycling [kg];
W_i = Mass of unrecoverable waste associated with product i [kg];
M_i = Mass of a product i [kg];
$W_{F,i}$ = Mass of unrecoverable waste generated when producing recycled feedstock for product i [kg];
$W_{C,i}$ = Mass of unrecoverable waste generated in the process of recycling parts of product i [kg];

An appropriate weight factor would thus be a function of the denominator of LFI_i. To simplify, the waste in the recycling process could be neglected, this would lead to:

$$w_i = \frac{2M_i + \cancelto{0}{(W_{F,i} - W_{C,i})/2}}{\sum_i \left(2M_i + \cancelto{0}{(W_{F,i} - W_{C,i})/2}\right)} = \frac{M_i}{\sum_i M_i} \tag{2.20}$$

Aggregation by total material flow

In the second approach, the material flows of products i are combined to describe the project level. This method naturally creates a weighted average, as the unit of the indicator and weights of the individual contributions are the same. The project MCI is determined as:

$$MCI_j = 1 - LFI_j \tag{2.21}$$

of which:

$$LFI_{proj} = \sum_i \frac{V_i + W_i}{M_i + (W_{F,i} - W_{C,i})/2} \tag{2.22}$$

The difference between the two approaches, is that in the first approach the LFI_i of the individual products is used, and in the second the overall project LFI_j is computed. This way, the product is tracked in the first, contrary to the second approach. The weighted average is in line with the MCI methodology, which focuses on the product level and can be aggregated to higher levels. As measuring the CE-performance is meant for future improvements, a bottom-up product focus is also more beneficial. The second approach, using the project LFI_j and preventing the use of a weight factor, is less time consuming, and could be used if only the project level indication is to be obtained.

3 Circular economic value at the project level

In this chapter, the CE sensu lato is covered by evaluating the economic value of materials at the project level. By doing so, the following research question is answered: *How can the economic value of circular material flows be determined on the project level?* As followed from the CE-indicator analysis in Section 2.1, this is carried out by using the MCI' from Jiang et al. (2022). In this indicator, the material flows in the MCI are replaced by economic value flows.

In Section 3.1, the features of the MCI' are explained, which reveals limitations in answering the research question related to this chapter. In Section 3.2, potential methods to remove these limitations are considered. The approach which is found most useful, is woven into the MCI' methodology. By performing a case study (see Chapter 5), the outcome of the modified MCI' is discussed in Chapters 5 to 7.

3.1. Selected method to measure the economic effects of a circular economy

In this section, the features of the MCI' are discussed. One of the key choices in the method, is that the economic valuation is based on costs, as described in Section 3.1.2. Next to this, the method uses the idea of added value, briefly depicted in Section 3.1.3. In Section 3.1.5, the limitations of the MCI' originating from the cost factors included are shown.

3.1.1. Economic effects of a circular economy

There are good reasons for increasing circularity, as emphasized by Stahels' 'inertia principle': "replace or treat only the smallest possible part in order to maintain the existing economic value of the technical system" (Stahel, 2010, p. 195). This idea can also be seen in the Value hill by Achterberg et al., 2016, see Figure 3.1. Improving the circularity of products will make sure that more value is captured for a longer period of time. This may be beneficial for the effects of a CE on all three pillars of sustainability: social, economic, and environmental.

To understand how value circulates, it has to be understood how value is build up. The key points of the definition of economic value are (Banton, 2023):

- Economic value is the value that a person places on a good or service, based on the benefit they get from it.
- Economic value is subjective and difficult or impossible to measure, though there are approaches to estimating it.
- Producers use estimates of economic value to set prices for their products taking into consideration tangible and intangible factors such as brand name.

Economic value is the willingness-to-pay for a product or service, based on the trade-off between the perception of benefits and sacrifices (Leszinski and Marn, 1997). As it is based on perception, the value is subjective. Part of the economic value is the 'added-value' to a product by a company, which economically enhances the product before selling it to a customer (De Chernatony et al., 2000; Hayes, 2022). The added-value, as seen in

Figure 3.1

Linear (left) and circular (right) Value Hill, describing the value life cycle of a product (Achterberg et al., 2016)

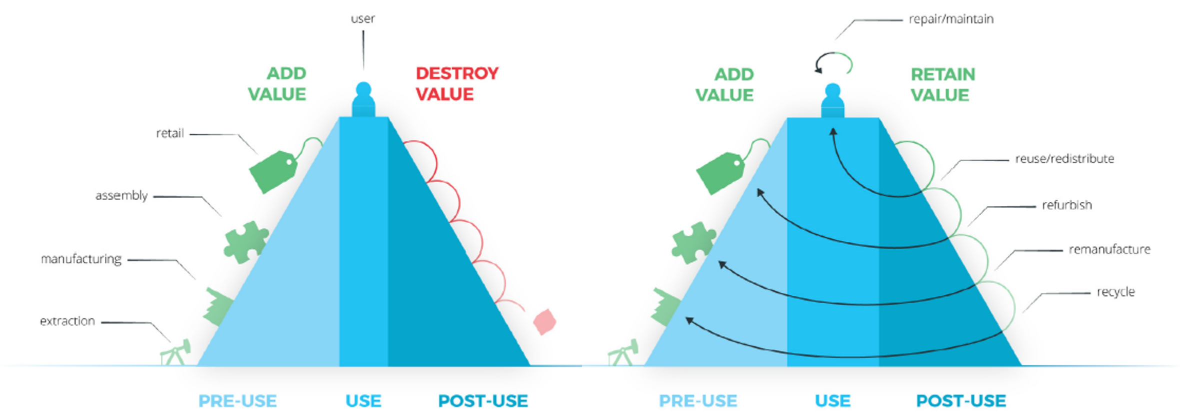


Figure 3.1, is why it is beneficial to increase the circularity of a product. Each time the product is processed, by design or composition, it increases in value. When at EoL a narrow resource loop is considered, most value is captured.

3.1.2. Cost-based economic value

The economic value is estimated by various means to provide information for price-setting. Some define economic value as the price someone is willing to pay for a product or service. The economic value of consumer goods can be estimated by, for instance, 'willingness to pay', 'hedonic pricing', or 'economic value to customer'. The latter is used for products and services, and is not based on mathematical formulas but on tangible and intangible values of a product or service. Economic value is different from market value. (Investopedia, 2021) Where the economic value depends on the benefit for an individual or company, leading to the maximum price someone is paying to fulfill the benefit. The market price depends on supply and demand, and can therefore be lower than the price derived from economic value. The market value and economic value, however, do influence each other, as they are both dependent on the perception of value for customers. In neoclassical economics, the perception of value is considered the driving force for price-setting, whereas in classical economics this is the cost of production. (Kenton, 2023). The neoclassical theory focuses on the supply and demand as the driving force behind production, pricing and consumption of goods and services.

As explained above, by maintaining the value of resources, waste is limited. However, determining the economic and/or market value, is based on qualitative data from expertise. As described in 2.1.1 (#8 units), a quantitative approach favors a qualitative one, as it allows for the evaluation of a great number of products. This leads to the conclusion that a cost-based economic valuation is necessary to evaluate multiple products without requiring qualitative input. As cost is dependent on price, which is in many cases derived from market value, cost does represent value. A cost-based economic valuation has similarities with Marx's value theory (Marx, 1894), and is chosen by others as a practical method to estimate economic value (Linder et al., 2017; de Pauw et al., 2022; Jiang et al., 2022).

3.1.3. Added value

In various circular economy metrics, such as in the Circularity Calculator (CC) and Product-level Circularity Metric (PCM), the economic value is based on added-value. The way value is added in the pre-use phase, and retained in the post-use phase, is visualized in the Value Hill (Achterberg et al., 2016), see Figure 3.1. The MCI' uses the added value approach from the PCM, to estimate the economic value of recirculated materials.

3.1.4. Relation between economic and environmental effects

Although the decision is made to focus on the economic effects of a CE — excluding environmental and social effects — a valuable correlation between economic and environmental effects must not to be ignored. This, namely, is the EU Emission Trading System (EU ETS), which has significant impact on the finances of large emitters. In steel production, 1.9 kg of CO2 is emitted per kg of steel produced through a blast furnace (Broadbent, 2016). As the European Union EU ETS on steel influences the steel price and, therefore, the price of new steel parts. This will create an increasing demand for using recirculated materials. The relative value of a circular alternative will increase.

3.1.5. Limitations of the economic value indicator

The MCI' follows the same procedure as the MCI, explained in Section 2.2. The difference is that the mass flows in the MCI are replaced by value flows in the MCI'.

The economic value of the virgin feedstock (V') is computed by subtracting the value of recirculated materials from the value of the material input in total (E). The value of recirculated flows may be from reused (Fu') or recycled (Fr') source, where the bio-based source is neglected in this research as these are not present in the materials streams. These are expressed as fraction of total value, leading to the virgin feedstock derived as (Jiang et al., 2022):

$$V' = E - F_u' - F_r', \tag{3.1}$$

where:

$'$ = to indicate that cost-based economic value is the measurement unit [-];
V' = economic value of material that is not from reuse, recycling [\$];
E = economic value of material input in total [\$];
F_u' = economic value of recirculated material flow from reuse [R3 reuse to R7 repurpose] [\$];
F_r' = economic value of recirculated material flow from recycling [R8 recycle] [\$].

The economic value of recirculated materials (r) is defined as follows. In the work of Jiang et al. (2022), adapted from Linder et al. (2017), this is expressed as:

$$\begin{aligned} r = \max[&\text{cost of parts including handling costs such as procurement and logistics costs;} \\ &\text{sum of market prices for virgin materials contained in the product;} \\ &\text{secondhand market price for used material or component}], \end{aligned} \tag{3.2}$$

where Equation 3.1 and 3.2 are related as:

$$r = F_u' + F_r' \tag{3.3}$$

The value of recirculated materials in Equation 3.2, is primarily based on replacement costs of a virgin alternative. The cost savings reusing materials can induce is defined by this replacement value. Beside the cost savings of fewer virgin materials or parts to be purchased, there are other cost factors which lead to savings or additional expenses. For instance, part of the manufacturing process may be skipped when using recirculated materials, creating cost savings. On the other hand, additional rework costs, such as dismantling, and logistical costs are induced when reusing materials. To get a better idea which cost factors lead to savings and which to additional expenses, an overview of these costs is made. Therefore, supported by the recommendations of various academia (Braakman et al., 2021), the rather basic definition of recirculated value (as in Equation 3.2) is expanded by using additional life cycle costs.

In the MCI', the value of recirculated parts is based on a simplistic approach adapted from the PCM (Linder et al., 2017). This value is the maximum of part costs, virgin material price, or second hand price of the recirculated parts. These costs (and/or prices) have a positive contribution to the economic value of the recirculated parts. None of the three options includes additional costs, such as inspection, and rework, which are sacrificial costs decreasing the value of recirculated parts. Therefore, to make a better estimation of the value of recirculated materials, more cost elements have to be included.

3.2. Enhancing the economic material circularity indicator

In the previous section, it was found that the MCI' should be adapted in such a way, that additional cost factors are included. The reason for enhancing an existing indicator, instead of creating another one, is because a circular measurement framework should "build upon existing standards" (Edgerton et al., 2018). To find a method which is capable of covering more cost factors, existing costing models which include the whole product life cycle are consulted, described in Section 3.2.1. Thereafter, the appropriate method is included to create an enhanced version of the MCI', evaluated in Section 3.3.

3.2.1. Potential methods to enhance the economic indicator

In this section, methods to take a life cycle approach when including cost factors, are described. Starting with the total cost of ownership, followed by life cycle costing, and ending with the cost breakdown structure.

Total cost of ownership

To identify all costs induced in the life cycle of a product, the total cost of ownership (TCO) approach could be used. The TCO is the combination of the purchase price and hidden costs related to an asset, over the ownership period and/or (useful) life (Bhutta and Huq, 2002). In Figure 3.2 (Barbusová et al., 2019, adapted from Porter, 1985), the principle of TCO is visualized as an iceberg, with the life cycle costs apart from purchase hidden below the surface. As a rough estimate, the hidden costs are 75% of all life cycle costs part of TCO (Porter, 1985).

The costs included in the TCO are (Barbusová et al.):

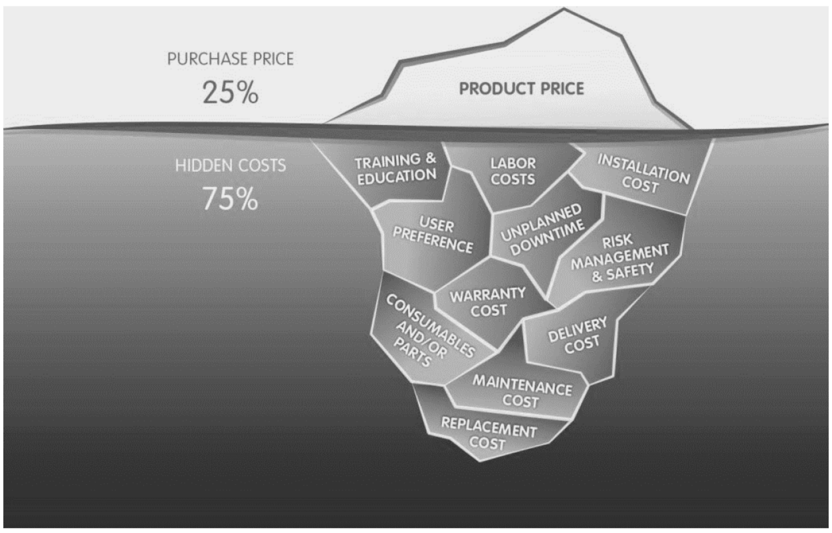
- Initial: purchase or product price
- Operation: installation, testing, operator training, energy to run equipment.
- Maintenance: planned maintenance (cleaning, inspection, lubrication, adjustments) and reactive maintenance.
- Downtime: delayed labor, lost production, lost customers.
- Production: comparison between equipment output levels and (environmental) impact.
- Remaining value: influenced by depreciation and longevity

The TCO is part of strategic cost management (Ellram and Siferd, 1998), as it considers the impact of purchasing decisions on the organization (Barbusová et al., 2019). The TCO model can support strategic cost management based on three themes: value chain analysis, strategic positioning analysis, and cost driver analysis (Govindarajan and Shank, 1992). Value chain analysis — similar to supply chain management — results in an external focus, considering all added-value activities, from the raw material source through the production process to the ultimate user (Ellram and Siferd, 1998). To evaluate the cost of equipment taking on a life cycle approach, TCO is beneficial for the following reasons (Ellram, 1995):

- provides a focus and sets priorities regarding the areas in which supplier performance would be most beneficial (supports continuous improvement), creating major opportunities for cost savings;
- improves the purchasers understanding of supplier performance issues and cost structure;
- provides an opportunity to justify higher initial prices based on better quality/lower total costs in the long run;

Figure 3.2

Principle of total cost of ownership (Barbusová et al., 2019; adapted from Porter, 1985)



- provides a long-term purchasing orientation by emphasizing the TCO rather than just price.

Because of this, TCO can drive major process changes and forecast (new) product or service performance. The forecast can be based on historical data (Ellram, 1995), but also on replacement (Ellram, 1995; Kaplan, 1992), budget or target cost (Kaplan, 1992). The approach of total cost rather than purchase price, gives a more thorough outlook on the costs associated to a product's life (Ellram, 1995). However, a major barrier for many organizations is the availability of accounting and costing data (Ellram, 1995). Therefore, a way to reduce this issue has to be found.

An advisable way to limit data availability issues, is to only include most important and significant costs (Ellram, 1995), of which the collection or generation of cost data is most valuable. To Ellram (1995), this is vital as part of TCO:

> total cost of ownership is a complex approach which requires that the buying firm determines which costs it considers most important or significant in the acquisition, possession, use and subsequent disposition of a good or service. In addition to the price paid for the item, TCO may include such elements as order placement, research and qualification of suppliers, transportation, receiving, inspection, rejection, replacement, downtime caused by failure, disposal costs and so on.

As noted (Ellram, 1995): "The costs which are significant and relevant to decision making vary on the basis of many factors such as the nature, magnitude and importance of the buy". From a case study on TCO, Ellram (1994) concluded that the following costs are considered critical costs: yield factors, warranties, manufacturer's response to warranties, reliability, and spare parts. These costs are considered important due to their critical nature in the product lifetime. Defining importance and significance is clearly a subjective task, which makes the setup of the cost-based economic valuation model qualitative. To limit the sensitivity of the cost factors chosen, a standard TCO model should be developed. A standard TCO model is generally used for (Ellram, 1994):

1. The firm purchases many items of a similar nature such as component parts for production.
2. The firm can specify the key TCO elements of interest for those items.
3. The TCO elements are common across items.

There are two major approaches to determining TCO used by organizations: dollar-based and value-based approaches. The dollar-based (or euro-based) approach is solely cost-based, whereas the value based approach adds other performance data to the equation. The latter is rather complex as it transforms qualitative data into quantitative data. Based on the same argumentation for the economic value indicator based on costs, as discussed in Section 3.1, the practical TCO approach is also cost-based.

Life cycle costing

Another option to identify life cycle costs, is life cycle costing (LCC). The approach is a variation of and, therefore, closely aligned with TCO (Ellram, 1994; Ellram, 1995), but many disagree on the differences. Ellram (Ellram, 1995) argue that LCC primarily focuses on capital or fixed assets, and TCO is broader in scope by including pre-purchase costs associated with a particular supplier. Barbusová et al. (2019), on the contrary, finds LCC broader in scope by including research costs next to the post-acquirement ownership costs.

The LCC method, in contrast to TCO, uses present value techniques, by implementing a discount rate, inflation rate and escalation rate of materials (Braakman et al., 2021). This is expressed by the following equation (Braakman et al., 2021):

$$LCC = C_0 + \sum C_t/(1+i-j-k)^t \tag{3.4}$$

where:

C_0 = initial costs (initial and construction phase);
C_t = present value of all recurring costs (operational and EoL cost) at year t;
t = year of cash flow;
i = discount rate;
j = inflation rate;
k = escalation rate of materials.

Although the definitions of TCO and LCC may vary, the methods are focused on a life cycle approach. To identify the significant and relevant costs present in the equipment life cycle, a structured procedure has to be followed. This can be done by using a cost breakdown structure, as discussed in the next section.

Cost breakdown structure of project equipment

The costs occurring in the ownership are composed of several cost categories. These are set out in a cost breakdown structure (CBS), such as from Fabrycky and Blanchard (1991), in Figure 3.3. Numerous CBS-types exist, therefore, it is important to make sure all costs are covered and no costs are counted twice (ten Brinke, 2002).

3.2.2. Modified cost breakdown structure

The CBS of Fabrycky and Blanchard (1991) is used as a basis in this research, as it conveniently aligns with the product use-cycle phases as in the Value Hill (see Figure 3.1). These phases are supportive in distinguishing between the value added in the pre-use phase and destroyed predominantly in the post-use phase. Incorporating the three phases — pre-use, use, and post-use — of the Value Hill into the CBS, shows how a cost-based economic valuation (as discussed in Section 3.1.2) can be justified. Namely, economic value is based on costs, but are inherited in a value framework supplied by the Value Hill.

The first cost category of the CBS in Figure 3.3 consists of administrative costs, stretching over the entire product life cycle. The second to fourth category are in line with the respective phases: pre-use, use, and post-use. To align with the costs occurring in the use cycle of project equipment, a CBS is made distinguishing the use-cycle phases. For the application to offshore equipment, this is shown in Figure 3.4. These include the relevant cost factors as identified in the life cycle of offshore project equipment, however, the same setup applies to any project equipment.

Pre-use phase costs

The first phase of the equipment use cycle is the pre-use phase. In the case study, the cost factors as listed in the CBS in Figure 3.4 are identified. The idea of a CBS, is that it sets a framework, but cost factors can be added or excluded per branch. It is important to include all significant and relevant costs (Ellram, 1995), and to make a standard setup for many product types to be compared. This is achieved by including the cost factors which are deemed significant or relevant for at least one product type analyzed.

Specific for the case study, as emphasized in the problem definition (see Section 1.1), is that the offshore TIR contractor designs and manufactures many fabricated steel themselves. In contrast to purchased equipment, for which most pre-use cost factors are replaced by a purchase cost. If this is applicable, all cost factors can be set to zero, apart from the manufacturing cost which now covers the purchase cost. If the contractor is responsible for the design and manufacturing, this supports design and manufacturing with a CE mindset. By analyzing the cost-based economic value of project equipment, this research justifies a CE approach.

3.2.3. Significant and relevant costs

As emphasized by Ellram (1995), a vital part of the TCO, is to define the significant and relevant costs to be included. Based on the results of the case study (see Chapter 5), the CBS is reduced by maintaining the

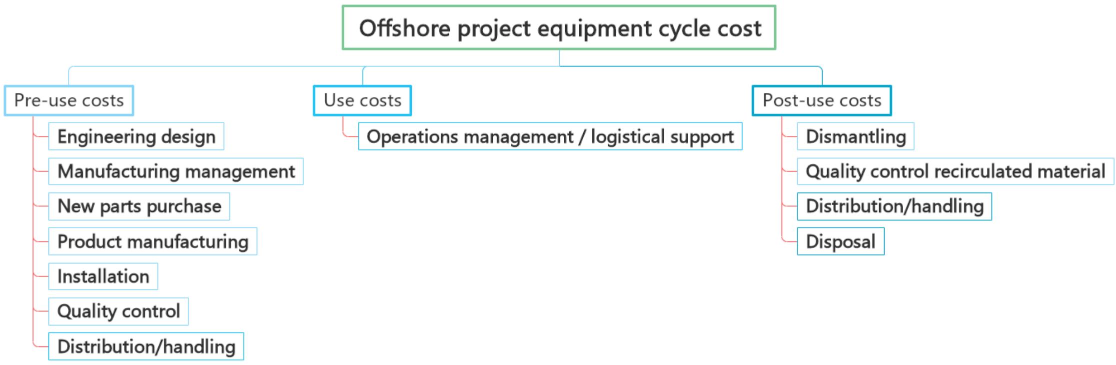
Figure 3.3

The cost breakdown structure (Fabrycky and Blanchard, 1991; adapted from Asiedu and Gu (1998)

Total product cost			
Research and development cost	Production and construction cost	Operations and maintenance cost	Retirement and disposal cost
- Product management - Product planning - Product research - Design documentation - Product software - Product test and evaluation	- Manufacturing/ construction management - Industrial engineering and operations analysis - Manufacturing - Construction - Quality control - Initial logistic support	- Operations/ maintenance management - Product operation - Product distribution - Product maintenance - Inventory - Operator and maintenance training - Technical data - Product modification	- Disposal of non-repairable - Product retirement - Documentation

Figure 3.4

Cost breakdown structure of offshore equipment with main levels



significant costs. The relevant costs can be determined based on the life cycle of the specific product, in this research project equipment. As can be seen in Figure 5.1, the equipment manufacturing consists of raw material extraction, part manufacturing and assembly. This distinction of manufacturing stages in the CBS is deemed necessary, as the recovery loops flow back into manufacturing process at different stages. For example, when materials are recycled after end-of-life (EoL), these have to be manufactured into parts. On the other hand, if remanufacturing occurs, the parts are maintained and return to the assembly stage of the manufacturing process.

As explained in Section 2.1.1, the usage of the c-indicators is to describe the current CE performance in a retrospective manner. When reviewing historic, the costs are already made and, as such, the significant and relevant costs to be included in the analysis can be identified. However, the method of only including significant and relevant costs also favors a prospective approach. If the method would be adapted for prospective purposes, similarly the most significant and relevant costs can be included. In this case, these costs should be based on more estimations, and, therefore, the result will be more sensitive.

3.3. Including additional life cycle costs in the economic indicator

When all significant and relevant costs are identified, the life cycle costs need to be incorporated in the original MCI' methodology. To follow the same procedure as for the MCI in Chapter 2.2, a top-down approach is taken to explain the methodology, from the MCI' to the material flows included. As in the MCI of Chapter 2.2, in this chapter the material flows and MCI' represent the project level. Both MCI and MCI' are translated to the product and company level in Chapter 4.

3.3.1. Economic material circularity indicator

The MCI' is created in a similar way as for the MCI in Section 2.2.1. Again, no utility is included in the expression for the single project use cycle of a product. Therefore, the MCI' is expressed as the value of circular material flow:

$$MCI' = 1 - LFI' \tag{3.5}$$

where:

MCI' = Material Circularity Indicator using cost-based economic value as the measurement unit [-];
LFI' = Linear Flow Index with economic value [-].

3.3.2. Linear flow index

The linear flow index (LFI') defines the fraction of the economic value of linear material flows relative to the total value. In the original MCI' methodology, the LFI' is a function of virgin material flow (V'), unrecoverable waste (W'), and economic value of material input (E). In the original methodology, a residual product value is included too. As this is also included by a remaining value in the TCO, or rated value in LCC, it is an important part of a life cycle approach. However, for simplicity reasons this is excluded from this research. Thus considering a residual product value equal to initial product value, the LFI' is expressed as:

$$LFI' = \frac{V' + W'}{2E} \tag{3.6}$$

where:

V' = Economic value of material that is not from reuse, recycling [\$];
W' = Economic value of unrecoverable waste associated with a product [\$];
E = Economic value of the material input in total [\$].

As noted as one of the limitations of the original MCI' methodology, there is a strong focus on material costs instead of life cycle costs. Because only material costs are considered, a split can be made between costs designated to virgin and recirculated material flow (see Eqs. 3.1-3.3). When including life cycle cost factors, not focusing solely on material costs, this division is no longer feasible. For instance, when virgin and recirculated materials are assembled, it is difficult to designate these costs to either of the two economic value flows. One could consider an economic value share based on mass or material value, but it is questionable whether this is fair. In Section 3.3.3, a solution to this is described. This implication changes the expression of LFI', which is:

$$LFI' = \frac{E_\sigma + W'}{2E_\nu} \tag{3.7}$$

where:

E_σ = economic value added of circular variant [\$];
W' = economic value destroyed [\$];
E_ν = economic value added of virgin variant [\$].

As in the LFI, Eq. 3.7 consists of an inflow and outflow part. As for the LFI, these can be split as follows:

$$LFI'_F = \frac{E_\sigma}{E_\nu} \tag{3.8}$$

$$LFI'_C = \frac{W'}{E_\nu} \tag{3.9}$$

where:

LFI'_F = Linear Flow Index with economic value of inflow [-];
LFI'_C = Linear Flow Index with economic value of outflow [-].

The circular fraction of these are:

$$MCI'_F = 1 - LFI'_F \tag{3.10}$$

$$MCI'_C = 1 - LFI'_C \tag{3.11}$$

where:

MCI'_F = Material Circularity Indicator with economic value of inflow [-];
MCI'_C = Material Circularity Indicator with economic value of outflow [-].

In Section 3.3.3, the creation of Eq. 3.7 is initiated by describing the feedstock of economic value. In Section 3.3.4, the outflow of economic value is outlined.

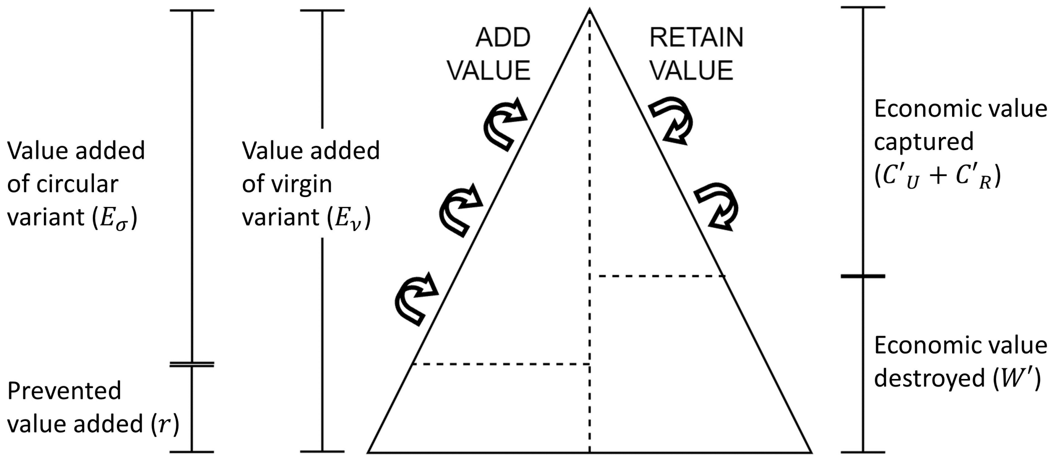
3.3.3. Economic value of material feedstock

The idea is best explained by using the Value Hill (see Figures 3.1). In the Value Hill, value is added on one side and retained on the other side. In Figure 3.5, two variants are compared: a virgin variant (ν) and circular variant (σ). The entire triangle represents the virgin variant, which is made from virgin material only and is fully discarded after use. In this section the focus is on material feedstock, which is the added value side of the Value Hill. In the next section, the value retention part is covered.

The total economic value embedded in the virgin variant is shown in Figure 3.5 as E_ν. This is composed of all added value, were the product made entirely out of virgin material. The circular variant is made at least partly out

Figure 3.5

Introducing a virgin and circular variant in the Value Hill to enhance the Material Circularity Indicator based on economic value (MCI') methodology of Jiang et al. (2022)



of recirculated material. If the circular variant requires less added value compared to the virgin variant, to reach the same level of economic value, some added value is prevented ($r > 0$). The virgin and circular alternatives in this methodology are compared as such, that total embedded value is the same. This is deemed a fair approach, as for industrial practices it is assumed that both variant should meet the same standards (in terms of quality, performance, availability, etc.). The prevented economic value added is:

$$r = E_v - E_\sigma \tag{3.12}$$

where:

r = prevented economic value added [$].

To persist the cost-based economic value approach of the MCI', the added value is also cost based. These costs mostly occur in the pre-use phase, but also in the use or post-use phase costs can add value to the product. An example are transportation costs after use, which bring the product at the right location for recirculation. As can be seen in the Value Hill of Figure 3.1, the narrower the resource loop, the higher the economic value captured compared to destroyed. For the added value prevented (r) to be high, it is, therefore, preferred to use recirculated material which is as close to a finished product as possible. Using recycled material, which is a relatively wide resource loop, still requires an intensive production process with high added value required.

In Eq. 3.7, two variants are compared: a virgin variant and circular variant. The virgin variant is the base case and consists of all virgin material. It has to be noted that this is a virgin variant which meets industry standards. For instance, when using new steel, there is always a certain amount of scrap (or recycled) steel in the material. So in this case the virgin variant does consist of some recirculated material, as no fully virgin variant exists. In the circular variant, more recirculated material is used to increase material circularity. Hopefully, this is also beneficial in terms of economic value, which is studied in this research.

The costs or added value of the circular alternative consists of multiple value flows:

$$E_\sigma = V' + r_{prep} + rV' \tag{3.13}$$

where:

V' = costs associated to virgin material flow [$];
r_{prep} = additional costs associated to recirculated material flow [$];
rV' = costs associated from the point where the virgin and recirculated materials are assembled [$].

As the costs can also be part of the assembly, this shows why a true split between economic value designated to virgin or recirculated material flow is unachievable. Special clarification is needed for the additional costs associated to recirculated material flow (r_{prep}). These costs are additional costs arising for a circular variant, which are not present for a virgin alternative. Examples are material retrieval costs, dismantling costs, and costs in the manufacturing process for preparing used material (also known as rework costs). These are increasing the costs of the circular variant, which should, therefore, be minimized to make the circular variant cost effective compared to the virgin variant. In Section 5, measures to limit these costs are discussed.

As explained in Section 3.3.4, post-use costs of a product are shared by a 50/50 approach between the present and following use cycle. Therefore, the additional costs associated to the recirculated material flow (r_{prep}) should at least consist of half of the post-use costs of the previous use cycle. This does not apply to the initial use cycle of the product, as in this case there are no post-use costs of a previous use cycle.

3.3.4. Unrecoverable waste

The economic value gone to waste is calculated in similar manner as in Section 2.2.4. In the MCI' calculations (Jiang et al., 2022), a value change from pre-use to post-use is applied. However, for simplicity reasons this is neglected, resulting in the total value of material input ($E = E_V$) maintained through a project's use cycle. Another reason for neglecting this, is that, in general, a product maintains its value during a relatively short project use cycle. In occasions where a product reduces in value, and is kept in use, the reduction is often counteracted by repair and maintenance. And various other factors, such as lead-time of new products, influence the value of recirculated materials and products. This shows the complexity of economic value, and the limitations of a cost-based estimation.

The value loss to incineration and landfill is expressed as the total value minus the value retained in reuse and recycling (Jiang et al., 2022):

$$W'_0 = E - C'_U - C'_R \tag{3.14}$$

where the total value E is replaced by the total value of a new alternative E_V (see Section 3.3.3:

$$W'_0 = E_V - C'_U - C'_R \tag{3.15}$$

where:

W'_0 = Economic value of unrecoverable waste going to landfill or energy recovery [$];
C'_U = Economic value of product going to component reuse [$];
C'_R = Economic value of product going to recycling [$].

The value retained through recycled equals the scrap revenue, as this is the market value of the recycled material. With the scrap revenue per kilogram (f_s), this is expressed by:

$$C'_R = C_R \cdot f_s \tag{3.16}$$

The value retained by reusing materials requires a more elaborate explanation. In essence, if an entire product is recovered, the embedded value may be captured to its full extent. However, there are always post-use costs to be made, which reduce the retained value in the product. Such costs factors are take-back transportation, quality control, and storage. To include these post-use costs (E_{post}), and thereby reduce the value of materials for reuse, a 50/50 approach is considered. Here, half of the post-use costs are covered by the project of interest, and half by the (potential) future project. This is the same approach as explained in Section 2.2.4, and is chosen for consistency in the waste calculation for material circularity and economic value. One may argue that a product is retained specially for the next project. By implementing a shared approach, projects share responsibility in making sure products and components are recirculated as much as possible. This leads to the post-use value of equipment for reuse (C'_U) as:

$$C'_U = \frac{C_U}{M}\left(E_V - \frac{1}{2}E_{post}\right) \tag{3.17}$$

In the calculation of the unrecoverable waste of the MCI (see Section 2.2.4), also the waste resulting from the recycling and reuse process are included. These will not be included in determining the economic value of the waste in the MCI'. The reason for this is that the value wasted in the recycling process, is already included in the material cost (pre-use) and scrap revenue (post-use). For the reuse processes pre- and post-use, material is wasted with an efficiency based on mass as E_{FU} and E_{CU}. This can for instance occur when dismantling a piece of equipment, or when clearing up a surface before welding. Estimating the economic value gone to waste due to these reuse processes, can be done based on the value of replacement material. That is, the material cost of the material per kg (p_m), multiplied by the mass of the material to waste. That is:

$$W'_F = p_m \frac{(1-E_{FU})F_U}{E_{FU}} \tag{3.18}$$

$$W'_C = p_m (1-E_{CU}) C_U \tag{3.19}$$

where:

W'_F	= Economic value of unrecoverable waste generated in the manufacturing process	[$];
p_m	= Material cost	[$/kg];
E_{FU}	= Efficiency of manufacturing process	[-];
W'_C	= Economic value of unrecoverable waste generated in the post-use recycling process	[$];
E_{CU}	= Efficiency of dismantling process	[-].

This leads to a total economic value waste:

$$W' = W'_0 + \frac{W'_F + W'_C}{2} \tag{3.20}$$

4

Circular performance on a product and company level

Following a bottom-up approach between the CE levels, the project level from Chapters 2 and 3 is translated to the product and company level in this chapter. In this chapter, the following research question is covered: *How to translate the circular economy performance on a project level to a product and company level?* In Section 4.1, first, the MCI at the product level is covered. As the MCI and MCI' have the same setup, the same procedure can be followed to translate the MCI' from the project to the product level. In the last section of this chapter, the translation to the company level is covered. This is both showed from the project to company, as from the product to the company level.

4.1. Material circularity on a product level

During its life cycle, a product may be modified on various occasions. This may be because of planned maintenance or because of the requirements of a project. If the product's integrity and original function are retained, the resource loop associated is either repair (R4) or refurbish (R5) (see Figure 1.3). If the product loses its integrity and/or fulfills a different function, it is remanufactured (R6) or repurposed (R5). In the first case, the product's life is extended, whereas in the second case a new product is made. Throughout its life cycle the material circularity of a product changes when repaired or refurbished. During these processes, often additional material feedstock is used. As a result, the total mass of materials used in all modification steps (M_T) is greater than the mass contained in the final product (M). These changes to the product's MCI, are accounted for by the following procedure (EMF et al., 2019).

4.1.1. Virgin feedstock

Assuming in the initial fabrication step of the product ($\psi = 1$), a feedstock of mass m_1 is used. In a modification step ψ (for $\psi = 2 : \Psi$), additional feedstock of mass m_ψ is used. The additional feedstock may be from virgin or recirculated source. The mass is always positive ($m_\psi > 0$) as negative feedstock is not possible. Any reductions of the mass contained in the product should be accounted to the post-use mass flow. The total mass M_T used, is expressed by:

$$M_T = \sum_{\psi=1}^{\Psi} m_\psi, \text{ for } m_\psi > 0. \quad (4.1)$$

where:

M_T = Total mass of materials used in the product for all modification steps combined [kg];
ψ = Modification step [#];
m_ψ = Added mass in modification step ψ [kg].

Using Equation 2.12, in combination with the additional feedstock, the virgin feedstock of all modification steps combined (V_T) becomes:

$$V_T = \sum_{\psi} \left(m_\psi - F_{R,\psi} - F_{U,\psi}\right) \quad (4.2)$$

where:

V_T = Total virgin mass used for all modification steps combined [kg];
$F_{R,\psi}$ = Added mass of recycled feedstock in modification step ψ [kg];
$F_{U,\psi}$ = Added mass of reused feedstock in modification step ψ [kg].

4.1.2. Unrecoverable waste

The total unrecoverable waste of a product is calculated by:

$$W_T = W_{0,T} + \frac{W_{F,T} + W_{C,T}}{2} \tag{4.3}$$

where:

W_T = Total mass of unrecoverable waste generated in all modification steps combined [kg];
$W_{0,T}$ = Total mass of unrecoverable waste to landfill or energy recovery [kg];
$W_{F,T}$ = Total mass of unrecoverable waste in pre-use recycling process [kg];
$W_{C,T}$ = Total mass of unrecoverable waste in post-use recycling process [kg];

where the total waste during each fabrication step is:

$$W_{0,T} = \sum_{\psi} \left(m_{\psi} - C_{U,\psi} - C_{R,\psi} \right) \tag{4.4}$$

where:

$C_{U,\psi}$ = Total mass of reused material after use [kg];
$C_{R,\psi}$ = Total mass of recycled material after use [kg].

The waste in the recycling process pre-use ($W_{F,T}$) and post-use ($W_{C,T}$) are (EMF et al., 2019):

$$W_{F,T} = \sum_{\psi} \frac{(1 - E_{F,\psi}) F_{R,\psi}}{E_{F,\psi}} \tag{4.5}$$

$$W_{C,T} = \sum_{\psi} (1 - E_{C,\psi}) C_{R,\psi} \tag{4.6}$$

where:

$E_{F,\psi}$ = Efficiency of recycling process of modification step recycled feedstock [-];
$E_{C,\psi}$ = Efficiency of recycling process of modification step after use [-].

4.1.3. Linear flow index

The linear flow index of the product (LFI_p) can now be expressed similar to Equation 2.4, as:

$$LFI_p = \frac{V_T + W_T}{2M_T + (W_{F,T} - W_{C,T})/2} \tag{4.7}$$

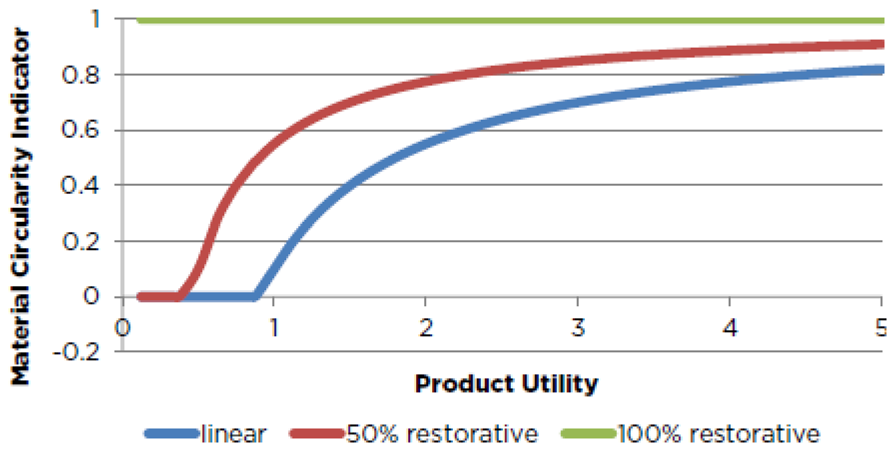
This can also be split into pre-use and post-use parts. In Section 2.2.2, this is explained in detail, and will not be reproduced here.

4.1.4. Utility

The utility (X) is expressed as the lifetime (L) multiplied by the intensity of use (U). The aspect of an indicator to address these two factors has been noted by others (European Environment Agency, 2016, Linder et al., 2020), as this would reward sharing models and relatively durable products (Linder et al., 2020). The lifetime and use intensity are expressed as a factor of product averages. For the application to project equipment, the intensity of use is given as the allocation rate (#) over the lifetime. The allocation rate is the amount of times a product is allocated to a project. This means that the product is mobilized for the project, but this does not necessarily mean that the product has been used. For project equipment, often because of redundancy duplicate pieces are

Figure 4.1

Chart showing the impact of product utility on the Material Circularity Indicator (EMF et al., 2019)



mobilized, in case one fails. The reason for choosing one single measure of intensity of use for all product types, is that it makes it easier to compare the performances. The utility is expressed by:

$$X = \left(\frac{L}{L_{avg}}\right) \cdot \left(\frac{U}{U_{avg}}\right) = \left(\frac{L}{L_{avg}}\right) \cdot \left(\frac{\#/L}{(\#/L)_{avg}}\right) \tag{4.8}$$

where:

X	= Utility	[-];
L	= Lifetime	[yr.];
L_{avg}	= Industry or company average lifetime	[yr.];
U	= Intensity of use	[1/yr.];
U_{avg}	= Industry or company average intensity of use	[1/yr.];
#	= Project allocation rate	[#].

The lifetime average and intensity of use average, only include company actual values. This means that increased utility will result in an increase company average, creating an ever existing drive for improvement. The averages are mass-weighted averages, because the utility factor X is influencing the need for material feedstock. In that respect, products with a higher mass should strive for a higher utility.

4.1.5. Material Circularity Indicator

The MCI of the product (MCI_p) is expressed as:

$$MCI_p = MAX[0, 1 - LFI \cdot F(X)] \tag{4.9}$$

where $F(X)$ is a factor affecting the linear material flow. In the original MCI methodology, $F(X)$ is set in the form a/X. This way an improvement of the utility, acts as a reductive factor on the LFI. which in turn increases the MCI. The impact of the utility influencing the MCI, is shown in Figure 4.1 (EMF et al., 2019). The value of a is originally chosen as 0.9, to create an MCI of 0.1 for a fully linear product ($LFI = 1$) with $X = 1$. However, to make sure that the MCI equals the circular flow indicator ($CFI = 1 - LFI$) under these circumstances, a is set to 1.0. This way, the linear flow is not reduced for average utility. The downside of this, is that a fully linear product has the same MCI for average compared to below average utility. This effect will not be profound, as most project equipment does at least consist of some recirculated material. This results in the utility factor being:

$$F(X) = \frac{1.0}{X} \tag{4.10}$$

4.1.6. Economic value on a product level

For computing the MCI', similar steps are followed as in previous sections. In this case, the mass is replaced by economic value. The total economic value increases proportional to the value of a virgin alternative. As with the MCI, the same utility X is used for the MCI'.

4.2. Company level circular economy performance

After expressing the product level material circularity and economic value, the company level can be determined. As seen in Figure 1.4, this is the highest sub level of the micro level. To represent the company level circular performance, two routes can be followed. Either the project performances or the product performances are combined. Picking one or the other, tells a different story. To consider both pathways, these are described in the following sections, after which the differences are analyzed.

4.2.1. Aggregation principle

To determine the circularity and economic value on a project, product, and company level, a way of connecting between the levels has to be found. This can be done either bottom-up or top-down, be aggregating or disaggregating between the levels, respectively. The main distinction between these approaches, is that the former is data driven and the latter objective driven (Saidani et al., 2017b). The main advantage of a data driven approach, is that it is a quantitative approach, enabling for scaling the method for a great number of products. Next to this, it allows for tracing down to the single products which lack behind in the individual circularity or economic value scores. This is beneficial for deciding which types or pieces of project equipment to start improving.

As described in Section 2.1.2, the most widely method to aggregate between levels is the weighted sum (Becker, 2016), also known as weighted average. This method is also used to combine products within the project level, and is used in this research to translate between the levels as well.

4.2.2. Combination of projects to the company level

To start with the project performance, this tells how well a project performs in using recirculated materials and saving costs by doing so, and restoring materials for future projects and capturing economic value by this. When combining the performance of various projects, this tells how well resource flows are closed and narrowed, and what the economic benefit is of this. It reviews the equipment used per project and combines the performances of multiple projects. However, the slowing of resource flows is neglected, as no product utility is included. In essence, it is not about the product view of resource flows, but the project view.

Aggregating multiple projects to the company level, can be done by similar means as aggregating different products within a project (see Section 2.2.5). As discussed in the introduction of this section, there is no utility present at the project level. This is due to utility chosen as a function of the (project) allocation rate, as explained in Section 4.1.4.

Combination of project-level Material Circularity Indicators

For the MCI on the company level, a weighted sum is taken. This approach is similar to the methodology of the original MCI (EMF et al., 2019). That is:

$$MCI_{comp}(j) = \sum_{j} w_j \cdot MCI_j \tag{4.11}$$

where:

MCI_{comp}	= Material Circularity Indicator on the company level	[-];
j	= Project with index j	[#];
w_j	= Weight factor of project j	[-];
MCI_j	= Material Circularity Indicator of project j	[-];

This weight factor w_j can be chosen as preferred, for example as product mass or sales revenue (EMF et al., 2019). The idea of decoupling the mass and economic value by using the MCI and MCI' separately, requires the product mass and economic value as weight factor separately as well. This is best described by decomposing Equation 4.11. As there is no utility present for a project, the MCI is adapted from Equation 2.3:

$$MCI_{comp}(j) = \sum_{j} w_j \cdot MCI_j = \sum_{j} w_j \cdot MCI_j \tag{4.12}$$

The weight factor w_j can be chosen as preferred. depends on the mass of the final product M_p. This is chosen for simplicity reasons, neglecting the influence of waste generated in the recycling processes pre- and post-use. Although a double summation arises in computing the MCI, what remains is simpler compared to Equation 4.13. The weight factor is:

The MCI formula is similar to the project level (see Equation 2.3), namely:

The LFI is based on the different material flows, and is taken as the weighted sum of each project j. The weight factor w_j is taken as the denominator in the original LFI equation (see Equation 2.4), that is:

$$LFI_{comp} = \sum_j w_j \cdot LFI_j = \sum_j \frac{2M_j + (W_{F,j} - W_{C,j})/2}{\sum_j \left(2M_j + (W_{F,j} - W_{C,j})/2\right)} \cdot LFI_j \tag{4.13}$$

where:

LFI_{comp}	=	Linear Flow Index on the company level	[-];
w_j	=	Weight factor or normalization factor of project j	[-];
LFI_j	=	Linear Flow Index of project j	[-];
M_j	=	Mass of the products allocated to project j	[kg];
$W_{F,j}$	=	Waste generated when producing recycled feedstock for the products of project j	[kg];
$W_{C,j}$	=	Waste generated in the process of recycling parts for the products of project j	[kg].

Instead of using the weighted sum, resulting in a double summation, it is simpler to use the input data. This is done by combining the material flows of all considered projects. This way the LFI of total material flow is computed, essentially losing track of individual products. The total LFI is:

$$LFI_{comp} = \sum_j \frac{V_j + W_j}{2M_j + \left(W_{F,j} - W_{C,j}\right)/2} \tag{4.14}$$

where:

V_j	=	Mass of material of project j that is not from reuse or recycling	[kg];
W_j	=	Mass of unrecoverable waste associated with the products of project j	[kg].

Combination of project-level Economic Value Indicators

For the MCI', the methodology is the same. This leads to the following set of equations:

$$MCI'_{comp} = 1 - LFI_{comp} \tag{4.15}$$

$$LFI'_{comp} = \sum_j \frac{E_{\sigma,j} + W'_j}{2E_{\nu,j} + \left(W'_{F,j} - W'_{C,j}\right)/2} \tag{4.16}$$

where:

MCI'_{comp}	=	Economic Value Indicator on the company level	[-];
LFI'_{comp}	=	Economic value Linear Flow Index on the company level	[-];
$E_{\sigma,j}$	=	Costs to products in project j	[\$];
W'_j	=	Economic value wasted in project j	[\$];
$E_{\nu,j}$	=	Costs to new alternative products in project j	[\$];
$W'_{F,j}$	=	Economic value wasted when producing recycled feedstock for the products of project j	[\$];
$W'_{C,j}$	=	Economic value wasted in the process of recycling parts for the products of project j	[\$].

4.2.3. Combination of products

Looking at the product performance, the utility is indeed included, by including the use intensity and lifetime of the product. When aggregating the performances of multiple products to the company level, this shows how well the products perform within the company. The way products are aggregated to represent the company level, is done using a normalizing factor. This normalizing, or weight, factor can be chosen as preferred, for example as product mass or sales revenue (EMF et al., 2019). However, the idea of decoupling the mass and economic value by using the MCI and MCI' separately, requires the product mass and economic value as weight factor separately as well. This results in:

$$MCI_{comp}(p) = \sum_{p} w_p \cdot MCI_p, \tag{4.17}$$

where:

MCI_{comp} = Material Circularity Indicator on the company level [-];
p = Product with index p [#];
w_p = Weight or normalization factor of the product [-];
MCI_p = Material Circularity Indicator of the product [-].

The weight factor w_p depends on the mass of the final product M_p. This is chosen for simplicity reasons, neglecting the influence of waste generated in the recycling processes pre- and post-use. Although a double summation arises in computing the MCI, what remains is simpler compared to Equation 4.13. The weight factor is:

$$w_p = \frac{M_p}{\sum_p M_p} \tag{4.18}$$

where:

M_p = Mass of final product p [kg].

For the MCI' this is computed similarly:

$$MCI'_{comp} = \sum_{p} w'_p \cdot MCI'_p \tag{4.19}$$

where the weight factor w'_p depends on the total embedded economic value of the product $E_{v,p}$:

$$w'_p = \frac{E_{v,p}}{\sum_p E_{v,p}} \tag{4.20}$$

The (dis-)aggregation of CE indicators to and from different levels by means of a weighted sum, is discussed extensively in the academic field. In this research, a consistent methodology is followed, by using a weight factor based on the same unit as the LFI or LFI', mass or economic value respectively. One could argue what the results would be of the MCI weighted by economic value or MCI' weighted by mass. If this leads to useful results, it could save time in data collection and computation, as using the MCI in combination with two weight factors would satisfy. However, due to limitations set on the scope of this research, the results of these interrelations will not be further investigated.

4.2.4. Difference between project or product aggregation

There is a difference in both methodologies, and associated advantages and disadvantages. The first methodology describes the CE performance from a project perspective, which may be a beneficial approach for a project-based organization. The issue with this approach, is that it neglects an important aspect of the CE, which is indeed included in the second approach. Aggregating the product level, namely, includes the utility of a product. This part of the MCI introduces the slowing of resources into the equation, which is one of the three aspects of a CE sensu stricto. Inheriting the unit time is vital for a qualitative measurement framework.

One of the main benefits of aggregating from the product level, is that it considers a product life cycle approach. The product is followed through its life cycle, with associated material flows due to modifications made to fit the project requirements. When combining products into the company level CE performance, the focus is on the product perspective, which allows for product-specific or product group specific improvements. When taking the other route, by combining projects instead of products, the focus is project-based. As pointed out in Section 1.1, the project focus is one of the roots of the problem, as it refuses to take a whole life cycle approach, which is necessary for less exhaustive resource use.

5
Case study

To show the application of CE indicators for a project-oriented organization, a case for offshore project equipment is studied. This case study is chosen as followed from the problem announced in Chapter 1. The case study supports the research questions of the previous chapters, as well as the following research question covered at the end of this chapter: *How do the material circularity and economic value performance compare for the case of offshore project equipment?*. Before addressing the results of the case study, background information is given in Section 5.1 to provide the circumstances of the study. From Section 5.2 onward, each section covers the results of the case study corresponding to a research question. Starting with the material circularity at the project level on research sub-question A, followed by the economic evaluation at the project level on question B in Section 5.4. Thereafter, the research sub-question C is covered on the product level in Section 5.4, and on the company level in Section 5.5. The last Section 5.6, covers the comparison between the material circularity and economic value performance on multiple CE levels, thereby, answering research sub-question D. But, first of all, the background of the case study is described.

5.1. Background

In this section, the CE levels of the case study are described in a top-down approach. Starting with the highest level of the company, the offshore contractor used in the case study is introduced in Section 5.1.1. In Section 5.1.2, the different types of existing offshore equipment as well as the chosen ones for the case study are outlined. In the same section, the life cycle of this equipment is described, to clarify the resource flows specific to this equipment. In Section 5.1.3, the project chosen for the case study is described.

5.1.1. Offshore transport, installation, and removal contractor

As the case study is performed in cooperation with offshore contractor Heerema Marine Contractors (HMC), its practices and use of resources are described in this section. The offshore contractor is specifically active in the offshore part the maritime industry. The practices in the offshore industry are mainly focused on energy exploitation, including but not limited to oil and gas, offshore wind, telecommunication. The offshore contractor is one of the players in this industry, and is responsible for the transport, installation, and removal (TIR) of offshore structures. This means either transporting and installing new structures, or the removing — also known as decommissioning — of old structures. With predominant activity on oil and gas structures in the past, this is strongly shifting towards offshore wind.

Offshore wind is a development favoring the energy transition and supporting sustainable development, but creates a difficult paradox. Installing wind turbines offshore is, namely, a resource intensive activity, which has a negative effect on sustainability. Offshore TIR vessels are large and heavy, for which large amounts of materials and energy is required in all phases of its life cycle. The feeling is that the positive impact of offshore wind on the energy transition outweighs the negative impact on resources, but it is a duel to bear in mind.

5.1.2. Offshore project equipment

In this section, the project level is described, with offshore project equipment as the case study. In the first part of this section, the types of offshore equipment are explained, with specific equipment chosen for the case study. In the last part, the equipment life cycle of offshore equipment is described.

Types of offshore equipment

The offshore TIR contractor uses various types of equipment for its operations. Similar to, for instance, contractors in road and rail construction, the equipment used is not the main source of income. However, the equipment is vital for smooth operations, and (in a niche sector) can be of great a competition value. Although this research focuses on measuring CE performance to improve in the future, one should bear in mind that the sophisticated equipment has strict technical and operational requirements. These should under no circumstance be jeopardized.

The project equipment is one of many resources used by the offshore TIR contractor. In Figure 1.1, these are shown in the light of a CE. On the left-hand side are the resources which, when taken care of by sustainable manners, can be reused by multiple projects. This includes human resources and technical equipment. Where the human resources can benefit from a CE, as social effects are one of the three pillars of sustainability. The equipment can be divided in floating and non-floating resources. Floating equipment — consisting of vessels, cargo barges, tugs — are built for a lifetime of generally over 25 years and, therefore, are reusable resources. On the other hand, the fuel running through the vessel its engines, is a consumable. Although out of this research scope, a circular power source would be nuclear energy.

The non-floating equipment can be divided in two types: with and without moving parts. The static equipment consists mainly of fabricated steel and has no electric or hydraulic parts, therefore, also named *static* or "dead" equipment. This are, for instance, transport frames or rigging (slings, shackles, spreader bars/frames). In many cases, the smaller/lighter pieces of equipment are seen as consumable resources. Contradictory, the larger/heavier and, therefore, more expensive equipment, is generally managed as reusable resources. In business terms, these equipment pieces are called *assets*. The *dynamic* equipment consists of equipment such as portable cranes, hydraulic pile driving hammers, all sorts of lifting tools, and remotely operated vehicles (sub-sea survey submarines). For all equipment it is important to get a return on the investment from the projects where it is used. For large projects, where project-specific equipment is required, this may be within one project. Such equipment is then handled as a consumable resource. But for all other assets, both static and dynamic, the equipment investment is returned through multiple projects.

For the case study in this research, the decision is made to only analyze the static equipment. This is the type of equipment which is often a project-specific consumable resource, and, therefore, benefits from a more circular approach. This decision does not imply that improving the circular performance of static equipment, will result in greater sustainable benefits compared to the dynamic equipment. However, when comparing the total mass of static with dynamic equipment purchased per year (see Figures B.1 and B.2), the former represents a much greater share. Knowing that new steel used in the static equipment has a high fraction of virgin material, targeting this equipment group is most beneficial in the light of a CE.

To support the reuse of fabricated steel — part of static equipment — HMC built a *Steel Marketplace* software, where used components or entire pieces can be allocated. From the launch in December 2018, this enabled practical guidance for engineers to reuse steel. Although material data to show reuse rates was not collected prior to this date, the feeling is that this increased the reuse of materials. Reuse rates from 2020 to 2023 are shown in Figure B.1b, which are fluctuation with a deviation of approximately 7% from the average. Reasons for these fluctuations can be found in project types, such as the share of installation versus decommissioning projects, where decommissioning enables for higher reuse rates due to the contractor in charge of the design and fabrication of steel. Next to this, the type of structure to be lifted and/or transported, with related task requirements for fabricated steel, is of influence. Where the more specific tasks often result in lower reuse rates.

Equipment life cycle

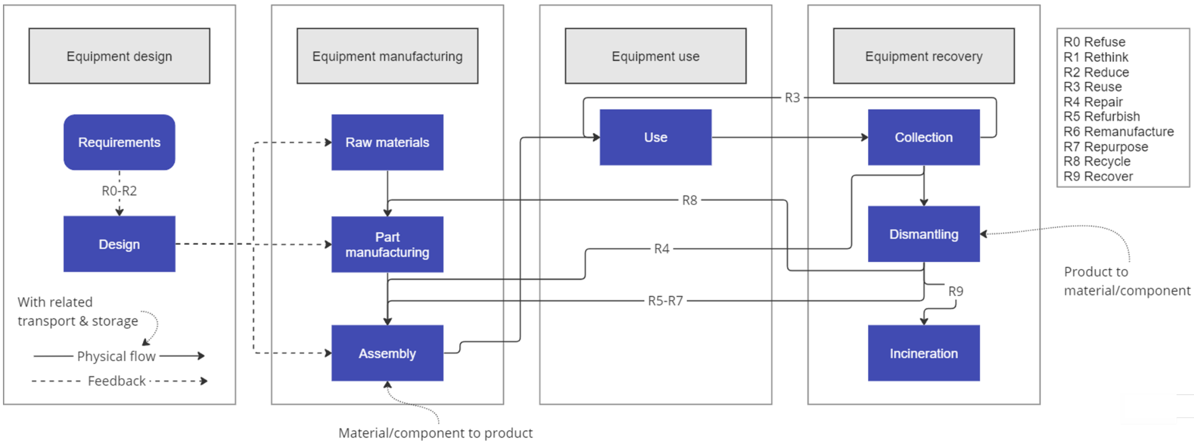
In this section, the equipment life cycle is discussed, specific to offshore equipment. In Figure 5.1, the life cycle of equipment is visualized, which is similar for offshore equipment. The life cycle starts with the pre-use phase, which includes the first two blocks of equipment design and manufacturing. After manufacturing, the equipment is used in a project. Finally, the product is collected and a resource loop from the 9R framework is taken. The life cycle phases from pre-use to use to post-use, are followed every time the equipment is modified.

Pre-use phase

The pre-use phase starts with equipment design and ends with manufacturing. The design phase occurs before the piece of equipment is manufactured, which therefore forms the basis for the equipment life cycle (see Figure 5.1). Depending on the type of equipment, the design is carried out internally or is outsourced. For equipment which is purchased of the shelf or rented, the design is controlled by the seller. The design starts with a project need for a piece of equipment, caused by a function it should fulfill in the project. The project needs are owned

Figure 5.1

Interactions in the equipment life cycle, adapted from Gungor and Gupta (1999)



Note. The recovery loops corresponding to the 9R framework (PBL, 2017a), as presented in Figure 1.3.

by various stakeholders which are involved in the product development and/or will be involved in the product use. Because in most cases equipment requirements are dictated by one project's needs, extending the lifetime of equipment is proven to be difficult. If equipment has a substantially high value and/or a procedure is performed multiple times, multi-project equipment is acquired. This clearly expands the requirement package of the product, inducing smart design solutions. The implications for projects dictating equipment requirements, grounds from the project-based organizational structure.

For the manufacturing of the simple or "dead" steel equipment, used in heavy offshore transport, high-strength steel (HSS) is used. This type of steel is produced in a blast furnace or using an electric arc furnace (EAF), for which the latter is predominantly fed by scrap steel (Broadbent, 2016). Whether the blast furnace or EAF is used, depends on the steel product type. Steel plates and large rolled pipes come from the blast furnace, and mostly extruded steel, which are standard small shapes such as tubulars and beams, come from EAF. As large quantities of scrap steel are used in the EAF furnace, the recycled content is approximately 90% (Bowyer et al., 2015).

The recycled content for all relevant equipment is shown in 5.1. This shows high content rates for lift-off guides, rigging platforms, and vessel set down guides, as their components are predominantly made from standard steel shapes. The larger equipment made from plates, as accounts for large rolled tubulars, has a recycled content of 30%. Spreader bars and frames are partly made from large rolled tubulars, with heads made from cast iron. This cast iron is made through the EAF leading to higher recycled content rates. The slings are made from steel wires, which are made with blast furnace, thus lower recycling fraction. The reduction of 1% from 30% recycled content in blast furnace steel, arises due to the presence of fat which has no recycled content.

For TIR contractors, the production of steel structures can be outsourced or manufactured at owned construction yards. Not every TIR company owns such yard, but some do produce their own equipment. As the TIR contractor provides a service, the manufacturing of equipment is not of primary importance, although it does benefit a strategic market position. Until recent years, mostly new steel was acquired to manufacture steel structures. However, due to rising steel prices and to make more efficient use of valuable assets, more often used steel is reused. For example, the HSS prices rose from 0.75 €/kg in 2021 to 2.5 €/kg in 2022, under the influence of the Russo-Ukrainian war (Heerema Marine Contractors (HMC), pers. comm., April 20, 2023). This stressed the need for more efficient use of resources, which will release some of the dependency on resource prices. Depending on the R-loop, as depicted in Figure 5.1, a piece of steel equipment can be entirely reused or additional remanufacturing has to be performed. The amount of remanufacturing differs per steel equipment type. For instance, SPBs require minor remanufacturing, by shortening or lengthening the main tubular. On the other hand, G&S structures often require extensive remanufacturing in order to match the vessel and lift structure characteristics.

The manufacturing of dynamic equipment is often outsourced to other producers. These work together with

Table 5.1

Mass flow and utilization per product group of decommissioning project Dunlin Alpha

Product group	f_R [%]	E_F [%]	E_C [%]	F_E [%]	F_L [%]	L_{avg} [yr.][a]	U_{avg} [#/yr.][a]
			Fabricated steel				
Barge G&S[b]	30%	91%	91%	0%	0%	1.8	1.4
Lift-off guides	90%	91%	91%	0%	0%		
Liftpoints	30%	91%	91%	0%	0%		
Miscellaneous	30%	91%	91%	0%	0%		
Reinforcements	30%	91%	91%	0%	0%		
Rigging platform	90%	91%	91%	0%	0%	6.0	1.5
Spreader bar	50%	91%	91%	0%	0%	11	0.59
Spreader frame	50%	91%	91%	0%	0%		
Vessel G&S[b]	30%	91%	91%	0%	0%	1.8	1.4
Vessel set down guides	90%	91%	91%	0%	0%	2.1	1.5
			Rigging				
Slings[c]	29%	91%	91%	0%	2%	8.9	0.46

Note. With recycled content of new material (f_R), recycling efficiency of feedstock (E_F) and post-use (E_C), material to energy recovery (F_E), and material to landfill (F_L). With life time (L) and intensity of use (U) as in Eq. 4.8.
[a] L_{avg} and U_{avg} are calculated as a mass-weighted company average.
[b] The barge and vessel G&S are combined when determining the average L and U. They are listed to indicate that in reality, barge and vessel G&S has different utilization.
[c] The sling average L and U is a combination of sling types: cable laid and superloop slings, and cable laid grommets.

their own constructors. As the manufacturing is not in hands of the TIR company, the processes are often not controlled by this company. It is, therefore, hard to influence the use of secondary resources, and one can expect that for generally sophisticated equipment, mostly virgin resources are applied. In dynamic equipment, many material types and components are assembled, which influences the EoL recycling.

Use phase

The use phase of static equipment is more straightforward than for dynamic equipment. Namely, static equipment is often installed and no operator is required to control it, as opposed to dynamic equipment. Although rigging may be installed and/or lifted offshore, the operations are related to the lift of the offshore structure. Static equipment does not include any use processes, as it ultimately is "dead" steel. However, slings are a strange product group as they lose weight during offshore operations. In production, a conservation layer is applied to slings to limit corrosion as a result of sea water. It is known that this fat layer is approximately 2% of total sling mass, which is partly disposed unintentionally at sea. To show this waste stream, it is assumed that all is disposed to landfill, as included in Table 5.1.

Post-use phase

Especially for dynamic equipment, reuse rates are high. This equipment is costly and is often used for 15 to 20 years (HMC, pers. comm., March 31, 2023). This equipment is maintained well and serves its purpose in various projects. Sometimes, extremely sophisticated equipment is designed and manufactured for single-project use. However, this is often the case for wind installation projects, where a project consists of repeating steps of installation. Only in this case, such expensive equipment is worth it.

When reusing simple steel equipment, reuse is less common. Mostly, the steel is custom-made for a certain project, and either components are reused (remanufactured) and/or it is scrapped and recycled. In the case of reuse, structural steel always has to be inspected by non-destructive testing on the welds. For lifting equipment, 100% of the welds have to be tested and for transport steel only the welds coping with critical stresses are inspected. When reuse requires recertification, as is described in Section 1.2.2, this circular loops is referred to as 'refurbish'.

Before reviewing the recycling circumstances of steel recycling, the definitions of recycling are explained. First, a distinction can be made between closed and open loop recycling. According to ISO 14044: 2006 (International Organization for Standardization, 2006), open loop recycling is described as material which is recycled in a new different product or where inherent material properties change. Closed loop is when materials are recycled to the same product type or where inherent properties do not change. (Broadbent, 2016) Therefore, steel can be considered recycled in closed loop, as 'the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials' (International Organization for Standardization, 2006).

As explained in Section 5.1.2, some structural steel is made with in an EAF (Bowyer et al., 2015), using large amounts of steel scrap (Bowyer et al., 2015; Broadbent, 2016). When using scrap to make steel in an EAF, about 8% (Bowyer et al., 2015) to 9% (Broadbent, 2016) of material is lost in the process, ending up as recaptured contaminants, air emissions or slag (Bowyer et al., 2015). Meaning, after 8 re-cycles half of the material is left. Next to material wasted in the process, Yellishetty et al. (2011) note that each time scrap is recirculated, the amount of contaminants rise. Although structural steel can handle some contamination due to its size, there is a limit.

5.1.3. Project

For the case study, a project is chosen which can be used as an example for the calculations. This is the decommissioning, or removal, of oil platform Dunlin Alpha (see Figure 5.2), which was executed from November 2021 to February 2022. A decommissioning project is chosen as these projects often reuse high amounts of fabricated steel, because the G&S is arranged by the contractor. In contradiction to installation projects, where the G&S predominantly comes from the construction yard of the to-be-installed structure. As a result of a large fabrication scope for decommissioning projects, the fabrication is well documented, including material flow and cost data.

The case study at the project level is described in Sections 5.2 and Section 5.3. From the Dunlin Alpha project, all fabricated steel is included in the study, and, additionally, one sling. The reason for not including all slings, is that slings are treated similarly. Therefore, a sling with average mass and size is used, to represent the entire project. In Table 5.2 relevant project information is given, regarding the project and project equipment.

Figure 5.2

Fly By photograph of Dunlin Alpha platform in 2018 before decommissioning (photo courtesy of HMC, pers. comm., December 13, 2023)

5.2. Material circularity at the project level

In this section, the results of the material circularity at the project level are shown. For the case study, all fabricated steel is included, and an example lifting sling. In Chapter 2, the following research question was answered: *How can the material circularity of circular material flows be determined on a project level?*. Now, the outcome of the method on the material circularity is discussed.

On the left-hand side of Figure 5.3, the material circularity for the Dunlin A decommissioning project is shown. To indicate the significance of each product group to the total material mass of the project, the percentage of grand total is shown on the right. The most significant product groups by mass, are the lift points, spreader bar and frame, and vessel G&S. The high material circularity of these product groups arises from the input and output of material.

On the input side, the material feedstock consists of high fractions of recirculated material, mainly through refurbishment and remanufacturing. In Figure 5.4, the fractions of reused and recycled content are shown on the left-hand side, where in the reused content R3 Reuse to R7 Refurbish from the 9R framework are summed up. As can be seen in this figure, on average the lift points have approximately 50%, and the spreader frame and vessel G&S between 90% and 100% reused content. The higher the reused content, the lower the use of new material. As the new steel is where the recycled content is embedded, the higher reuse rate reduces the recycled content (as seen in Figure 5.4.

To quantify the influence of recycled content on the MCI, the right-hand side of Figure 5.4 shows the results when excluding recycled content. This is achieved by including the recycled material as a virgin material flow. When excluding the recycled content, the materials with high recycled content are most affected, resulting in a reduced MCI. This is most drastic for the product types without any reused content — being lift-off guides, miscellaneous steel, and platform reinforcements — for which no material circularity remains. Although these products are insignificant in overall mass, no material is recovered in a narrower loop than recycling.

On the output side, a high MCI for the most significant product types is generated because most material is kept, thus stored, for reuse. For some assets it is known that these are indeed refurbished or remanufactured partially, or reused as entire pieces. For other products — such as the lift points for the crane suspended transport of the modular support frame (see research cover photo) weighing 347 mT in total — the assets have yet to be used again, after almost 2 years of project finalization. Should these lift points be scrapped without being used again, this would reduce the MCI of the product. When recycling is included as a circular material flow, the difference is limited, as the MCI would be reduced from 0.82 to 0.77. However, if recycling is not included, the MCI would reduce from 0.75 to 0.25. This both emphasizes the effect of including recycling, as well as the effect of changing the MCI from having a retrospective to a prospective perspective. Namely, for products put in stock

Table 5.2

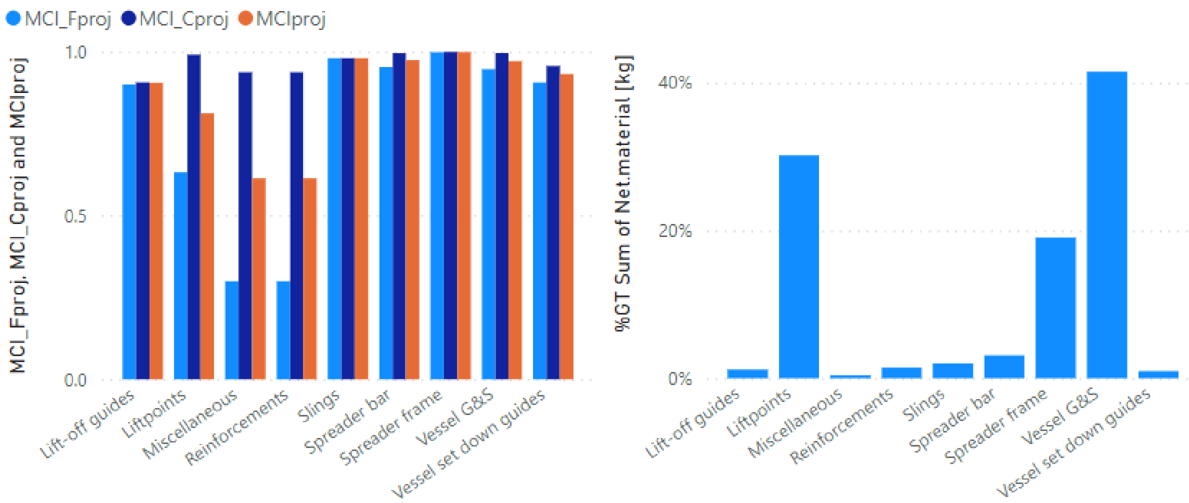
Mass flow of equipment in Dunlin Alpha decommissioning project

Product group	Pieces [#]	M [mT]	F_U [mT]	New ($V+F_R$) [mT]	C_U [mT]	C_R [mT]
			Fabricated steel			
Lift-off guides	8	14	-	14	-	14
Liftpoints	12	361	171	190	347	13
Miscellaneous	2	5	-	5	-	5
Reinforcements	7	17	-	17	-	17
Spreader bar	2	37	34	4	35	2
Spreader frame	1	228	227	1	227	1
Vessel G&S	14	495	458	38	471	25
Vessel set down guides	8	12	1	11	11	1
			Rigging			
Slings	2	25	24	0	24	0
Total	**54**	**1,169**	**890**	**280**	**1,091**	**78**

Note. With mass of product (M), mass of product feedstock from reused (F_U) and recycled sources (F_R), mass of material not from reuse or recycling (V), mass of material for reuse (C_U) and recycling (C_R) after use.

Figure 5.3

Material circularity indicators of Dunlin Alpha decommissioning project



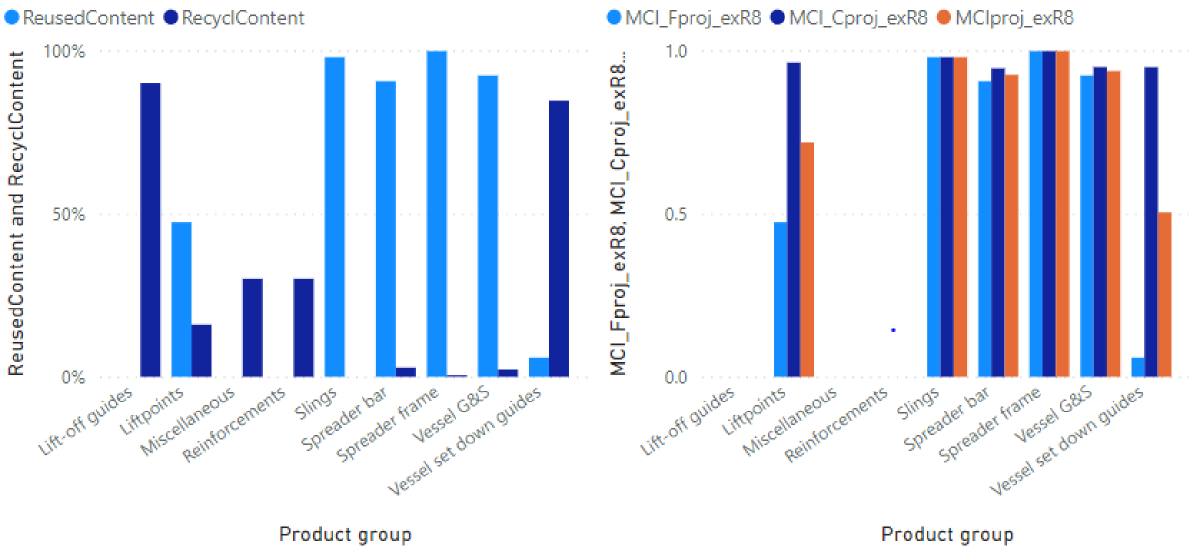
Note. Legend from left to right: material circularity of product types for feedstock ($MCI_{F,proj}$), outflow ($MCI_{C,proj}$), and total (MCI_{proj}) respectively (as in Eqs 3.10 to 3.5).

the expected MCI can be higher than the actual, if material is disposed before being reused. Further research could identify the influence of reuse potential, and the effect on product design. In this research this is one of the reasons why it is important to not only consider the project level, but also the life-cycle approach of the product level.

It can be seen that all product types in Figure 5.3 have an MCI above the 2030 target of 0.5. However, here

Figure 5.4

Influence of recycled content on material circularity indicators of Dunlin Alpha decommissioning project



Note. Left: reused and recycled content (new material only) of material feedstock per product type. Right: material circularity of feedstock ($MCI_{F,proj,exR8}$), post-use ($MCI_{C,proj,exR8}$), and total ($MCI_{proj,exR8}$), excluding recycling in the circular material flow.

only the project performance is shown, which does only cover one project or use cycle as part of the entire product life cycle. Sufficient MCI on the project level is a step in the right direction, but does not necessarily mean the product performs well enough on the product level.

Although the method is used for retrospective purposes, analyzing the results can support in improving the CE performance. At this point in the research, this is only based on the MCI and, as such, solely related to mass flow. What stands out for the most significant product types by mass, are the lift points — equaling approximately one third of total equipment weight (see Figure 5.3) — which under-perform compared to other significant equipment. The main reason are the lift points — apart from the modular support frame lift points — which are all made from new steel, and scrapped after use. There are multiple reasons why lift points are generally not reused, for instance: lift points are attached to structure when left behind at decommissioning yard, the customization required for these lift points, and challenges due to fatigue.

5.3. Economic value using life cycle costs

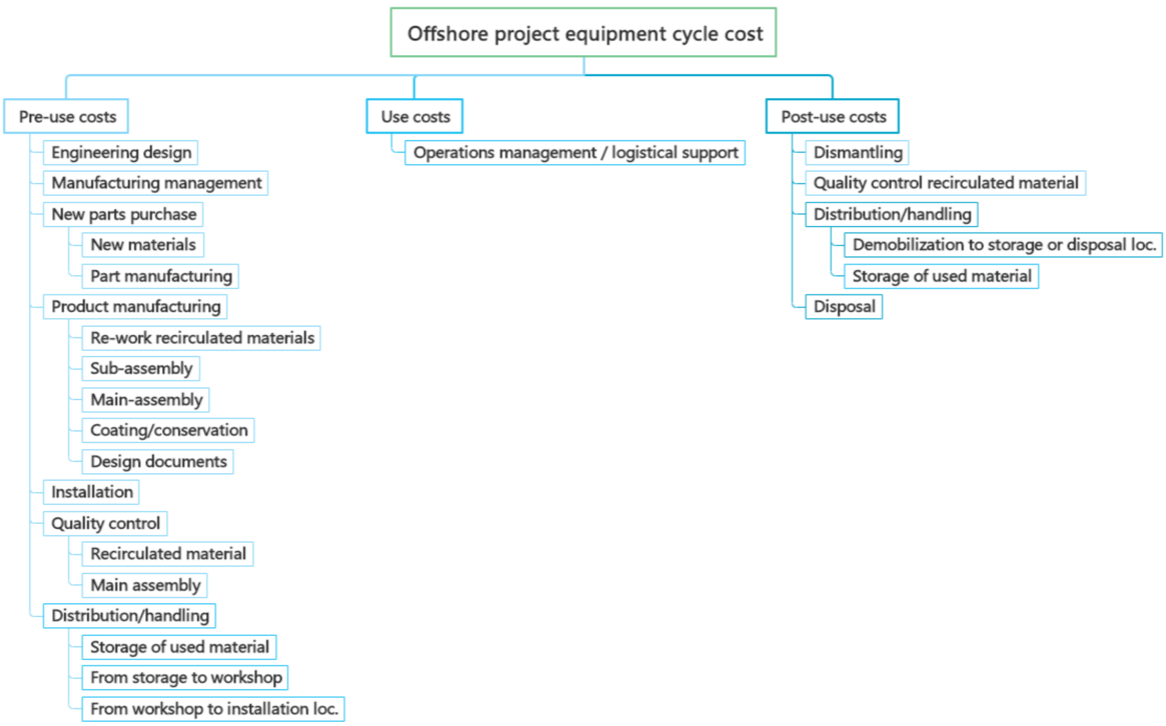
In this section, the following research question is covered: *How can the economic value of circular material flows be determined on the project level?* As input to the calculations, the life cycle costs specific to the case study are presented in Section 5.3.1. In the following section, the results are displayed and discussed.

5.3.1. Life cycle costs

In the modified CBS displayed in Figure 5.5, the life cycle costs of offshore project equipment are identified. The CBS is tailored to the Value Hill (from Achterberg et al., 2016), which is composed of three phases: pre-use, use, and post-use. In this section, the cost factors per phase are described. The costs factors of fabricated steel are listed in Table 5.3, including the equations for computing the circular and new alternatives. In Table 5.3, the factors different for the sling product group, compared to fabricated steel, are listed. For the circular alternative to be beneficial in terms of costs, the right-hand column of the tables should be positive, indicating that the benefits outweigh the burdens.

Figure 5.5

Cost breakdown structure of offshore equipment from case study



1. Pre-use phase

The pre-use phase covers all cost factors from engineering design to distribution and handling, as shown in Figure 3.4. The reasoning for each of the main levels (1.X) are covered in the following paragraphs. As slings are not designed nor manufactured by the offshore TIR contractor, the cost factors of 1.1. Engineering design and 1.2. Manufacturing management, equal zero for this product type.

1.1. Engineering design

The engineering cost of fabricated steel is based on the average hourly rate of an engineer times the hours spend on the design. From more than half of the designs (31 of 54) part of the case study project, the engineering hours are found in management data. This is on average 300 hours per design. From the remaining 23 designs, which represent a smaller share of total material mass (32%), this is set to a below-average value of 100 hours per design.

Based on their own experiences, engineers pointed out that it is highly likely that engineering hours, thus engineering cost, increase when used material is fed into the design (, pers. com., September 19, 2023). As no quantification could be given on this extent, an educated guess was made to increase engineering hours by 20% for designs with used material. A fixed number is used, independent of the fraction of used material, for simplicity reasons and because the effect could not be quantified in the first place.

1.2. Manufacturing management

Manufacturing management is included as a cost factor, but is set to zero. This is because the costs could not be identified. It remains there, because the management of resource, also during manufacturing, tends to require more labor if circular practices are enhanced. Therefore, it is considered a relevant cost factor to be included when comparing linear versus circular equipment.

1.3. New parts purchase

For fabricated steel, the new material purchase cost is included in the part manufacturing cost. This is because the assembler purchases pre-cut steel, which makes it a manufactured part. Through the years, this has evolved as the assembler experienced that cutting steel from new plates and beams, is more costly than ordering pre-cut steel. The part manufacturing cost is estimated as the material mass times a price factor which depends on the material type. These are listed in Appendix C, and increase from plates, to thin pipes, to thick pipes.

The material cost of new parts is based on price, which makes it sensitive for price changes. This sensitivity was evident as steel prices more than tripled in 2022, as a result of the Russo-Ukrainian war (as discussed in 5.1.2). Another factor influencing the steel price, which is less unpredictable, is the GHG pricing of the EU ETS. Although the influence of GHG pricing will not be analyzed, it is evident that this will increase the steel price, thus enlarging the cost benefit of using recirculated materials.

For the slings, the new material cost is also included in the part manufacturing cost. The parts purchase cost, is the cost of the entire sling when it is newly purchased.

1.4. Product manufacturing

The product manufacturing cost factor represents multiple steps in the fabrication process: re-work of recirculated materials, sub assembly, main assembly, coating and conservation, and design documentation. The re-work of used material is only present for the circular alternative, as it is a function of the amount of reused material. The cost is based on historic data from the HMC Steel Marketplace (see Appendix C).

The decision is made to split the assembly costs into sub assembly and main assembly. This is because sub assembly entails the preparation of new material, whereas main assemblage is performed for the combination of new and used material. The main assembly covers the fitting (i.e. positioning) of the components to be welded together. The case study clarified that no such data exists which specifies the assembly stages, so an educated guess is made to give sub assembly one-third of the total, and main assembly the remaining two-third.

The coating and conservation is set to zero for fabricated steel, but is present for slings. For fabricated steel coating and conservation cost does indeed exist, however, relevant cost data is only starting to be collected. As the cost is relatively low compared to other product manufacturing cost, it is set to zero for now. For slings, on the other hand, coating and conservation is the main cost when reusing slings. After a sling is used offshore, subjective to sea water, it has to be cleaned with freshwater and a new fat layer has to be applied before storing. This cost is in the order of magnitude 40 times smaller than purchase cost of a new sling, compared to storage cost which is approximately 3 times smaller than cleaning and coating cost.

Table 5.3

Life cycle cost factors of fabricated steel

Level	Cost factor	Variable	Eq. of new alternative ($E1_{v}$)	Eq. of circular alternative ($E1_{\sigma}$)	Benefit (+) / burden (-)
1.1	Engineering design	$E1_{ED}$	$= c_{eng} \cdot t_{eng}$	$= 120\% \cdot E1_{ED,\sigma}$	-
1.2	Manufacturing management	$E1_{MnfMng}$	$= 0$	$= 0$	=
1.3	New parts purchase	$E1_{Prt}$	$= E1_{PrtMnf}$	$= E1_{PrtMnf}$	+
1.3.1	New material		Included in $E1_{PrtMnf,v}$	Included in $E1_{PrtMnf,\sigma}$	N/A
1.3.2	Part manufacturing[a]	$E1_{PrtMnf}$	$= (V + F_R) \cdot c_{mat}(type)$	$= (V + F_R) \cdot c_{mat}(type)$	+
1.4	Product manufacturing	$E1_{PrdMnf}$	$= E1_{re} + + E1_{doc}$	$= E1_{re} + + E1_{doc}$	N/A
1.4.1	Re-work recirculated materials	$E1_{re}$	$= 0$	$= F_U \cdot c_{re}$	-
1.4.2	Sub-assembly[a]	$E1_{sub}$	$= (V + F_R) \cdot c_{sub}$	$= (V + F_R) \cdot c_{sub}$	+
1.4.3	Main-assembly	$E1_{main}$	$= F_U \cdot c_{main}$	$= F_U \cdot c_{main}$	-
1.4.4	Coating/conservation	$E1_{coat}$	$= 0$	$= 0$	=
1.4.5	Design documents	$E1_{doc}$	$= M \cdot c_{doc}$	$= M \cdot c_{doc}$	=
1.5	Installation	$E1_{Instal}$	$= 0$	$= 0$	=
1.6	Quality control	$E1_{QC}$	$= E1_{QC,main}$	$= E1_{QC,re} + E1_{QC,main}$	=
1.6.1	Recirculated material	$E1_{QC,re}$	$= 0$	$= 0$	=
1.6.2	Main assembly	$E1_{QC,main}$	$= 0$	$= 0$	=
1.7	Distribution/handling	$E1_{DiH}$	$= E1_{DiH,wi}$	$= \frac{1}{2}(E1_{Dmb} + E1_{store}) + E1_{DiH,sw} + E1_{DiH,wi}$	-
1.7.1	Demobilization to storage pre-use	$E1_{Dmb}$	$= 0$	$= \left(c_{Dmb} + \frac{1}{3}c_H\right) F_U$	-
1.7.2	Storage of used material	$E1_{store}$	$= 0$	$= c_{store} \cdot F_U \cdot t_{store}$	-
1.7.3	From storage to workshop	$E1_{DiH,sw}$	$= 0$	$= F_U \cdot \frac{1}{2}c_H$	-
1.7.4	From workshop to installation loc.	$E1_{DiH,wi}$	$= M \cdot \frac{1}{2}c_H$	$= M \cdot \frac{1}{2}c_H$	=
2.1	Operations management / logistical support	$E2_{OpsMng}$	$= 0$	$= 0$	=
3.1	Dismantling	$E3_{Dsm}$	$= 0$	$= 0$	-
3.2	Quality control recirculated material	$E3_{QC}$	$= 0$	$= c_{QC} \cdot F_U$	-
3.3	Distribution/handling	$E3_{DiH}$	$= E3_{Sc}$	$= \frac{1}{2}(E3_{Dmb} + E3_{store})$	-
3.3.1	Demob. to storage/disposal post-use	$E3_{Dmb}$	$= 0$	$= E1_{Dmb}$	-
3.3.2	Storage of used material	$E3_{store}$	$= 0$	$= E1_{store}$	-
3.4	Disposal	$E3_{Sc}$	$= (-1)c_{Sc} \cdot (M - C_U)$	$= 0$	-

Note. For the parameters used in the equations, see Appendix C.
For remaining variables, see Section 2.2.1.
[a] Based on new material, a combination of raw and recycled material: $M_{new} = V + F_R$.

Design documentation is a cost factor identified on the manufacturing invoice, but statistical data has not been retrieved from it. Therefore, for now, this is set to zero. However, the share of total manufacturing costs is limited.

1.5. Installation
The installation cost is set to zero both for fabricated steel as slings, as relevant data could not be found. As it still plays a crucial role in a transition to a CE, it is a cost factor to consider. Equipment which is easy to install and remove from a vessel or barge deck, will induce lower costs when brought back to storage. Next to this, it will result in a smoother (bottom) surface, which does not require repairs before reused.

1.6. Quality control
quality control (QC) of reused material and of the entire assembly, is now included in the product manufacturing cost. However, a split between QC of the reused material and inspection after assembly, could result in better understanding of the costs occurring. Quality control of the slings in use, is an ongoing procedure which is performed onboard the vessels. This yearly cost is divided as an average over all slings. It has to be noted that the inspection procedure for large slings stored at a subcontractor, and the smallest slings stored onboard the vessels, is somewhat different. But for simplicity reasons, the inspections onboard are used for all slings.

1.7. Distribution and handling
The distribution and handling performed in the pre-use phase, are changing when introducing CE practices. By recirculating materials, the need for storage and additional transportation arises. As these cost factors are generally higher for increased circulation, it is important to include these to show the extend of its influence.

One of the concerns within the company, are the effect of increased storage cost on the viability of circular practices. To include this cost factor, historical and current cost data is implemented. For the fabricated steel, storage cost is based on yearly average plot rental cost, divided by total stored mass. This is used as a cost per mass, equal for all fabricated steel. This assumption is not adequately representing reality, as storage cost is influenced by other factors — such as bottom surface area, stacking capability, and geometry. However, sufficient qualitative data on these factors is not readily available, which is a necessity for performing the case study. The storage of slings is outsourced to the manufacturer, for which the costs are based on the 2023 budget. Total storage cost is divided by the total number of times a sling is allocated to a project, in a year. This way, each allocated sling has equal storage cost.

The storage cost occurring between projects, is shared on a 50/50 basis. In reality, storage is out of project scope, and, therefore, managed by the equipment management of the company. However, to simplify the methodology, by refusing the introduction of cycles apart from the project cycle, storage is designated to the pre- and post-use project. The shared financial responsibility will also incentive a life cycle approach, which is deemed necessary when successfully applying the CE concept.

The handling of used materials from storage to the workshop, and from the workshop to the vessel or barge, is assigned to the project using these materials. This cost factor is present for recirculated material, which would otherwise be included in new purchased material. The handling of fabricated steel is based on yearly handling cost of all steel at the fabrication yard. This is split into three even parts: handling from stock to workshop, from workshop to installation on a barge or vessel, and from the barge or vessel to storage or scrapping. The total handling costs are divided by total handling by mass. For lifting and transportation, mass is deemed an appropriate unit. The handling of slings is based on yearly budget of the sling manufacturer, divided by allocation rate. Each sling, unrelated to mass or size, thereby induces the same handling cost. This is a rough simplification, as handling cost is indeed influenced by mass and size. As all significant and relevant cost factors of the pre-use phase are covered, the costs of the use phase are covered in the next section.

Use phase

As can be seen in Figure 5.5, the use phase only includes operational management and logistical support. The reason for this is that static equipment, as opposed to dynamic equipment, are used offshore without further operational expenses. A cost factor not included here is the conservation layer applied to slings, which is (partly) lost during the use in offshore conditions. As this is considered waste, it is added to disposal described in the next section.

Post-use phase

After the equipment is used offshore, the most important phase of enabling CE practices is entered. The post-use phase is where materials are recovered for potential use in future applications. The cost factors identified in the case study are: dismantling, quality control of recirculated materials, distribution and handling, and disposal. The first three are costs generally higher for increased recovery, whereas disposing steel comes with a scrap revenue. Below, each cost factor is described.

The dismantling of used equipment has a different consideration for fabricated steel as for slings. For now, the dismantling cost of fabricated steel is set to zero, as in most cases a product is dismantled before it is used for a new project. As such, it is covered by the re-work in the pre-use phase. For slings, it is assumed that they are either reused or disposed in one piece. In reality, the eye(s) of slings may dismantled and refurbished afterwards.

The inspection of used equipment is set to zero as it is covered in the quality control of recirculated material in the pre-use phase. In reality, however, the demobilized equipment is indeed inspected and assessed on recirculation potential. Although the cost of this procedure could not be identified, the cost factor is included to show its presence.

The distribution and handling is dealt with in the same way as for the pre-use phase. The demobilization and storage is, thus, also shared in a 50/50 approach with two adjacent projects. The demobilization of equipment to the storage location can have different shapes. In some cases, all equipment is loaded on a vessel or barge which was planned to go to the storage location. This does not induce any additional transportation costs. In other circumstances, which is often the case for steel which is attached to the decommissioning platform modules, the equipment ends up at a different yard. This induces additional transportation costs, for handling and barge rental, to get the equipment to the desired storage location or directly to the workshop for recirculation. In the case study, a worst-case scenario is adopted, and all recirculated material induces demobilization costs. These costs are based on a parameter, which is adapted from one example only as other information could not be collected (see Table C.1. As this is for a set voyage, and based on one example, the results are sensitive to this parameter.

As discussed in previous section, part of the disposal cost is the sling conservation layer (partly) wasted during the use phase. The fat applied to slings can be seen as an operation consumable, which should be added to the waste stream. This has been done for the slings, which after each project are cleaned from sea water and conserved with fat (2 mass%), to be stored afterwards. Part of this conservation layer is wasted into the sea during the project use, and should therefore be added to the waste stream (W_0/W_0') of the equipment within the project. The mass of this waste is equal to the weight of the conservation material, and the value of this waste is equal to the cost of the conservation.

5.3.2. Results

As the MCI' from Jiang et al. (2022), is enhanced by introducing additional life cycle costs, the improvement is shown in this section. In Table 5.4, the difference in costs included is shown, as well as the outcome for the MCI'. The original MCI' only includes the costs of parts to obtain E and r, whereas the enhanced MCI' uses additional life cycle costs (see Chapter 3). This leads to V' only consisting of the parts costs of new materials, resulting in the fraction of economic value feedstock from circular source MCI_F' being much higher for the original compared to the enhanced MCI'. As V' is highly underestimated in the original methodology, this leads to overly positive results in terms of the economic CE-performance.

For the waste or post-use side, the results are more similar. For the G&S used as an example, no material is wasted, so the material circularity post-use (MCI_C) equals 1. As the original MCI' is based on the cost of parts including handling costs, W' equals zero. For the enhanced MCI', including additional cost elements, there is some value W' wasted. These occur due to handling costs which are not included in the original MCI' method. Because there is indeed economic value wasted when additional cost elements are included, the enhanced method is more accurate.

Overall the MCI' of the original and enhanced method are different, mainly influenced by the underestimation of the economic value of virgin feedstock. This results in too positive results for the former method.

Starting with the project perspective for the fabricated steel, a comparison is made between the costs if all resources were new with the actual — partly circular — case (see Figure 5.6a). This results in the circular feedstock (MCI_F') and circular post-use (MCI_C') indicators, and MCI' of the project (see Figure 5.6b). The combination of steel types leads to an MCI' of 0.63. The greatest cost savings are achieved by the lift points, spreader frame and vessel G&S, leading to a cost saving for the project of at least \$2.5M.

Although substantial cost savings are made, there is still much to gain. This can also be seen in the circular feedstock indicator, which indicate a cost saving of 20% and 40% relative to the total economic value, for lift

Table 5.4

Dunlin A project costs of GR-011-01 – GR-011-04 grillage beams

Cost element	Original MCI' method [k$][a]	Enhanced MCI' method [k$]
Economic value of material input in total (E or E_ν)	366	892
Economic value of recirculated materials (r)	MAX(356, 157, 0)[b]	436
Economic value of linear feedstock (V' or E_σ)	6	457
Circular feedstock indicator (MCI'_F)	0.98	0.49
Economic value of unrecoverable waste (W')	0	15
Circular feedstock indicator (MCI'_C)	1.00	0.98
MCI'	**0.99**	**0.74**

[a] For computing the original MCI', as opposed to the methodology, no depreciation (or residual value) is accounted for.
[b] The maximum value of r is in the same order as in Eq. 3.2.

points and vessel G&S respectively. Essentially, 60-80% of the value has to be added to reach the economic value of the products.

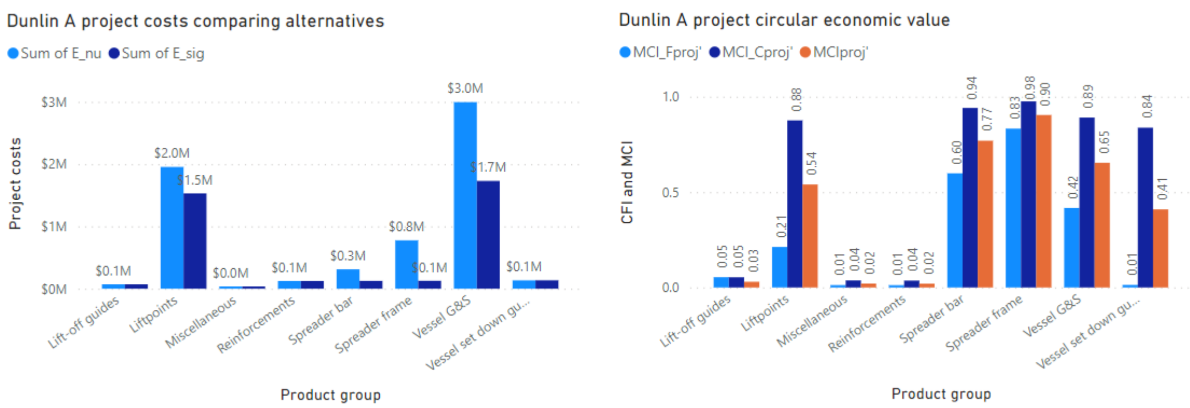
Looking at Figure 5.6b, it can be seen that for the vessel set-down guides, the feedstock indicator is negative. This means, that using recirculated resources resulted in higher project-cycle costs, compared to an all new alternative. The reason for this is that the refurbished set-down guide had relatively low weight, and consists of standard parts. If this is the case, it would be more cost effective to order new pre-cut parts, instead of refurbishing an existing piece.

To see how the costs of the new alternative and actual costs are build up, Figure 5.7 shows the cost breakdown. As can be seen in the breakdown, the savings of the actual — partly circular — outcome mainly arise because of the prevented costs for new parts. However, as is most significant for the vessel G&S, there are also substantial savings due to prevented product manufacturing costs. These arise due to the prevention of main-assembly costs which are existent in the case of all new or remanufacturing, but not when refurbishing. This difference is seen as G&S is mostly refurbished, whereas lift points are, in this case, remanufactured. As refurbishing takes a narrower loop than remanufacturing, the benefit of a narrow loop in terms of assembly costs is clear.

As said, the main cost savings comparing the new and circular alternatives, are due to the prevented costs

Figure 5.6

Dunlin A project costs for fabricated steel

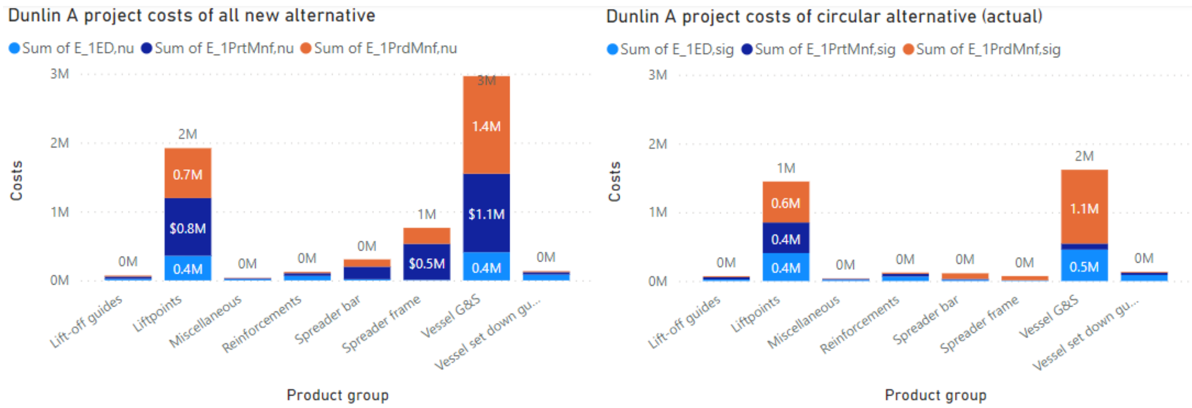


(a) *New (E_ν) and actual (E_σ) project costs* **(b)** *Economic indicators of project*

Note. Left: absolute project costs. Right: economic indicators — circular feedstock indicator (MCI_F), circular post-use indicator (MCI_C), and 50/50 combination (MCI').

Figure 5.7

Dunlin A project cost breakdown of new alternative (left) and actual (right)



Note. Legend from left to right: engineering design, part manufacturing (incl. material purchase), product manufacturing (incl. re-work (actual only), assembly, coating conservation, and design documentation).

of new steel parts (see Figure 5.7). As described in Section 5.3.1, these costs are based on current steel prices and are, therefore, sensitive to price changes. Two examples have been discussed as steel price changers: the over-triple surge due to the Russo-Ukrainian war in 2022, and the expected rise due to the EU ETS. As the main cost savings are based on steel part costs, the benefit of circular practices will increase with rising steel prices. With the EU ETS bridging the environmental and economic pillars of sustainability, the benefit of these will grow for rising GHG price in the future.

5.4. Aggregation from project level to product level

In this section, the following research question will be answered: *How can the project level be aggregated to the product level?* To show the result of the aggregation from the project level to the product level, a piece of equipment used in multiple projects is used as an example. These are a transport frame and a sling, which were also used by the aforementioned project. For both pieces of equipment, the material circularity, utility factor, and economic value is given, as evolving with every project use. The first project cycles in the case study represents the actual mass flows and derived cost flows of the projects. In reality, both the transport frame and sling are still in use. To show the influence of discarding the products, the decision is made to recycle the steel products after the last project cycle.

5.4.1. Transport frame

The transport frame — which is often called 'grillage' or in combination with sea fastening grillage and sea fastening (G&S) — is chosen because G&S is made in great quantities. As seen in Figure 5.8a, as example, the grillage beams are used to support a structure, and transfer the transport loads from the structure to the vessel or barge deck. Although increasingly G&S is made from recirculated materials and recovered after use, a part of G&S is still treated as consumable resource. Therefore, measuring the CE-performance of such project equipment, is beneficial for the entire company to support in setting targets and ultimately reduce resource use.

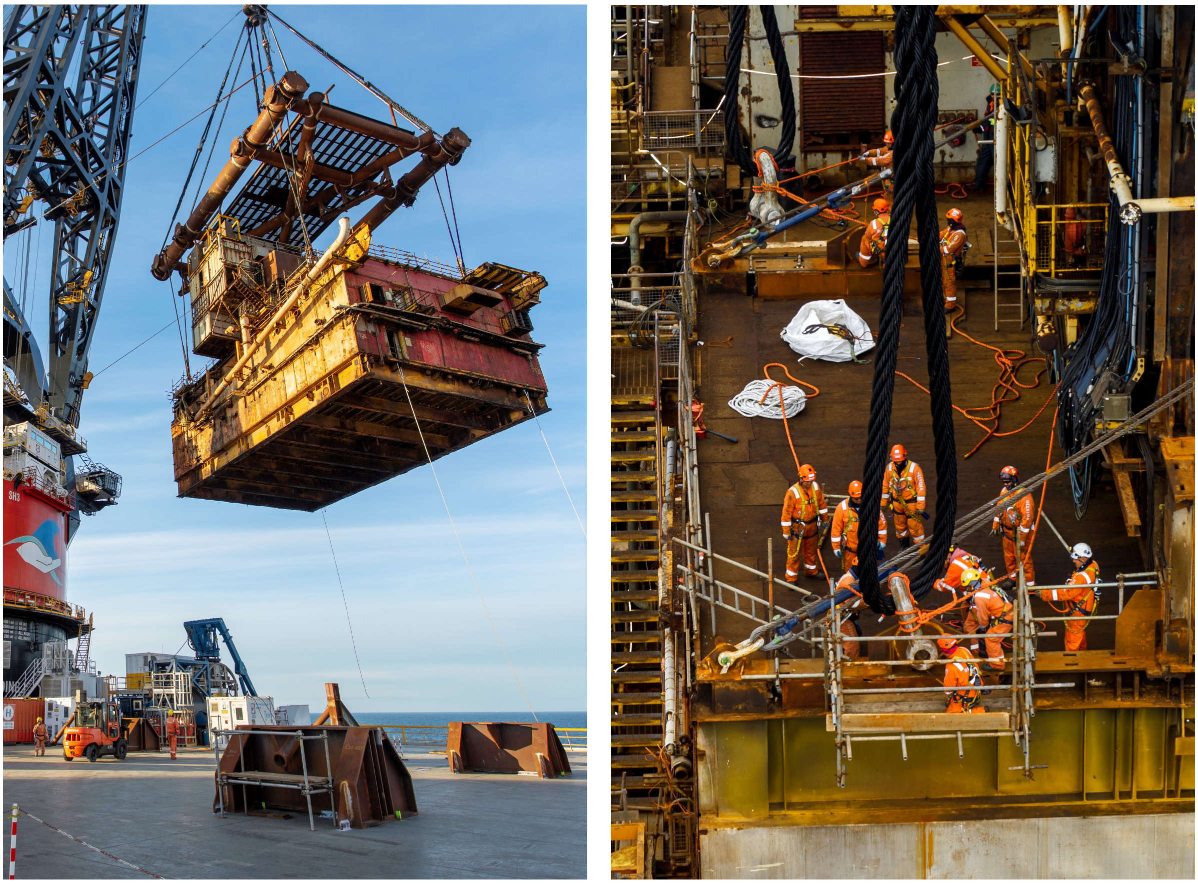
The specific grillage beams are chosen, because a review of the chosen project showed that these were the most costly to modify out of all fabrication scopes. Therefore, these assets are followed through other projects. The specifications of the grillage beams are given in Table 5.5.

As can be seen in Table 5.6, the MCI and MCI' evolve over the lifetime of the grillage beam. This is a result of modifications made by the project to the product mass, and costs spent on the product. First, the results of the MCI will be discussed, and thereafter the MCI'.

The MCI is increasing through the project cycles, which is mostly affected by the utility factor (X). Namely, through the projects, the product mass is increasing by adding virgin material, for which the modifications made per project are comparable. This results in the linear flow index (LFI) to remain constant, up until the last project

Figure 5.8

Examples of grillage beams and a sling (photos courtesy of HMC, pers. comm., December 13, 2023)



(a) *Grillage beams on deck* **(b)** *Sling*

Table 5.5

Specifications of GR-011-01 to GR-011-04 grillage beams, and SL8379 cable laid sling

Specification	GR-011	SL8379	Unit
Product family	Static equipment	Static equipment	
Product group	Steel	Rigging	
Product type	Grillage beam	Sling cable laid	
Materials	HSS, welds	HSS, fat (2 w%)	
Mass (last project)	324.000*	14.091	mT
Workload limit	N/A	700	mT
Length	10.550	63.2	m
Width	3.000	unknown	m
Height	3.525	unknown	m
Virgin content	70%	71%	w%
Recycled content	30%	29%	w%
Number of times allocated to project	5	6	#
Average mass added per project modification	Steel: 12.8 / 3.9%	Fat: 0.3 / 2%	mT / w%
Purchase cost (new)	975	40	k$

[a] Mass of the set of 4 grillage beams.

Table 5.6

Aggregation of projects for a grillage beam

Project cycle [#]	L [yr.]	U [#/yr.]	X [-]	LFI [-]	LFI' [-]	MCI [-]	MCI' [-]
1	0.9	1.1	0.38	0.36	0.5	0.06	0.00
2	1.6	1.3	0.81	0.36	0.5	0.55	0.38
3	2.4	1.2	1.12	0.36	0.51	0.68	0.54
4	3.8	1.1	1.62	0.36	0.51	0.78	0.69
5	5.4	0.9	1.89	0.38	0.71	0.80	0.62

Note. With life time (L), intensity of use (U), and utility (X) as in Eq. 4.8. See Table 5.1 for company average utility factors. And Linear Flow Index (LFI), LFI with economic value (LFI'), Material Circularity Indicator (MCI), and MCI with economic value (MCI').

cycle where, theoretically (in real life the beam is kept in use), the entire beam is recycled. The LFI increases because of the recycling efficiency being 91-92% for steel (see Section 5.1.2), thus resulting in unrecoverable waste. As the LFI is almost constant over the lifetime, the MCI changes mostly influenced by the changing utility X. The use intensity (U) varies around 1 (meaning one project use per year), so X is mostly influenced by the increasing lifetime L. As can be seen from the results, if the use intensity remains constant, the MCI will increase for increasing lifetime. In this way, the product is rewarded for being durable and usable for multiple products.

Also the MCI' is increasing through the project cycles, apart from the last cycle where the grillage beam is recycled. As no significant changes are made to the product, also the linear flow index (LFI') does not change during the lifetime. Only at EoL when economic value is wasted by recycling the product, despite some scrap revenue collected. The increase in LFI' leads to a decrease in MCI', however, this effect is minimized by the increasing utility X. Which, in turn, is a result of increasing life time L.

The Dutch government has the goal to use 50% fewer primary materials by 2030, with the ultimate target of a waste free economy by 2050 (Government of The Netherlands, n.d.). These targets can be translated to an MCI of 0.5 in 2030, and an MCI of 1.0 in 2050. For the grillage beam, the 2030 target is met after two project use cycles. With an actual use cycle count of 5, the grillage beam reaches an MCI of 0.80. This is above average and meets the target. If the same target would be set for the MCI', this would be reached after 3 project use cycles. However, here the economic value wasted when recycling is not included, which would reduce the LFI' by approximately factor 0.2 (see difference between cycle 4 and 5). Considering an LFI' of 0.71, this would lead to an MCI' of 0.56 after the 4th project cycle. So, in this case, 4 project use cycles are needed to reach the target.

5.4.2. Sling

The sling was chosen arbitrarily, as a sling used by the project, being not too old, and of average size and mass. An example sling used to lift a module is given in Figure 5.8b, which shows the size and handling issues of the high mass. In Table 5.5, the specifications of the sling are given. Although the sling itself has a relative low mass compared to the grillage beam, considering that the offshore contractor has roughly 2,000 active slings and grommets (continuous round sling without eyes) still means high total volume.

For the slings, the evolution of the MCI shows a slightly different pattern (see Table 5.7). Starting with the utility X it is clear that this increases, mostly due to the increasing lifetime. From cycle 4 to 5, the sling is used in two consecutive projects within one month, which leads an increase in utility mainly because of the increased use intensity. Now discussing the material flows, expressed by the LFI. For the refurbishment of slings, after every project use and before storing, the slings are cleaned from seawater and fat is applied. This fat goes to waste and has to be added after each project use. As the total mass of the sling remains the same, one can see this in the increasing LFI. This refurbishment is a cost which is not retained after project use, so this value wasted similarly increases LFI'.

Now the MCI is expressed as a combination of the utility and LFI. Because of the relatively low utility at the first use cycles, the MCI and MCI' remain low or even bound by zero. One can see that the MCI reaches the 0.50 target after 4 use cycles. This does not include the recycling of the sling at EoL, and because of steel recycling, this will only reduce the MCI by approximately 0.03 (due to waste from the recycling post-use). A target of 0.50 for the MCI' is reached after 5 project cycles. However, as the economic value wasted due to recycling at EoL

Table 5.7

Aggregation of projects for a cable laid sling

Project cycle [#]	L [yr.]	U [#/yr.]	X [-]	LFI [-]	LFI' [-]	MCI [-]	MCI' [-]
1	0.8	1.3	0.2	0.37	0.51	0.00	0.00
2	2.3	0.9	0.5	0.38	0.54	0.22	0.00
3	3.8	0.8	0.7	0.39	0.56	0.46	0.24
4	4.4	0.9	1.0	0.41	0.58	0.58	0.41
5	4.5	1.1	1.2	0.42	0.60	0.66	0.51
6	5.5	1.1	1.5	0.45	0.88	0.69	0.40

Note. With life time (L), intensity of use (U), and utility (X) as in Eq. 4.8. See Table 5.1 for company average utility factors. And Linear Flow Index (LFI), LFI with economic value (LFI'), Material Circularity Indicator (MCI), and MCI with economic value (MCI').

is not included, this would increase the LFI' by approximately 0.2. For an LFI' as high as 0.8 (= 0.62 + 0.2), a utility X of 1.7 is needed to reach an MCI' of at least 0.5. Considering a use intensity of 1 — which is already 2 times higher than company average — a lifetime of 7 years is required.

For slings with a company average use intensity, a lifetime of 33 years is needed to reach an MCI' of 0.5. Which does not seem realistic for existing slings. The main reason for the MCI' being low, is that slings are made from all new material. Although slings are made from almost 30% recycled steel, refurbishment of slings comes with a significant cost. Therefore, to increase the MCI' of slings, the refurbishment cost should be prevented or reduced. Now, slings need to be refurbished after each project, which is comparable (in extreme sense) to your phone needing a software update after each phone call. A way to solve this, is to make sure the resource loop is narrowed from R7 refurbish to reuse (R3). Slings with, for instance, a permanent coating, would not require refurbishment after each project use.

5.5. Aggregation to company level

In this section, the following research question will be answered: *How can the project or product level be aggregated to the company level?* This covers two parts: aggregating from the lower project level directly to the company level, and from the product level to the next company level. During the research it became apparent that translating from the project to the company level directly, is a less adequate representation of the CE. Namely, it does not include the important aspect of slowing resource loops (R-loops), covered in the MCI and MCI' as utility. Although it may be interesting to show the results of combining projects into the company level, it would require multiple projects to be analyzed. Due to the scope of this research, this is not performed. As this part is not included, only the results of aggregating from the product to the company level are discussed here.

To work from the product to the company level, the two pieces of equipment used in the case are aggregated. This is done using a mass- and cost-weighted average, as explained in Section 4.2.3. Instead of counting both the grillage beam and sling once, which would lead to an unfair comparison, the products are scaled to better represent the company level. This is done based on the case project, which is assumed to represent an average project within the company. As such, the scaled representation should approach the company perspective.

In order to carry out this scaling, the total mass per product group present in the case project is divided by the mass of the case product in that product group. For example, the total mass of G&S in the case project is twice the mass of specific asset GR-011. Therefore, asset GR-011 is counted twice when taking the weighted average with the sling. The scaling factors are shown in Table 5.8.

After the scaling, the weight factors are determined, as seen in Table 5.8. These weight factors are used in calculating the total MCI and MCI' based on a weighted average. The results show that the company level MCI and MCI', indicating a material circularity and economic value circulation including utility, of at least 0.6. An MCI' of 0.60 means there is room for improvement to turn the 40% linear or wasted costs into circular or regenerated costs.

Table 4.2.3 shows that both the mass-based and economic value based weight factors are higher for the G&S compared to the slings, due to the higher total mass and economic value, respectively. As a result, the total MCI and MCI' is closer to the values of the G&S than to the slings. This difference is even more profound for the

Table 5.8

Aggregation of product level to company level

Asset no.	Product group	Scaling factor [-][a]	M_T [mT]	$E_{v,T}$ [k\$]	MCI [-]	MCI' [-]	w_p [-]	w'_p [-]
GR-011	G&S	2	726	7,615	0.80	0.62	0.72	0.89
SL8379	Sling	18	279	894	0.69	0.40	0.28	0.11
Total			1,005	8,509	0.77	0.60		

Note. The values (apart from the scaling factor itself) include the scaling factorization. With total mass used in the product for all modifications steps combined (M_T), total economic value of virgin alternative ($E_{v,T}$), Material Circularity Indicator (MCI), Material Circularity Indicator based on economic value (MCI'), product weight factor based on mass (w_p) and on economic value (w'_p).
[a] The mass-based scaling factor is derived from project Dunlin Alpha.

economic value, forcing the overall MCI' towards the MCI' of the G&S. As this representation approaches the company level, this means that G&S has a higher influence on the CE performance at the company level compared to slings.

Based on the methodology of the weighted average, two factors are influencing the CE performance at the company level: the MCI and MCI' at the product level, and the weight factors. For a company it would, therefore, be good practice to evaluate these two factors for all product groups, on the basis of which measures can be taken to improve the CE performance at the company level. As seen in Table 5.8, the case study shows that the slings underperform in terms of MCI and MCI' relative to G&S, which could lead to a focus on improving the CE performance of slings. However, the weight factors of slings are significantly lower than G&S, which means that efforts on improving the CE performance of slings are less influential to the company performance. Thus, the weight factor can be seen as a multiplication effect on the efforts to improve the CE performance at the company level. Therefore, it is recommended to start by improving the CE performance of the product groups with the highest weight factors, as these efforts are of greatest impact.

Looking at the figures in Appendix B, it is shown that the total mass of fabricated steel per year is significantly higher than the total mass of commissioned dynamic equipment. This indicates that the mass-based weight factor for the fabricated steel is greater than for dynamic equipment, which would mean a focus on improving the CE performance of fabricated steel. The fabricated steel is also the product group for which it may be less difficult to improve the CE performance, as the design and manufacturing is managed by the offshore contractor. A focus made on the cost-based weight factor could not be given, as information regarding the total costs of fabricated steel and dynamic equipment is not available. It is suggested to collect this information before selecting a focus are, as both weight factors are part of the selection criteria.

5.6. Material circularity versus economic value performance

The results in this section will answer the research question: *How do the material circularity and economic value performance compare for the case of offshore project equipment?*

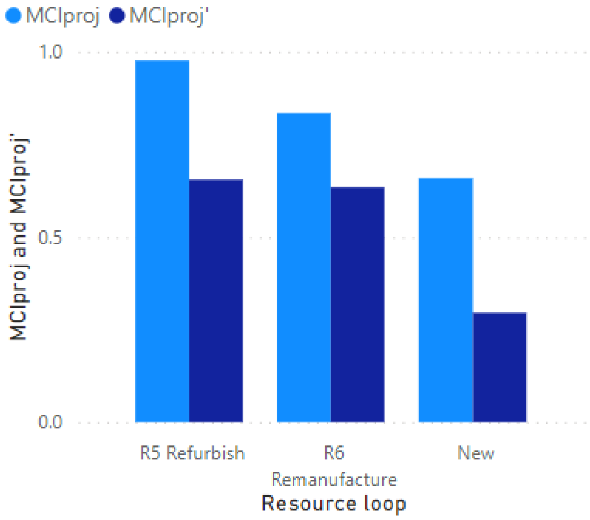
5.6.1. Project-level performance

In Figure 5.9 the MCI and MCI' are compared for various R-loops. These R-loops correspond to the circular strategy pre-use, so have no relation with what happens to the product after the project. It is clear that for any resource loop, the economic is lower than the material circularity performance. As the MCI is an index of material in- and outflow, the reasons arise from these two parts. On the inflow side, feedstock from recirculated materials may be high, the costs of the circular option (E_σ) are still high compared to an all new alternative (E_v). For the "new" resource loop, the average recycled content may be around 50%, the only savings are made by the economic value of the recycled content. As the latter is equal to the scrap revenue, this is a fraction of the total cost.

On the outflow side, the difference between the material and economic performance post-use is not as pervasive as pre-use. The reason for this is that most economic value is captured by high recovery rates. Most significant loss of economic value is due to the recycling of material, for which the value wasted equals the

Figure 5.9

Material Circularity Indicators with mass and economic value for fabricated steel used in Dunlin Alpha project



Note. With Material Circularity Indicator of project (MCI_{proj}) and Material Circularity Indicator based on economic value (MCI') of project (MCI'_proj). And resource loops R5 and R6 corresponding to 9R framework of PBL (2017a). New steel does contain varying fractions of recycled content, see Table 5.1.

embedded value minus scrap revenue. This leads to the conclusion that recycling contributes to a higher material circularity, it is not as favorable in terms of economic value.

Something else to consider from Figure 5.9, is that the difference between the MCI' of R5 Refurbish and R6 Remanufacture, is small. As noted at the beginning of this section, the R-loops correspond to the circular strategy pre-use. In this case, more materials of the remanufactured products where saved compared to the refurbished products. Meaning, for products manufactured following a narrower resource loop, a wider loop was taken after use. This resulted in less economic value captured for refurbished compared to remanufactured products, reducing the overall MCI'. One of the reasons for this could be that because higher investments where made for the remanufactured compared to refurbished products, the desire to keep these products for reuse is higher. Another possible reason, is that the refurbishments of the other products where too project specific, reducing the potential of reuse in the future.

5.6.2. Product-level performance

The MCI and MCI' are compared at the product level, for the grillage beams and sling (see Tables 5.6 and 5.7). It is clear that the MCI' is lower than the MCI for both the grillage beams and sling. As both the MCI and MCI' include the same utility factor, the reason for the difference lays in the linear flow index (LFI / LFI'). For the grillage beam, as for the project level described in the previous section, most costs arise due to new material used and value lost in recycling post-use. In order to increase the recirculation of economic value, it is vital to keep the materials within the company. The feeling is that transportation and storage costs are high, limiting the incentive for recirculating resources within the company. In contrary, the results show that design and manufacturing are the most significant cost factors, favoring a circular approach.

Although the MCI and MCI' at the product level are different, both are influenced by the same utility factor. Therefore, both parts of the CE performance at the product level favor an increase in utility. As this time factor is seen as a vital part of the CE concept its goal to slow resource use, this should get additional attention. This case study in an offshore contractor saw a focus on life time as part of utility. However, the equipment intensity of use was not analyzed. Therefore, the suggestion is to further review the benefit of intensifying the use of resources. The case study found that various types of slings have different intensities of use associated. For instance, cable laid grommets have a use intensity almost three times lower than cable laid slings. This means that grommets are idle more, leading to higher load on storage costs. If it would be known that grommets are more expensive to posses, the decisions of engineering and procurement departments could be instructed accordingly.

5.6.3. Company-level performance

The results of the aggregation to the company level are seen in Table 5.8. As the MCI' underperforms the MCI at the product level, this holds when aggregating to the company level. However, as products are combined, the difference becomes less profound. Where the MCI and MCI' for the individual products differ 0.2 to 0.3, the difference at the company level is 0.17 (see Table 5.8).

The CE performance at the company level is what matters for organizations to improve their overall use of resources. As seen, by taking a bottom-up approach, insights are provided in the performance of equipment at the project level and product level. These are the levels where changes are made, and scatter its effects into the company. As noted in Section 5.5, the first step for companies to improve their CE performance, could be to identify the weight factors of all product groups in terms of mass and economic value. The higher the weight factor, the higher the influence of the product on the company performance. A good example is the significant weight in terms of mass and costs of lift points (see Figures 5.3 and 5.6a, respectively). As most lift points are not recovered, this results in low material circularity and economic value recirculation. Changing the approach to lift point management, both in engineering and in resource management, will be beneficial for the CE performance of the company. Next to this, a life cycle approach is shown to be promising in identifying all relevant life cycle costs. Such holistic view is deemed necessary to provide adequate evaluation of project equipment in a CE.

Another way to improve the recirculation of resources, is to minimize consumables and force equipment to become assets. Because of the nature of both approaches, the fact that equipment is an asset, results in it to be managed in a more circular way. From that moment onward, the product management is more focused from a life cycle perspective. Which, in turn, results in better understanding of the life cycle modifications and life cycle costs. For assets, it is important to analyze the intensity of use, to eventually improve the utility and slow the use of resources (as discussed in Section 5.6.2). All of the aforementioned goes hand in hand with the more obvious aspects of implementing the CE concept, such as increased recirculated material use in design and design for recirculation.

6
Discussion

6.1. Scientific contribution to the field of circular economy metrics

This research uncovers the importance of including both the material circularity and economic valuation when determining the circular performance of project equipment on a project, product, and company level. By adapting a method for the circular economy (CE) both sensu stricto and sensu lato, improvements are made in covering the present definition of a CE. Instead of coupling the material circularity (unit mass) with the economic valuation (cost-based) — as proposed in the Material Circularity Indicator (MCI) (EMF et al., 2019) and applied in the Product-level Circularity Metric (PCM) (Linder et al., 2017) — the measurement units are used separately (similar to the Circularity Calculator (CC); de Pauw et al., 2022). As argued by Jiang et al. (2022), the MCI and Material Circularity Indicator based on economic value (MCI') are proven to be useful parallel methods, since the fundamentals are equal. This research draws similar conclusions specific to project equipment, as relevant for project-oriented organizations. Finally, building on the product level in the original MCI', this study evaluates three levels: the project, product, and company level.

A more accurate estimation of economic value in the MCI' is achieved by incorporating the most important and significant life cycle costs. In the original MCI' costs are predominantly based on material and parts costs, whereas the enhanced method includes production and transportation costs to a greater extend. In the PCM (Linder et al., 2017), production and transportation costs are indeed included but only cover a single modification cycle. In the CC (de Pauw et al., 2022), production costs are included, but transportation costs are missing. By taking a life cycle approach including multiple use and/or modification cycles, the enhanced MCI' is proven promising in describing the economic performance of project equipment.

The results show that the economic performance when measured by the enhanced MCI', lacks behind the material circularity represented by the MCI. This trend is the same when reviewing the material feedstock and outflow of material separately. This means that relatively less cost is saved than recirculated material is used, and that more economic value is lost than material is recovered. Since the CE performance based on mass outperforms the performance based on economic value, the latter is required as additional indicator to encourage adopting the CE concept, as concluded by Jiang et al. (2022) after analyzing building components.

6.2. Limitations and recommendations for further research

In this section, the limitations of the proposed method are discussed. Based on this, recommendations for further research are made.

6.2.1. Limitations

The limitations of the method used in this research arise because of different reasons. They originate from:

- the adopted models, such as the MCI and MCI', and still influential;
- the enhanced method of the MCI' based on life cycle costs;
- the aggregation method from project to product;
- the implications of the case study

Adopted models

One of the limitations of the MCI, identified by the original authors, is that it does not favor resource loops. That is, the performance is not graded higher for narrower loops. This limitations remains, but by comparing the MCI with the MCI', the problem is less vital. Namely, as the MCI' is based on economic value, it shows the advantage of closer resource loops resulting from avoided production steps. This effect is confirmed in the results, as presented in Figure 5.6. Furthermore, the results show that although the MCI does not include a higher grading for closer loops, naturally closer loops require less virgin materials and, therefore, have a higher MCI value.

Another limitation of the methodology is that the introduction of a stock on the project level changes the MCI from having a retrospective to a prospective perspective. As explained in Section 2.2.4, the material which is stored after project demobilization is allocated to the material flow for reuse. However, a later decision can be made to recirculate the piece only partially or — worse, in terms of energy recovery — recycle or recover the entire piece in a wide resource loop. To support the greatest potential of keeping equipment in stock, this circular material flow is positively weighing in the MCI. It should be understood that this gives the MCI at the project level a prospective perspective (as discussed in Section 2.1.1, #4 - Perspective). This is one of the reasons why it is important to also evaluate the MCI at the product level, taking a life-cycle approach.

MCI' based on life cycle costs

Although the enhanced method does include additional life cycle costs, it does not include the full life cycle costing concept. In that case, the present value would be adjusted by a discount rate, inflation rate, and escalation rate of materials. Including this would create a more accurate estimation of the economic value of the products at various moments in its life cycle.

Aggregation method from project to product

The aggregation from project to product uses the methodology of the MCI covering multiple production steps. A downside of this bottom-up approach is that it requires every modification step to be evaluated. This results in a relatively time-extensive procedure, which could endanger the applicability of the method. In terms of data availability, this has limitations on the retro- and prospective application of the indicator. For the historical data, it may be that not every modification step is adequately documented, both in terms of material mass as value flow. For the collection of data in the future, and for prospective purposes, the question is whether this approach is preferred. If this is not the case, a solution for both retro- and prospective data collection is to estimate the modification outcome. If so, it is strongly recommended to consult some cases, as following the proposed bottom-up aggregation method. This way, the implications of actual modifications to the product CE performance can be better comprehended.

Implications of the case study

The cost data used in the case study was based partially on actual data and partly on a parametric study. Especially for the manufacturing costs in the pre-use phase branch of the cost breakdown structure, the results are sensitive to changes. The manufacturing costs would, for instance, follow a different trend if the piece of equipment would have a less-standard design. As the manufacturing costs often cover the highest share of total costs, it is important to collect more and valuable data. By expanding the knowledge base of manufacturing costs, the advantages of the CE are expected to expand.

6.2.2. Recommendations for further research

Further research could enhance the MCI' by including the present value techniques of life cycle costing. Especially when using the MCI' for prospective purposes, these techniques will provide a more adequate value representation for the future.

Furthermore, the methodology could be further expanded by including a social and environmental evaluation. As these are on of the three pillars of sustainability, this should be part of a well-established CE framework. It is proposed to build on top of the MCI and MCI' methods instead of creating new ones, as others mentioned to be key for a transitioning concept like the CE (EMF et al., 2019; Edgerton et al., 2018 Jiang et al., 2022). A similar path as from the MCI to the MCI' could be taken, if so including social and environmental factors. Subsequently, the description of these factors can be improved in an iterative way. For which this research serves as an example, where the MCI' methodology is enhanced by including additional life cycle cost factors.

7 Conclusion

7.1. Introduction

The goal of this thesis was to develop a methodology to measure the circular economy (CE) performance of project equipment on multiple micro CE levels, as a step for project-oriented organizations to improve their CE performance.

The aim of a CE is to transform the linear take-make-waste economy into an economy where resource flows are closed, slowed, and narrowed (Bocken et al., 2016), requiring less raw materials, generating less waste, and resulting in fewer emissions and pollution (EPRS, n.d.). In a CE, the sustainable value — social, environmental, and economic — of materials is maintained at the highest level achievable during the three Value Hill phases (Achterberg et al., 2016). In the pre-use phase this is reached by using low fractions of raw material and high fractions of used material in manufacturing, in the use phase by lifetime extension and high intensity of use, and finally in the post-use phase by high recovery rates with the most narrow resource loop. As organizations and governments realize to a greater extent that maintaining sustainable value can have benefits for them, practices and studies in the field of CE are rapidly evolving. One of the companies which is at the initial phase of incorporating the CE concept into daily practices is the project-oriented organization, which experiences difficulties in doing so because of the strong project focus. A way forward is to meet the three levels of managing projects — single projects, project landscapes, and the organization — by evaluating the CE performance on the product, project, and company level. The first step in improving CE performance is to set targets, which are preceded by defining a measurement framework.

Based on a literature study into the definition of the CE concept, the decision was made to include material circularity and cost-based economic value as metrics for the CE sensu stricto and sensu lato, respectively. Creating a retro- and prospective indication of the CE performance on both circularity and economic value, is deemed a valuable communicator for accelerating CE practices. To create a scope which is able to capture the entirety of the research goal, without over including too many variables, the research focuses on project equipment specifically. This is formulated by the following main research question:

How to measure the material circularity and cost-based economic value of circular material flows from project equipment on a project, product, and company level?

In the following sections, the answers to this question are discussed. In Section 7.2, the main conclusions are drawn first. Thereafter, in Sections 7.3.1 to 7.3.4, the sub-research questions are answered.

7.2. Main conclusions

The main conclusions are summarized as follows, before these will be discussed in greater detail in the next section. In the quest to find a suitable metric to measure the CE performance of project equipment, the Material Circularity Indicator (MCI) and Material Circularity Indicator based on economic value (MCI') are found to be promising applications. The former is used to describe the material circularity and the latter for economic value. No indicator was found suitable to cover both aspects in one metric, but the study showed that using both indicators in parallel satisfies. Both the MCI and MCI' are used to describe the CE performance at three levels — the project, product, and company level —, and the weighted sum is used to translate bottom-up. At the project level, both MCI and MCI' showed to increase for narrower resource loops (R-loops), which confirms the expected benefits of the CE concept.

By focusing on the project level, however, a vital element of the CE concept, being the slowing of resource flows, is missed. Therefore, it is deemed necessary to take a wider life cycle perspective, which is found at the product level. By aggregating from the project to the product level, a data-driven approach provides detailed quantification of the modifications in the product life cycle. The product level does indeed include slowing of resource flows, by a utility factor in the MCI and MCI'. As identified in the study, a vital part of utility is the intensity of use of project equipment, which is found to receive too little attention in equipment management.

When comparing the MCI and MCI', it is clear that the MCI' underperforms the MCI at various levels, for various product types. This highlights the importance of measuring and indicating both the material circularity and economic value performance when evaluating CE performance.

7.3. Findings leading to the main conclusions

To elaborate on the main conclusions drawn in the previous section, the conclusions from the research question are explained in the following sections. These are described in order of appearance as listed in the introduction, and covered in the methodology and case study.

7.3.1. Sub-research question A

The first sub-research question, addressed in Chapter 2, covers the measurement of material circularity of project equipment on a project level:

How can the material circularity of circular material flows be determined on the project level?

For the evaluation of material circularity at the project level, the MCI was found best for purpose for multiple reasons: it covers the pre-use, use, and post use phase; the slowing of R-loops is included by a utility factor, and a similar setup for the MCI' allows for fair comparison between material circularity and economic value. The research showed that the MCI can be used to describe the project level, by formulating the project as one use cycle, and excluding the utility.

Starting with describing material circularity at the project level allows for a bottom-up aggregation to the product and company level, as it evaluates products on the level of project-specific modifications. This data-driven approach will, therefore, allow for improvements targeting the lower project level. Furthermore, the project level is of great interest for the project-oriented organization, as it is one of the key management levels.

On the other hand, it is shown that measuring material circularity at the project level focuses on one use cycle, instead of taking a whole life cycle approach. As a result, the product utility — consisting of lifetime and intensity of use — is ignored. The description of one project cycle, for the case of offshore project equipment, shows high MCI values for the most significant equipment types in terms of mass and economic value. On the pre-use side, these are a result of high recirculated material rates in the manufacturing of fabricated steel, and high reuse rates of existing assets. Higher material circularity is achieved by the narrower R-loops of reuse, refurbishment and remanufacturing, contrary to recycling. On the post-use side, these result from high recovery rates of the more significant equipment, of which most are saved in their entirety. Additionally, steel is a promising material for recycling, which recovers the remaining materials. Aggregating the individual products to represent the overall project MCI results in a high value. Although this describes a promising project performance, it only covers part of the product life cycle.

7.3.2. Sub-research question B

The second sub-research question, described in Chapter 3, relates to measuring the economic value performance of project equipment:

How can the economic value of circular material flows be determined on the project level?

To evaluate the economic value of equipment on the project level, the MCI' was the chosen metric. It conveniently aligns with the methodology of the MCI, which allows for fair comparison. The MCI' is a cost-based economic evaluation, which is required to form a quantitative methodology which can be scaled up for a large set of products to be evaluated. However, it was found that the MCI' was based on limited cost factors, which had to be expanded for a more accurate estimation of economic value.

This research implemented additional life cycle costs, by introducing a new cost breakdown structure (CBS) incorporating the pre-use, use, and post-use phases of the Value Hill. To ensure that the additional cost factors do not lead to an excessive time-consuming exercise, it is vital to only include the most important and relevant factors. These can be judged on the relative contribution to total costs, or on their relevance when comparing linear and circular alternatives. By comparing the original MCI' with the enhanced MCI, this research showed that including additional life cycle costs gives a more accurate representation of economic value circulation performance.

7.3.3. Sub-research question C

The third research sub-question, in Chapter 4, relates to the aggregation of the CE-performance on the product level to the project and company level:

How to translate the circular economy performance on the product level to the project and company level?

In this research, a bottom-up approach is adapted, starting with the project-as-customer level and aggregating to the product and company level. To do this, the methodology of the MCI of multiple production steps is applied. Each (project-)modification presents a production step, in which the additional material feedstock and unrecoverable waste generated are accounted for. These additional resources also represent additional costs, which are used in the economic valuation.

For this approach, it is necessary to have modification data available of each modification step. For a retrospective evaluation, this requires knowledge of the materials used and costs made in the entire life cycle of project equipment. In this research it became clear that this information is not always readily available. For prospective usage of the metric, the modifications can be based on experience and historical data, which can replace actual data with estimates. For usage of the metric in the future, it is necessary, and strongly recommended, to trace equipment modifications and couple them with the product. Strict asset management will result in better understanding of why some products perform well in terms of CE performance and some lack behind.

The latter becomes evidently more clear for the utilization of project equipment. As part of utility, lifetime and use intensity of project equipment is one of the vital parts which can improve CE performance. As utility is followed through the entire life cycle of project equipment, adequate documentation is necessary. Lifetime and intensity of use are within the sphere of influence of the owner, which thus can be in direct control of the CE performance.

7.3.4. Sub-research question D

The last sub-research question, covered in Chapter 5, involves both the material circularity and economic value as a CE-performance indicator of offshore project equipment:

How do the material circularity and economic value performance compare for the case of offshore project equipment?

When comparing the material circularity and economic value performance of project equipment, it is clear the former outperforms the latter. This means that relatively more recirculated material is used than cost saved, and more material is recovered than economic value captured. This relation was already identified for other industries — such as the building sector (Jiang et al., 2022) —, and is confirmed for offshore project equipment by this study. The main reason for this is that recycled material is part of the circular material flow in the MCI, but does not lead to similar benefits to the economic value. In the case study, this influence is profound, as steel consists of significant recycled content, and has high recycling efficiency. This results in high material circularity, but the cost of new steel and economic value lost in recycling result in low economic value performance. Therefore, material circularity, as a stand-alone indicator, is not sufficient for describing the potential economic benefits of enhancing the circular economy principles in managing project equipment. It is recommended for project-based organizations using project equipment to include an economic value-based indicator in their CE implementations.

When comparing the material circularity and economic value of different R-loops, it is shown that the narrower the loop the higher both performances. This indicates and confirms the statement of the Value Hill: the narrower the resource loop the more material and economic value is captured.

7.4. Recommendations for the offshore transport, installation, and removal contractor

A transition to a CE will not take place without any hurdles and requires firm cooperation between stakeholders. Building on the findings in this research, recommendations for practitioners in the industry will be given in this section. The first recommendations given are those for designers, who have the most direct influence on the physical products. In the following paragraph, advise for project engineers and managers are given. The final recommendations are of use to high-level company management, consisting of equipment managers, departmental managers, and the board.

7.4.1. Recommendations for equipment designers

As design is at the forefront of product existence, the decisions made in this stage will affect the entire product life cycle. Although this research did not provide direct guidance for equipment designers, there are interesting lessons to take from it. The key lesson is that design perspective is of strong influence for the circularity of project equipment. As of now, design engineers are given the task to make a design which is tailor-made for the project. In order to make equipment with extensive lifetimes, easy reusability, and high intensity of use, an engineer should get the chance to step outside of the project view and design for life. For this, a different mindset towards project budgets is required, which is not in the designer's sphere of control.

7.4.2. Recommendations for project engineers and managers

A suggestion for project engineers and project managers is to cooperate with structural engineers to find out which designs historically had a high material circularity and economic value performance, and clarify what influenced this. That way, lessons can be drawn from well-performing products. Next to this, the methodology proposed in this study, could give project engineers and managers a better insight into the economic benefit of recirculating fabricated steel. The results show that logistical costs, such as transportation and storage, are relatively small compared to design, material and manufacturing costs. As the material and manufacturing costs are lower when recirculating fabricated steel, this emphasizes the economic benefit embracing the CE concept can bring. However, the increased cost of circular designs should be further investigated. Project managers of consecutive projects should cooperate to increase the recirculation of fabricated steel, for which additional cost sharing could be a driver.

7.4.3. Recommendations for company management

Part of the company management consists of the equipment managers in charge of maintaining the assets in use. As concluded in this study, an important aspect of the CE concept is the slowing of resource flows. A way to achieve this is to increase the intensity of use of equipment. In this research, the intensity of use is adopted as the number of times an asset is used per year. Therefore, the equipment managers are encouraged to find means to increase the level of use intensity. One way to achieve this is to support project engineers and managers when making purchasing decisions. For example, as mentioned before, cable laid grommets have a much lower intensity of use compared to cable laid slings. Therefore, projects should be instructed to choose for the latter when purchasing new cables, if the lift design allows. This introduces equipment into the company which is found to have much higher intensity of use, reducing the number of cables required in the asset pool.

A specific example in which equipment management can make a change has to do with the way equipment is perceived. Lift points, for example, are known to be discarded after use. Due to many reasons, including: they remain attached to the installed or decommissioned structure, and/or the designs are so task specific that reuse is deemed uninteresting. A way forward is to change the way we look at this equipment. If the starting point is that all equipment is an asset, it will be managed like an asset. It will be designed in a more standardized way, retrieving programs will be more streamlined and, thereby, worth it, together favoring the CE concept.

As previously mentioned in the recommendations for equipment designers, increased cooperation between projects is also a piece of advice for departmental management. Taking a life cycle approach instead of project-specific equipment design, will reduce the extraction and disposal of resources. To achieve this, departmental management should broaden the project focus and improve the management of project landscapes.

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List of Abbreviations

BCI Building Circularity Indicator. 11, 13, 14, 73

C2C Material Reutilization Part. 13, 73
CBS cost breakdown structure. 26, 45, 59, 62
CC Circularity Calculator. 10, 13–15, 22, 58, 73
CE circular economy. ii, 1–4, 6–12, 14, 15, 20–22, 26, 27, 32, 37–39, 45, 48, 49, 51, 54–63
CEI Circular Economy Index. 13, 73
CEIP Circular Economy Indicator Prototype. 13, 73
ce-performance circular economy performance. 10
CEPI Circular Economy Performance Indicator. 13, 73
CE-strategies Strategies targeting a resource loop (as per PBL, 2017a). 4
CET Circular Economy Toolkit. 13, 73
CI Circularity Index. 13, 73
c-indicators circular economy indicators. 9–11, 27
circularity Measures the performance of the process of a circular economy, aiming to close, slow, and narrow resource loops. Also named resource efficiency. 4
CLC Closed Loop Calculator. 13, 73
CP Circular Pathfinder. 13, 73
CPI Circular Potential Indicator. 13, 73

EAF electric arc furnace. 40, 42
EoL end-of-life. 2, 22, 25, 27, 41, 53
EoL-RRs End-of-Life Recycling Rates. 13, 73
EU ETS EU Emission Trading System. 22, 23, 46, 51
EVR Eco-efficient Value Ratio. 13, 73

G&S grillage and sea fastening. 40–43, 49–51, 54, 55
GHG greenhouse-gas. 1, 46, 51

HMC Heerema Marine Contractors. i, 38–42, 46, 52, 71, 74, 75, 77
HSS high-strength steel. 40

IOBS Output Balance Sheet. 10, 11, 13, 14, 73

LCA life cycle analysis. 5
LCC life cycle costing. 25, 27, 59

MCI Material Circularity Indicator. ii, 11–21, 23, 27, 30, 32, 34–37, 43–45, 51, 53–62, 71, 73
MCI' Material Circularity Indicator based on economic value. ii, 10, 12–15, 21–23, 27–30, 32, 35–37, 49–51, 53–62, 71, 73

PCM Product-level Circularity Metric. 10, 11, 13–15, 22, 23, 58, 73

QC quality control. 48

RDI Resource Duration Indicator. 13, 73

RIs Recycling Indices. 13, 73
R-loops resource loops. 3, 4, 12–15, 54–56, 61, 62
RPI Reuse Potential Indicator. 13, 73
RRs Recycling Rates. 13, 73

SPB spreader bar. 40

TCO total cost of ownership. 24–27
TIR transport, installation, and removal. 1, 2, 6, 26, 38–41, 46

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A

Circular economy indicators selection

Table A.1

Micro level indicators used in the selection of a circular economy indicator for project equipment.

Circular economy indicators	Sources (develop by)
Recycling Rates (RRs)	Haupt et al., 2017
End-of-Life Recycling Rates (EoL-RRs)	Graedel et al., 2011
Circular Economy Performance Indicator (CEPI)	Huysman et al., 2017
Reuse Potential Indicator (RPI)	Park and Chertow, 2014
Recycling Indices (RIs)	van Schaik and Reuter, 2016
Circular Economy Indicator Prototype (CEIP)	Cayzer et al., 2017
Circular Economy Toolkit (CET)	Evans and Bocken, 2014
Circular Potential Indicator (CPI)	Saidani et al., 2017b
Product-level Circularity Metric (PCM)	Linder et al., 2017
Circular Economy Index (CEI)	Di Maio and Rem, 2015
Circularity Index (CI)	Cullen, 2017
Closed Loop Calculator (CLC)	Kingfisher, 2014
Circular Pathfinder (CP)	van Dam et al., 2017
Circularity Calculator (CC)	de Pauw et al., 2022
Material Circularity Indicator (MCI)	EMF et al., 2019
Building Circularity Indicator (BCI)	Verberne, 2016
Output Balance Sheet (IOBS)	MarcoCapellini, 2017
Material Reutilization Part (C2C)	Cradle to Cradle Products Innovation Institute, 2014
Eco-efficient Value Ratio (EVR)	Scheepens et al., 2016
Resource Duration Indicator (RDI)	Franklin-Johnson et al., 2016
Material Circularity Indicator based on economic value (MCI')	Jiang et al., 2022

Note. Apart from the Material Circularity Indicator based on economic value (MCI'), all indicators are part of the taxonomy of Saidani et al. (2019).