1-1-2019

Design for Circular Economy

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Recommended Citation

Elia, Maha, "Design for Circular Economy" (2019). *Electronic Theses and Dissertations*. 8163.
https://scholar.uwindsor.ca/etd/8163

Design for Circular Economy

By

Maha Elia

A Thesis

Submitted to the Faculty of Graduate Studies through the
Industrial Engineering Graduate Program
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the

University of Windsor

Windsor, Ontario, Canada

2019

Design for Circular Economy

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November 18, 2019

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ABSTRACT

In recent years climate change has become a big challenge affecting all human beings, living creatures and the entire ecosystem. Hence the importance of mitigating its effect and finding innovative solutions to combat and slow down its accelerating impact on the environment. One of the solutions is to reduce emissions and restore the earth which is the “circular economy” concept. This research is focused on the indicators that can be used to measure the circularity of a product. The analysis compares more than one assessment tool used as indicator then an in-depth research is performed on one of the methodologies proposed by the Ellen MacArthur Foundation which includes a main indicator known as the Material Circularity Indicator (MCI) and two complementary indicators known as risks and impacts complementary indicators.

The goal of the proposed study is a new methodology and a new tool to measure the product circularity that takes the complexity of the product into consideration. One way to measure the product complexity is to measure the ease of disassembly and the time and effort required to disassemble a product which can be reflected as the profitability of disassembly. The profitability of disassembly is calculated by finding out the amount of material that can be extracted feasibly from a product or, to put it in another way a decision must be made to recycle or not to recycle in advance, which is usually related to the material’s price as well as the time of disassembly. This is especially the case if there is no incentive to recycle or regulations to encourage recycling, where the profit factor becomes a dominant one in taking the decision to recycle or not.

The significance and novelty of this research comes from providing a more accurate measurement for the material circularity indicator proposed by Ellen Mac Arthur Foundation, as well as finding out the feasibility of recycling by looking at the different challenges related to the product’s complexity.

DEDICATION

To the two miracles God gave me, my children, Lourd and Christian. I could not do this without your love.

ACKNOWLEDGMENT

The author would like to express her appreciation to her advisor Professor Waguih ElMaraghy for his guidance, patience, and support during this journey. This thesis would not have been possible without his assistance. His support has gone beyond supervising and recommending topics. One of the most challenging moments was selecting a research topic, but with Professor Waguih ElMaraghy's help the process was smooth and the topic was innovative.

The author is also thankful for the valuable feedback from all the committee members.
Thanks go to Professor Hoda ElMaraghy and Professor Abdul-Fattah Asfour for their valuable comments, recommendations, and feedback during the committee meetings.

The author would also like to acknowledge the help and support from her fellow researchers and colleagues at the Intelligent Manufacturing Systems Centre (IMSC). Special thanks to Ms. Jessica Olivares Aguila for her help and advice.

Finally, I would like to thank all my family members, relatives and friends for believing in me. I would not been able to make it without your love and prayers. Thanks everyone for giving me so much support throughout the process.

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CHAPTER 1: INTRODUCTION

1.1.Overview

Circular economy as Tolio et al. refer is the new paradigm for sustainable development, the vision of this paradigm is to shift from the linear economy which is "Take-Make-Dispose" into a new one which is restorative and regenerative by intention and design (Tolio et al., 2017). It replaces product "end of life" concept with the concept of restoration and elimination of waste. "No longer can a product be designed considering the factors of cost and performance only but rather a shift from the traditional design practices must include consideration of the ultimate end of the product's life" (Johnson & Wang, 1998). From that perspective it is becoming a must to focus on the early stage of design to aid the process of economical material recovery and to address waste disposal in a proactive manner.

The circular economy is a concept that we have to embrace to face the different challenges ranging from material depletion of elements, such as gold, silver, iridium, tungsten and many others vital for industry that are expected to be depleted within the next 5–50 years (Lieder & Rashid, 2016), to the challenges of an increasing world's population which is estimated to be nine billion by 2030. With the limited resources of material and the increasing need of energy and resources to keep pace with the luxurious life in developed countries and the challenges facing poor counties a need of using of superior design of material, products, systems and business models becomes a must.

This research is analyzing the relationship between product complexity and Material Circularity Indicator (MCI) an indicator found by Ellen Mac Arthur foundation that measures the circularity of a product. The complexity of the product can be interpreted in different ways and measured by different methodologies. Complexity can be understood as the difficulty of disassembly or in another word the ease of disassembly. This research is looking at the difficulty of the disassembly of the product from different prospective by measuring the feasibility of the disassembly and how it can affect the efficiency of recycling and how that in turn affects the Material Circularity Indicator (MCI). By looking at different papers and different researches related to identifying the difficulty of the disassembling process, some papers and methodologies are studied below.

Chapter two includes a literature review on the circular economy concept, its definitions, its benefits and its contribution to the sustainable development concept. Then a more in-depth review on the circular economy concept is performed by looking at the levels of implementation, the business models used and finally the different methodologies and indicators used to measure the circularity of a specific product. One of the gaps found in the investigated product circularity indicators is the lack of measuring the complexity of the product and its effect on the circularity indicators. In order to understand the complexity and the different approaches to measure it another literature review on product complexity was performed in chapter three.

Chapter three includes a literature review on product complexity, first defining the complexity and the different terminologies used in the disassembly and recycling process, such as design for disassembly and design for recycling, then going through different methodologies and different approaches used to measure the product complexity/ease of disassembly. The disassembly feasibility is an important factor in the disassembly process, investing time and money to disassemble a product and recycle it, away from the environmental aspect, the feasibility of disassembly is a major factor we cannot ignore.

After analysing the methods used to measure product complexity/ease of disassembly in order to find its effect on circular economy, chapter four proposes a methodology which includes equations and formulas used to relate the product complexity to the material circularity indicator.

The main approach of this thesis is to find out the relation between the complexity and the circularity of a product through studying the effect of product complexity on the efficiency of recycling by taking the feasibility and profitability of disassembling and recycling into consideration first in order to decide to recycle or not, this is accomplished by drawing the relation between product complexity and the material Circularity Indicator (MCI).

Finally, a tool is designed, and a new indicator is created to measure the product circularity that takes the disassembly process and the product complexity into consideration when calculating product circularity.

This research contributes to the implementation of the circular economy, an important tool to reach the sustainable development goals. A literature review in the area of circular economy, circularity indicators and the other tools used to measure the circularity are investigated. In addition, a review was done on the complexity of the product and the different methods used to measure the complexity of disassembly. Some methods study the complexity of a product only from the point view of handling and removing of components other methods use time of disassembly or sequence of disassembly as an indicator for the complexity of a product. But no method studied the effect of complexity of the product on the efficiency of recycling by taking the profitability of the recycling into consideration.

Research Keywords

Circular Economy, S***ustainable Development***, ***Product Design for circular economy***, ***Remanufacturing and De-manufacturing***, ***Circularity Indicator***, and ***Product Complexity***

The research was done using different search engines such as Google, Google scholar and Scopus. In addition to looking at other websites of the big business consulting companies such as ***Boston Consulting Group (BCG)*** and ***McKinsey& Co.*** (2014)in order to understand their vision, their projects and approach in implementing the sustainability and circular economy concepts.

1.2.Motivation

The world's population is expected to reach nine billion by 2030, and our resources, the earth's raw materials, are not limitless. As a result, global labour and raw material costs are on the increase. From here comes the importance of embracing the circular economy. Though using it, business opportunities can offer new ways to mitigate these risks to allow more grow and diversify. In a circular economy, products and materials keep circulating in a high value state of use, through supply chains, for as long as possible. Greenpeace estimates that every year (20–50) $*10^6$ tons of waste is generated from discarded electronic products alone, this waste has a significant impact on the environment that we live in since waste that humans generate pollutes the land, air, and water that is essential for human life.

Recycling considered one good way to reduce the impact of this waste, where this process will ensure collecting and processing materials that would otherwise be discarded as trash and turning them into new products. (Xia, Gao, Wang, Li, & Chao, 2015) . It is obvious that the amount of resources required to recycle a material is less than the amount used for creating new material. For example, recycling aluminum uses only 5% of the energy required by virgin production (The Aluminum Association,2011). In spite of the benefits of recycling, only 34% of the solid waste generated in the U.S was recycled in 2014 (Beck, 2016). This ratio could increase if product designers had a tool that would enable them to determine the recyclability indices of design concepts early in the design process.

1.3.Research Objectives

The overall objectives of this research are:

- To investigate the methodologies, tools and indicators used to measure the circularity of a product and come up with an indicator that takes the complexity of the product into consideration.
- To find the effect of product complexity on product circularity by taking different factors into consideration such as the time of disassembly, purity and profitability of recycling.
- To Create a conceptual management tool and design a new Indicator that takes the disassembly process into consideration

1.4.Research Scope:

This research focuses on the circular economy and the different indicators and tools used to measure the product circularity. The complexity of a product and the methods used to measure it are further investigated by understanding the different ways of measuring the complexity of a specific product and how the product complexity could impact the product circularity.

Some terminology and concepts will be included, such as Design for Disassembly (DFD), Design for Assembly (DFA), and design for Recycling (DFR). In addition to explaining in depth the recyclability indices, such as the ***material recyclability index*** that is related to a specific material, some methods used for measuring will be included.

Then, the method used to conduct the case studies is described, followed by the case studies and result analysis for each case study. The discussion section details the various inferences that are drawn from the results of the case studies. The aim of this study is to create a conceptual management tool and design a new indicator that takes the disassembly process into consideration, this tool is represented by an excel sheet at the end of discussion section. Finally, the conclusions and future work are presented.

1.5.Research Gaps and Novelty:

By looking at the different indicators used to measure the circularity, the Material Circularity Indicator (MCI) is one of the indicators that are interesting to investigate more since it is the only one found to measure the amount of the material recycled. However, this indicator does not explain the impact of the complexity of the product on the material circularity indicator.

Literature review on the product complexity is performed in order to understand the meaning of product complexity and how to measure it. Different ways were found to interpret the product complexity and ease of disassembly. One method chosen was through calculating the profit behind disassembling and recycling the materials of a specific product, where the time of disassembly and cost of disassembly in addition to the reclamation value of each material is considered the main factors affecting the decision of recycling.

A novel method to calculate the circularity indicator is proposed here where the recycling efficiency of the product is considered dependent on the product complexity and the later one assumed to be defined by the easy of disassembly and the time required for disassembly by taking the profitability of disassembly into consideration to decide to recycle or not.

The significance of the proposed research has three important aspects: First, understanding how the profitability of disassembly of a product is measured. Second calculating the recycling efficiency of the whole product based on the outcome of the decision made in phase one then finally to measure the product circularity based on the calculated recycling efficiency through using the material circularity indicator.

1.6.Research Plan

The introduced research approach follows a framework which consists of three levels.

1. At the first level, different definitions of the circular economy will be included then a more in-depth analysis will be performed on the different levels of circular economy, its mechanism and different strategies/ business models. Finally, three different indicators used to measure the product circularity will be investigated.

2. The second level will include definitions for different terminologies such as product complexity, disassembly, recyclability index and other circularity related terminologies. Then looking at different methods used to measure the product complexity such as ease of disassembly and the feasibility of disassembly where “a reduction of the disassembly time and the related costs will increase the economic feasibility of product lifetime extension and therefore increase the viability of a circular economy in industrialized regions”(Vanegas et al., 2018, p 323). From there a close view on the effect of time of disassembly and profitability of disassembly will be considered.

3. The third level will be finding the relationship between product complexity and product circularity, then designing a new tool to measure the product complexity base on first calculating the profitability of disassembly and recycling

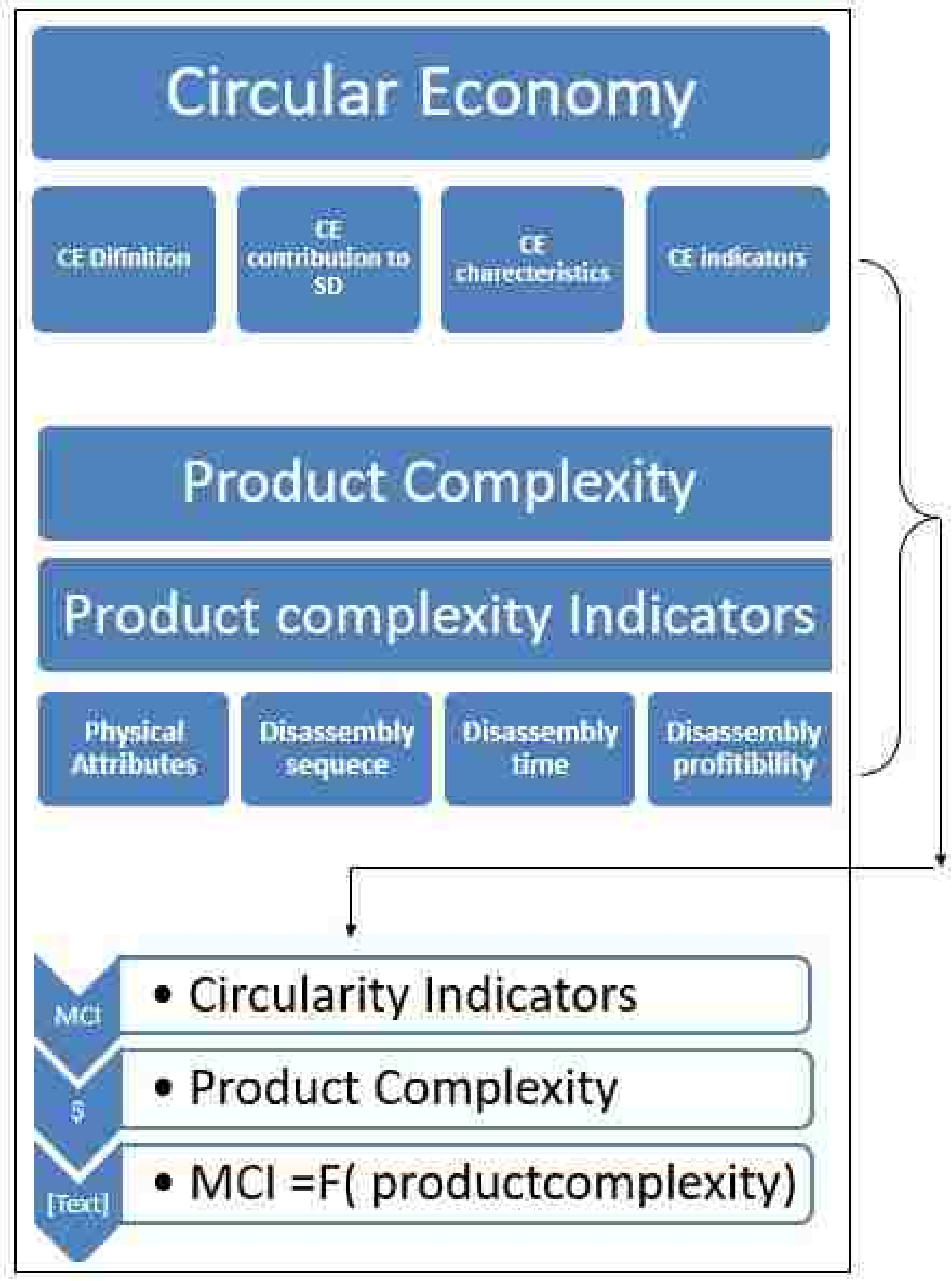


Figure 1.1 Research Framework

1.7. Thesis Hypothesis

The present study aims to test the hypothesis which is the effect of product complexity on product circularity where complexity is interpreted by the profitability of disassembly and how it is dependent on different variables affecting the disassembly process such as time of disassembly and value of reclaimed material.

CHAPTER 2-THE CIRCULAR ECONOMY (CE)

Following will be a literature review on different terminologies and concepts that are related to the concept of circular economy, different definitions of circular economy will follow then the relation between the circular economy and sustainable development will be investigated next by understanding how it contributes to the sustainable development concept. After that a research on the levels of implementation will be performed, in addition to the tools and different circularity indicators used to measure the circularity of a product.

2.1.CE Definitions

Different definitions were found related to the circular economy concept, how did this concept develop and evolve, what are the early signs of this movement and its contribution to the sustainable development movement. All these questions will be answered in the next sections

The circular economy cannot be tracked back to one single date or author, (Tolio et al., 2017) but rather to several schools of thoughts, some of those are: the theory of "Regenerative design" by lyle in late seventies which explains that the concept of resource regeneration can be implemented and included as part of sustainable development concept (Lyle, 1996). Also Stahel was one of the pioneers in introducing the economic basis for a transition to a non-linear industrial model.(Stahel & Reday-Mulvey, 1981) then after that the idea of "Cradle-to-Cradle" design was reformed, a concept where the idea of an efficient and waste free systems is the ultimate goal in an economic, industrial and social framework.

Different definitions were found, some were adapted by policy makers and business advocacy bodies such as the Ellen MacArthur Foundation (EMF). In addition to other definitions found using variety of keywords searching different engines such as Google, Google scholar and Scopus as follows:

"The CE has been defined as an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse and return to the biosphere, and aims for the elimination of waste through the superior design of materials, products, systems and business models." (Hobson, 2016)

The concept of circular economy (CE) is simply represented by shifting our way of thinking from the linear thinking of take-make-use-dispose linear pattern of production and consumption, to a circular system in which the value of products, materials and resources is maintained in use as long as possible.

Different definitions of CE were adopted and overlapped with other terminologies based on a collection of ideas derived from a variety of scientific disciplines and semi scientific concepts.

In ***industrial ecology***: (Frosch and Gallopoulos, 1989) ; Lifset and Graedel, 2001; Graedel, 1996) explain how the industrial ecology shared the same mindset and focus on closing and slowing resource cycles, looking to natural systems for insights about closing loops and increasing resource efficiency. (Korhonen, Nuur, Feldmann, & Birkie, 2018)

In ***ecological economics***, which has a long tradition in recycling and its related issues as defined by (Georgescu-Roegen, 1971; Daly, 1996; Ring, 1997; Boulding, 1966; Ayres, 1999) aims to improve and expand economic theory to integrate the earth's natural systems, human values and human health and well-being. (Korhonen et al., 2018)

CE also takes part in other research streams, include ***industrial ecosystems*** as defined by (Jelinski et al., 1992) and ***industrial symbioses*** (Chertow and Ehrenfeld, 2012), ***cleaner production*** (Ghisellini, Cialani, and Ulgiati, 2016); Lieder and Rashid, 2016; Stevenson and Evans, 2004), ***product service systems*** (Tukker, 2015), ***eco-efficiency*** (Huppes and Ishikawa, 2009; Haas et al., 2015 ; Welford, 1998), ***cradle-to-cradle design*** (Braungart et al., 2007); McDonough and Braungart, 2003) , ***biomimicry*** (Benyus, 2002) ***resilience of social-ecological systems*** (Folke, 2006; Crepin et al., 2012), ***the performance economy*** (Stahel, 2010; EMAF, 2013), ***natural capitalism*** (Hawken et al., 2008), the ***concept of zero emissions*** (Pauli, 2010) and others (Korhonen et al., 2018)

2.2.CE Contribution to Sustainable Development

This section will discuss the contribution of circular economy concept to the bigger concept of sustainable development which is a concept that has a huge impact on the human's well being through its effect on the three pillars of sustainability.

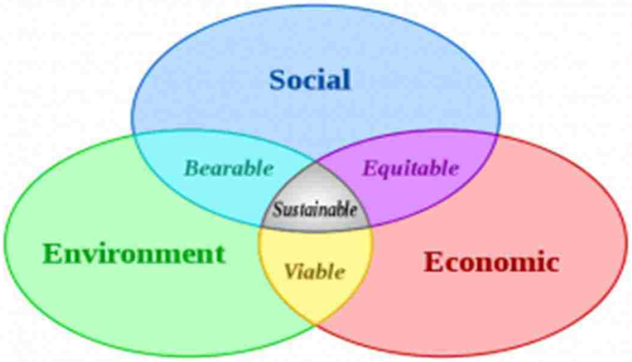


Figure 2.1 Sustainable Development Pillars (thwink, 2014)

The positive contribution to the environment as well as the economic and the social aspect of the sustainable development can be seen where the economic development is conducted without depletion of natural resources and by thinking not only in this generation, but also the next generation as we can see from the definition of sustainable development "it is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs"(Suárez-Eiroa, Fernández, Méndez-Martínez, & Soto-Oñate, 2019).

Next is a review on the UN 17 that explains the SDG (***sustainable development goals***) and how the circular economy can contribute to the implementation of these goals, specifically the social part of it.

2.2.1. Sustainable Development Goals

The Sustainable Development Goals are a UN Initiative, the Sustainable Development Goals (SDGs), Global Goals for Sustainable Development, ***17 Global Goals***, Global Goals or simply ***the Goals*** are a collection of 17 global goals set by the United Nations General Assembly in 2015. The SDGs are part of Resolution 70/1 of the United Nations General Assembly "Transforming our World: the 2030 Agenda for Sustainable Development". That has been shortened to "2030 Agenda". These are broad and interdependent goals, yet each has a separate list of targets to achieve. Achieving all 169 targets would signal accomplishing all 17 goals. The SDGs build on the principles agreed upon in Resolution entitled "The Future We Want" a non-binding document released as a result of Rio + 20 Conference held in 2012 (Schroeder, Anggraeni, & Weber, 2019)

Figure 2.2 The 17 Sustainable Development Goals (World Bank, 2015)

The SDGs cover social and economic development issues including:

1. **No Poverty**: the end of poverty in all its forms everywhere**.**
2. **Zero hunger: "**End hunger, achieve food security and improved nutrition, and promote sustainable agriculture**"**
3. **Good health and well-being for people:** ensure healthy lives and promote well-being for all at all ages.
4. **Quality education: "**Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all**.**
5. **Gender equality:** Achieve gender equality and empower all women and girls.
6. **Clean water and sanitation:** "Ensure availability and sustainable management of water and sanitation for all**.**
7. **Affordable and clean energy:** Ensure access to affordable, reliable, sustainable and modern energy for all.
8. **Decent work and economic growth:** Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

9. **Industry, Innovation, and Infrastructure**: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
10. **Reducing inequalities**: Reduce income inequality within and among countries.
11. **Sustainable cities and communities:** Make cities and human settlements inclusive, safe, resilient, and sustainable.
12. **Responsible consumption and production: "**Ensure sustainable consumption and production patterns.
13. **Climate action:** "Take urgent action to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy.
14. **Life below water:** Conserve and sustainably use the oceans, seas and marine resources for sustainable development**.**
15. **Life on land:** Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**.**
16. **Peace, justice and strong institutions:** Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels**.**
17. **Partnerships for the goals:** Strengthen the means of implementation and revitalize the global partnership for sustainable development.

By matching circular economy practices with the sustainable development goals, we notice that the implementation of the circular economy with its operational principles in fact serve the above SD goals and, potentially, can contribute directly to achieving a significant number of SDG targets. Specifically, goal number twelve "responsible consumption and production", where the circular economy's aim is to make the producer and consumer more aware of utilizing the different products and keeping it in use in a more efficient way as well as extending its life time.

Patrick Schroeder in his paper titled" **The Relevance of Circular Economy Practices to the Sustainable Development Goals**" identifies the extent to which circular economy (CE) practices are relevant for the implementation of the Sustainable Development Goals (SDGs) he mentions that the relationship between CE practices and SDG targets show that CE practices, potentially, can contribute directly to achieving a significant number of SDG targets. (The strongest relationships exist between CE practices and the targets of SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land)). He also identifies several potential trades-offs between targets for decent work, safe working environments, human health and current CE practices relating to recycling of municipal waste, e-waste and wastewater, and provides suggestions how these can be overcome. The paper concludes that CE practices can be applied as a "toolbox" and specific implementation approaches for achieving a sizeable number of SDG targets. He emphasizes the importance of further empirical research to determine which specific types and means of implementation are required to apply CE practices in the SDG context.(Schroeder et al., 2019).

2.2.2. The Social Pillar of Sustainable Development

The Social pillar of sustainable development deals directly with the human being rights such as “social equity, livability, health equity, community development, social capital, social support, human rights, labour rights, placemaking, social responsibility, social justice, cultural competence, community resilience, and human adaptation” (Yugendar, 2014). A second, more recent, approach suggests that all the domains of sustainability are social: including ecological, economic, political and cultural sustainability. We can see the social pillar of sustainable development reflected in most of the sustainable development goals set by the United Nations, this set of goals is investigated to measure the social pillar of sustainable development where the ultimate goal is a better standard of living and human rights to live a decent life without any kind of discrimination.

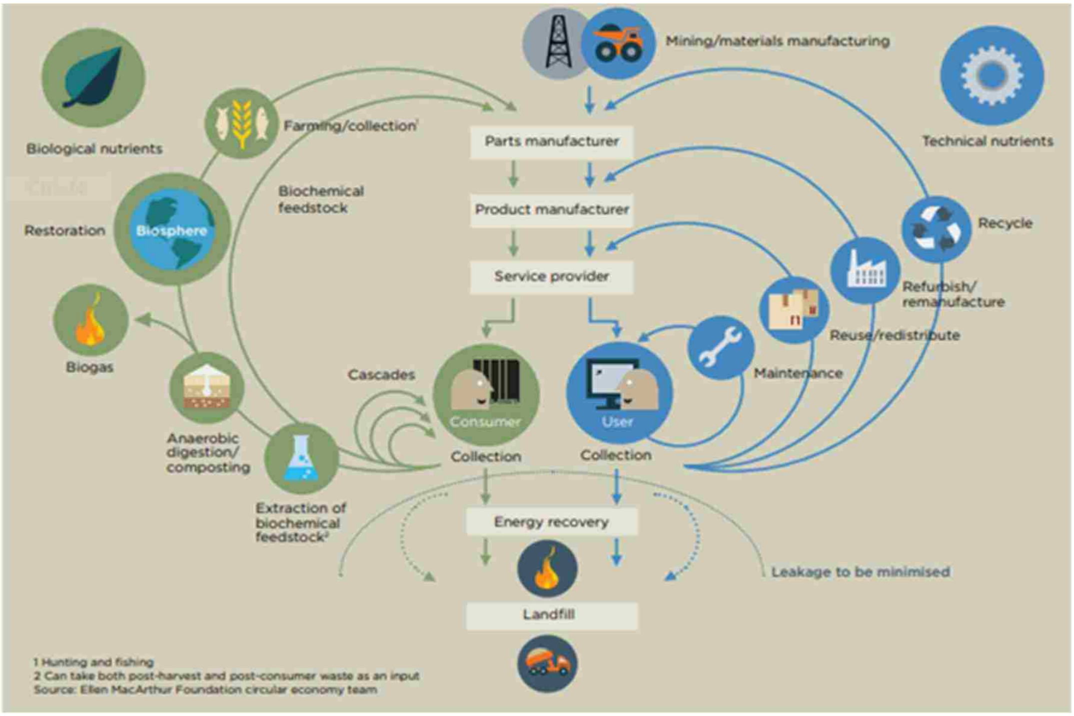
2.2.3. The Environmental Pillar of Sustainable development

The Environmental aspect of the sustainable development can be defined as a state in which the demand placed on the environment can be met without reducing its capacity to allow all people to live well, now and in the future. In order to reach this state, we should make sure that the amount of resources used does not exceed the amount of resources we have so that the environment can cope with the demand. Not all the resources are renewable as we can see from Figure (2.3) The Butterfly Diagram explains two types of waste, the Biological and the Technical Waste.

It is important to distinguish between the two types of outputs: biological wastes and technical wastes as mentioned by Ellen MacArthur Foundation. Biological wastes are biodegradable compounds flowing through biogeochemical cycles that will eventually be reconverted into natural capital. On the other hand, there are the technological wastes that are not biodegradable, this kind of wastes require a process of human transformation in order to be reintroduced into the economic system again. Hence technical wastes need to be minimized, or even eliminated, a conclusion that can be also drawn from the conceptual model for CE described by Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015a)

Technical materials, such *as metals, plastics and fossil* fuels are finite and cannot be renewed, from here comes the importance to manage properly using them. Through focusing on value retention, Materials are recovered from residual streams after use through the technical cycle. While the biological materials such as food, water, cotton and other biological waste can be taken back into the ecosystem by means of biological processes, it is important to ensure that the ecosystem and biological processes are enabled to function properly as long as the materials flows are not contaminated with toxic substances and the ecosystem are balanced theses biological materials are renewed.

The following figure explains the two types of waste output and the different loops used to process the industrial waste and return it back to the system again.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input
Source: Ellen MacArthur Foundation circular economy team

Figure 2.3 The Butterfly Diagram (Ellen MacArthur Foundation, 2015a)

2.2.4. The Economic Pillar of Sustainable development

The economic pillar includes a broad array of issues, from trade and investment to employment growth and private sector development. Economic policy-making takes into consideration both domestic and international trends and assets and develops a mix of instruments that include, among others, tax policy, public-private partnerships, trade and employment policies, national and international finance, etc.

There is a strong relation between the economic pillar and the sustainable development goals. Poverty eradication or alleviation, decent and productive jobs; employment creation; security of jobs versus contract labour without benefits; income inequality; local economic development all these issues are related strongly to the sustainable development goals

Several SDG (Sustainable Development Goals) reflects how the economic pillar of sustainable development has a direct impact on the humans' rights, such as: SDG 1: End poverty in all its forms everywhere SDG 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all SDG 10: Reduce inequality within and among countries

On the other hand we can see the direct effect of the economic pillar on the standards of living, where elements such as gold, silver, iridium, tungsten and many other vital for industry are expected to be depleted within the next 5–50 years (Lieder & Rashid, 2016). The prices of these metals are expected to increase, in fact, commodity prices rose overall by almost 150% in 2002-2010. In addition to the fact of a growing population that is expected to reach 9 billion by 2013. From here comes the importance to emphasize on rethinking the way society uses material and the importance to shift from the linear economy to the circular economy.

From the above we can understand how the circular economy can contribute to the implementation of the sustainable development concept. By shifting to the Circular Economy thinking new jobs will be generated, huge investments will be created, and little waste will be produced to the environment, where the output from ecosystem can be balanced with the input.

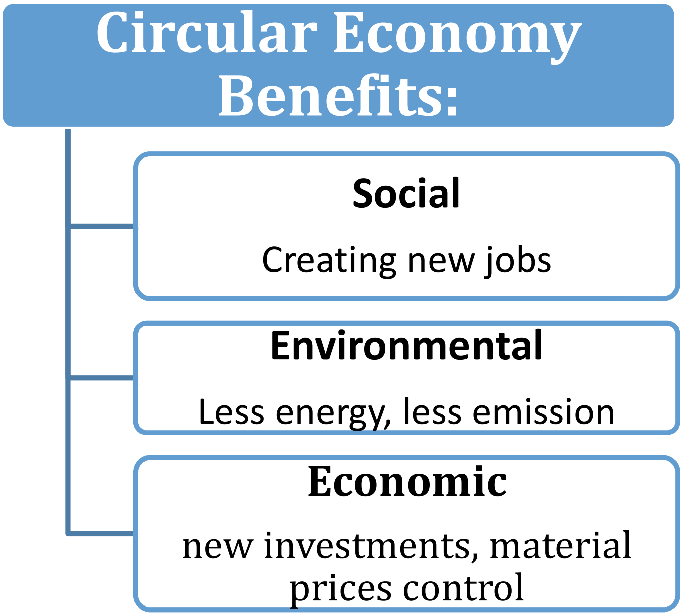


Figure 2.4 The Circular Economy Benefit

2.3.CE Principles and Fundamental Characteristics

Circular Economy (CE) is a concept, aims to overcome the take-make-dispose linear pattern of production and consumption, proposing a circular system in which the value of products, materials and resources is maintained in use as long as possible (Ellen MacArthur Foundation, 2015a).

In the next sections we take a close look at the (Circular Economy) concept, the levels of implementation as well as the different loops of circular economy then the different methodologies, tools and indicators used to measure the circularity. A close search was done particularly to find the circularity indicators used to measure the circularity of a product in different industries.

One of the interesting methodologies was the one proposed by ***Ellen MacArthur Foundation***, a foundation launched in 2010 its main goal is to accelerate the transition towards the circular economy. In 2015 the Ellen Mac Arthur Foundation collaborated with other companies such as ***Granta Design*** and other firms to launch a project in order to come up with a way of measuring how effective a company is in making the transition from 'linear' to 'circular' models. This project or methodology aims to develop indexes consist of a main indicator, known by the Material Circularity Indicator (MCI), measuring how restorative the material flows of a product or company are, and complementary indicators that allow additional ***impacts*** and ***risks*** factors to be taken into consideration.

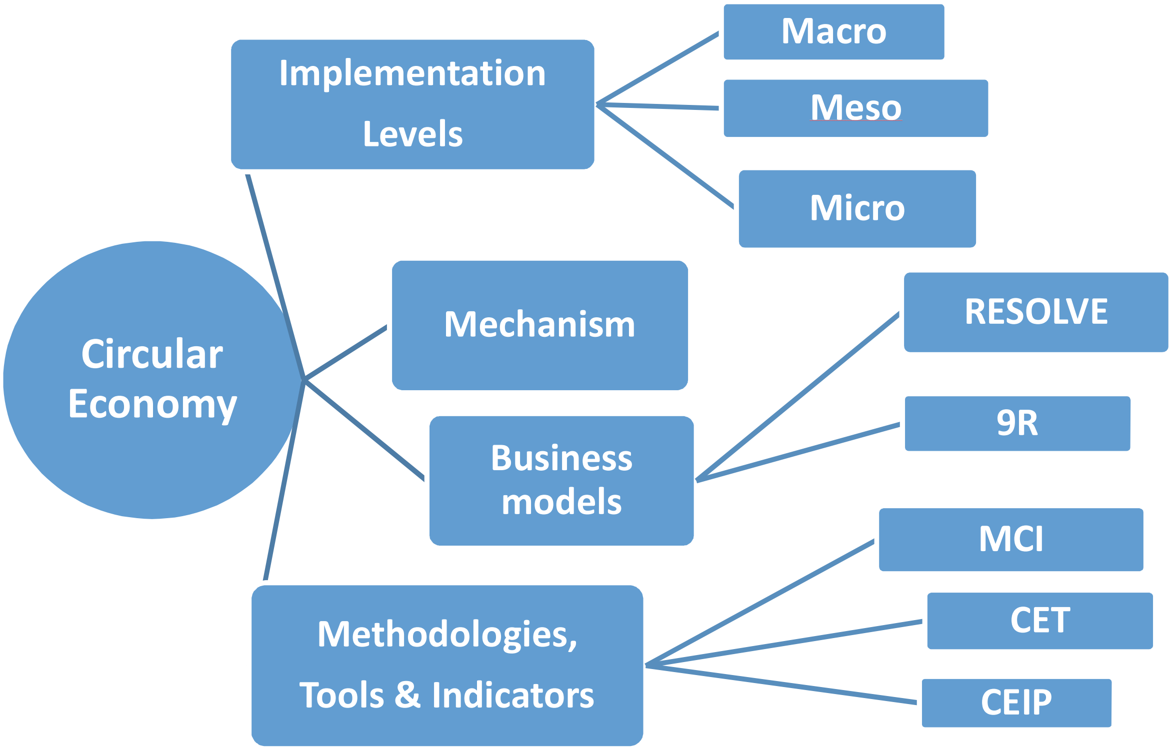


Figure 2.5 CE Characteristics

2.3.1. Implementation Levels of (CE)

Balanay and Halog mentioned three systematic levels of implantation for the circular economy: the Macro which refers to the city, province, region, nation, the Meso level fits with eco-industrial parks, while the Micro level corresponds to single company or consumer (Balanay & Halog, 2016).

Figure 2.6 Levels of Implementation of CE (Balanay & Halog, 2016)

A fourth level -the Nano level - suggested by (Saidani, Yannou, Leroy, & Cluzel, 2017) is a “more refined level focusing on the circularity of products, components and materials, included in three wider systemic levels, all along the value chain and throughout their entire lifecycle”. That level “i.e., an operational and product-level including components and Materials could serve as a common denominator within these three levels, and could enable not only to make the links between these levels but also to have a closer look at the effective performance of circular economy implementation”(Saidani et al., 2017)

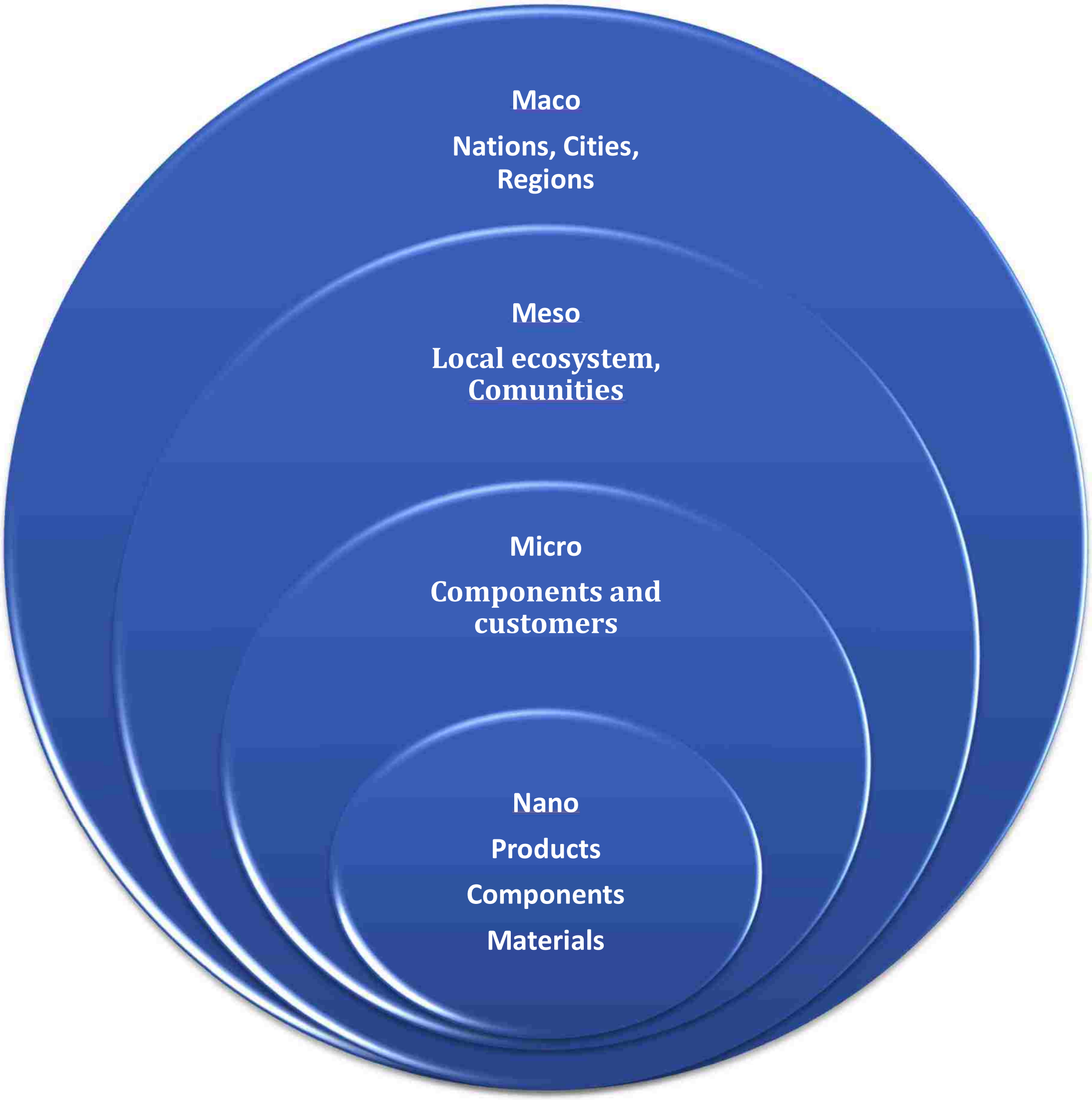


Figure 2.7 Level of Implementation of CE suggested by (Saidani et al., 2017)

From the previous discussion, different levels of implementation can be found and for each level there are different approaches and business models applied to implement the concept. Figure (2.8) illustrate some of those approaches, next section will be explaining the different business models.

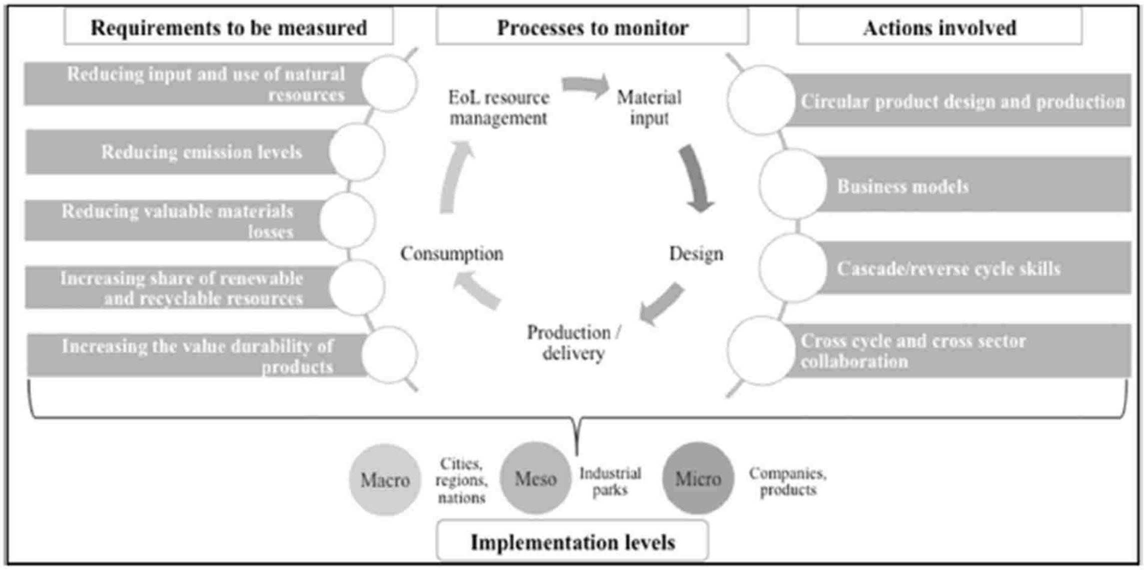


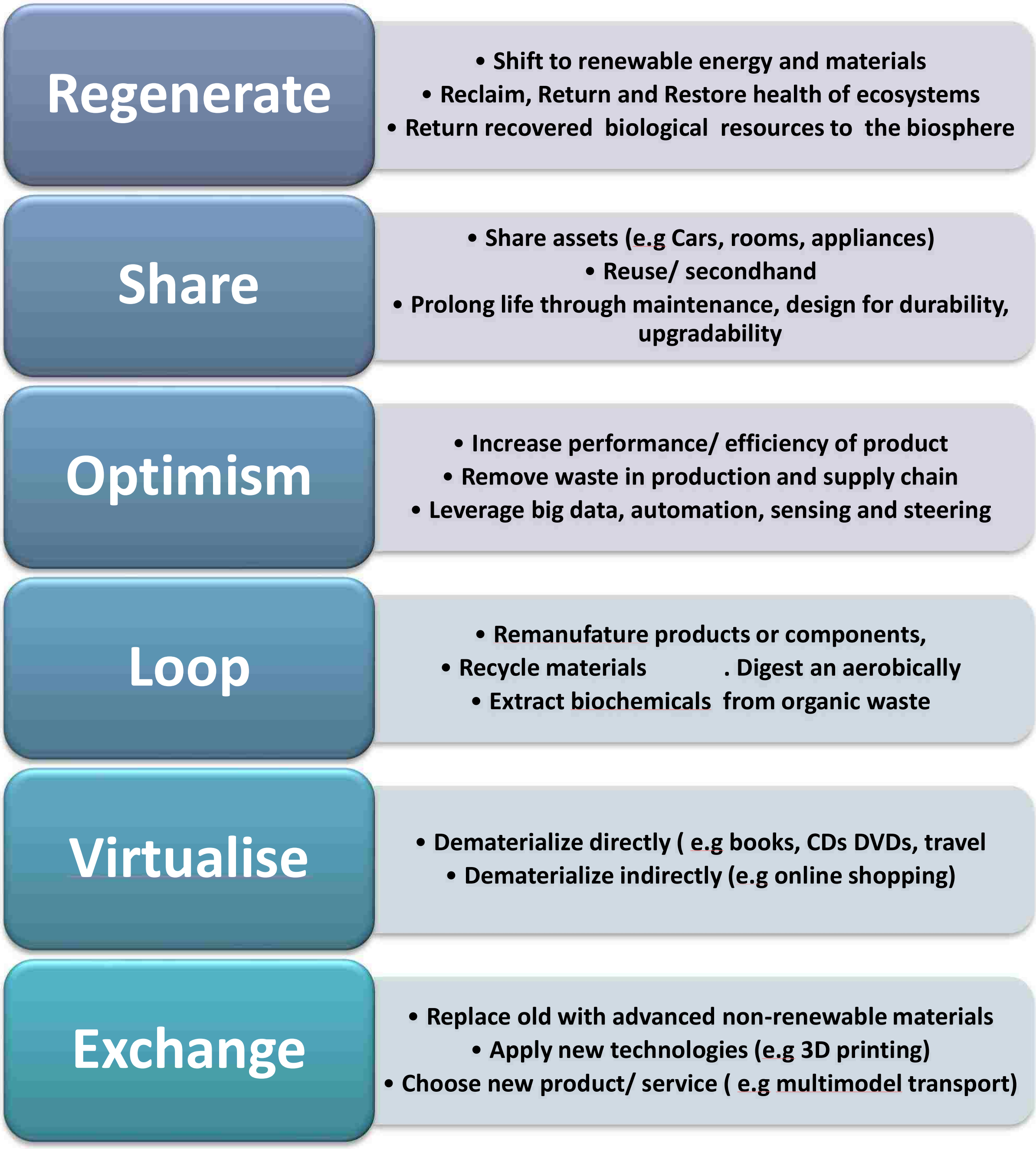
Figure 2.8 CE Implementation Levels (Macro, Meso, Micro) (Elia, Gnoni, & Tornese, 2017)

2.3.2. Business models / Strategies of Circular Economy implementation

Circular business models represent fundamentally different ways of producing and consuming goods and services. They have the potential to drive the transition towards a more resource efficient and circular economy. These models include recycling, reuse, and repair, Product Service System (PSS) which is the provision of access to products, rather than ownership of them.

- **Business Models: ReSOLVE framework by Ellen MacArthur Foundation**

Ellen MacArthur Foundation proposed a framework, or a business model called (ReSOLVE) to implement the circular economy, an overall approach to transition from a linear to a circular economy. The ReSOLVE framework takes the core principles of circularity and applies them to six actions: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange, the following figure illustrates this framework:



Regenerate

- Shift to renewable energy and materials
- Reclaim, Return and Restore health of ecosystems
- Return recovered biological resources to the biosphere

Share

- Share assets (e.g Cars, rooms, appliances)
- Reuse/ secondhand
- Prolong life through maintenance, design for durability, upgradability

Optimism

- Increase performance/ efficiency of product
- Remove waste in production and supply chain
- Leverage big data, automation, sensing and steering

Loop

- Remanufature products or components,
- Recycle materials . Digest an aerobically
- Extract biochemicals from organic waste

Virtualise

- Dematerialize directly (e.g books, CDs DVDs, travel
- Dematerialize indirectly (e.g online shopping)

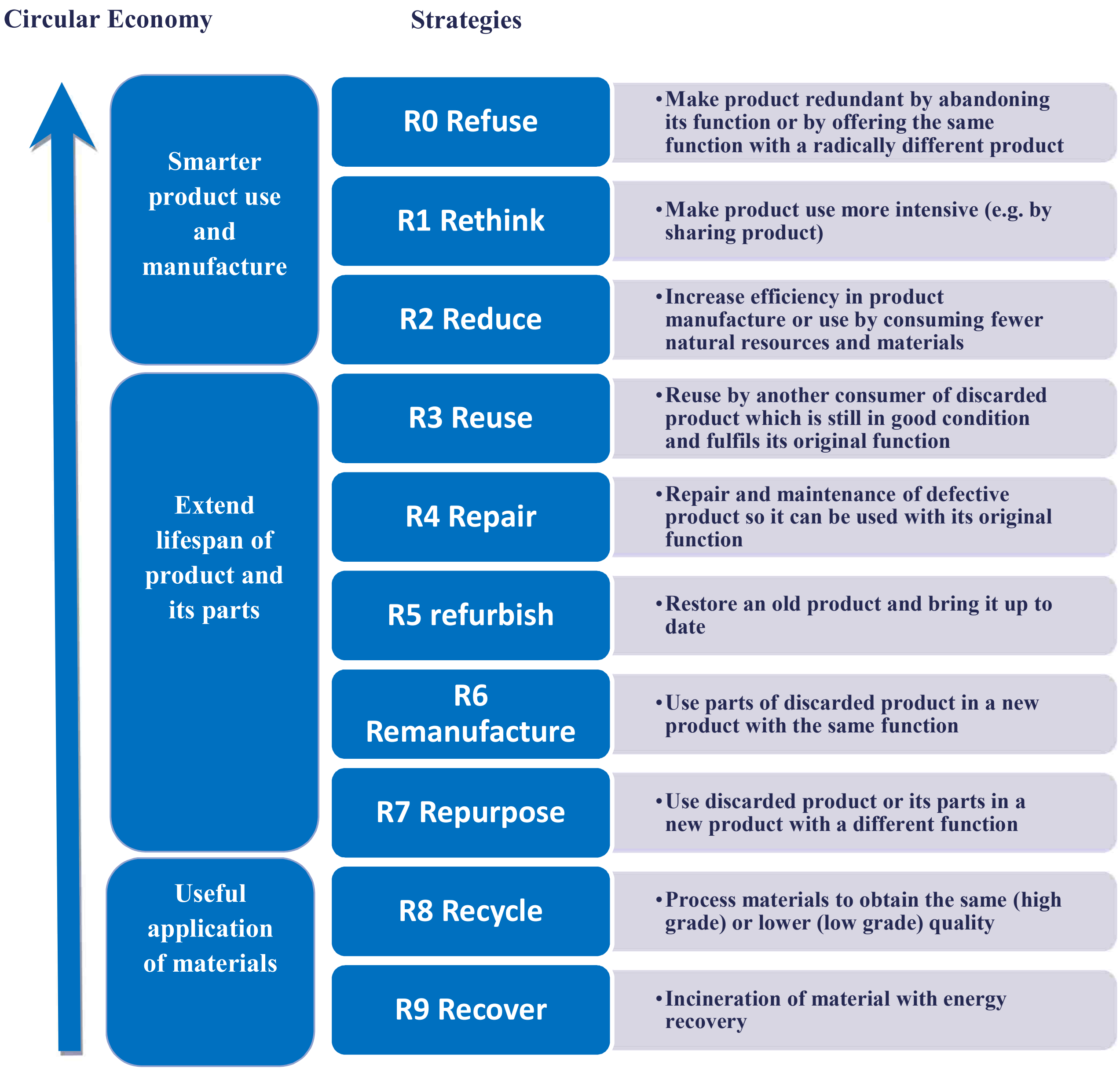
Exchange

- Replace old with advanced non-renewable materials
- Apply new technologies (e.g 3D printing)
- Choose new product/ service (e.g multimodel transport)

Figure 2.9 ReSOLVE framework– (Ellen MacArthur Foundation, 2015b)

Business Models: 9R framework

Another framework is the 9R that can be explained in Figure 2.10.



Circular Economy	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Figure 2.10 The 9R Framework (Potting, Hekkert, Worrell, & Hanemaaijer, 2017)

2.3.3. Mechanism of Circular Economy

As far as the mechanism of circular economy, Tolio et *al*, identify four different mechanisms for value creation in Circular Economy that offer opportunities compared to the linear usage (Tolio et al., 2017) , it is described below as:

1. ***The power of inner circle***: the closer the product gets to direct reuse, i.e., the perpetuation of its original purpose, the larger the cost savings will be in terms of material, labour, energy, capital and the associated externalities.

2. ***The value of circling longer***: value created by keeping products, components, and materials in use longer within the Circular Economy. This can be achieved by enabling more cycles or by spending more time within a single cycle.

3. ***The power of cascaded use***: value created by using discarded materials from one value chain as by-products, replacing virgin material in another.

4. ***The power of pure circles***: uncontaminated material streams increase collection and redistribution efficiency while maintaining quality.

Another approach to restore and recovery from physical product point view can be recognized by looking back into Figure 2.3 that illustrates the butterfly Diagram proposed by Ellen Mac Arthur Foundation, two main paths can be recognized one is the ***biological cycle*** and the other is known by the ***technical cycle***. In the technical cycle four different cycles to restore the technical materials are noticed (four sources of value creation), these cycles are explained below from the inner cycle to the outer one:

Repair and maintenance: Restoring products during use to extend the lifespan of products

Reuse and Redistribution: Direct reuse through product reuse or sales.

Refurbish & Remanufacture: The thorough renovation and repair of product by the manufacturer.

Recycle: Parts or materials are recovered from the product to use them again

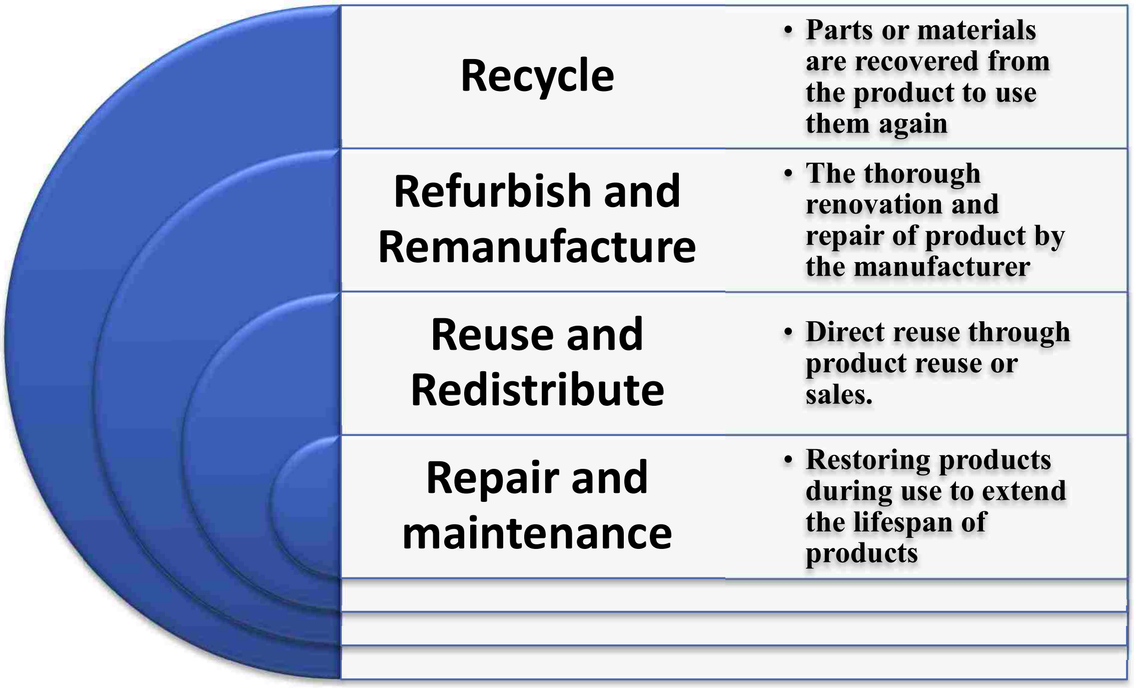


Figure 2.11 Four sources of value creation- (Ellen MacArthur Foundation, 2013)

2.4. Methodologies and indicators used to measure CE

Literature review on different Product Circularity Indicators proposed by different resources was performed to find out how to measure the circularity of a product, process and a system. In order to do that, different methodologies were investigated to find out how to measure the circularity of ***a product*** which represents the micro level in the implementation of circular economy concept.

Three different tools or indicators were found. The first tool is the ***Circular Economy Toolkit (CET)***, the second tool is the ***Circular Economy Indicator Prototype (CEIP)*** and finally the methodology proposed by Ellen Mac Arthur Foundation, a methodology used to assess the circularity of products. This methodology uses an indicator called by the ***Material Circularity Indicator (MCI)*** in combination with complementary indicators to identify relevant risks and impacts, these complementary indicators know by ***Complementary risk indicators*** and ***Complementary impact indicators.***

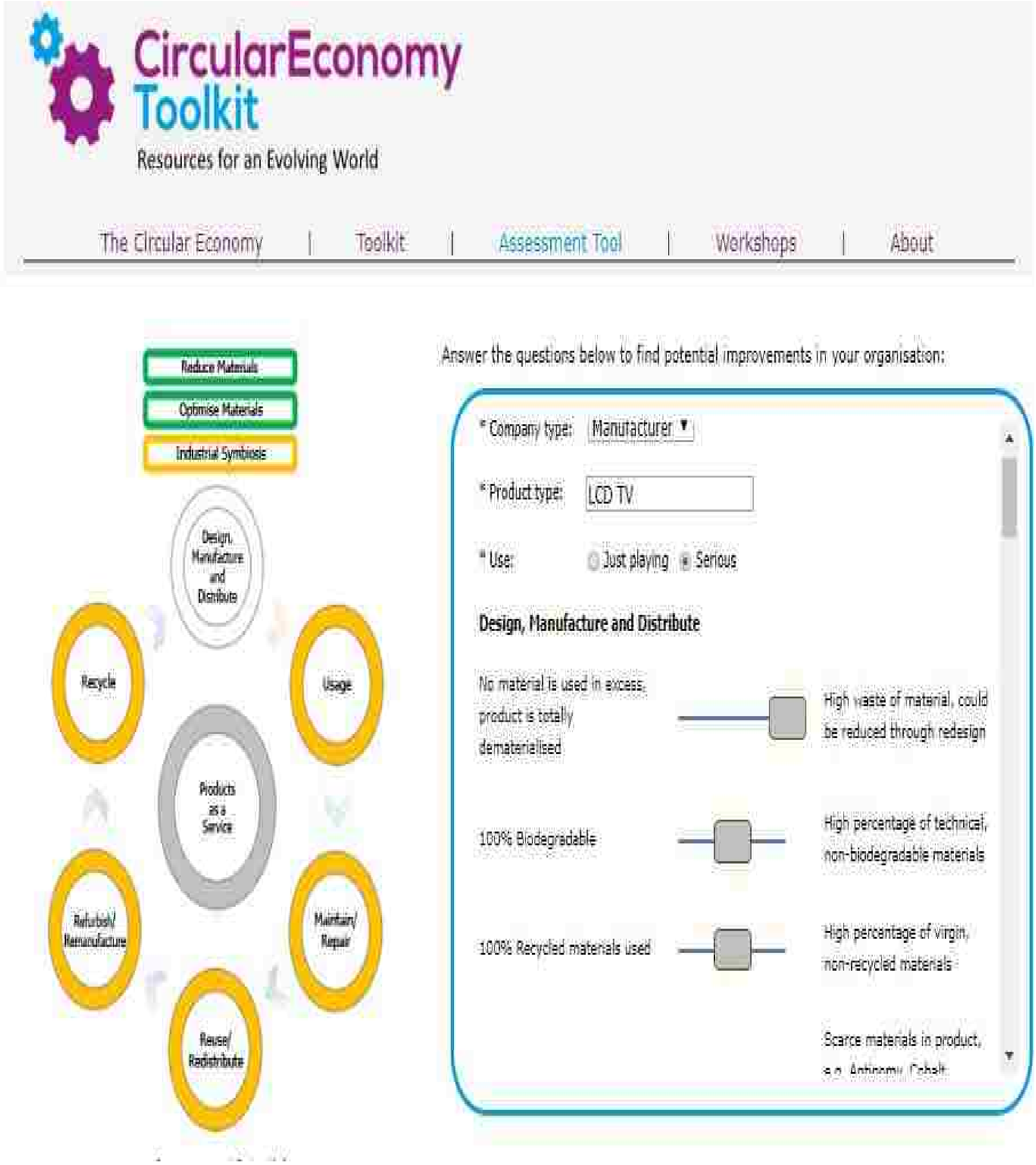
2.4.1. Circular Economy Toolkit (CET):

It’s a free online tool offered for different businesses to help find opportunity in circular economy in order to enhance the circularity of their businesses. This tool divided into seven areas of improvement (Design Manufacture and Distribution, Usage, Maintenance/repair , Reuse/ redistribute, refurbish/remanufacture, product recycling and finally products as a service) it consists of answering - in a trinary format (yes/partly/no or high/medium/low) -33 questions divided into 7 sub-categories, similarity to the lifecycle stages considered in an environmental qualitative assessment: 7 questions related to design, manufacture and distribute; 3 related to usage; 6 related to maintenance and repair of the product; 3 related to reuse and redistribution of the product; 10 related to refurbish and remanufacture; 2 related to product-as-a-service; 2 related to product recycling at end-of-life. (Saidani et al., 2017)

The main *advantage of this tool* is that it considers both business opportunity and product design in the qualitative assessment, where it assesses business opportunities (including financial viability and market growth potential), also this tools considered user friendly and easy to understand even for non-expert in circular economy. (Saidani et al., 2017)

Limitation of this tool:

This toolkit may be considered as too superficial to encompass the actual complexity of circular economy, this toolkit is actually similar to a qualitative environmental checklist assessment with a trinary-based questionnaire. With the ternary scale, the user has the habit to put the cursor in the middle. In addition, some questions could lead to different interpretations (e.g., what is considered as many or few mechanical connections?)(Saidani et al., 2017)



Answer the questions below to find potential improvements in your organisation:

* Company type: Manufacturer

* Product type: LCD TV

* Use: ○ Just playing ● Serious

Design, Manufacture and Distribute

No material is used in excess, product is totally dematerialised — High waste of material, could be reduced through redesign

100% Biodegradable — High percentage of technical, non-biodegradable materials

100% Recycled materials used — High percentage of virgin, non-recycled materials

Scarce materials in product, e.g. Antimony, Cobalt

Figure 2.12 Circular Economy Toolkit (Circular Economy Toolkit, n.d.)

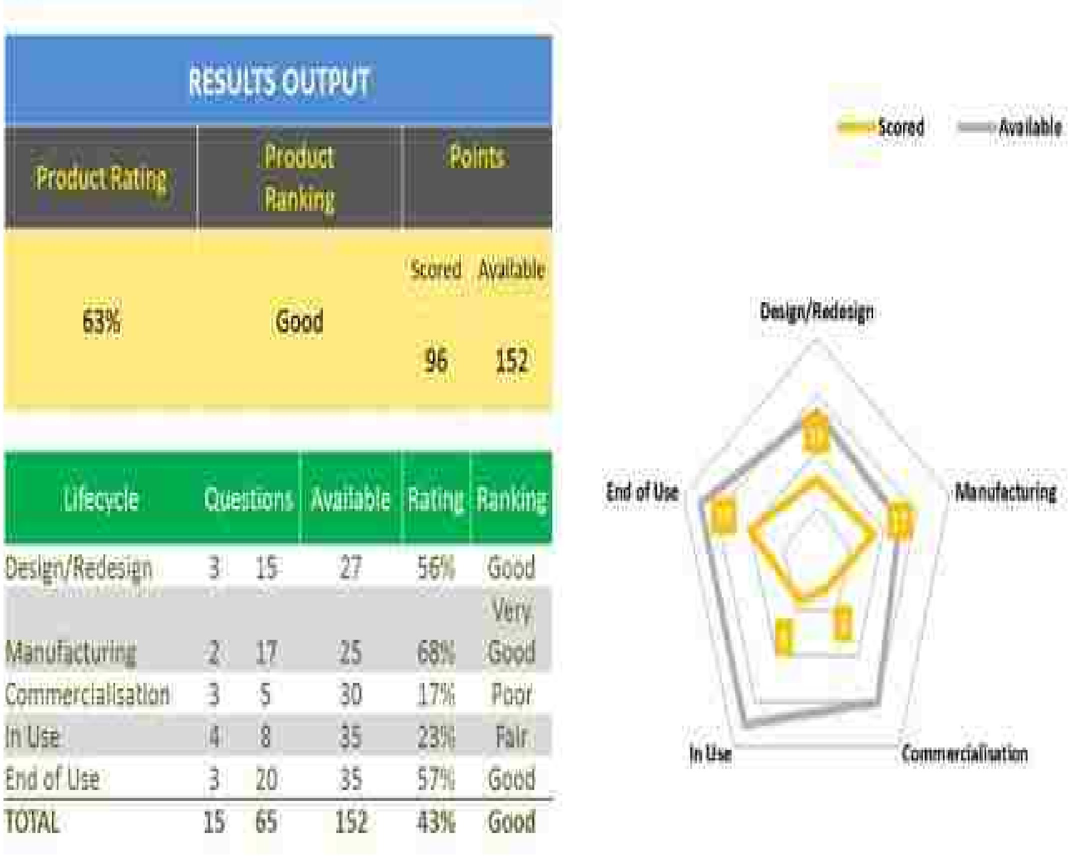
2.4.2. Circular Economy Indicator Prototype (CEIP)

Another tool found to measure the Circular Economy is the ***Circular Economy Indicator Prototype*** (CEIP) developed by Griffiths and Cayzer (Griffiths & Cayzer, 2016), available on demand, aims at evaluating product performance in the context of circular economy. The CEIP is designed on an Excel calculation sheet. The CEIP uses a points-based questionnaire. Fifteen weighted questions are divided into 5 lifecycle stages, as following: *design or redesign; manufacturing; commercialization; usage; and end-of-life.* Once the questionnaire is completed, one gets an overall score of the product circularity performance plus a spider diagram showing circularity performance across different parts of the life cycle. (Saidani et al., 2017)

The CEIP is initially intended to be used by manufacturing and/or retail companies of tangible goods with access to bill of materials. They would use the CEIP to measure and evaluate the performance of their products against the EMF CE principles

Limitation of this tool:

The ***Circular Economy Indicator Prototype*** (CEIP) interpretation through a single score hides the true circular economy complexity. The binary scoring system used for some questions could be quite reductive for some questions. Authors of the CEIP (Griffiths & Cayzer, 2016) acknowledge a superficial commitment with decision-makers and that the reliability of the questionnaire is based on the case study specific context: the 15 questions are mainly focused on the manufacturing and end-of-life stages of the product lifecycle, and therefore neglect certainly other circular economy crucial aspects. Several attributes suitable to move towards an efficient circular economy of products are not taken into account such as***, modularity***, ***design for disassembly***, ***upgradability***, used of new technology or connected devices: for instance, sensors to enable product traceability.(Saidani et al., 2017)



RESULTS OUTPUT

Product Rating	Product Ranking	Points	
		Scored	Available
63%	Good	96	152

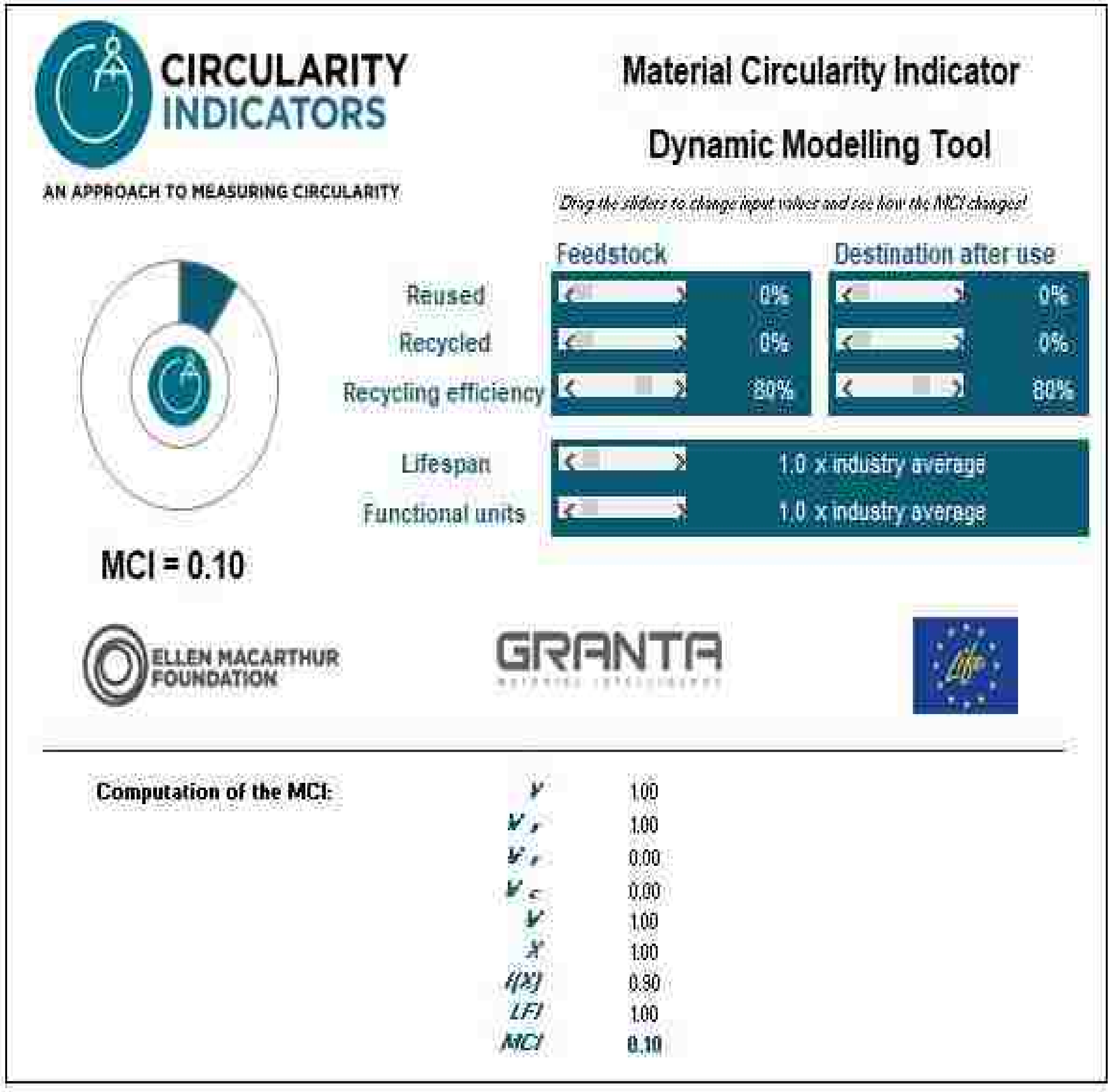
Lifecycle	Questions		Available	Rating	Ranking
Design/Redesign	3	15	27	56%	Good
Manufacturing	2	17	25	68%	Very Good
Commercialisation	3	5	30	17%	Poor
In Use	4	8	35	23%	Fair
End of Use	3	20	35	57%	Good
TOTAL	15	65	152	43%	Good

Figure 2.13 Circular Economy Indicator Prototype (CEIP) (Cayzer, Griffiths, & Beghetto, 2017)

2.4.3. Circularity Indicators by Ellen Mac Arthur Foundation

The Circularity Indicators developed by The Ellen MacArthur Foundation are indicators that assess how well a product or company performs in the context of a circular economy, thereby allowing companies to estimate how advanced they are on their journey from linear to circular (Ellen MacArthur Foundation, 2015a). These indicators can be used as ***decision-making tool*** for designers, in addition to several other purposes including ***internal reporting***, ***procurement decisions*** and the ***evaluation or rating of companies***.

This Methodology consists of main indicator called Material Circularity Indicator (MCI) in addition to other complimentary indicators called (risk and impact indicators). The indicators in this methodology are used to measure the circularity of a product and a company. Figure 2.14 illustrate a Circularity Indicators tool that has been developed by Granta Design Ltd. (a materials engineering software company) and used in the calculation of the material circularity indicator on the product level.



	Feedstock	Destination after use
Reused	0%	0%
Recycled	0%	0%
Recycling efficiency	80%	80%

Lifespan: 1.0 x industry average
Functional units: 1.0 x industry average

MCI = 0.10

Computation of the MCI:

V	1.00
W_0	1.00
W_F	0.00
W_C	0.00
W	1.00
X	1.00
$F(X)$	0.90
LFI	1.00
MCI	0.10

Figure 2.14 MCI- Dynamic Modeling Tool

(Ellen MacArthur Foundation, 2015c)

2.5 The Ellen MacArthur Methodology (In depth approach)

“The Circularity Indicators Project aims to address the need for developing indicators that assess how well a product or company performs in the context of a circular economy, thereby allowing companies to estimate how advanced they are on their journey from linear to circular (Ellen MacArthur Foundation, 2015a). These indicators can be used as ***decision-making tool*** for designers, in addition to several other purposes including ***internal reporting***, ***procurement decisions*** and the ***evaluation or rating of companies***.

The Ellen MacArthur Foundation was founded in 2010 and works in education, business and insight and analysis to accelerate the transition to a circular economy. While Granta Design, is the world leader in materials information technology. Their software tools, materials data and materials database solutions help engineering enterprises to manage vital materials data, enable better materials decisions, design for environmental objectives and regulations, and provide materials support for engineering design, analysis and simulation.
This methodology focuses exclusively on technical cycles and materials from non-renewable sources, where the developed indexes consist of a main indicator, the ***Material Circularity Indicator*** (MCI), measuring how restorative the material flows of a product or company are, and complementary indicators that allow additional impacts and risks to be taken into consideration.

Material Circularity Indicator (MCI)

The Material Circularity Indicator (MCI) is an indicator that measures how restorative the material flows of a product or a company is, it is used to measure the extent to which linear flow has been minimized and restorative flow maximized for its component materials and how long and intensively a product is used compared to a similar industry-average product.

The MCI is essentially constructed from a combination of three product characteristics: the mass
$\boldsymbol{V}$of virgin raw material used in manufacture, the mass $\boldsymbol{W}$of unrecoverable waste that is attributed to the product and a utility factor $\boldsymbol{X}$ that accounts for the length and intensity of the product's use.

Any product that is manufactured using only virgin feedstock and ends up in landfill at the end of its use phase can be considered a fully ‘linear’ product. On the other hand, any product that contains no virgin feedstock is completely collected for recycling or component reuse and where the recycling efficiency is 100% can be considered a fully ‘circular’ product. In practice, most products will sit somewhere between these two extremes and the MCI measures the level of circularity in the range 0 to 1. “MCI is an indicator that provides an indication of how much a product's materials circulate, it neither takes into account what these materials are, nor does it provide information on other impacts”. (Ellen MacArthur Foundation, 2015a).

This indicator can be used in the ***design of new products*** to take circularity into account as an input for design decisions, where many aspects of product design can influence the circularity scores range from material choices to new business models for the product. In addition to that these indicators can be used for ***internal reporting purposes*** were companies can compare different products regarding their circularity and capture the benefit related to raw material price savings as those allow these organizations to use the indicator as part of their procurement decisions, for example, by defining a minimum threshold for the products they buy. (Ellen MacArthur Foundation, 2015a).

The Material Circularity Indicator (MCI) developed in this methodology focuses on the restoration of material flows at product and company levels and is based on the following four principles:

i) using feedstock from reused or recycled sources – Feedstock reuse and recycle
ii) reusing components or recycling materials after the use of the product- Post use reuse or recycle

iii) keeping products in use longer (e.g., by reuse/redistribution) – Product life
iv) making more intensive use of products (e.g. via service or performance models)- Product utility

The lifetime and Utility of a product

A product is considered more circular if it is used longer, even if it is land filled after its use. Circular Economy is all about the initiatives that can create an important impact in materials use. In fact, an increased serviceable life or higher usage intensity leads to substantial materials savings. Longer serviceable lives also enable the creation of repair, reuse and/or resale (e.g. refillable products or second-hand shops) and are therefore well suited to the idea of increased circularity and correspond to inner, short cycles. ((Ellen MacArthur Foundation, 2015a).

In the development of the MCI the proportion of the product being restored (through component reuse and recycling, (either feedstock or post used recycled or reused materials) and coming from reused or recycled sources is described as the restorative part of the flow, while the linear part of the flow is the proportion coming from virgin materials and ending up as landfill (or energy recovery).
The product life extension and product utilization mentioned above are treated as improvements on the utility of a product and considered as additional component in the derivation of the MCI that depends on the linear part of the flow.

As part of the project, the Ellen MacArthur Foundation has provided an easy to use Excel-based model (Dynamic Modeling Tool) as can be seen from Figure 2.12. It is used to illustrate the functioning of the methodology on the product level. This is downloadable from the Circularity Indicator Project website (Ellen MacArthur Foundation, 2015c).

While the MCI provides an indication of how much a product's materials circulate, it neither takes into consideration what these materials are, nor does it provide information on other impacts of the product which makes it a general indicator. As additional support to decision making, this methodology recommends an approach to prioritize product improvements by using the MCI in combination with other complementary indicators to identify relevant risks and impacts, these indicators are described next.

Complimentary Indicators

There are two complimentary indicators used in the Ellen MacArthur foundation in addition to the material circularity indicator known by, the risk and the impact indicators:

1. **Complementary risk indicators**: an indication on the ***urgency of implementing*** circular practices which are related to the drivers for change from the current linear model. These include, measures of ***Material scarcity*** (which has a substantial impact on the value of recovering the materials), ***Material Price Variation Risk***, ***Material Supply Chain Risks***, in addition to a ***Measure of toxicity*** (which impacts the risks and costs of manufacture reverse logistics and public safety liabilities).

2. **Complementary impact indicators:** giving an indication of some of ***the benefits*** of circular models. They include a measure of the ***energy usage***, ***CO2 Emissions*** and ***water impacts*** of a given setup.

Assumptions and Limitations:

The model of this methodology has been built on the following assumptions (Ellen MacArthur Foundation, 2015a):

1. The indicator does not explicitly favour closed loops. For example, that material recovered for recycling does not need to return to the original manufacturer.

2. It is assumed that recovered material at the end of use can be processed to a similar quality as the original virgin material.

3. It is assumed that there are no material losses in preparing collected products for reuse.

4. It is assumed that all material is cycled in ***technical cycles***; biological cycles are not taken into consideration.

5. It is assumed that the mass of the product does not change from manufacture to the end of use. This means that no part of the product is 'consumed' (e.g. eaten or burned) during its use.

2.5.1. Terminology used in this methodology:

Following are some definitions of principal terms and variables used by Ellen MacArthur foundation to measure the circularity of a product.

Table 2.1 Terminologies used in CE (Ellen MacArthur Foundation, 2015a).

	Term	Definition
1	**Biological cycles**	In biological cycles, non-toxic materials are restored into the biosphere while rebuilding natural capital, after being cascaded into different applications.
2	**Technical cycles**	In technical cycles, products, components and materials are restored into the market at the highest possible quality and for as long as possible, through repair and maintenance, reuse, refurbishment, remanufacture, and ultimately recycling
3	**Biosphere**	The biosphere denotes the global sum of all ecosystems on the planet, including all life forms and their environment. This corresponds to a thin layer of the earth and its atmosphere – extending to about 20 km
4	**Natural capital**	Natural Capital can be defined as the earth's stocks of natural assets, which include geology, soil, air, water and all living things
5	**Linear economy**	A linear economy consists of 'take, make, dispose' industrial processes and associated lifestyles resulting in a depletion of finite reserves. Virgin materials are used to create products that end up in landfills or incinerators.
6	**Circular economy**	A circular economy is a global economic model that decouples economic growth and development from the consumption of finite resources. It is restorative by design, and aims to keep products, components and materials at their highest utility and value, at all times.
7	**Life cycle assessment (LCA)**	LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service. It is derived by compiling an inventory of relevant energy and material inputs and environmental releases and evaluating the potential environmental impacts associated with identified inputs and releases
8	**Service model**	A business model in which customers pay for services instead of products. For example, this would include leasing, short-term hire or performance-based usage contracts.

Table 2.2 Terms and variables used to measure product circularity (Ellen MacArthur Foundation, 2015a)

	Term	Definition
1	**Virgin material**	Material that has not been previously used or consumed, or subjected to processing other than for its original production
2	**Feedstock**	Feedstock is anything used to produce a new product. This in particular includes raw materials (from either virgin or recycled sources) but can also include components from old products used in a new product.
3	**Linear flow**	The linear part of the material flow of a product is the part that comes from virgin materials and ends up as landfill (or energy recovery)
4	**Closed loop**	In a closed loop, used products come back to the original manufacturer and components or materials are used again to produce new products of the same type.
5	**Restorative flow**	The restorative part of the material flow of a product is the proportion that comes from reused or recycled sources and is restored through reuse or recycling.
6	**Reuse**	To reuse a product is to reintroduce it for the same purpose and in its original form, following minimal maintenance and cosmetic cleaning. Within this methodology, this is considered via an increase of the product's utility (lifetime or functional units). If a product cannot be reused as a whole, individual components can be reused in a functional way. Within this methodology this is considered through the fraction $\boldsymbol{F_U}$ of the mass of feedstock for the product from reused sources and the fraction $\boldsymbol{C_U}$of mass of the product going into component reuse
7	**Refurbishment**	Refurbishment is the process of returning a product to good working condition by replacing or repairing major components that are faulty or close to failure and making cosmetic changes to update the appearance of a product, such as changing fabric or painting
8	**Remanufacture**	Remanufacture denotes the process of disassembly and recovery at the sub-assembly or component level. Functioning, reusable parts are taken out of a used product and rebuilt into a new one. This process includes quality assurance and potential enhancements or changes to the components.
9	**Recycling**	Recycling is the process of recovering materials for the original purpose or for other purposes. The materials recovered feed back into the process as crude feedstock. Recycling excludes energy recovery
10	**Upcycling**	Upcycling denotes a process of converting materials into new materials of higher quality and increased functionality
11	**Downcycling**	Downcycling is a process converting materials into new materials of lesser quality and reduced functionality.
12	**Lifetime**	The lifetime is the total amount of time a product is in use, including potential reuse of the whole product. The lifetime can be increased by repair or maintenance.

	Term	Definition
13	**Use phase**	The use phase of a product starts when it reaches its first users and ends when it is not reused any more as a whole. After the use phase, components can be reused and the rest of the product can go into recycling, energy recovery or landfill
14	**Material Circularity Indicator**	The main indicator developed in this methodology. It assigns a score between 0 and 1 to a product (or company) assessing how restorative or linear the flow of the materials for the product (or the company's products) and how long and intensely the product (or the company's products) is used compared to similar industry-average products
15	**Fully linear product**	A product is called fully linear if it is made purely from virgin material and it completely goes into landfill or energy recovery after its use, that is, LFI = 1.
16	**Total mass flow**	The total mass flow for a product is derived as the sum of the amounts of material flowing in a linear and a restorative fashion.
17	**Unrecovered waste**	Unrecoverable waste includes waste going to landfill, waste to energy and any other type of process after the use of a product where the materials are no longer recoverable
18	**Functional unit**	is a measure of the product's use. For example, it could be one kilometer driven for a car, or one wash cycle for a washing machine
19	**Utility**	The utility of a product measures how long and intensely it is used compared to an average product of the same type. The utility is derived from the lifetime and functional units of a product (compared to an industry-average product of the same type)
20	**Complementary impact indicators**	The complementary impact indicators described in this methodology are designed to give an indication of some of the benefits of circular models. For example, they include measure of the energy and water impacts of a given setup
21	**Complementary risk indicators**	The complementary risk indicators described in this methodology give an indication on the urgency of implementing circular practices. These are related to the drivers for a change from the current linear model and include measurements for material scarcity or toxicity.
22	**Sub-assembly**	A unit assembled separately but designed to be incorporated with other units into a larger manufactured product.
23	**Component**	In general, a component is part or element of a larger whole, for example, a product, especially a part of a machine or vehicle.
24	**Component reuse**	Individual components being reused in a functional way. Reuse in this definition excludes a direct use of the product as a whole, which is taken to be part of the use phase. It is also assumed that there are no material losses in preparing components of collected products for reuse.

Table 2.3 Symbols used in calculating the MCI (E MacArthur, 2015)

	Symbol	Definition
1	$\boldsymbol{M}$	Mass of a product
2	$\boldsymbol{F_R}$	Fraction of mass of a product's feedstock from recycled sources
3	$\boldsymbol{F_U}$	Fraction of mass of a product's feedstock from reused sources
4	$\boldsymbol{V}$	Mass of virgin feedstock used in a product
5	$\boldsymbol{C_R}$	Fraction of mass of a product being collected to go into a recycling process
6	$\boldsymbol{C_U}$	Fraction of mass of a product going into component reuse
7	$\boldsymbol{E_C}$	Efficiency of the recycling process used for the portion of a product collected for recycling
8	$\boldsymbol{E_F}$	Efficiency of the recycling process used to produce recycled feedstock for a product
9	$\boldsymbol{W}$	Mass of unrecoverable waste associated with a product
10	$\boldsymbol{W_0}$	Mass of unrecoverable waste through a product's material going into landfill, waste to energy and any other type of process where the materials are no longer recoverable
11	$\boldsymbol{W_C}$	Mass of unrecoverable waste generated in the process of recycling parts of a product
12	$\boldsymbol{W_F}$	Mass of unrecoverable waste generated when producing recycled feedstock for a product
13	$\boldsymbol{LFI}$	Linear Flow Index
14	$\boldsymbol{F(X)}$	Utility factor built as a function of the utility $\boldsymbol{X}$ of a product
15	$\boldsymbol{X}$	Utility of a product
16	$\boldsymbol{L}$	Actual average lifetime of a product
17	$\boldsymbol{L_{av}}$	Actual average lifetime of **an industry-average product** of the same type
18	$\boldsymbol{U}$	Actual average number of functional units achieved during the use phase of a product
19	$\boldsymbol{U_{av}}$	Actual average number of functional units achieved during the use phase of **an industry-average product** of the same type
20	$\boldsymbol{MCI_P}$	Material Circularity Indicator of a product

2.5.2. Calculation of Material Circularity Indicator

The following figure explains the flow diagram for a product from the cradle to the crave based on Ellen MacArthur foundation methodology

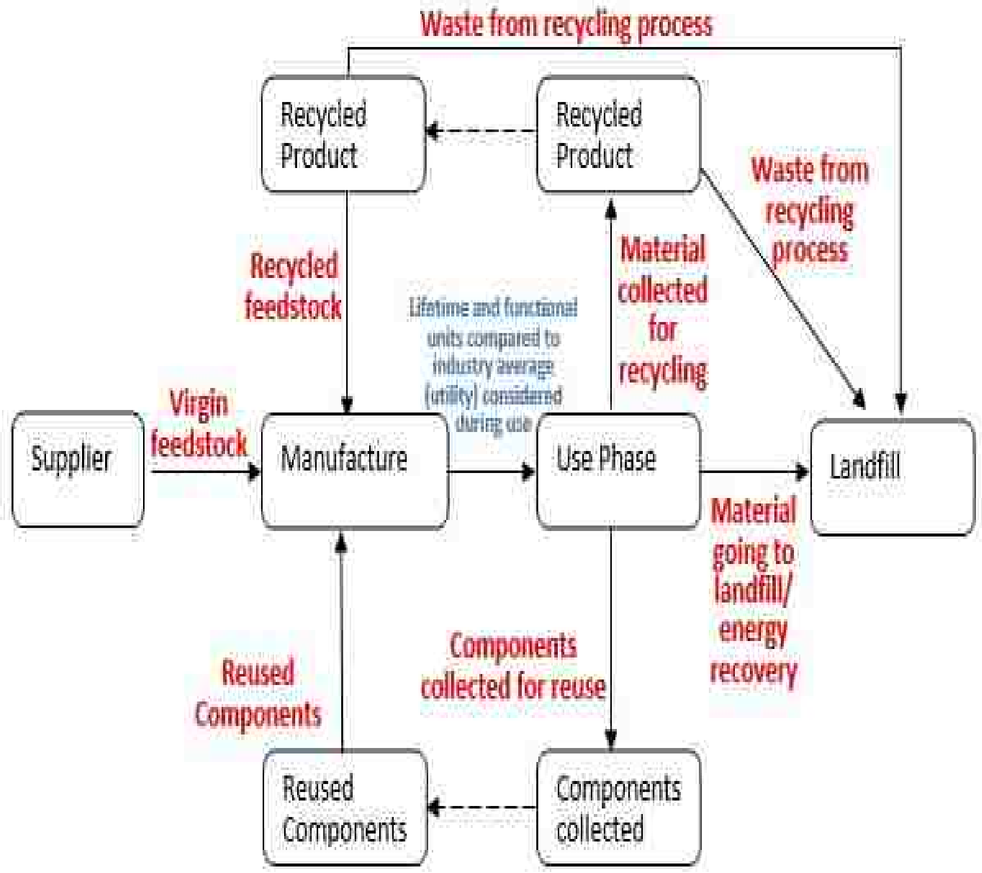


Figure 2.15 Material Flow Diagram Adapted from (Ellen MacArthur Foundation, 2015a).

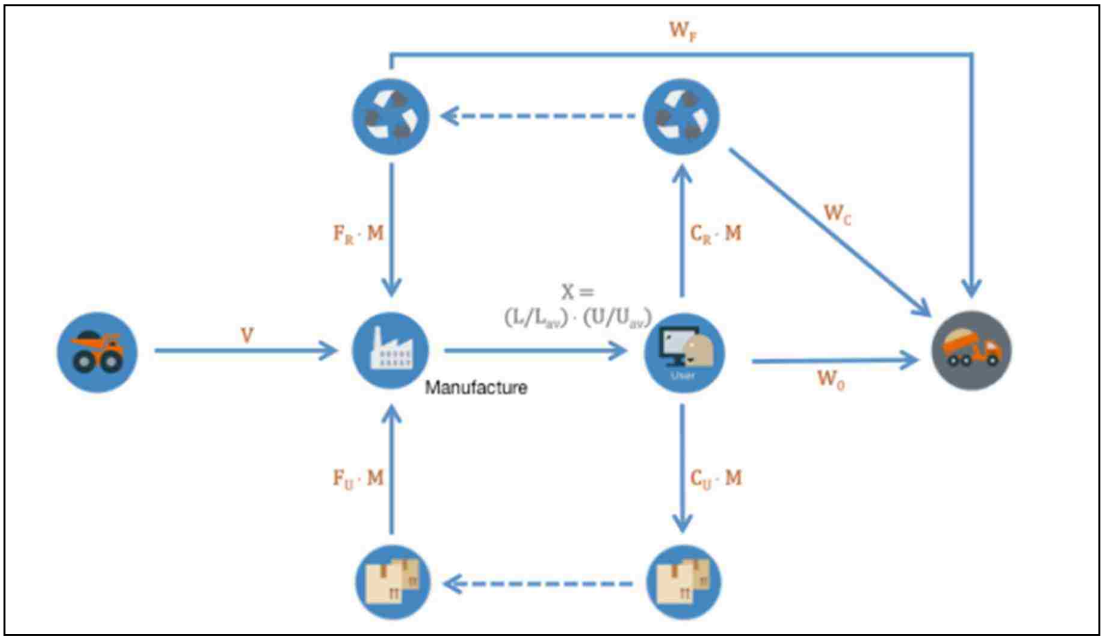


Figure 2.16 Material flow showing symbols used (Ellen MacArthur Foundation, 2015a).

Following are the equations used by Ellen MacArthur Foundation to calculate the **Material Circularity Indicator (MCI)**:

1- **Calculating Virgin Feedstock:**

$$V = M(1 - F_R - F_U) \tag{2.1}$$

M : is the mass of the finished product
F_R: is the fraction of feedstock derived from recycled sources
F_U: is the fraction from reused sources

2- **Calculating Unrecoverable Waste**

$$W_0 = M(1 - C_R - C_U) \tag{2.2}$$

C_R: **is** the fraction of mass of the product being collected for recycling at the end of its use phase
C_U: is the fraction of the mass of the product going into component reuse
W_0: is the amount of waste going to landfill or energy recovery

3- Waste generated in the recycling process

$$W_C = M(1 - E_c)\,C_R \tag{2.3}$$

E_c : is the efficiency of recycling process used to recycle the product at the end of its use phase
W_C : is the quantity of waste generated in the recycling process

4- Waste generated to produce any recycled content used as feedstock

$$W_F = M\frac{(1 - E_F)F_R}{E_F} \tag{2.4}$$

F_R : is the fraction of mass of a product's feedstock from recycled sources
E_F: is the efficiency of the recycling process used to produce the recycled feedstock
W_F: is the waste generated to produce any recycled content used as feedstock

Values for E_c and E_F are material and recycling process specific and will depend on a wide range of factors as described in the next section.

This methodology does not require a closed loop so the recycled feedstock may come from sources other than the original product, Hence, E_c is not necessarily equal to E_F and it is important to make a distinction between the recycling process used to produce the feedstock and the one used to recycle the product after collection. But in case of a closed loop, $E_c = E_F$ or in another word there will be one recycling efficiency which can be represented by E_c

5- The overall amount of unrecoverable waste is given by:

$$W = W_0 + \frac{W_F + W_C}{2} \tag{2.5}$$

6- Calculating the Linear Flow Index (LFI)

The Linear Flow Index (LFI) measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste. The LFI is computed by dividing the amount of material flowing in a linear fashion by the sum of the amounts of material flowing in a linear and a restorative fashion (or total mass flow, for short). The index takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow

LFI= liner flow / total (linear + restorative)

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{2.6}$$

LFI =1 (completely linear flow). When V and W are both equal to M, that is, when there is no recycled (or reused) content and no collection for recycling (or reuse).

$\boldsymbol{LFI}$ =0 (completely restorative flow). Occurs when $\boldsymbol{V} = \boldsymbol{W} = 0$, that is when there is 100% recycled (or reused) content and 100% collection for recycling (or reuse).

In order to ensure that $0 \leq \boldsymbol{LFI} \leq 1$, and that the $\boldsymbol{LFI}$ still represents the right proportion for situations when$\boldsymbol{E_c}< 1$ and/or $\boldsymbol{E_F}< 1$, the term $\frac{W_F-W_C}{2}$ needs to be included in the denominator of Equation (2.7). This is because

- Owing to the 50:50 approach, half of W_C is neither part of the linear nor the restorative flow as it is not assigned to the product being recycled, but to a different product that will use the recycled material as feedstock. Hence $W_C/2$ is not part of the total mass flow and needs to be subtracted from $2M$ in the denominator of Equation (2.7).

- W_F is not part of the mass M of the product but is needed additionally to create the recycled feedstock. Therefore, it is part of the total mass flow. Again, because of the 50:50 approach, the actual amount that needs to be added to the denominator of the expression in Equation (2.7) is $W_F/2$

7- Calculating the Utility

The utility $\boldsymbol{X}$ has two components:

1-Length of the product's use phase (lifetime)
2-Intensity of use (functional units)

The length component $(\frac{L}{L_{av}})$ accounts for any reduction (or increase) in the waste stream in a given amount of time for products that have a longer (or shorter) lifetime L than the industry average L_{av}, while the intensity of use component $(\frac{U}{U_{av}})$ reflects the extent to which a product is used to its full capacity.

Increasing a product's use intensity results in a more efficient use of any resources that take a linear path in the material flow, and hence an improvement in the final Material Circularity Indicator.

These two components are combined to form the utility $\boldsymbol{X}$ as

$$\boldsymbol{X} = \left(\frac{\boldsymbol{L}}{\boldsymbol{L_{av}}}\right) \cdot \left(\frac{\boldsymbol{U}}{\boldsymbol{U_{av}}}\right) \qquad (\mathbf{2.7})$$

Increasing the lifetime L when the industry average L_{av} remains fixed leads to an increase in X and, correspondingly, to an increase (and thus an improvement) in the product's MCI. Conversely, if the industry average increases (e.g. because most producers start producing more durable or repairable products) while the assessed product's lifetime remains constant, its MCI will decrease.

While this means that the MCI is affected by factors outside of a producer's control, this feature has the benefit of encouraging continuous improvement. The same argument applies to functional units. It is expected that in most cases either lifetimes or functional units, but not both, will be used to calculate X.

If lifetimes are used exclusively, this means assuming $\left(\frac{U}{U_{av}}\right)$ = 1.
If functional units are used exclusively, this means assuming $\left(\frac{L}{L_{av}}\right)$ = 1.

If the user wishes to use both lifetimes and functional units, it is important to make sure that any given effect is only considered once – either as an impact on lifetimes, or on intensity of use – but not both.((E MacArthur, 2015)

8- Calculating the Material Circularity Indicator

The Material Circularity Indicator of a product can now be defined by considering the *Linear Flow Index* of the product and a factor $\boldsymbol{F(X)}$, built as a function $\boldsymbol{F}$ of the utility $\boldsymbol{X}$that determines the influence of the product's utility on its MCI

$$\boldsymbol{MCI_P^*} = \mathbf{1 - LFI\,.\,F(X)} \qquad (\mathbf{2.8})$$

This value can be negative for products with mainly linear flows ($\mathbf{LFI} \approx 1$) and a utility worse than an average product($\mathbf{X} < 1$), to avoid this; the Material Circularity Indicator is defined as:

$$\boldsymbol{MCI_P} = \boldsymbol{max(0, MCI_P^*)} \qquad (\mathbf{2.9})$$

Given the computation of $\boldsymbol{MCI_P^*}$ as of Equation (2.10), the function $\boldsymbol{F}$ should hence have the form $\frac{a}{x}$ for some constant $\boldsymbol{a}$ Setting $\boldsymbol{a}$ = 0.9 ensures that the MCI takes, by convention, the value 0.1 for a fully linear product (i.e., LFI= 1) whose utility equals the industry average (i.e., $\boldsymbol{X}$ = 1). So $\boldsymbol{F}$ takes the form:

$$\boldsymbol{F(x)} = \frac{\mathbf{0.9}}{\boldsymbol{x}} \qquad (\mathbf{2.10})$$

If the utility of a product is lower than industry average, (i.e, X <1) this decrease the material circularity indicator. This means that for a product with LFI = 1 and $X < 1$, the MCIwill be smaller than 0.1 and will quickly approach zero, this allows the MCI to differentiate between a fully linear product whose values for lifespan and functional units are equal to an industry-average product of similar type (i.e., $\boldsymbol{X = 1}$ resulting in MCI_P = 0.1) and a fully linear product with lower lifespan or functional units than industry average (resulting in $0 \leq MCI_P < 1$ as indicated by Equations (2.8) and (2.9). This explains why the MCI of a fully linear product with industry-average utility has been chosen to be 0.1 instead of 0. The following chart shows how the Materials Circularity Indicator of a fully linear product varies according to its utility.

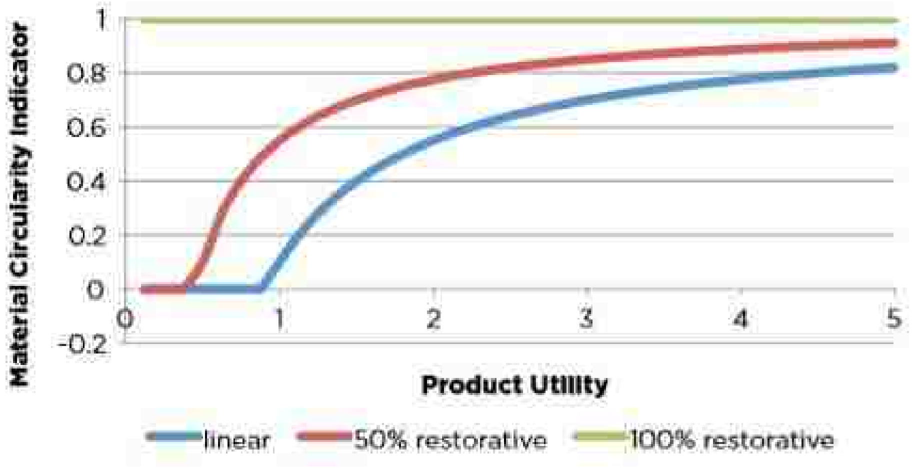


Figure 2.17 Impact of product utility on the MCI (E MacArthur, 2015)

As can be noticed from Figure 2.17, the Material Circularity Indicator of a specific product (MCIp) receives the full score of 1 for a product with fully restorative flow irrespective of the product's utility. Also note that a product's utility has much more influence on its MCI for a fully linear product compared to one with a 50% restorative (i.e. 50% linear) flow.

For Comprehensive Approach

In reality, most of the products will be produced using number of components: sub-assemblies, parts, and/or materials. If this level of detail is known, for example, via a detailed bill of materials, the Material Circularity Indicator can be built up by summing over each individual sub-assembly, part, and/or material χ.

This leads to a revised set of equations. A subscript (χ) on all the symbols previously defined is used to denote a quantity for a specific sub-assembly, part, or material χ. For example, $M(X)$refers to the mass of sub-assembly, part, or material χ, and the total mass M is then the sum over all $M_{(X)}$.Based on the previous equations, the following quantities are defined:

1-The amount of virgin material for each sub-assembly, part, and/or material

$$\boldsymbol{V_{(X)} = M_{(X)}\left(1 - F_{R(x)} - F_{U(X)}\right)} \qquad \mathbf{(2.11)}$$

2-The total amount of virgin material (derived by summing across all sub-assemblies, parts, and/or materials):

$$\boldsymbol{V = \sum\nolimits_{X} V_{(X)}} \qquad \mathbf{(2.12)}$$

3-The amount of waste generated at the time of collection for each sub-assembly, part, and/or material:

$$\boldsymbol{W_{0(X)} = M_{(X)}\left(1 - C_{R(x)} - C_{U(X)}\right)} \qquad \mathbf{(2.13)}$$

4-The quantity of waste generated in the recycling process:

$$\boldsymbol{W_{C(X)} = M_{(X)}\big(1 - E_{C(x)}\big)C_{R(x)}} \qquad \textbf{(2.14)}$$

5-The waste generated to produce any recycled content used as feedstock:

$$\boldsymbol{W_{F(x)} = M_{(X)} \frac{\big(1 - E_{F(x)}\big).\, F_{R(x)}}{E_{F(x)}}} \qquad \textbf{(2.15)}$$

6-The total amount of waste generated:

$$\boldsymbol{W = \sum_{X}\left(W_{0(X)} + \frac{W_{F(X)} + W_{C(X)}}{2}\right)} \qquad \textbf{(2.16)}$$

7-Linear Flow Index:

$$\boldsymbol{LFI = \frac{V + W}{2M + \sum_{X}\frac{W_{F(X)} - W_{C(X)}}{2}}} \qquad \textbf{(2.17)}$$

Calculation of the MCI remains as per Equations (2.10) and (2.11). It is also possible to consider several levels: a product may be constructed from subassemblies, where each sub-assembly is built up from a number of components (which may themselves be sub-assemblies or parts), and each part is made from one or more materials. Going into additional levels of detail offers much more insight into the product.

A modeling tool was proposed by Ellen MacArthur Foundation to Measure the Circularity of a product as shown previously in Figure 2.14. It represents an Excel-based model to illustrate the functioning of the methodology at the product level. In addition to measuring the circularity of the product, this same methodology is proposing a tool to measure the circularity of a company as illustrated in Figure 2.18 which is out of the scope of this thesis.

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Select normalising factor: product mass

No.	Name of product range	Total product mass of product	MCI of ref. product
1	*Product range 1*	1,000	0.10
2	*Product range 2*	500	0.65
3	*Product range 3*	100	0.10
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			

Total product mass 1,600
Combined Material Circularity Indicator 0.27

Combined Material Circularity Indicator

MCI = 0.27

Figure 2.18 MCI Company level -Dynamic Modeling Tool - (Ellen MacArthur Foundation, 2015d).

2.5.3. MCI and LCA differences and commonalities

The MCI presents the following differences and communalities with Life-Cycle Assessment (LCA) methodologies (Ellen MacArthur Foundation, 2015a).:

- An LCA focuses on deriving the environmental impacts throughout the life cycle of a product for different scenarios, whereas the MCI concentrates on the flow of materials throughout the use of a product. It specifically encourages the use of recycled or reused material and recycling or reusing it at the end of use, while recognizing increased utility of a product (i.e. durability and usage intensity).

- Many of the input data required for an LCA are the same as for the MCI and some of the complementary impact indicators are derived from an LCA approach (relevant standards to assess the Carbon footprint of a product are used). Additionally, in the future, the MCI could be one of the parameters considered as an output from an LCA or eco-design approach alongside those already typically used(Ellen MacArthur Foundation, 2015a).

2.5.4. Profitability Impact of Circular Initiatives

As circular economy is also about creating and retaining value from products and materials, this methodology also provides guidance on assessing the ***profitability impact*** of moving to more circular business models. Businesses can capture significant economic benefits from circular economy principles: ***materials and energy cost savings***, ***new markets and sources of revenue***, and a ***greater resilience to external shocks***.

Profitability - Four Key Strategies:

Four key strategies to capture profit (Ellen MacArthur Foundation, 2015a) are as following:

1. ***Resale and Use Period Extension***

The profitability will come from capturing new markets, for example, by offering a more cost-effective option for a high-performing product, Activities such as ***repair*** and ***maintenance*** help to achieve the product's best performance for as long as possible, and when these are offered as services, they can translate into new revenue streams.

2. ***Refurbishment and Remanufacturing***

Refurbishment refers to returning a product to good working condition by replacing or repairing major components that are faulty and can also include making 'cosmetic' changes to update the appearance of a product. Remanufacturing restores at a component level: reusable parts are taken out of a used product, potentially repaired and rebuilt into a new one. This process usually includes quality assurance and products can be sold 'as-new'. Both approaches retain major parts of the integrity and complexity of a product, and therefore can also enable savings in materials and energy costs.

3. ***Service and Performance Models***

Service and performance models allow companies to preserve ownership of their products and facilitate their after-use recovery. They include models such as rentals (e.g. clothing rental model), pay-per-use (e.g. a pay-per-wash model for a washing machine) or a service offering including the maintenance, repair and upgrade of the product

4. ***Recycling.***

If there is no possibility for reuse, refurbishment or remanufacture, the materials in a product can still be recycled. While in this case all the integrity and complexity of the product is lost, the value of the materials contained in the product can be preserved. A company might decide to sell the recyclable parts of a product to a third-party treatment plant or reuse the recycled materials for its own production. In the first case, the company creates a new revenue source, while in the second case, it captures materials cost savings, but it also secures a safe supply of materials.

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It is obvious that reusing components of a product preserves more of its integrity, embedded energy, and complexity than recycling it, which consists in only recovering its basic materials but in some cases were the recycling is the only remaining option we still have to think of how to maximize the benefit of recycling by looking at different ways to improve the efficiency of recycling. Purely from the perspective of materials savings, the recycling principle is reflected in the Material Circularity Indicator through the inclusion of a factor representing the efficiency of the recycling process, while reuse is assumed to have an efficiency of 100%.

In this regard, a question was raised regarding the effect of recycling efficiency and its impact on the circularity on a product. Defiantly the improvement in design can greatly improve the profitability of the recycling process, for example by enabling easier disassembly or using pure and easy to-recycle materials. This can help to optimize the revenue or saving costs depending on the case

2.5.5. Factors affecting the recycling process efficiencies:

The variable E denotes the efficiency of the recycling process for a specific material and recycling process. Values for E will depend on a wide range of factors (Ellen MacArthur Foundation, 2015a) such as:

- **The material(s)** – some materials, for example metals, are inherently easier to recycle and will often have higher recycling efficiency.
- **The quantity of material(s) involved** – when a product is recycled the principal components by mass are often recycled with higher efficiencies than those at lower overall concentrations. Recycling efficiency is also affected by the presence of pollutant in material scrap and/or the presence of coatings.
- **The recycling preparation process** – *higher efficiency can be expected when product disassembly takes place prior to material recovery*; lower values are more likely when a product comprises number of components of different material types and is fragmented prior to some form of materials separation process.

2.5.6. Recycling, Downcycling and upcycling

As it was mentioned before, if there is no possibility for reuse, refurbishment or remanufacture, the materials in a product can still be recycled. In this case all the integrity and complexity of the product is lost but the value of the materials contained in the product could still be preserved. But there are different types for recycling, there is the *recycling* where is the material extracted after recycling can be used for the same level of quality and the economic material value or there is the term *downcycling* which is often used to describe a recycling process that reduces the quality and economic value of a material or product. Similarly upcycling is used to describe a recycling process that increases the quality and economic value of a material or product.

Both terms (Upcycling and downcycling) are open to very wide interpretation and no standard definitions have been generally adopted. In practice, there exists a continuum of varying degrees of down- and upcycling. This methodology (Ellen MacArthur's methodology) does not incorporate any form of sliding scale to accommodate these. Rather, the following rules and guidance should be followed when material is considered as being collected for recycling.

General requirement for recycling

Following are assumptions used for recycling by (Ellen MacArthur Foundation, 2015a):

1. The collected material should be able to be separated into its component materials using a proven, financially viable process. It should not remain as an inseparable mixture of different materials.

2. A mixing of colors and minor contaminations are acceptable

3. If it can be proven that the material mix is used in products for which a further recycling process exists that allows the material mix to be recovered and recycled again, the downcycling into the material mix can be considered recycling.

   If downcycled material is used as a feedstock, it is generally acceptable to consider this as recycled material (bearing in mind that the material cannot be considered as collected for recycling at the end of use unless the above requirements are satisfied). For example, consider a product that contains aluminum and plastic that cannot be economically separated after the product's use. The mix of those two materials could theoretically be used in similar applications as the plastic on its own. However, in this example, it is assumed that currently there is no market for this material and no recycling stream at the end of use for a product using this mixed material as a feedstock. Hence the portion of the mass of the original product represented by these two materials cannot be considered as collected for recycling.

Advantage of Ellen MacArthur methodology

Circularity Indicators proposed by MacArthur are tools used to measure the product circularity as well as the company circularity. It is particularly intended for use in *product design* but could also be used in *internal reporting* or *for procurement and investment* decisions. Furthermore, variants or extensions of the indicators could be used in *education, research, rating or policy making*. (Ellen MacArthur Foundation, 2015a)

It is mainly ***quantifying*** the restoration of material flows and the development of a Material Circularity Indicator (MCI) which represents the main indicator in addition to considering other factors such as (toxicity, scarcity and energy) which are considered as complimentary indicators. It is used for different products and is not limited to specific family of products.

It is a standardized indicator, measurable where the amount of material recovered and the recycling efficiency are taken into consideration in addition to other factors such as the material price variation, material supply chain risk and the material toxicity which are considered as complimentary risk indicators and the CO2 emission and water impact as complimentary impact indicators.

Limitation of Ellen MacArthur methodology

This methodology did not take the product complexity into consideration and there was no corrective action for the products that are considered linear were the score or MCI approaching zero. In another word the following concepts such as design for disassembly, design for recycling, upgradability and modularity were not taken into consideration to make the product more recyclable.

2.6. Comparison between the three indicators:

The following table represents a comparison between the three circularity indicators:

Table 2.4 Comparison between the three indicators (CET), CEIP) (EMFM):

	Circular Economy Toolkit (CET)	Circular Economy Indicator Prototype (CEIP)	Ellen Mac Arthur Foundation Indicator EMFM
Measurable/ Quantitative		✓	✓
Recycled / non recycled material	✓	✓	✓
Material Toxicity	✓		✓
Product Life time	✓	✓	✓
Product utility	✓		✓
Product recovery		✓	✓
Ease of Disassembly	✓		
Product Modularity and upgradability	✓		
Recycled Efficiency			✓
scarce materials/ precious material use	✓		✓
environmental assessment (Carbon, Water, energy)	✓		✓
waste sent to landfill	✓	✓	✓
%Recycled & reused feedstock			✓
%Recycled & Reused after use			✓

2.7. Research Gap related to Circularity Indicators:

From Table (1) we can notice that the Ellen MacArthur Foundation methodology was more accurate indicator especially because the other two indicators (CET) & (CEIP) are a qualitative way of assessment with questionnaire format used to assess the circularity of the product while the Ellen MacArthur Methodology (EMFM) with its main indicator (MCI) and the complementary indicators considered more accurate indicator to measure the product circularity.

In the latter methodology the main indicator (MCI) assigns a score between 0 and 1 to a product (or company) assessing how restorative or linear the flow of the materials for the product (or the company's products) and how long and intensely the product (or the company's products) are used compared to similar industry-average products. This indicator is used to measure many aspects that are relevant to make progress towards a more circular mode.

Although this methodology proposed by Ellen MacArthur Foundation to measure the product circularity is considered more accurate that the two other indicators, there are still some aspects that were not taken into consideration some of them are the product complexity, modularity and ease of disassembly and other improvements such as upgradability, connectivity, or design for preventive maintenance of products which are recognized as enablers of an efficient circular economy are not considered here. Another important factor that will not be discussed further in this thesis is the collaborations between stakeholders, inside the actor's network, or reverse logistic, which are also crucial elements for a strong and functioning circular economy are either not explicitly considered

Next chapter will be a literature review on the complexity of a product and the methodologies used to measure the ease of disassembly. A review investigating the available methods is required to find the effect of product complexity on the recycling efficacy and in turn on the Circularity of a product.

CHAPTER 3. PRODUCT COMPLEXITY

3.1.Introduction:

“No longer can a product be designed considering only the factors of cost and performance but rather a shift from the traditional design practices must include consideration of the ultimate end of the product’s life” (Soh, Ong, & Nee, 2015). From that perspective it is becoming a must to focus on the early stages of design to aid the process of economical material recovery and to address waste disposal in a proactive manner.

In this literature review, a research will be performed to understand the meaning of product complexity, factors affecting disassembly, such as the time required to disassemble a product and the sequence of disassembly and how the product complexity affect recycling a specific product. A paper by (Johnson & Wang, 1998) introduced a procedure to improve the efficiency of the disassembly planning process and proposed a method to generate an optimal disassembly sequence which maximizes profit. In this paper the authors embrace the method of profitability and looks at the feasibility of disassembly by calculating if disassembling a product and recycling it would be profitable than discarding it. That raised a question of the reason behind disassembly for recycling, why we invest time and money to disassemble a product and recycle it? Actually, some recycling companies would go for shredding the products first then sorting and collecting the useful material rather than disassembling it. Away from the environmental aspect the feasibility of disassembly is a major factor cannot be ignored.

One paper by (Soh et al., 2015) interprets the product complexity by looking at the difficulty of disassembling a product based on factors related to the shape and size of the product such as factors affecting the handing and removal of different components, while other paper (Vanegas et al., 2018) explains a method for ease of disassembly know as (eDiM) where the difficulty of disassembly is measured based on the time required to disassemble a product, and finally a detailed review on a method uses the time of disassembly and the value of material disassembled as factors to measure the profitability of recycling will be included.

Before going into detail about each method, different terminologies will be explained such as the process of disassembly, types of disassembly, disassembly sequence generation, time of disassembly and ease of disassembly. In addition to different methods used in design such as Design for Disassembly (DFD) and Design for Recycling (DfR) as well as material circularity index.

3.2Disassembly and types of disassembly:

Disassembly process: is defined in Cambridge dictionary as the process of separating a machine or structure into its different parts, other paper defines the disassembly process as a systematic method for separating a product into its constituent parts, components and subassemblies (De Mello & Sanderson, 1990). The disassembly process is usually performed manually or automatically.

From the disassembly point of view, there are two main types of disassembly methods. One is **complete disassembly** which involves disassembling of all the components of an assembly or a complex object. In some cases, it is not considered the optimal solution due to the high costs of the disassembly process.

Alternatively, **selective disassembly** is a disassembly which requires only a portion of an assembly with high value to be disassembled and it is usually more appropriate for demanufacturing applications, such as: maintenance, repairing or recycling. Another definition for s***elective disassembly*** is the reversible dismantling of complex products into fewer complex subassemblies or single parts (Nevins & Whitney, 1989) , usually the most economical assembly sequences is not the most economical disassembly sequences.

Destructive disassembly: is a disassembly in which a component is removed from the product, by destroying or damaging some other components of the product while **(no-destructive disassembly)** is a disassembly in which each one of the components can be removed without affecting any of the others (Pomares, 2004)

Design for Disassembly. a formal method by which designers and engineers consider the disassemblability of a product during the initial phase of design. This is motivated by various factors including, but not limited to: maintainability, serviceability, repairability, recyclability, component reuse, and waste. Specifically, disassembly is the "process of systematic separation of a product into its components, subassemblies, materials, and other groupings" (Ilgin & Taşoğlu, 2016)

Design for disassembly is a technique which focuses on designing the product for easier disassembly and material retrieval. (Desai & Mital, 2003)

Product disassembly analysis

Disassembly mode analysis is the method of describing which disassembly analysis is important to the designers. There are three ways of analyzing disassembly (Johnson et al., 1998)

1- ***Component-based analysis***: focused on a particular component or group of components in a product (e.g. the dashboard and console of an automobile).

2- ***Material-based analysis***: focused on a particular material type or group of materials types in a product (e.g. all ABS polymers in a photocopier).

3- ***Product-based analysis*** (or product disassembly analysis or PDA): is focused on the entire product including all materials and components

Design for recycling

Design for Recycling (DfR) can be defined as a design for ease of product recycling and maximum output. It involves number of general guidelines on hazardous materials, connections, construction and accessibility of parts. DfR can be seen as a part of Design for Environment and Sustainability (DfES), where the main goal being sustainability and responsibility towards future generations. (Hultgren, 2012)

Disassembly advantage (Product disassembly Vs product shredding for recycling):

The efficient disassembly of products as opposed to recycling a product by shredding has many advantages including the following:

1. Components that are of good quality can be refurbished or reused.
2. Metallic parts can be separated easily into categories which increases their recycling value.
3. Disassembled plastic parts can be easily removed and recycled.
4. Parts made from other material such as glass or hazardous material can easily be separated and reprocessed.

Recyclability

The term recyclability in general is defined as the "recycling potential" of the product. It takes into consideration its chemical content, which materials are used, how materials are combined and how components are connected. It includes materials that can be diverted from the waste stream and returned to use as a part or raw material for the manufacture of a new product. This should be possible to perform through a process that is widely available at present (Hultgren, 2012).

Recyclability of a part or subassembly depends on its ease of disassembly from the remainder of the product and there are number of pre-existing rating systems that compare the ease of disassembly of different types of joints as will be discussed later.

Recyclability is also can be defined as the ability of a material to regain the properties it possessed in its virgin state, where virgin state refers to the material in its purest form before being processed or shaped for a specified use defined by the designer. (Simon, 1993)

This can be estimated by devaluation of the respective material's cost (Bebb, 1990). This is performed by factoring cost of the material after first use, the cost associated with recycling the material (disassembly cost, processing, transportation, distribution, etc.), and the cost of the recycled material.

Recyclability Rate:

In order to calculate the recyclability rate, a method by (Umeda, Fukushige, Mizuno, & Matsuyama, 2013) was used where the recyclable mass of each component in the product is calculated first then the recyclability rate of the entire product is calculated by dividing the total recyclable mass of its components over the total mass of the product.

$$\boldsymbol{R_{cyc}} = \frac{\mathbf{M_R}}{\boldsymbol{M}} = \frac{\sum_{\mathbf{k}} \mathbf{M_K}}{\mathbf{M_{Total}}} \qquad (\mathbf{3.1})$$

$$\boldsymbol{M_k} = \sum_{i} \boldsymbol{r_i^j}\ \boldsymbol{m_i} \qquad (\mathbf{3.1a})$$

Where:

$\mathrm{M}_{\mathrm{Total}}$: is the total mass of the product

$\boldsymbol{r_i^j}$: is the material recyclability

$\boldsymbol{m_i}$: is the mass of the $\mathbf{i_{th}}$ material in the component

Material Recyclability Index

Villalba proposed a *material recyclability index* based on market values of any material (Villalba, Segarra, Chimenos, & Espiell, 2004). Recyclability of the material is calculated by Eq. (3.2), which is based on value of materials at three different stages of product life cycle. The three values being *value of material during first production or virgin state, value of material after its use, and value of material after it undergoes recycling*. The value of recycled material is always less than the value of material in virgin state because recycled material loses mechanical properties due to recycling process. **Recyclability index of material** lies between 0 and 1, with 0 representing non-recyclable material and 1 representing perfectly recyclable material (i.e., recycled material retains all the properties of the virgin material) (Yadav, Patel, & Morkos, 2018)

$$\boldsymbol{MR = 1 + \frac{V_p - V_r}{V_m} - \frac{V_m - V_r}{V_m} = \frac{V_p}{V_m}} \qquad (\mathbf{3.2})$$

Where:

MR= Material Recyclability Index
$\boldsymbol{V_p}$: is the value of material after it is recycled (in USD),
$\boldsymbol{V_m}$: is the value of virgin material (in USD), and
$\boldsymbol{V_r}$ **:** the value of material (in USD) after 1st use

It is important to note the difference between recyclability index of the material and how much the material is actually recycled. Since the recyclability index is based on price instead of mass, if the material has a high recyclability index, it does not necessarily mean that most of the material used in the product is recuperated.

3.3. Product Disassembly-For recyclability purposes (remanufacture, reuse or recycle)

Recyclability of a part depends on its ease of disassembly from the remainder of the product. There are number of pre-existing rating systems that compare the ease of disassembly of different types of joints. (Yadav et al., 2018) For products that will be recycled at the end of life cycle, the designer must consider its disassembly sequence and deciding that sequence can be a difficult decision at early stage of the product design. Also, the time of disassembly is another important factor in the disassembly process. All these factors play an important role in the decision of disassembly where these factors are used as an input to calculate the profitability of disassembly.

Bras suggested a multiplicative model for recyclability rating based on **type of material**, their **mass**, and **type of joint** (Bras & Emblemsvåg, 1996) . The materials are categorized based on how easily recyclable they are with current technology. The joints are rated based on their separability. A more time-consuming joint or one that requires tools or machining gets poor rating.

3.4.Disassembly Aspects- Product complexity indicators

Different methodologies were found to analyze the complexity of the product, one measure the complexity based on handling and removing the parts, second one looks at it from the prospective of time of disassembly by measuring the time required to disassemble a product, third paper analysis the complexity by working on optimizing the sequence of disassembly. Finally by looking at the complexity from the profitability point view, as was proposed by (Johnson & Wang, 1998) where an approach was used to enhance the disassembly sequence by looking at the cost of disassembly. The last approach seems more holistic since it combines the factors of time, sequence of disassembly and the material reclamation value all together in making the disassembly decision. In the following sections a literature review on the methods used to measure the complexity is listed below were Figure 3.1 below illustrate different approaches investigated to measure the disassembly process.

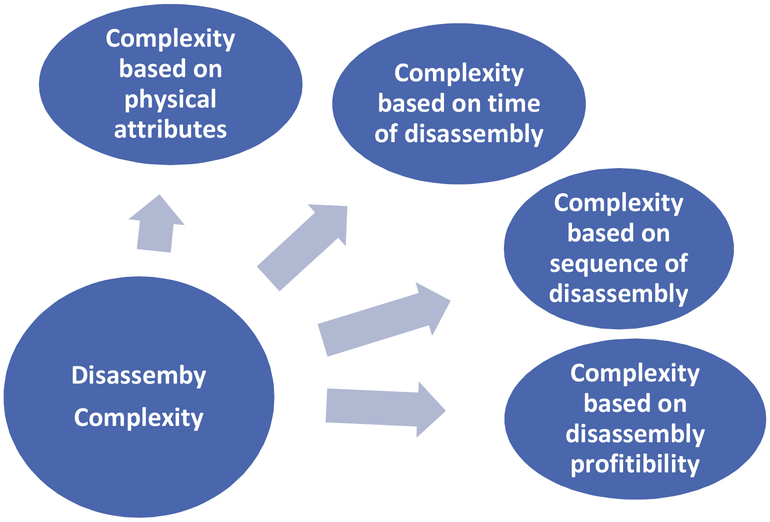


Figure 3.1 Product Complexity / disassembly Indicators

3.4.1. Complexity based on the physical attributes

In his paper (**Application of Design for Disassembly from Remanufacturing Perspective)**, S.L. Soh, S.K. Ong, A.Y.C(Soh et al., 2015) explains using metrics combination, by means of z-score computation, where part accessibility and complexity of the disassembly process, is used to measure complexity. Methodologies have been developed to evaluate assembly complexity by assigning difficulty factors to various attributes for handling and insertion during assembly (Samy & ElMaraghy, 2010)

Here the difficulty of disassembly is interpreted by the author as product complexity in the disassembly context to which individual parts or sub-assemblies have geometrical/physical attributes that can cause difficulties or problems during handling and removal of components but the limitation on this method is that it only takes the physical attributes into consideration. It is limited to investigating the product that is made of metal and it does not take the time of tool change and manipulation into consideration.

3.4.2. Disassembly sequence generation

The main objective of generating a disassembly path or sequence is to determine an optimal disassembly path based on the least effort, which is a primary objective for disassembly

Some existing studies on End of Life (EOL) option decision models assume that all components are completely disassembled. Others see that it is unnecessary disassembly cost that may be incurred in such cases of complete disassembly(Lee, Cho, & Hong, 2010) and prefer to apply selective disassembly where the optimal disassembly sequence is required to determine the shortest possible route to reach the core.

Many methodologies propose an optimal disassembly sequence in the form of mathematical models. Examples of these include optimization algorithms, algorithms based on economic analysis; CAD-based algorithms, etc.(Desai & Mital, 2005). Other methods such as the And/Or graph representation (De Mello & Sanderson, 1990) and the Petri-Net (Moore, Güngör, & Gupta, 2001) are some of the models that have been proposed to establish the relationships between the subassemblies and components, and the possible routes to disassemble a product. some papers explain the importance of finding the optimum sequence of disassembly by first generating all feasible disassembly sequences of a product (assuming complete non destructive disassembly) which provides the liaison relationship for each of the parts and subassemblies and then to determine the number of feasible disassembly routes of a part (to be retrieved). This is an important step in any disassembly process.

From recycling point view, we can notice that disassembly for recycling is totally different than disassembly for remanufacturing because in the latter case, it is important to retrieve specific important parts in non-distractive way and the parts or subassemblies that are not remanufacturable can be dismantled as a whole or can be subjected to destructive disassembly while in the case of disassembly for recycling different factors taken into consideration such as the purity of material extracted from disassembly in order to recycle it and use it and whether it is going to be recycled, upcycled or downcycled. Other important factor is the profitability of recycling which in turn is related to the time of disassembly which is other way to measure the ease of disassembly (how difficult and complex the product to be disassembled), in other word the decision to recycle or discard is related mainly to the profitability of recycling as will be seen later.

3.4.3. Complexity based on the time of disassembly -ease of disassembly

One way used to evaluate the (degree of easiness of disassembly) or disassemblability is by using the absolute metrics such as time, energy or entropy. But since energy and entropy are more difficult to measure the time has been used as a valid metric for disassembly to measure the ease of disassembly.

Many studies have used the time of disassembly as a measure to evaluate the product ease of disassembly or in another word the disassemblability. The disassembly time is ranked as the most important criterion for selecting the best disassembly sequence since a sequence based on this measure requires the minimum disassembly time and hence lower disassembly cost.(Hu, Hu, & Li, 2002).In recent publications by the JRC on the integration of resource efficiency criteria in European product policies “extraction time” has been identified as a good proxy to evaluate the easiness of disassembly(Ardente, Mathieux, & Recchioni, 2014). In addition to that time present a realistic view of the difficulty in disassembly.

Time of disassembly is used to ***compare alternative product designs*** and as a ***performance indicator*** to measure recoverability (Movilla, Zwolinski, Dewulf, & Mathieux, 2016) Therefore, a standard method to determine the ***disassembly time*** to extract components represents the basis for evaluating easiness of disassembly for ecodesign to support the enforcement of product requirements that facilitate lifetime extension strategies and improve EoL treatment.

Methods used to calculate disassembly time:

Two alternatives methods were identified to determine the *partial* or *complete* disassembly time:

1. **Direct measurement**: It is a measurement performed by several operators with varying experience on products of the same category; this approach is ***labour intensive***, ***non-reproducible*** and ***influenced by several human factors.***
   One drawback is that this method does not allow to easily quantifying the effect of product design changes without performing new measurements(Vanegas et al., 2018) but on the other hand it is the most straightforward method

2. **Calculations based on product parameters**: Some methods used to measure the time of disassembly based on product parameters are listed below:

Methods-time measurement (MTM):

It is one of the most widely accepted techniques used for DFD analysis. MTM provides a set of predetermined time data for various actions required to perform in order to disassemble a product with manual labor. This process is a time-consuming process where it requires data such as *weight of the part* and precise *distance moved by the part/tool* (Dewhurst, 1993). Therefore, this method cannot be standardized and generalized since almost all real-life disassembly processes vary with one another to some degree.

Maynard operation sequence technique (MOST):

In the 1970 s, Zandin developed a new work measurement technique, Maynard operation sequence technique (MOST) based on MTM technique. It provides predetermined time data based on sequence of basic motions that a worker would perform (Zandin, 2002).The basic principle behind MOST is that all disassembly operations can be divided into sub-activities. These sub-activities follow a certain repetitive pattern, which can be generalized such as “reach the object,” “grasp the object,” “move” and then “place it to the desired location.” It was also observed that these sub activities usually occur in the same order except for changing the tool or some other minor operations. MOST follows three standard set of sequence models to estimate the time required to disassemble by an average skilled worker: general move sequence for movement of unconstrained objects, controlled move sequence for movement of constrained objects, and tool use sequence for hand tools. (Yadav et al., 2018) These sequences are then used to calculate time measurement units (1 TMU=0.036 s) based on activities carried out by worker. It is advantageous over other time measurement techniques primarily because it is much faster, efficient, and consistent (Patil, Shinde, Katikar, & Kavade, 2004).

Another method useful to quantify the efficiency of a design in terms of assembly for both manual and automatic operation is Boothroyd–Dewhurst Method for DFA which was first proposed in 1980 by Boothroyd and Dewhurst (Boothroyd, 1983)

In **Boothroyd–Dewhurst method** for DFA, the objective was to eliminate the redundant parts instead of reducing the assembly cost. In this way the time of disassembly was optimized. In this method the following parameters were obtained by using the Boothroyd–Dewhurst method of DFA: number of parts, number of different materials, type of material, number of fasteners type of connection between parts/subassemblies, and the accessibility to joints (Yadav et al, 2018)

An approach was by Dowie and Kelly were tables for disassembly time similar to DFA table by Boothroyd and Dewhurst presented. These tables are based on **direction of motion**, **degrees-of-freedom**, **resistance to disassembl**y, **accessibility**, type **of operation (manual or tool assisted)**, and **type of joint (screws, snap fits, adhesive, etc.)** (Dowie & Kelly, 1994)

Another interesting method used is the (DeiM) by (Vanegas et al., 2018) which is a method that mimics an average disassembly setup where the required disassembly time is calculated with a standardized formula, using as input geometrical and physical product parameters verifiable on the product itself. In his paper Paul Vanegas identifies two approaches to calculate the time of disassembly one is based on the properties of the product and connectors and second is based on basic motions of disassembly tasks. In his calculations he makes the measurement reproducible and verifiable, a concern that was addressed by (Recchioni, Ardente, Mathieux, & Commission, 2016)

(DeiM) is a method that could be applicable within a policy framework, enabling the categorization of products with respect to their ease of disassembly. His approach is using a calculation sheet to measure the (eDiM) by calculating the disassembly time given the sequence of actions and basic product information, the following equation is used in his calculations:

$$\boldsymbol{eDiM} = \sum_{i=1}^{i=n} (\boldsymbol{ToolChange_i} + \boldsymbol{Identifiying_i} + \boldsymbol{Manipuation_i} + \boldsymbol{Positioning_i} + \boldsymbol{Disconnection_i} + \boldsymbol{Removing_i}) \qquad \mathbf{3.3}$$

The following Figure 3.2 is illustrating the calculations of (eDim) which is proposed by Paul Vanegas:

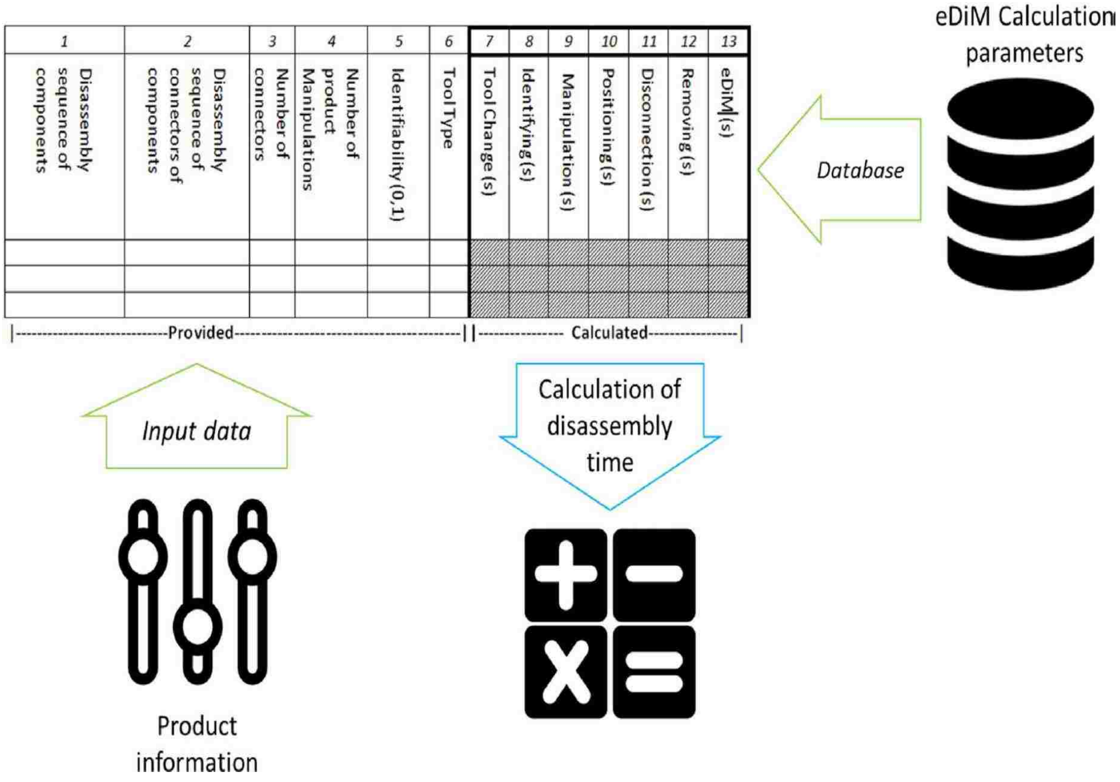


Figure 3.2 eDiM (ease of disassembly) (Vanegas et al., 2018)

The later method (eDiM) is more suitable and applicable on the component level of disassembly rather than the material level. t we can notice the limitation of the later method since it only takes the time of disassembly into consideration based on the number of parts and number of joints but does not consider other factors such as material composition, color, purity and quality of the disassembled material were sometimes there is unnecessary disassembly that can be avoided if the parts are made of the same material and the main purpose of disassembly is recycling. So, considering sorting based on color or quality of material is an important factor in disassembly for recycling as we can see later since it affects the profitability of recycling.

From the previous discussion it was concluded that it is important to find the time required to disassemble a specific product and this time of disassembly could be found using either direct methods of measurement (through taking it from industry) or by calculating it using one of the methods mentioned before. After finding the time calculating the feasibility of disassembly in term of profitability looks more accurate way of measuring complexity as can be seen from the next section.

3.4.4. The disassembly from a profitability point view:

Another approach to measure the complexity of the product and its relation to the disassembly process is to measure the feasibility of the disassembly process by calculating the ***economical material recovery*** and how the disassembly process could be enhanced to increase the efficiency of recycling.

Environmental and Economic Parameters Affecting the decision for EOL Scenarios-Recycling profitability:

In most cases the End of Life (EoL) scenarios are not considered during the earlier design phases but are estimated when the product arrives at the dismantling center in order to select the specific disposal scenario. In most cases the management of EOL scenarios is based on the experience of the dismantlers(Lowe & Bogue, 2007). In fact, dismantlers know the real value of the product or constituent components very well and choose the best scenario to maximize profits using the cost/benefits analysis tool. In addition, dismantlers know the hazardousness of special materials or chemical substances.

In the case of closed-loop scenarios the common costs can be summarized as follows (Favi & Germani, 2014):

- Disassembly costs;
- Cleaning plant and operation costs;
- Reverse logistic costs (transportation, sorting and plants);
- Remanufacturing/Refurbishing/Regeneration costs (only for the Remanufacturing process).

In addition to the previous costs other detailed costs should be evaluated case by case for each closed-loop scenario

On the other hand, the company profits are based on the specific EOL scenarios which refer to the component. A list of benefits and revenues are reported below (Favi & Germani, 2014):

- Revenues due to the sales of reused/remanufactured/recycled parts or materials;
- Cost savings as virgin materials and production energy are not required;
- Energy savings due to the fact that the energy required for the recycling process is less than the energy required for material extraction (embodiment).

In addition to the previous benefits there is also the revenue created from saving due to government subsidy and regulations

There are different papers referring to the calculation of the feasibility of disassembly as an important factor in the recycling process. One paper by (***M. R. Johnson & M. H. Wang***) the (***Economical evaluation of disassembly operations for recycling, remanufacturing and reuse***) (Johnson & Wang, 1998) introduced a procedure which integrates economical factors into the scheduling of disassembly operations for Material Recovery Opportunities (MRO) where MRO are defined as opportunities to reclaim post-consumer products for recycling, remanufacturing and reuse.

While this paper, proposes a quantitative method of disassembly analysis, its aim is to improve the efficiency of the disassembly and in turn that will improve the efficiency of recycling which is based on maximizing the profit of recycling. This proposed method by ***M. R. Johnson et al*** is based on economic indices to evaluate the trade-off between reclamation and disposal of individual components.

Three criteria are established in this paper to reduce the search space and facilitate recovery opportunities: (1) Material compatibility, (2) Clustering for disposal, and (3) Concurrent disassembly operations.

Next the equations used to calculate the profitability of recycling that are proposed by M. R. Johnson *et al.* are included below but first the terminologies used in calculations will be listed as follow:

Table 3.1 Notation used in calculating profit of recycling (Johnson & Wang, 1998)

$\boldsymbol{Rv_k}$	Reclamation value of component k ($).
$\boldsymbol{mv_k}$	Material value of component k ($/unit weight).
$\boldsymbol{df}$	Depreciation factor between 0 and 1
$\boldsymbol{Cd_k}$	Disassembly cost for the $\boldsymbol{k_{th}}$ component ($)
$\boldsymbol{Cd_T}$	Total disassembly cost for all components disassembled ($)
$\boldsymbol{t_k}$	Disassembly time for the $\boldsymbol{k_{th}}$ component
$\boldsymbol{C_L}$	Labour rate ($/unit time).
$\boldsymbol{Cp_k}$	Disposal cost for the $\boldsymbol{k_{th}}$ component ($)
$\boldsymbol{Cp_R}$	Current disposal rate ($/unit weight)
$\boldsymbol{Cp_T}$	Total disposal cost for m components ($)
$\boldsymbol{PLM_T}$	Total profit/loss margin of reclamation and disposal ($)
$\boldsymbol{PLM_{MAX}}$	Point in disassembly process where $\boldsymbol{PLM_T}$ is maximized ($)
$\boldsymbol{PLM_{RECOVERY}}$	A decision index for recovery: profit/loss margin of reclaiming component k ($)
$\boldsymbol{PLM_{DISPOSAL}}$	A decision index for disposal: Profit/loss margin of disposing component k ($)
$\boldsymbol{PLM_{FINAL}}$	The resultant $\boldsymbol{PLM}$generated in the cost analysis ($). Used as input in the disassembly sequence generation
$\boldsymbol{n}$	Total number of components reclaimed
$\boldsymbol{m}$	Total number of components within product
$\boldsymbol{d1}$	Total number of components disassembled but disposed of
$\boldsymbol{d2}$	Total number of components disposed of (without disassembly).

Upon disassembly, a specific component k is defined as having an individual reclamation value ($\boldsymbol{Rv_k}$) of:

$$\boldsymbol{ReclamationValue(Rv_k) = materialvalue(mv_k) \times weight(wt_k) \times (df)} \qquad \textbf{(3.4)}$$

Where:
$\boldsymbol{mv_k}$: **represents the material value of the** $\boldsymbol{k_{th}}$ **componentand**
$\boldsymbol{df}$: **is the depreciation factor specified by the user which falls between 0 and 1**

The depreciation factor accounts for the condition of the component upon disposal.
For example, some materials are exposed to certain environmental conditions (ultra-violet or corrosive exposure, etc.) during its use which may substantially deteriorate the material value.

The disassembly cost associated with the removal of the $\boldsymbol{k_{th}}$ component can be represented as:

$$\boldsymbol{Cd_k = t_k \times C_L} \tag{3.5}$$

Where**:**

$\boldsymbol{t_k}$: the disassembly time for the kth component
$\boldsymbol{C_L}$: is assumed to be the labour rate

The disposal cost associated with landfilling the k_{th} component can be representedas:

$$\boldsymbol{Cp_k = Cp_R \times wt_k} \tag{3.6}$$

Where:

$\boldsymbol{Cp_R}$: is the current disposal rate
$\boldsymbol{wt_k}$: is the weight of the kth component

Within the previously defined parameters, the profit/loss margin (PLM) of recovering the $\boldsymbol{k_{th}}$ component for material recovery can then be expressed as:

$$\boldsymbol{PLM_{RECOVERY,k} = Reclamationvalue(Rv_k) - Disassemblycost(Cd_k) + Disposalcost\ (Cp_k)} \quad \boldsymbol{(3.7)}$$

$$\boldsymbol{PLM_{RECOVERY,k} = Rv_k - Cd_k + Cp_k (k = 1, 2, \ldots., n)} \tag{3.8}$$

Where:

$\boldsymbol{Cp_k}$: $isthesavingsfromnotpayingthedisposalcostofthe\boldsymbol{k_{th}}component$

The disposal cost ($\boldsymbol{Cp_k}$) may be quantified as a tangible benefit to the manufacturer when recovery is implemented (assuming the manufacturer has taken responsibility for product disposal).

The values of Equation (3.8) $\boldsymbol{Rv_k}$, $\boldsymbol{Cd_k}$ and $\boldsymbol{Cp_k}$ are positive for all $\boldsymbol{m}$ components.

From a recycler's perspective, the disposal cost ($\boldsymbol{Cd_k}$) associated with Equation (3.8) is actually the revenue associated with the initial act of recovery.

This value is also known as the tipping fee, which is paid to the recyclers from the liable party (i.e., manufacturer). In both cases, the revenue of recovery is based on the total reclamation value and the disposal cost.

The only other alternative is disposal. The profit/loss margin of disposing the$\boldsymbol{k_{th}}$ component can then be expressed in one of the following 2 forms:

$$PLM_{DISPOSAL,\ k} = \begin{cases} -Cp_k Disposalcostonly(k = 1, 2, \ldots., d1) & (3.9) \\ \\ \quad -Cp_k - Cd_k Disposalcostplusdisassembly \\ cost(k = 1, 2, \ldots., d2) & (3.10) \end{cases}$$

Equation (3.9) represents the ***disposal cost*** of the k_{th} component.
Equation (3.10) represents the disposal cost plus the disassembly cost of the k_{th} component.

This may occur when disassembly is still required because of the need to recover a valued part which is attached to it.

Equations (3.8), (3.9) and (3.10) are quantitative indices of the 3 decision elements ***(Recover, Dispose, Disassemble and Dispose***) to consider in product disassembly analysis. The disassembly process may be optimized using these decision elements to assess the trade-off between recovery and disposal of individual components. Disassembly will be profitable if the reclamation value plus the savings of non-disposal is greater than the disassembly cost (i.e. $(Rvk + Cpk) \geq CDk$

The main approach in this paper is the generation of an optimal disassembly sequence in terms of the economic considerations of material recovery opportunities at the end of the life-cycle. Where the life-cycle of a product can be defined as stages of possible environmental detriment which may occur at each of the following stages: raw material extraction (i.e. birth of material), processing, transportation, manufacturing, use and final disposition.

The outcome of this level of analysis will include the following:

(1) Cost estimates are generated for recovery versus disposal of individual components.
(2) Unprofitable disassembly operations are abandoned from further analysis.
(3) Material reclamation values are maximized from the available material markets.
(4) An optimal economic index called the (PLM_{FINAL}) is affixed to each disassemblyoperation under consideration in the scheduling process.

Product disassembly for MRO requires ***disassembly times and costs to be minimized and the value of the resulting `pile of parts' to be maximized***. Moreover, small changes in the prices of reclaimed materials can tip the scales and make certain disassembly operations unprofitable. From recyclers standpoint, it is often more economical to cluster materials for a lower market value because of the high cost associated with disassembly

3.4.5. Economic analysis

One of two actions must be taken within the disassembly process: reclaim the component (i.e. for a specific MRO) or dispose it. At the forefront of this decision, three decision elements should be considered:

(1) The option of recovery; its costs and benefits;
(2) The present disposal cost of the component, and;

(3) The possibility that disposal of the component is the best alternative, but disassembly is still required because of the need to recover a valuable part which is attached to it; the cost of disassembly and disposal.

The main idea behind this method is to develop economic indices to assess the possible trade-off considerations between the above three elements.

Stakeholders in this process:

Two major groups are identified here who would be interested in this analysis.

a) ***Recyclers***. Recyclers are presented with the problem of dismantling products which were designed as long as fifteen years ago, without thought to their ultimate disposal. (GE Plastics (1992) predicts that a large majority of durable products (e.g. small appliances, business equipment, major appliances, and automobiles) have a lifetime of less than 15 years.) Many of these designs make reclamation and disassembly of products a costly and unprofitable process.

b) ***Manufacturers***. There is a growing number of manufacturers and designers who are interested in the implementation of product stewardship programs and the ultimate costs associated with MRO. (The term `designers refers to all decision makers who participate in the early stages of product development. This includes a wide variety of disciplines: industrial designers, engineering designers, manufacturing engineers, graphic and packaging designers, as well as managers and marketing professionals (US Congress 1992).

3.4.6. Cost-benefit analysis to disassembly

Recyclers must often have to concentrate on maximizing throughput of materials in order to offset the high costs of disassembly. The criterion of clustering for maximum reclamation value is most appropriate for improving the economics associated with the disassembly process rather than being considered an element of design, where generating a disassembly sequence based on either disassembly costs or material values alone will not be optimal.

From a design standpoint, material compatibility is important to ensure that the quality and value of recovered materials will be maintained for second and third product generations.

A clear cost-benefit analysis to disassembly is important to decide if it is economically feasible to disassembly or maybe it will be feasible to disassemble if after assembly the extracted material weights reached to a profitable amount or if the disassembly time is reduced using automation (in that case each extracted material is proportionately increasing in weight) or if the manual disassembly becomes economically justified.

The following assumptions are provided (Johnson & Wang, 1998) to help in appropriate application area of this method, its boundary of analysis, and the best circumstances for its utilization.

(1) This method of cost analysis is most appropriate for improving the economics associated with disassembly of products for material reclamation.

(2) Certain calculated parameters were identified as having the greatest impact on the costs and benefits associated with material recovery which are: ***reclamation value***, ***disassembly cost*** and ***disposal cost***

(3) The calculated parameters assume certain data will be available. ***Material values***, ***labor rates*** and ***disposal rates*** are normally known by recyclers.

(4) A preliminary study of the product being disassembled must analyze the following:
    (1) the various ***disassembly operations*** and the components released during such operations;
    (2) the ***disassembly time associated with such operations*** (taking into consideration the resulting learning curve in manual disassembly); and
    (3) the ***weight of the components released***.

(5) The procedure outlined in this paper is most suitable for a continuous flow of products being disassembled. For manual disassembly it is important to establish a learning curve and improve the efficiency of the disassembly process.

(6) The variety of products on the disassembly line at one time should be minimized to one variety (i.e. preferably by product type, manufacturer and model). Also, this assumes that the analysis is carried out when there is a sufficient volume of the same products to disassemble. The analysis is very suitable for automated disassembly using robotics, this is because once the most profitable disassembly plan is determined, programming a robot to carry out the operations is only a matter of programming without any learning curve effects.

3.5.Research Gap related to Product complexity:

Determining the best strategy for recycling a product has led several researchers to use cost estimating techniques. By looking at all the previous methods used to assess the product complexity through looking at it from the disassembly point view of a product, the last method which measures the complexity of product disassembly based on profitability of disassembly looks more practical since it does not study the process of disassembly only from the theoretical point of view but rather tries to apply the method in reality. The later approach takes the material composition and time of disassembly as important factors in the disassembly process

In order to calculate the efficiency of recycling taking the disassembly from the prospective of profitability looks more accurate since this approach in taking the decision of recycling based on understanding the required threshold to make the process of recycling profitable.

After calculating the amount of products extracted from the disassembly by taking the feasibility of the disassembly process into consideration next step will be calculating the efficiency of recycling and some important factors that should be taken into consideration are material composition, ease and efficiency of part separation measured by time of disassembly, and product complexity based on the profit of recycling. A higher efficiency can be reached when product disassembly takes place prior to material recovery while lower values are more likely when a product includes number of components of different material types and is fragmented prior to some form of materials separation process

Recycling profitability is important since it can help finding the necessary improvement in design the can reduce time and effort of disassembly, for example by enabling easier disassembly or using pure and easy to-recycle materials or making most of the parts of similar materials all this can help to optimize the revenue or saving costs of recycling. The main goal of studying product complexity affect on the recyclability is to make the disassembly easier by using design for disassembly principles, using pure materials and easy to separate parts. Also, for some cases were recycling is not profitable, ways to maximize the recycling profitability by improving the recycling efficiency should be investigated. Disassembling a product manually may not be cost effective due to the inefficient disassembly design for many products, which increases the time to disassemble resulting in higher labour cost so the automatic disassembly might be an alternative option where it might be not economically feasible until the sub-assembly weighs becomes higher than a specific amount or disassembly time is reduced using automation (with each component proportionately increasing in weight)

CHAPTER 4. PROPOSED METHODOLOGY AND ANALYSIS OF CE METRICS

4.1 Overview

Looking back at the Material Circularity Indicator (MCI) that was proposed by Ellen MacArthur Foundation and as it could be seen from the literature review performed previously in chapter two the material Circularity Indicator is a good indicator to measure the product circularity but it is still lacking taking some factors that are important into consideration such as the product complexity and ease of disassembly. From there came the necessity to perform another literature review on the product complexity and ease of disassembly methods in order to find away to measure the complexity and incorporate it into the product circularity.

Then after performing a literature review on product complexity we found several methodologies explaining the meaning of product complexity and ease of disassembly but one methodology proposed by (Johnson & Wang, 1998) interpreted the product complexity (in other word ease of disassembly) through applying cost analysis to decide if product disassembly for recycling will be profitable or not

Now in order to relate the product complexity with the material circularity indicator, and by looking back at Ellen Macarthur Foundation methodology we notice that the efficiency of the recycling process is considered as a fixed value so one of the gaps investigated was finding the relation between the complexity of the product and the efficiency of recycling considering that the efficiency is not a fixed one but rather dependent on other factors.

Steps used in the proposed methodology:

- Performing cost benefit analysis by using the equations proposed by (Johnson & Wang, 1998) , which requires finding other parameters such as (time of disassembly, material value, labour cost, disposal rate… etc. which will be taken from the industry)
- If the disassembly and recycling is profitable, next step will be calculating the efficiency of recycling. The recycling profitability is related to many factors such as the *time of disassembly*, *value of material* as well as the *labour cost*. A shorter time of disassembly will be leading to a profit from disassembly
- Calculating the recycling efficiency $\boldsymbol{E_c}$based on how much material will be extracted from recycling the product.
- Calculating the Material Circularity Indicator (MCI). Some assumptions will be used to simplify the equations proposed by Ellen MacArthur Foundation Methodology (EMFM) to understand the effect product complexity on the recycling efficiency and in turn the material circularity indicator (MCI)

4.2. Development of the Methodology:

A new methodology to relate the product complexity to the material circularity indicator (MCI) is proposed next. By looking back at the Material Circularity Indicator MCI proposed by Ellen MacArthur Foundation the efficiency of the recycling process is considered as fixed number in the calculation of MCI , one of the gaps investigated was finding the relation between the complexity of the product and the efficiency of recycling considering that efficiency is not a fixed one but rather dependent on other factors., on the other hand the complexity of product and its effect on MCI will be calculated using detailed knowledge of a product's component parts and materials. A good understanding of the typical recovery and recycling processes is important. Where the data input into the model should ideally be based on knowledge of the product being assessed, and generic industry data or best approximations may be used to illustrate the proposed methodology

In order to explain the basic formulation in a simpler way, the next sections will describe the phases used to create this methodology. ***First phase*** will be applying the methodology proposed by (Johnson & Wang, 1998) to calculate the profitability of recycling a specific product by analyzing the components and materials that this product is made from, then a decision to recycle or not will be based on the profitability of the process based on the formula used by (Johnson & Wang, 1998). ***Second phase*** will be calculating the amount of material that will be reclaimed from the recycling then calculating the mass efficiency of recycling each material which represents the amount reclaimed after recycling over the weight of the product which represents the amount input to the recycling. ***Third phase*** will be using the efficiency calculated to measure the circularity of a specific product by calculating the material circularity indicator (MCI) of the product ***Finally*** a tool will be created to measure the product circularity by taking to product complexity into consideration.

Phase one

Performing cost-benefit analysis to find out how much material is actually recycled in a way that takes the profitability of recycling into consideration, this is done by using the equations proposed by (Johnson & Wang, 1998) to analyze the decision to recycle or not based on the profitability, a decision to recover or dispose a specific product will result in proceeding to the next phase to find the recycling efficiency and the material circularity indicator for a specific product. If the recycling is not profitable some suggestions should be considered by looking at the different factors affecting the profitability.

In order to calculate the recycling profitability, the following are the equations used some of them proposed by (Johnson & Wang, 1998) and discussed earlier in detail in chapter three :

$$\boldsymbol{ReclamationValue(Rv_k) = material\ \ value\big(\,(V_p)_k\big) \times weight(wt_k)} \qquad \textbf{(4.1)}$$

$$\boldsymbol{Product\ ReclamationValue = \sum Material\ ReclamationValue(Rv_k)} \qquad \textbf{(4.2)}$$

$$\textbf{Product Disassembly Cost}(\mathbf{C_d}) = \textbf{DisassemblyTime (t)} \times \textbf{Labour cost (}\mathbf{C_L}\textbf{)} \qquad \textbf{(4.3)}$$

$$\textbf{Disposal cost}(\mathbf{Cp}) = \textbf{disposal rate}(\mathbf{Cp_R}) \times \textbf{Product weight}(\mathbf{Wt}) \qquad \textbf{(4.4)}$$

By neglecting the cost of disposal at the beginning, the profitability will be calculated as below:

$$\boldsymbol{PLM}_{\text{Recovery}} = \boldsymbol{Product\ Rec\ Value} - \textbf{Product Disassembly Cost}(\mathbf{C_d}) \qquad (\mathbf{4.5})$$

$$\boldsymbol{Product\ Reclamation\ \ Value} > \textbf{Product Disassembly Cost}(\mathbf{C_d}) \rightarrow \textbf{Recycle}$$

$$\boldsymbol{Product\ Reclamation\ \ Value} \ll \textbf{Product Disassembly Cost}(\mathbf{C_d}) \rightarrow \textbf{Don't Recycle}$$

The following table summarize the equations used to measure the profitability of recycling then a decision to recycle or not will be based on the profitability of recycling.

Table 4.1 Equations used in calculation of the disassembly profitability

Components	**Material composition**	**Material value $(V_p)_k$**	**Material weight $\mathrm{wt_k}$**	$\boldsymbol{ReclamationValue}$ $\boldsymbol{Rv_k = (V_p)_k \times wt_k \times \mathrm{df}}$	$\boldsymbol{Total\ Disassembly\ Time}$	$\boldsymbol{Disassemblycost}$ **DisassemblyTime (t) × Labour cost ($\mathrm{C_L}$)**	**Disposal rate$\boldsymbol{Cp_R}$**	$\boldsymbol{Disposalcost}$ $\boldsymbol{Cp_k = Cp_R \times wt_k}$	$\boldsymbol{PLM_{RECOVERY,k} = Rv_k - Cd_k + Cp_k}$	$\boldsymbol{Product\ Reclamation\ \ Value} >$ **Product Disassembly Cost($\mathrm{C_d}$)**
Total										

Some assumptions were included above. First a complete disassembly is assumed because the methodology here does not aim to enhance the disassembly sequence at the beginning but rather to consider a complete disassembly. Second assumption is to take the time of disassembly for the whole product rather than time for disassembling for each part. Third assuming the depreciation factor equals one. Another assumption is neglecting the disposal cost for some products as can be seen in the following three case studies. Also, assuming the sequence of disassembly is already optimized and then by using an example from the industry where a specific product is disassembled, and the time required to disassemble and extract each material is calculated. Then after getting all the necessary information the profitability of recycling is calculated.

In order to calculate the *Reclamation value* and the *disassembly cost* data from the industry or generic data such as (the components of a specific product, the material for each component, then material value, material weight, depreciation factor and the disposal cost (if we want to take it into consideration), the time of disassembly, labour cost,

The amount of recycled material is now a function of several factors such as the time of disassembly which is an important factor since taking long time to disassemble it will make it not feasible to disassemble and recycle, other factor is the value of material reclaimed whether it is valuable or not.

If the process is profitable next will be phase two were the amount of material recovered will be calculated, then the efficiency of recycling each material will be found.

If the process is not profitable then some corrective steps should be considered such as the time of disassembly of the product, how to make it efficient so that the disassembly cost will be less than the reclamation value because it is sometimes not worth it to disassemble and recycle since the disassembly will take a long time. Another important factor is the value of the extracted material is it valuable enough to justify the recycling and investing the time to extract it. It might be not profitable unless the extracted weight exceeds specific limit, or the time of extraction become less that specific number. Last factor could be the labour cost. Outsourcing the recycling process and sending it to other location with less labour cost might be an option.

In this phase of the proposed methodology the following parameters are obtained:

- Number of parts
- Number of different materials
- Type of materials- material composition

In order to find the material value after recycling, the following Equation (4.6) will be used where the material recyclability index is calculated using Eq. (3.2) which was mentioned in chapter three, this equation proposed by Villalba to calculate the ***material recyclability index*** based on market values of any material (Villalba et al., 2004). Equation (4.6) below uses the same Equation (3.2) but using only the value of virgin material $\boldsymbol{V_m}$ and the value of material after recycling $\boldsymbol{V_p}$

$$\boldsymbol{MR} = \frac{Value\ of\ material\ after\ recycling\ \$\ (\boldsymbol{V_p})}{Value\ of\ Virgin\ material\ (\$)(\boldsymbol{V_m})} \tag{4.6}$$

Where:

$\boldsymbol{MR}$: is the material recyclability (\$/\$)
$\boldsymbol{V_p}$: is the value of material after it is recycled (in USD)
$\boldsymbol{V_m}$: is the value of virgin material (in USD)

The value of recycled material is always less than the value of material in virgin state because recycled material loses mechanical properties due to recycling process. Recyclability index of material lies between 0 and 1, with 0 representing non recyclable material and 1 representing perfectly recyclable material (i.e. recycled material retains all the properties of the virgin material).

Phase two

Product Recyclability and Recycling Efficiency

In order to calculate the product **recycling efficiency** $\boldsymbol{Ec}$ we need to find out the total amount of material extracted from the recycling process ($\boldsymbol{M_R}$), the following method is used to calculate it, where the efficiency here is considered as the mass efficiency or in some papers it is considered the recyclability rate (Umeda et al., 2013) which represents the amount of material extracted from recycling over the total weight of the product.

The efficiency of recycling specific material will be found from applying the following equation:

$$\boldsymbol{Recycling\ efficency\ of\ a\ product\ (Ec) = R_{cyc} = \frac{M_R}{M} = \frac{\sum_k M_K}{M_{Total}}} \qquad (\mathbf{4.7})$$

Where:

$\boldsymbol{R_{cyc}}$ **:** Product recyclability = Product mass efficiency

$\boldsymbol{M_{Total}}$ **:** Total weight of the product

M_K : Recyclable weight of the k_{th} component

In order to calculate the mass $\boldsymbol{M_K}$ extracted for each material from a specific component:

$$\boldsymbol{M_k = \sum_i r_i m_i} \qquad (\mathbf{4.8})$$

Where

$\boldsymbol{r_i}$: is the recyclability rate of the $\mathbf{i_{th}}$ material in the $\mathbf{k_{th}}$ component

$\boldsymbol{m_i}$: is the mass of $\mathbf{i_{th}}$ material in the $\mathbf{k_{th}}$ component

$\boldsymbol{M_k}$: is the recyclable mass of the $\mathbf{k_{th}}$ component,

Once a range of material streams has been produced from a product with multiple components, different material recovery processes will have different efficiencies. A good understanding of the typical recovery and recycling processes for a given product is required to obtain accurate values for $\boldsymbol{E_C}$. Ideally, there should be a value for each material and for each specific recycling process but generic values for r_i have to be used because the real values are likely to vary with time, by application, recycling technology and demand. These values for the recyclability index $\boldsymbol{r_i}$ can be used from various sources, one resource is the paper published by (Umeda et al., 2013).

Following Table 4.2 show a list of the recyclability rates $\boldsymbol{r_i}$ for different components and material types. The data in the table were acquired from research reports on the current recycling activities in EU. (Umeda et al., 2013)

Table 4.2 Recyclability rates of materials (Umeda et al., 2013)

	Material	r_i (%)
1	Aluminum	95
2	Copper	95
3	Steel	94
4	PET	94
5	ABS	94
6	PS	100
7	LCD panel	0
8	CCFL	80
9	Cable (high)	33
10	Cable (Low)	24
11	PCB (high)	18
12	PCB (low)	14

Phase Three

As we concluded from the literature review on CE, there are different circularity indicators used to measure the product circularity but the one proposed by Ellen MacArthur Foundation was found more representing and a good indicator. But still this indicator is lacking the effect of product complexity. Important factors affecting the product complexity are time of disassembly and profitability of disassembly. This phase will be about calculating the product recyclability based on the recycling efficiency which was obtained from phase two.

Equations used to measure the Material Circularity Indicator (MCI) were simplified in order to find the relation between the product complexity and recycling process through the recycling efficiency.

Assumptions:

Some assumptions were taken to simplify the calculations are as follows:

1. Assuming closed loop- were the waste generated from recycling the post used product is the same as the waste generated from recycled feedstock- no recycled material comes from other manufacturers only recycled from this manufacturer

   $F_R = 0, W_F = 0$

2. No component reuse is considered- all the components going to recycling

   $F_U = 0, \; C_U = 0$

3. Assuming that the life time of the product (L) equal to the average life time (L_{av}) and the utilization of the product (U) equal to the average utilization in the market (U_{av}) that means X assumed fixed and equal to 1 here and does not affect the calculations of MCI

   If $L = L_{av} \& U = U_{av}$, Then $X = \left(\frac{L}{L_{av}}\right).\left(\frac{U}{U_{av}}\right) = 1$ which leads to

$$F(x) = \frac{0.9}{X} = \frac{0.9}{1} = 0.9 \qquad (4.9)$$

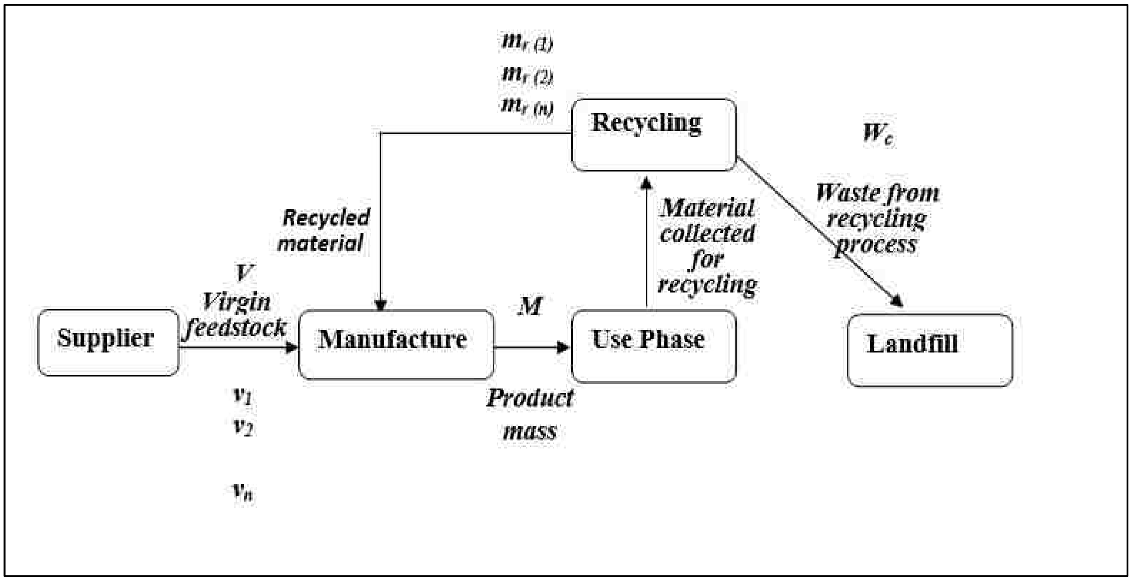


Figure 4.1 Proposed material flow analysis- new assumption

After applying the previous assumptions, in order to measure the MCI, the following equations will be used:

1-Calculating Virgin Feedstock:

Since
$F_U = 0$, ***(no reused components only recycled)*** and
$F_R = C_R$ ***(closed loop, all the collected for recycling is used)***

Then $$V = M - M_R \quad = M(1 - C_R) \qquad (4.10)$$

2- Calculating Unrecoverable Waste
Assuming all the collected mass of post used product goes to recycling

$$W_0 = 0 \qquad (4.11)$$

3-Waste generated in the recycling process

Assuming all the post used product collected for recycling and no waste is produced from the collected product but whatever waste is produced in through the recycling process

$$W_C = M(1 - E_c)\, C_R \qquad (4.12)$$

$$W = W_C = M(1 - E_c) \quad = \mathrm{V} \qquad (4.13)$$

4- Efficiency of recycling:

$$\boldsymbol{E_c} \quad = \frac{\boldsymbol{M - W_c}}{\boldsymbol{M}} \quad = \frac{\boldsymbol{M - W}}{\boldsymbol{M}} \quad = \frac{\boldsymbol{M_R}}{\boldsymbol{M}} \qquad (\mathbf{4.14})$$

$$\boldsymbol{W_F = 0}$$

Assuming all the post used product collected for recycling and no waste is produced from the collected product but whatever waste is produced in through the recycling process

5- Calculating Linear Flow Index (LFI):

$$\boldsymbol{LFI} = \frac{\boldsymbol{V + W}}{\boldsymbol{2M - \frac{W}{2}}} \quad = \frac{\boldsymbol{2(V + W)}}{\boldsymbol{(4M - W)}} \qquad (\mathbf{4.15})$$

6- Calculating the Material Circularity Indicator

$$\boldsymbol{MCI_P^*} \; = \mathbf{1 - LFI\,.\,F(X)} \qquad (\mathbf{4.16})$$

Since F(X) assumed to be 0.9 the MCI becomes a function of (Linear Flow Index (LFI)

The equation becomes

$$\boldsymbol{MCI_P^*} \; = \mathbf{1 - \; 0.9 * LFI.} \qquad (\mathbf{4.17})$$

Finally,

7- Calculating $\mathbf{MCI_P}$ using the following equation

$$\boldsymbol{MCI_P} \; = \boldsymbol{max(0, MCI_P^*)} \qquad (\mathbf{4.18})$$

Table 4.3 Equations used to measure the MCI based on new assumptions:

	Mi $(Material\ mass)$	Virgin Material Mass M_R $(recycledmaterialmass)$	V Virgin Material Mass $V = M - M_R$	Efficiency of recycling $Ec = \frac{M_R}{M}$	W =M*(1-Ec) = V	$LFI = \frac{2(V+W)}{4M-W}$	$X = \left(\frac{L}{Lav}\right) \cdot \left(\frac{U}{Uav}\right)$	$F(x) = \frac{0.9}{X} = \frac{0.9}{1}$	$MCI_P^* = 1 - LFI . F(X)$	$MCI_P = max(0, MCI_P^*)$
1	100							0.9		
2										

In this phase after calculating the efficiency of recycling the whole product Ec the Material Circularity Indicator (MCI) of the product will be calculated by first using Equations (2.12), (2.13) and (4.15) to find the liner flow indicator (LFI) where the virgin material and waste for the whole product will be calculated then after that using Equations (4.17), (4.18) and (4.19) to find the MCI for the whole product.

4.3. IDEF 0 (Parent-Child) diagram

Following is IDEF 0 diagram where the input as product design and product (assembly/disassembly) complexity and the output is the Product circularity. The controlling factors are (No. of components, material characteristics, time of disassembly, material value, labor rate, material toxicity and recyclability rate and the mechanism used (physical attributes, cost of disassembly, reclamation value, recycling technology and the recycling efficiency)

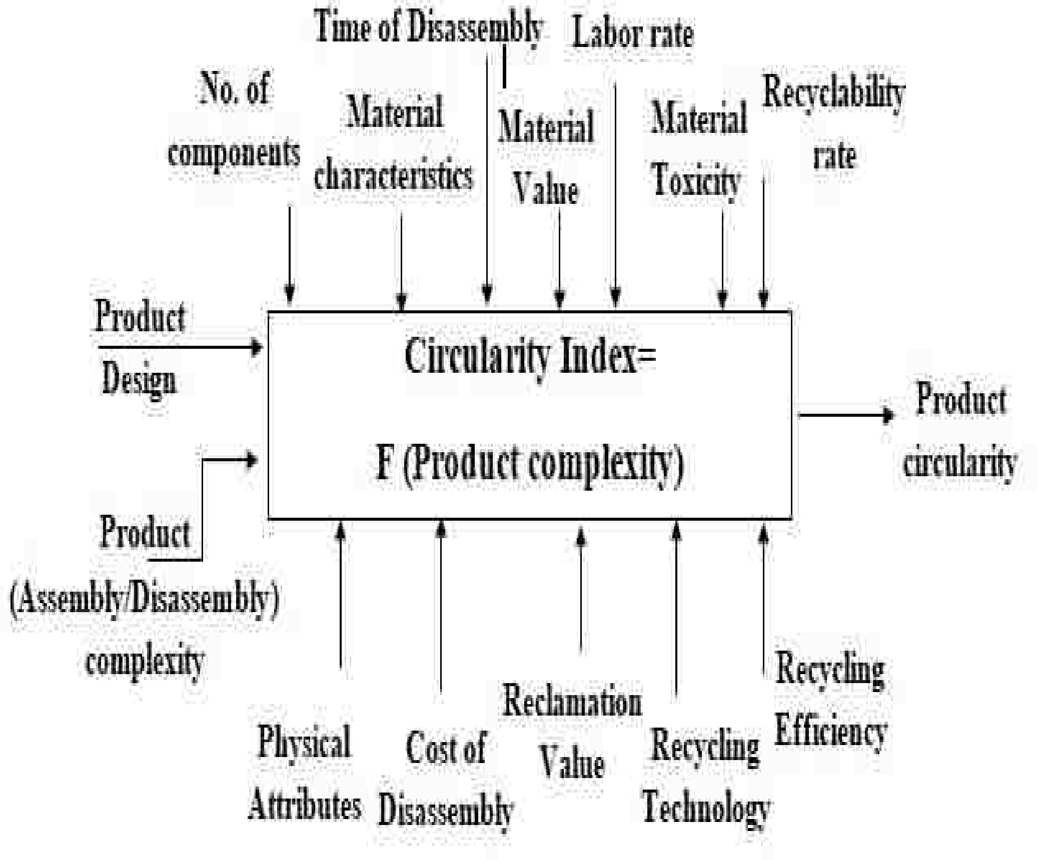


Figure 4.2 IDEF0 (Parent Diagram)

Next Figure 4.3 explains in more detail the steps used in implementing the methodology, where first the product design and complexity are assessed based on the profitability of disassembly. If the disassembly is feasible and profitable, then the process of disassembly will be next and after that the product recyclability will be calculated based on the amount of material extracted. If the disassembly is not profitable, another assessment should be done to make it profitable.

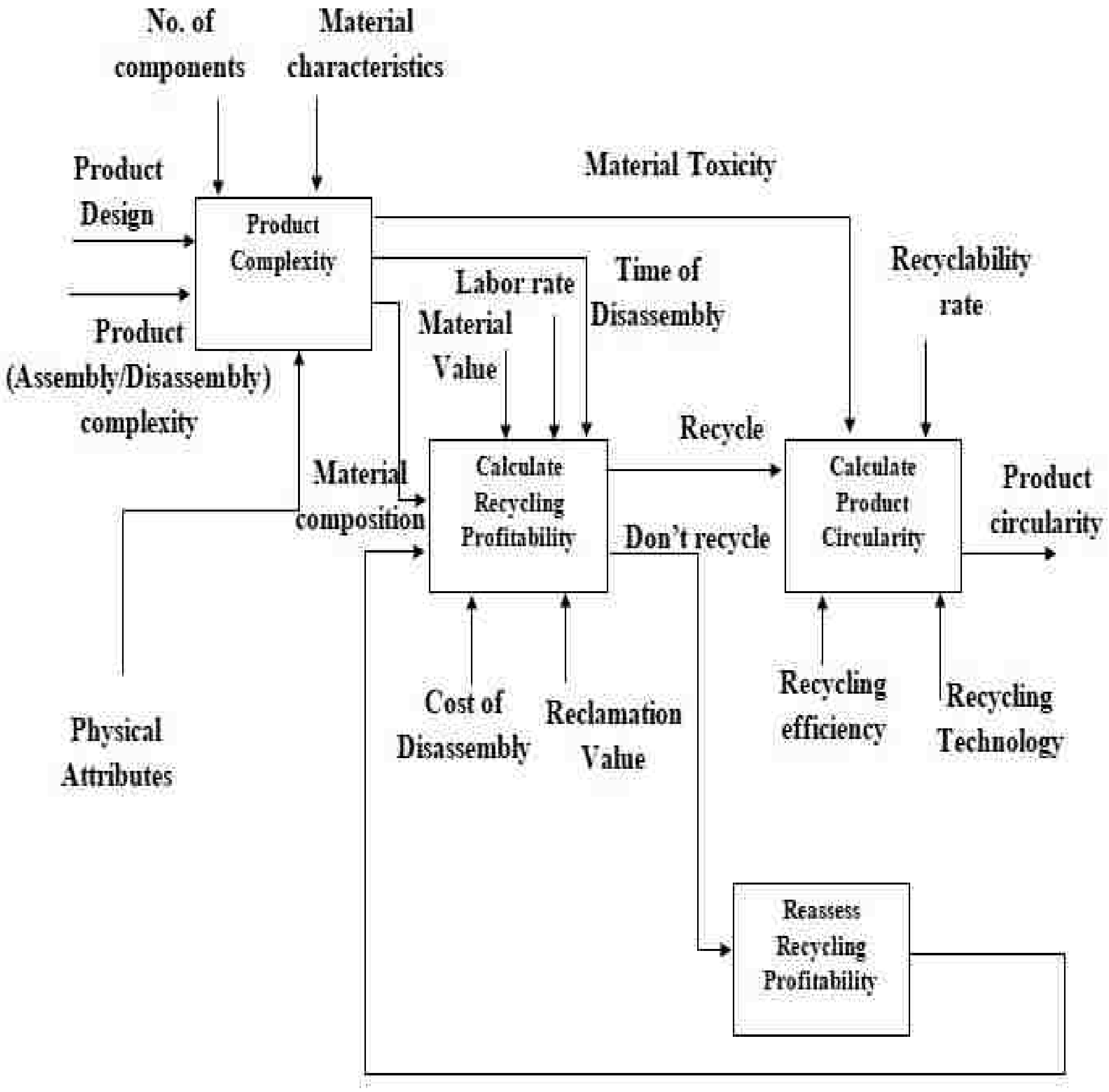


Figure 4.3 IDEF0 (Child Diagram)

Next chapter will include three case studies explaining the steps of calculation used in this methodology.

CHAPTER 5. METHODOLOGY VALIDATION AND APPLICATION

Following are three case studies used to explain the proposed methodology were first phase is performed to demonstrate the clear cost-benefit analysis to disassembly based on profitability, using the equations proposed in chapter four, Equation (4.1) and (4.2), (to measure the reclamation value and then calculating the disassembly cost using Equation (4.3) and from there comes the decision to recycle or not recycle based on the profitability as mentioned before in chapter four.

In order to simplify the calculations, we can assume:

1- $\boldsymbol{Labor\ Cost\ (C_L) = 10\ {}^{\$}/_{hr}}$
2- A part that can be used without any operations except for disassembly (DfReuse) after the product life cycle is also considered perfectly recyclable (Yadav et al., 2018)

Following Table 5.1 explains three case studies with different levels of complexity. Complexity here is represented by the easy of disassembling a product based on time required to disassemble the product and the value of material reclaimed after disassembly which is reflected on the profitability of disassembly and its effect on product circularity.

Table 5.1 complexity of three different products

	Complexity	Average No. of components	Time of disassembly (s)	No. of material used	Profitability	Product circularity
Case Study 1	Low	10	154.3	2	\$1.13 Profitable	0.94
Case Study 2	Medium	16	198.2	10	\$6.2 Profitable	0.65
Case Study 3	High	9	338.3	7	-0.27 No profit	---

From the previous table we can notice that the material composition has a big impact on the profitability of recycling. Although the number of materials used are less in the third case study than the second case study, the time of disassembly was higher and the reclaimed material value was small, which led to no profit of recycling and a decision not to recycle was made.

5.1.Case Study 1: Three Hole Punch

The steps in this case study are listed as follows:

Step 1: The product (**Three Hole Punch**) with its components and the material composition was taken from a case study in a paper (Yadav et al, 2018) where these data used to find the reclamation value.

Step 2: From the same paper (Yadav et al, 2018), the handling time, insertion time, and total assembly time for all the components were calculated using Boothroyd– Dewhurst DFA tables then this time of disassembly was taken and used here to calculate the cost of disassembly

Step 3: using the ***profit to loss margin*** of recycling (PLM) for the purpose of economic evaluation of disassembly which is proposed by (Johnson & Wang, 1998) to determine whether or not it is economically feasible to disassemble the product to recover the materials for recycling .

Step 4: calculating the product recycling efficiency

Step 5: Calculating the product circularity using the MacArthur Foundation methodology's main indicator which is known by MCI

Step 6: After finding the product recyclability using MacArthur Foundation methodology , the results will be compared with the Product Recyclability index found by (Yadav et al., 2018). The data will be analyzed to identify the correlations between the different variables.

Figure 5.1 Three- Hole Punch ((Yadav et al., 2018)

Table 5.2 Analysis of Three-hole punch Adapted from (Yadav et al., 2018)

	Part name	**Material composition**	**Operation Time (s)**	**Material recyclability Index (MR)**
1	Base	Steel	2.63	0.97
2	Connector	Steel	17.9	0.97
3	Handle	Steel	8.95	0.97
4	Punch guide base	Steel	8.95	0.97
5	Punch spring	Steel	23.68	0.97
6	Punch guide	Steel	23.4	0.97
7	Punch	Steel	27	0.97
8	Spring	Steel	28.89	0.97
9	Chip tray	ABS	3.95	0.7
10	Lock	Steel	8.95	0.97
	Total		**154.3**	

In order to calculate the profitability of disassembly, Equations (4.1), (4.2) and (4.6) mentioned in chapter four will be used to measure the reclamation value for the product then Equation (4.3) will be used to calculate the disassembly cost and based on Equation (4.5) then a decision to recycle or not will be made.

As it was noticed from the previous table 5.2 the material for the components is steel for all the parts except the tray which is made of ABS, by assuming that the three-hole punch weight is 500 gm and the tray weight is 50 gm that is 10% of the total punch weight. Following is the reclamation value for the product.

Table 5.3 Reclamation Value calculation

	Part Name	**Material**	**Wt kg**	**Virgin Material Value (V_m) ($/kg)**	**Material Recyclability (MR) ($/$)**	**Reclamation Value Rv_k $**
1	Chip tray	ABS	0.05	0.67	0.7	0.0235
2	Base	Steel				
3	Connector	Steel				
4	Handle	Steel				
5	Punch guide base	Steel				
6	Punch spring	Steel				
7	Punch guide	Steel				
8	Punch	Steel				
9	Spring	Steel				
10	Lock	Steel				
			0.45	3.5	0.97	1.5278
	Total					**1.5512 ≈ 1.56**

The virgin material value for the steel was used based on a list of commodity prices which was taken from ***Trading Economics*** (n.d.) and the ABS virgin material price was taken from (Virgin-ABS-Plastic-Granules, n.d.). While the material recyclability index (MR) which appears in Table (5.2) was taken from (Yadav et al, 2018) and was used in Equation (4.6) to calculate the value of material after recycling.

Next step is to calculate the cost of disassembly using Equation (4.3) where the total time of disassembly will be used from Table 5.2 based on (Yadav et al, 2018) , the total time of disassembly here is **154.3 s** and after multiply it by the labor cost, the cost of disassembly for the whole product will be calculated.

Product Disassembly Cost$(\mathbf{C_d})$ =154.3 s * 0.0028 \$/s = \$ 0.43

Then the profit of disassembly for the whole product is now calculated after a complete disassembly using the Equation (4.5) and by assuming the cost of disposal is zero, the profit of disassembly will be calculated as follows:

$\boldsymbol{PLM_{RECOVERY,k}} = 1.56 - 0.43 = \$\ 1.13$

Since the disassembly operation is profitable, we can now calculate the mass recovered of each material using Equation (4.8) as follows, where the recyclability rate for the steel and ABS material is used from Table 4.2

$\boldsymbol{M_{Steel} = 0.94 * 0.45\ \mathrm{kg} = 0.423\ \ \mathrm{kg}}$

$\boldsymbol{M_{ABS} = 0.94 * 0.05\ \mathrm{kg} = 0.047\ \ \mathrm{kg}}$

Then using Equation (4.7) the recycling efficiency of the product can be calculated using the recyclability rate which is considered the mass efficiency for each material.

(Ec) product = $\frac{\mathbf{0.423 + 0.047}}{\mathbf{0.5}} = 0.94$

After that the Circularity Indicator will be calculated using Equations (**4.15**), (**4.17**) and (**4.18**). Table 5.4 explains the calculations used to find the Product Circularity Indicator using the calculated product recycling efficiency that was found previously.

Table 5.4 MCI calculations for Three-Hole Punch

	Part Name	Material	Wt kg	Material Recyclability rate	Recycled material	V (kg)	W (kg)
1	Chip tray	ABS	0.05	0.94	0.047	0.003	0.003
2	Base	Steel					
3	Connector	Steel					
4	Handle	Steel					
5	Punch guide base	Steel					
6	Punch spring	Steel					
7	Punch guide	Steel					
8	Punch	Steel					
9	Spring	Steel					
10	Lock	Steel					
			0.45	0.94	0.423	0.027	0.027
	Total		**0.5**			**0.03**	**0.03**

From Equation (4.15) the Linear Flow Index (LFI) for the product will be found after calculating the total amount of waste and virgin material for the whole product. After that Equation (4.17) and (4.18) will be used to calculate the MCI for the product.

$$\text{LFI} = \frac{2(\,0.03+0.03)}{(4*0.5-0.03)} = 0.061$$

$$\boldsymbol{MCI_P^*} = 1\text{- } 0.061*0.9 = 0.96$$

$$\boldsymbol{MCI_P} = 0.96$$

Results and findings

- By comparing the circularity indicator using the proposed methodology the result was 0.96, while the circularity indicator found by (Yadav et al., 2018) was 0.667. The main reason behind that was because in the paper mentioned above the circularity indicator was calculated by taking another factor into consideration which is named as the (disassembly rating) that it not included directly in these calculations. This later factor was not included here because the disassembly performed here for the purpose of recycling only mainly.

- The recycling efficiency for the whole product (Ec) was similar to the recycling efficiency (recyclability rate) of its material components of the steel and the ABS since both of them has the same recycling efficiency and the product is not complex from the material composition point view.

- The recycling efficiency for the whole product was calculated here based on the amount of material extracted and recycled over the total weight of the product while in Macarthur foundation methodology the calculation was based on the recycling efficiency of each material. In this case study the recycling efficiency was equal to the recyclability rate of each material which is here the same for Steel and ABS = 0.94 but for more complex product it will be different as we can see from the case study 2.

5.2. Case Study 2- LCD monitor

The second case study is an LCD monitor that has an average product complexity, the selected product is a ***14" LCD Philips monitor from 2002***, the components, the total weight of the product (***2618)*** g and total measured disassembly time of **198.2** s was taken from a paper by (Vanegas et al., 2018), while the material composition was taken from (Salhofer, Spitzbart, & Maurer, 2011) and the recyclability rate was taken from Table 4.2 (Umeda et al., 2013)

Figure 5.4 shows the front and back of the case study product (Vanegas et al., 2016), and Figure 5.5 depicts the distribution of its components (Vanegas et al., 2018). The total eDiM as mentioned before is calculated as 198.2 seconds.

The disassembly sequence was set to optimize the extraction of components, starting with the back of the monitor facing the operator and disassembling the housing first. Screws of the same type were disassembled in sequence to minimize tool changes.

Figure 5. 2 Front and back view of the LCD monitor (Vanegas et al., 2016)

Assumptions used in this case study are:

1. The disassembly sequence of the product is considered to be known by the operator, so no time is accounted for deciding which task is to be performed next

2. Time of disassembly is used from the paper by (Vanegas et al., 2018) were the paper refers to disassembling of 28 LCD monitors of different brands , On average the investigated LCD monitor required 644.11 s with SD 199.2 s for complete disassembly but the same paper refers to the previously mentioned monitor which is used here as a case study as an interesting model because it was considered the most efficient in regard to disassembly time . The 14'' LCD Philips monitor from 2002 had a total time of disassembly of 198.2 ***s*** and weight of ***2618 gm***

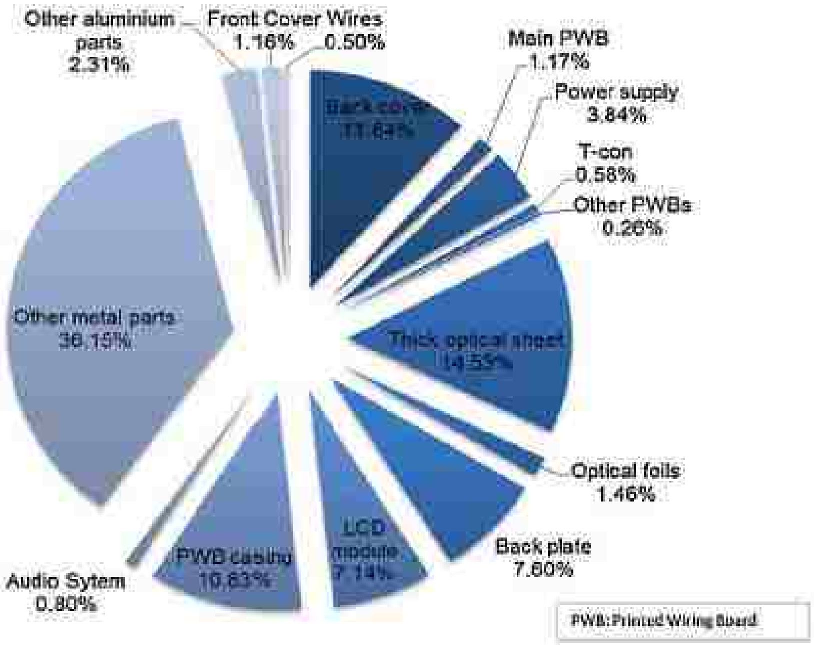


Figure 5.3 Material composition of 28 LCD monitors (Vanegas et al., 2018)

The following Table 5.6 includes the material composition for the LCD monitor (Salhofer et al., 2011). The virgin material value for the metals was taken from (Trading Economics, n.d.) while the plastic price from (The Plastics Exchange, n.d.) and the material recyclability index used from (Yadav et al., 2018). For the cable price it

Table 5.5 Material Composition of 28 LCD monitors, adapted from (Vanegas et al., 2018)

	Components	Wt%	wt of materials
1	Front cover	1.16	30.4
2	Wires	0.05	1.3
3	Back cover	11.64	304.7
4	Main PWB (printed wiring board)	1.17	30.6
5	Power supply	3.84	100.5
6	T- con	0.58	15.2
7	Other PWB	0.26	6.8
8	Thick optical sheet	14.53	380.4
9	Optical foil	1.46	38.2
10	Black plate	7.6	199.0
11	LCD module	7.14	186.9
12	PWB casing	10.83	283.5
13	Audio System	0.8	20.9
14	Other metal parts	36.15	946.4
15	Other aluminum parts	2.31	60.5
16	Other	0.48	12.6

Table 5.6 Reclamation value from LCD monitor disassembly

	Material Composition	**Material mass (Mi) (kg)**	**Virgin Material Value ($/kg)**	**Material Recyclability Index MR ($/$)**	**Reclamation Value (Rv_k) $**
1	Steel	1.771	3.5	0.97	6.0
2	Aluminum	0.130	1.7	0.98	0.2
3	Printed Circuit board	0.410	0	0	0
4	Cables	0.340	1.2	0.9	0.4
5	Black light	0.002	0	0	0
6	LC display	0.645	0	0	0
7	ABS	0.360	0.7	0.7	0.2
8	PC	0.520	0	0	0
9	PMMA	0.450	0	0	0
10	Other Plastics	0.651	0	0	0
	Total	5.279	3.34		$ 6.8

The material recyclability index (for Steel and ABS) in the above table was taken from the paper by (Yadav et al., 2018) and the virgin material value for the metal (steel and Aluminum) was taken as commodity prices from Trading Economics website (Trading Economics, n.d.) while for the plastics virgin material value was taken from The Plastics Exchange (The Plastics Exchange, n.d.)

Calculating cost of disassembly for the product as follows:

$\boldsymbol{Disassembly\ cost}\ (\boldsymbol{Cd_k})$= 198.2 s * 0.0028 $/s = $ 0.555 ≅ $ 0.6

Profit from full disassembly for the LCD monitor is calculated below after considering the cost of disposal is zero.

$\boldsymbol{PLM}_{\boldsymbol{RECOVERY,k}} = 6.8 - 0.6 = \$\ 6.2$

Next step is to calculate the mass efficiency of each material as shown in the following table then the material circularity Indicator:

Table 5.7 MCI calculations for LCD monitor

	Material	**Mass (kg) Mi**	**Recyclability rate (ri)**	**Recycled material Mr(i) (Mi*ri)**	**V= M(i)-Mr(i)**	**W**
1	Steel	1.771	0.94	1.665	0.106	0.106
2	Aluminum	0.130	0.95	0.124	0.006	0.006
3	Printed Circuit board	0.410	0.18	0.074	0.336	0.336
4	Cables	0.340	0.33	0.112	0.228	0.228
5	Black light	0.002	0	0	0.002	0.002
6	LC display	0.645	0	0	0.645	0.645
7	ABS	0.360	0.94	0.338	0.022	0.022
8	PC	0.520	0	0	0.52	0.52
9	PMMA	0.450	0	0	0.45	0.45
10	Other Plastics	0.651	0	0	0.651	0.651
	Total	5.279		2.313	2.966	2.966

By using Equation (4.7) we can now calculate the efficiency of recycling the ***14" LCD Philips monitor from 2002***

$$\text{Efficiency of recycling} = \frac{2.313}{5.279} = 0.438$$

$$\text{LFI} = \frac{2*(2.966+2.966)}{4*5.279-2.966} = 0.65$$

MCI = 1- 0.9*0.65 = 0.42

From the previous calculations, it can be noticed that the circularity Indicator of the ***14" LCD Philips monitor from 2002*** was low compared to the first case study with product recyclability of 0.94, the main reason was due to higher complexity as a result of many components with different materials and different recyclability rates in this product.

Salhofer et al. (2011) estimated that the total mass of EoL products with LCD screens will account for 569 ktonnes in the EU-25 by 2018, which amounts to 1.2 kg per capita per year. This makes the EoL of flat panel displays (FPDs) one of the fastest growing waste streams.

The challenge in recycling this LCD monitor comes from the complexity of the product, with different materials especially the plastic material used, where it contains a large amount of engineering plastics and precious metals, which have significant economic value, Generally, FPDs have a layered construction; a metal casing contains three or four plastic optical sheets that diffuse the light of the backlight unit, a light guiding plate made of a thick plastic sheet, and the backlight. The actual LCD screen, consisting of glass and liquid crystals, is located on top of the sheets. On the other side of the metal casing, at the back of the FPD, several printed circuit boards (PCBs)4 are protected by a plastic cover. The power supply and the main board are usually protected by a metal casing in LCD monitors, but in some cases are only covered by the plastic back cover.

5.3. Case study 3: Keyboard disassembly

The following case study is a disassembly of a keyboard which was performed using automated disassembly, the material composition and the time of disassembly was used from a paper by (Langerak, 1997)

Table 5.8 Reclamation value from disassembly of Keyboard

	Material Composition	**Material Mass (gm)**	**Material Value ($/kg)**	**Material Recyclability Index MR ($/$)**	**Reclamation Value (Rv_k) $**
	PBT	174.3	0.99	0.7	$0.12
	PBT	10	0.99	0.7	$0.01
	Fe	30	0.09	0.97	$0.003
	PVC	272.5	0.95	0.97	$0.25
	Div	26.34		0	
	PS	21.55		0	
	Rubber	38.28		0	
	Div	0.65		0	
	PVC	329.1	0.95	0.97	$0.30
	PS	50		0	
	Total	5.279	3.34		**0.68**

The material value for PBT (Polybutylene terephthalate) was used from (The Plastics Exchange, n.d.), (Fe) price was taken as a commodity price from Trading Economics website) (Trading Economics). PVC price was taken from a report from (ICIS) (Independent Commodity Intelligence Services, n.d)

The recyclability index for PBT and Fe was assumed to be the same as for ABS and Steel in case study 1, while the recyclability index of PVC= 0.97,

Time of disassembly for the keyboard is (**338.3 S)** was taken from the paper mentioned above (Langerak, 1997) . Following is the calculated for cost of disassembly:

Cost of disassembly = 338.3 s * 0.0028 $/s = $ 0.95

Then the profit from recycling will be calculated as follows:

$$\boldsymbol{PLM_{RECOVERY,k}} = 0.68 - 0.95 = \$\ (-0.27)$$

The previous calculations show no profitability of recycling the keyboard, in order to make the recycling process more profitable one of the factors that could be changed is improving the time of disassembly or reducing the labor rate below 10$/h.

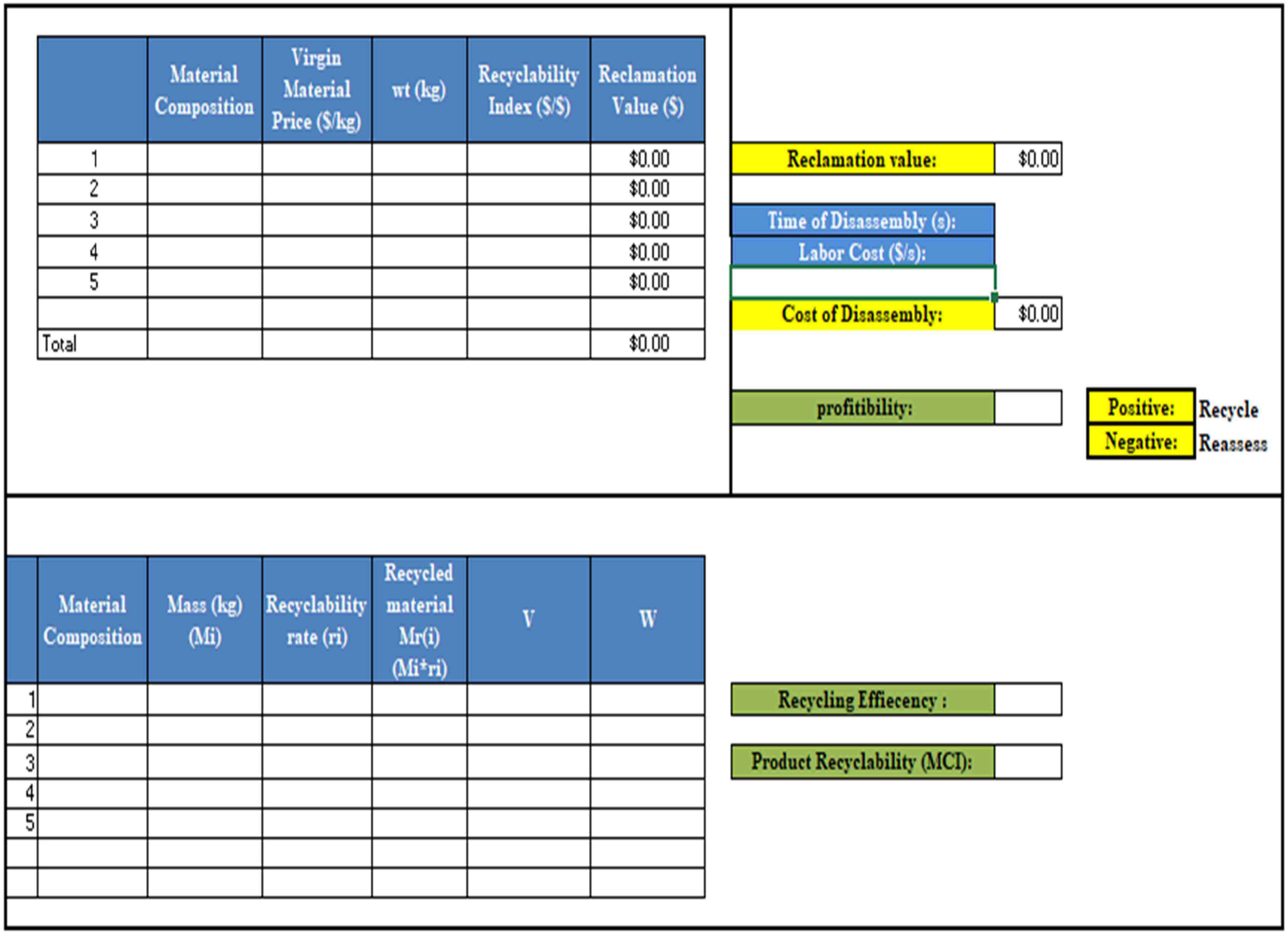
CHAPTER 6. DISCUSSION AND CONCLUSION

6.1. Discussion

The previous case studies indicate that the complexity of the material is the result of different factors. The cost of disassembly is one important factor as it depends on the time of disassembly as well as the labor cost; in addition, the sorting of the material is based on the material types and the purity of the separation plays an important role here. The labor cost was estimated at 10$/h = 0.0028 $/s. In order to increase the recycling profitability, it is an essential factor that the time of disassembly is reduced, and the amount of material recovered is increased.

Taking the complexity of a product and the ease of disassembly into consideration at the early stages of design is essential. Many factors should be taken into consideration when calculating the recyclability of a product. One factor is the complexity of the product and whether it contains parts that can be recycled easily or contain hazardous material that should be handled carefully to avoid environmental contamination as well as endanger the health and safety of the workers. The findings from the previous case studies can be summarized as follows: increase the use of materials with a high recyclability rate, reduce the variety of materials, allow for easier material and component sorting, reduce handling, and reduce waste.

Figure 6.1 represents a proposed tool to measure the product circularity based on the product's complexity. This tool calculates the reclamation value of the product and the cost of disassembly. Then, the profitability is calculated by subtracting the cost of disassembly from the reclamation value. If the result is positive the next step is to recycle the product and calculate the recycling efficiency by dividing the amount of recycled material over the entire weight of the product. Then this efficiency is used to calculate the product's circularity. The following assumptions were made: no parts are reused, and all will be recycled, and that this is a closed loop where there are no components coming as feedstock from other manufacturers. This tool could be developed further to accommodate more variables. Also, the complimentary risk and impact indicators proposed by the MacArthur Foundation (Ellen MacArthur Foundation. 2015a) could be included in this assessment in the future.



	Material Composition	Virgin Material Price ($/kg)	wt (kg)	Recyclability Index ($/$)	Reclamation Value ($)
1					$0.00
2					$0.00
3					$0.00
4					$0.00
5					$0.00
Total					$0.00

Reclamation value:	$0.00
Time of Disassembly (s):	
Labor Cost ($/s):	
Cost of Disassembly:	$0.00
profitibility:	

Positive:	Recycle
Negative:	Reassess

	Material Composition	Mass (kg) (Mi)	Recyclability rate (ri)	Recycled material Mr(i) (Mi*ri)	V	W
1						
2						
3						
4						
5						

Recycling Effiecency :	
Product Recyclability (MCI):	

Figure 6. 1 Proposed toot to measure the product recyclability based on product complexity

6.2.Conclusion

The circular economy is an important concept that promotes a superior design of materials, products, systems, and business models. From the literature review on product circularity, three circularity indicators were investigated: The ***Circular Economy Toolkit (CET)***, ***the Circular Economy Indicator Prototype (CEIP)*** and the ***Material Circularity Indicator (MCI)***. The first two indicators are limited and focus more on the environmental part of the circular economy; In addition to that, the first two are missing the amount of materials recovered from recycling, the percentage of recycling. and they have other limitations.

On the other hand, the Material Circularity Indicator (MCI) is a better representation to identify and measure the circularity of the product where there are other complimentary indicators, known as Complementary Impact and Risk Indicators, included in the Ellen MacArthur Foundation methodology. However, after choosing the material circularity indicator as a good tool to measure the circularity of a product, missing factors were found that were not included in this indicator, such as the effect of complexity of a product and its ease of disassembly.

Another literature review on product complexity was performed to understand and analyze the different existing methods used to measure the complexity and ease of disassembly. A relationship was found between the time of disassembly and recycling efficiency (Ec), as the time of disassembly affects the profitability of disassembly as well as the decision to recover or dispose of a specific material.

A new set of equations and calculations was used in order to find the recycling efficiency (Ec) based on the profitability of disassembly, and from there the Material Circularity Indicator (MCI) can be calculated. Three case studies are presented to illustrate this proposed methodology that measures the efficiency of recycling for different materials and finds out how this can affect the Product Circularity using the Material Circularity Indicator.

As Vanegas et al. mention in their paper “A reduction of the disassembly time and the related costs will increase the economic feasibility of product lifetime extension and therefore increase the viability of a circular economy in industrialized regions” (Vanegas et al., 2018, p.323). Based on this work the focus will be on investigating the role of the complexity and how the complexity of the product can affect the recycling efficiency.

Different methods are used to measure the disassembly time. (Vanegas et al,2018) explain two approaches: the first one is direct measurement, and the second is calculation based on product parameters; for the calculations used here the disassembly time was used based on papers estimating the most efficient time of disassembly.

A metric that accounts for how much of a product is designed to be recoverable at the end of its useful life is an important factor. This metric requires not only understanding what materials can be recycled, but also if those materials would be pure enough to be recycled, upcycled or downcycled. Also, whether a product can be effectively recycled at the end of its useful life can be considered as an indicator of how well a product is designed for circularity, as these factors determine whether the resources in the product can be cycled or not.

Although most products can be disassembled eventually, lengthy disassembly does not make for economic recycling as the cost of disassembly is likely to be much higher than the revenue gained through recycling the parts and materials from the product. For this reason, it is important to design products for easy disassembly, which has increased in popularity enabling more of the product to be recycled economically.

Shredding is a quick way of recycling materials, but its main drawback is the impurity of the recovered (produced) material. Thus, in order to decrease the material's impurity and to reclaim higher value components, effective methods of dissembling the products appear imperative.

The economics associated with the disassembly and reclamation of durable products is an important aspect of disassembly due to which manufacturers and recyclers question the profitability of recovering durable products. They usually use heuristics to analyze the breakdown of products and the associated costs. This often means that once high value components are identified from within products, product disassembly continues (regardless of its profitability) until such materials are recovered.

6.3 Recommendations for future research

Future research should involve investigating in more depth the other factors affecting the product complexity; for example, there are certain limitations in the research that must be addressed in future. To determine the recyclability of the product, it is assumed that all assembled parts will eventually be disassembled. For example, if the parts assembled with each other are comprised of the same material their part recyclability would be high as they are made up of the same material and do not require disassembly. Also, the results obtained in this study could be improved by conducting more case studies, future work should include more details in the calculations such as calculating the cost of recycling by taking the other costs into consideration as an example (cost of operation and the reverse logistics costs, which includes transportation and sorting cost).

The original intention was to develop a tool that designers could use during the design process to help design products that are more suitable for recycling. For this, a live case study and/or a protocol study could be performed in which designers and engineers use the model and data collected to analyze if and how the proposed model or tool makes any significant contribution to the product design.

In current practice, most recyclability indices treat the product as a single amalgam of materials (Li, 2018) instead of an assembly that needs to be disassembled before recycling. This paper takes a step toward including the disassembly process in determining the recyclability of products. However, the disassembly ratings discovered in existing literature have limitations, and in order to overcome the limitations, it would be necessary to develop a new disassembly rating method that takes the factors of quality and purity of the disassembled materials into consideration.

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