Ahmed Eltayeb

MAPPING AND ASSESSING TECHNOLOGY CATALYSTS THAT ACCELERATE CIRCULAR ECONOMY TRANSITION

Multiple case study

Tampere University
Master of Science Thesis
Examiner: Associate Professor Leena Aarikka-Stenroos
Examiner: Doctoral student Valtteri Ranta
November 2019

ABSTRACT

Ahmed Eltayeb: Mapping and assessing technology catalysts that accelerate Circular Economy transition: multiple case study
Master of Science Thesis, 99 pages
Tampere University
Industrial Engineering and Management
November 2019
Examiner: Associate Professor Leena Aarikka-Stenroos
Examiner: Doctoral student Valtteri Ranta

The demanded, expected and continuous economic growth has a big burden on the environment because of the resources scarcity and limited availability. Circular Economy concept has been considered as an alternative paradigm that can eliminate waste and support the continual use of resources. Many companies are trying to deploy the CE concept through innovation and technological advancements. However, succeeding in that requires assessing the developing technologies to fit with circularity concept in order to be sustainable. To explore this phenomenon and address the issue while developing theory in this research area, this study aims at answering the following research question: *What are the technology catalysts that accelerates Circular Economy transition? What is the criteria for assessing developing, and sustainable Circular Economy technologies? With the following sub-question; how the technology advances Circular Economy and sustainability? How ready is the technology?*

To answer these questions, a multiple case study of 7 different cases is conducted. Various technologies were selected as the cases in order to cover a wide range of technology streams. The collected data is primarily qualitative, gathered from qualitative interviews. Five semi structured interviews were held, all the interviews were recorded and transcribed by the author. The data was analysed in each separate case using the framework developed to answer the research questions. Then from the data collected a cross case analysis is conducted on technologies per se level to pinpoint to any patterns across assessed technologies and on technology streams level, to identify the commonalities and differences among technology streams criteria for assessing Circular Economy technologies.

Results identify that developing and sustainable Circular Economy technologies should be assessed based on the criteria of circularity, sustainability and technological readiness. Each criterion has different deciding methodologies. Most of the methods and approaches used for assessment were mainly quantitative. Also, it is was identified that most immature technologies are the ones that follow a strong circularity strategies of reuse and reduce. Furthermore, most technology developers lack the importance of considering the social dimension of sustainability while developing their technologies. They rather link environmental benefits to social impact. The results also indicate that most technology streams can accelerate Circular Economy transition. Nevertheless, digital technologies, manufacturing technologies and bio-technologies were highlighted. Therefore, this study contributes to the qualitative assessment of Circular Economy literature and develops an assessment approach for managers, policy and decision makers for deciding upon technologies that fulfil a strategy of sustainable Circular Economy technologies.

Keywords: Circular Economy, technology catalysts, technology assessment, sustainability, sustainable technology development

PREFACE

This thesis is conducted as a part of CICAT2025 Finnish project. The project aims at facilitating the transition from linear to Circular Economy through identifying Circular Economy catalysts. I am glad that my thesis is part of this project and will contribute towards its goal. I would like to express my gratitude to all of my colleagues in CITER research group for their help, support and for the great memories we shared for almost 8 months. I am glad that I met and made friends from such wonderful group.

I would like to specially thank Leena Aarikka-Stenroos for her superb support and guidance during this thesis. Also, for the different insights and knowledge she provided in order to add more in-depth to my research topic. Also, for her valuable feedback on my thesis progress during the research process. Also, I would like to thank Valtteri Ranta for his continuous support, assistance in building the thesis framework and encouragement throughout the research process. I am thankful for you being there.

Last, I want to sincerely thank my beloved family for their immense support and love. They had always been and will always be my backbone in every step in my life. They have filled my life with joy and I am grateful for that. Also, I want to thank my friends for their continuous encouragement, support and their understanding.

By the end of this thesis, my master's journey in Finland ends. Yet, my career is ahead and a new journey to be started. I am heading for a new challenge and I am glad and proud of what I have accomplished so far in my life. I am also grateful for all the great moments and memories I shared during my university years. This will always be memorable.

Tampere, 22 November 2019

Ahmed Eltayeb

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

9R	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover
AM	Additive Manufacturing
CAD	Computer Aided Design
CE	Circular Economy
CTPs	Critical Technology Parameters
DEA	Data Envelopment Analysis
DES	Discrete Event Simulation
DfX	Design for X
DfD	Design for Disassembly
DfEol	Design for End-of-life
Em	Emergy approach
Ex	Exergy approach
GL	Guidelines
I-O	Input-Output
IoT	Internet of Things
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCA	Material Cost Analysis
MCDM	Multi Criteria Decision Methods
MFA	Material Flow Analysis
MFCA	Material Flow Cost Accounting
NASA	National Aeronautics and Space Administration
RFID	Radio Frequency Identification
RQ	Research Question
TAU	Tampere University
TUNI	Tampere Universities
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level

1. INTRODUCTION

1.1 Background

Companies seek economic prosperity, growing their business and bringing in more money through different strategies. For many companies, technology development is the main strategy and road map for growth; promising technologies encourage optimistic new-product business cases that seek converting the raw technology into profit (Clausing & Holmes, 2010).

Technologies have been in a constant exponential development. For instant, in the last three centuries, the technological advancement was so quick and momentous that it was considered as the age of technology (Grubler, 1998; Musango & Brent, 2011).

Furthermore, technology development is a continuous process (Clausing & Holmes, 2010). It has the potential of providing the advantage of economic growth, societal benefits, as well as, making it easier to minimize the negative environmental effects (Musango & Brent, 2011).

Nevertheless, the relation between the environment and technology is complicated and contradictory (Grubler, 1998). In many occasions, technologies are creating unwanted by-products, using scarce resources and placing stress on the environment (Musango, Brent, Amigun, Pretorius, & Hans, 2012). On the other hand, technologies can also lead to a better resources management, improved efficiency, and less environmental stress (Musango & Brent, 2011). The latter perspective is known as sustainable technology development (Weaver, Jansen, van Grootveld, van Spiegel, & Vergragt, 2017).

Musango and Brent (2011), argues that sustainable technology development is not autonomous and needs management to be achieved. Also, many companies acquire losses in their revenues because they start manufacturing new innovation without assessing their technologies (Clausing & Holmes, 2010). In order to manage and improve any system there should be a way to measure and assess it (Drucker, 2005). Therefore, assessing technologies is important and essential for deciding upon the benefits to be acquired by any technology.

Technology assessment is one of the most important and essential fields of technology management (Tran & Daim, 2008). As argued by Mankins (2009) that the assessment of technologies is an important component of the effective management of technologies and any innovative technologies should be tested under certain engineering and manufacturing conditions long before it is transferred to a commercial product. Therefore, technology assessment can create a competitive advantage for many companies by reducing risks accompanied to the development process of the technologies, provide information that support decision making in defining the track of research and development, determine the technologies to be adopted and the ones to be improved, as well as, the capital expenditure on the new technologies (Henriksen, 1997).

Currently, companies are looking for alternative paths for achieving their growing and continuous improving sustainability standards. The established growth model represented in linear economy which is based on take-make-dispose philosophy is consuming a lot of scarce resources and contributing towards waste generation (Pagoropoulos, Pigosso, & Mcaloone, 2017). Especially, in a world of finite resources and the economic development on a rise (Fonseca, Domingues, Martins, & Zimon, 2018). The existing resources are scarce and limited in terms of restocking in an infinite way (Sassanelli, Rosa, Rocca, & Terzi, 2019). Hence, finding an alternative paradigm that has a new philosophy of maintaining resources and limiting waste generation is important (Sariatli, 2017). Therefore, companies are looking for future competitive advantage through addressing the Circular Economy concept.

Proposing the concept of Circular Economy (CE) as an alternative paradigm to the linear model was introduced by different researchers. It has become an interesting and important field of academic research with an increasing number of journals and articles covering the topic since its introduction (Geissdoerfer, Savaget, Bocken, & Jan, 2017). Circular Economy became a very popular and widespread concept in literature after many years of investigations (Sassanelli et al., 2019; Winans, Kendall, & Deng, 2017). Circular Economy can demonstrate a better strategy to meet the continuous economic growth, it is characterized as a restorative and regenerative economy (Pagoropoulos et al., 2017; The Ellen MacArthur Foundation, 2013). Therefore, instead of extracting new resources, use them for manufacturing or any other purposes and then disposing them at the end of their lifetime cycle, Circular Economy aspire at keeping materials and products that can offer value in a closed loop, as well as, encourage different circularity strategies that can promote better management to exiting products and materials. Then, the goal is to keep the added value of a product as much as possible within the economy as a usable resource which can be reused while eliminating waste (Sariatli, 2017).

Since Circular Economy is a technology driven concept, companies and their stakeholders are realizing the potential opportunities promised by Circular Economy lately (Geissdoerfer et al., 2017). Therefore, many companies started to develop Circular Economy technologies and shift into Circular Economy manufacturing while adopting new designing methods. Hence, assessing new Circular Economy technologies is important to achieve the maximum technological benefits.

According to Sassanelli et al. (2019) Circular Economy concept has been impelling the redaction of legislative directions mainly in Europe and China. Therefore, there is a high need of a broad and well integrated technology assessment tool that is able to assess sustainability of any technology, so technology developers, policy and decision makers will be able to define the convenient technology options that support the perspective of sustainable technology development (Musango & Brent, 2011). Although the final decision is not necessarily provided to managers or policy makers by technology assessment, however, it will improve the chances of achieving the best technological benefits (Henriksen, 1997). In other words, technology assessment has changed for decision and policy making key players from being a simple evaluation tool to a strategic planning tool for adopting new technologies (Musango & Brent, 2011). Furthermore, from a tool that assesses only the technological side from engineering point of view to a tool that incorporates both the engineering and management point of views.

Thus, as discussed earlier the value offered by technology assessment has been efficient in addressing different technological problems, yet the need of finding different and more methods of assessment that covers new emerging technologies from different backgrounds is essential (Tran & Daim, 2008). Therefore, after research investigation*…*

…it is obvious that there is a gap in the literature that does not cover an assessment approach of sustainable Circular Economy technologies, in particular in an early phase and on a technology development level.

Most of the relevant literature is covering only a quantitative assessment of the material flow in the whole system, or the environmental impact of Circular Economy technologies or in some occasions covering the whole sustainability concept. Moreover, other literature focused on discussing the assessment of the performance of Circular Economy by focusing on the circularity degree like Sassanelli et al. (2019), or focused on developing a quantitative tools that assess the industrial symbiosis of Circular Economy in certain industry like Wen and Meng (2015), or focused on developing a framework for assessing the complex value of recovered resources in Circular Economy context like Iacovidou et al. (2017), or focused on developing an assessment tool for the end of life product recovery strategies in Circular Economy like Brissaud (2019).

Therefore, this thesis develops a framework for assessing *developing sustainable technologies in Circular Economy*, with the aim of providing a common and consensus understanding on a holistic assessment model for Circular Economy technologies in their development phase. The framework is designed to ensure that technology development in the field of Circular Economy incorporates and couples different type of indicators that can demonstrate the technologies circularity, readiness and sustainability impact. Those indicators together enable the evaluation of the aggregate technology competence and further ease the strategic planning and assessment of the technologies.

1.2 Objective

This study is aiming to fulfill the research gap of identifying a common assessment approach to be used in assessing sustainable Circular Economy technologies, which are in their development phase. While the Circular Economy assessment have had a big interest in literature lately (Sassanelli et al., 2019), the focus have been mostly on assessing the performance of existing and operating Circular Economy technologies. Therefore, the need of identifying more and different assessment tools is important (Tran

& Daim, 2008), to be able to assess technologies at an early stage while they are undergoing development to prevent acquiring revenue losses by companies and creating unwanted by-products (Clausing & Holmes, 2010; Mankins, 2009), which is the main target of effective technology management, and the main gap to fulfill by this study.

Moreover, fulfilling the main gap of this study will require detecting various developing Circular Economy technologies, then identify from technology developers perspective, the technology streams that are witnessing many technological innovations and contributing for a fast transition towards Circular Economy. Such technology streams acting as a catalyst for enabling Circular Economy business Ecosystems will be identified and covered throughout this study.

Therefore, to address the main gap of this study which is revolved around the approach of assessing developing sustainable technologies in Circular Economy, the main research question of this study is:

1. *What is the criteria for assessing developing and sustainable Circular Economy technologies?*

To better argue the main research question, a set of sub-questions are used to add more in depth to the study and to cover the terms ''developing'', ''sustainable'' and ''Circular Economy''. Also, to be used as a reference in analyzing the selected cases later in this study. The sub-questions are:

- *How the technology advances Circular Economy and Sustainability?*
- *How ready is the technology?*

Then, to identify what are the technology streams that are contributing towards a Circular Economy transition with a wide range of technological advancements, the second research of this study is:

2. *What are the technology catalysts that accelerate Circular Economy transition?*

To answer these questions, then detecting various technologies from different scientific fields and backgrounds is essential, so the possibility of detecting common assessment criteria while covering wide spectrum of technologies. As well as, identify the technology catalysts from different technology stream point of view. Therefore, a multiple case study was conducted as a convenient research design for this study to answer these questions, since case study research is an effective method at finding more information through analyzing and cross-compare collected data (Saunders, Lewis, & Adrian, 2009).

The previous research questions/sub-questions will guide and assist in conducting the study. Thus, the objective of the thesis is*…*

… Mapping Circular Economy technologies within Tampere University while providing the policy and decision makers with an assessment criteria that allow them to holistically

assess developing Circular Economy technologies. Also, present technology catalysts that are enabling and accelerating Circular Economy…

The thesis has an exploratory nature and to answer its research questions and meet the study objective, a multiple case study is conducted. Morris & Wood (1991), argue that the case study strategy is effective at helping the practitioner conducting the study for gaining better understanding of the context of the study. Moreover, Saunders, Lewis, and Adrian (2009); Yin (2014), discuss that case study strategy most often used in exploratory research which is evident that case study strategy was convenient choice for conducting this research.

Since the aim is to identify criteria for assessing Circular Economy technologies and the concept of Circular Economy can be used in technological advancements within different technology stream. Then, it is inconvenient to select only one technology represented in a single case to conduct this research. However, using multiple case study approach in conducting this thesis will generate a more generic level of details and scattered information rather than very specific compared to the using single case study (Yin, 2014). Nevertheless, this generic level of detail can be very beneficial for policy and decision makers to provide guidelines for the knowledge needed for deciding and assessing upon Circular Economy technologies. Furthermore, for technology developers, it can provide a roadmap that covers different focuses to follow while developing their technologies.

1.3 Structure of Thesis

The thesis is structured in a way that serves the asked research questions, to fulfil the introduced gap and cover the literature topics of interest to this study. Hence, it is divided into seven chapters as follows:

1. First chapter introduced the background, the main objective of the study along with introducing the research gap. Also, the main research questions and sub-questions that are supposed to cover the research gap.

2. Second chapter discusses the sustainable circular economy, this chapter is the first section of a two literature sections that sum-up the theoretical background of this study. The chapter is divided into two parts. First part covers the difference between linear and circular models, the accelerating actors affecting it and the R-strategies of circularity. Second part discusses what is meant by sustainability, its three dimensions and the relation between Circular Economy and sustainability in literature.

3. Third chapter is the second section of literature in this study, it introduces the technology development and its assessment. Then discuss the Circular Economy technologies assessment and the readiness concept, the motives and drivers of researchers to develop circular economy technologies. At the end, the assessment tool to be used in assessing the technologies mapped in this study while explaining the tool limitations

4. Fourth chapter demonstrates the research methodology, what is the research design of the study, the framework developed for assessing technologies, the case selection procedures and the data gathering methods applied in all the research activities and its analysis.

5. Fifth chapter introduces the technologies mapped for this study, describes them and discusses their impact on Circular Economy and sustainability. Also demonstrate their readiness and an overview for each technology.

6. Sixth chapter present the cross case analysis that took places between the mapped technologies. Demonstrate the analysis from technologies per se perspective and from technology streams perspective. Also, reviews the new findings realized by the end of the study and

7. Seventh chapter concludes and sum-up the whole thesis findings, explains how the study met the objective and describes what the theoretical and managerial implications of this study are. Also, what can be done better/differently for better research outcomes.

Therefore, this thesis focuses on the assessment of three different areas and applying different tools and strategies that can be linked together to attain a sustainable and ready Circular Economy technology. First is Circular Economy technologies, second is sustainability and third is technological readiness. An assessment tool or approach will be used to cover each focus area as shown in the figure next.

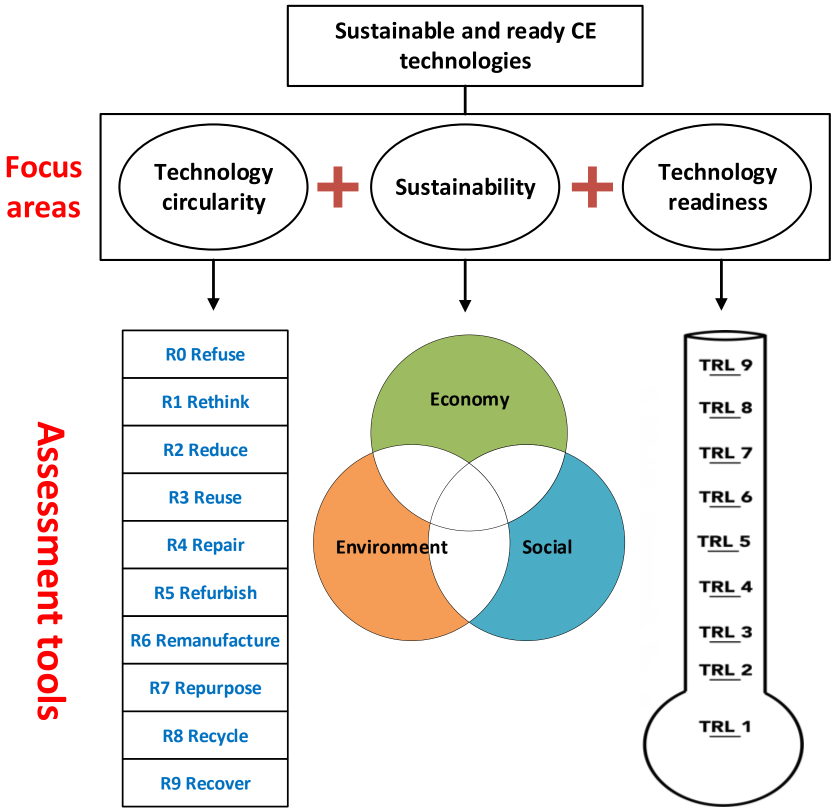

Figure 1. *Thesis research areas and their relations*

These combined focus areas and their assessment tools can provide the understanding of sustainable and ready Circular Economy technologies. In addition, provide an assessment tool for developing Circular Economy technologies and help policy and decision makers determine technologies that serve their desired plan and road map.

2. SUSTAINABLE CIRCULAR ECONOMY

2.1 Linear and Circular Models

The human existence had been characterized by its cycle, the distant past is always viewed as better than the present and future, at the best case, the present and the future are similar to the past (Bonciu, 2014). This whole idea changed by the modern concept of linear improvement where the future is estimated to be far better than the past due to the accumulation of knowledge, experience and wealth. Similarly, that was the common idea to the economic growth, the more of extracting natural resources and the more of manufacturing then the more of economic prosperity. Besides that, the availability of cheap materials made industrial communities to rely on extensive use of materials. Accordingly, the linear economy growth and intrinsic mechanics was dependent on the wasteful concept of take-make-dispose (Sariatli, 2017).

As shown in the figure below, at a certain point the global economy was representing a small fraction to the global ecosystem. As a result, the idea of unlimited production known as linear economy seemed feasible and unlimited resources where the source of our economies.

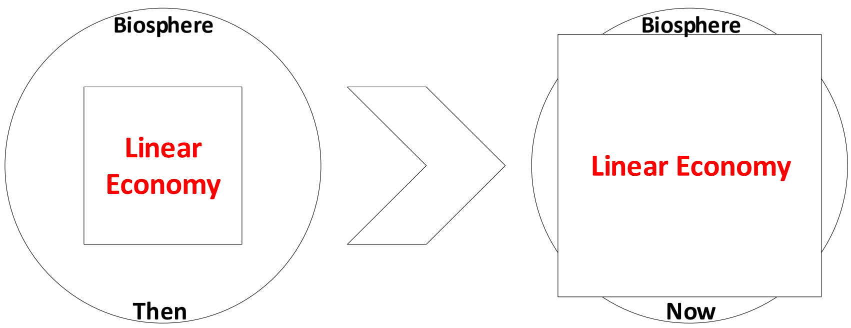

Figure 2. *Relation between linear economy and biosphere. Adapted from Bonciu (2014); Fern, Gonzalo, and Soto-o (2019).*

However, the linear, continuous boost of production in a world of limited resources is not practical (Bonciu, 2014). Also, resources are becoming scarce for a wide range of materials (Pagoropoulos et al., 2017). Along the years, the linear economy became bigger in size than the global ecosystem in terms of waste elimination, consumption and extraction rates (Bonciu, 2014; Fern et al., 2019).

The gradual increase of awareness of the limits to be reached by linear economy, different and new consumption practices have been proposed over the last few years to replace the current established linear model (Pagoropoulos et al., 2017). One of the most promising economic models of maintaining and improving the well-being of people that can be implemented while keeping the consumption rates and waste eliminated in the environment within the same level is known as Circular Economy (Bonciu, 2014; Pagoropoulos et al., 2017). As argued by most authors, the aim of Circular Economy is to achieve a closed loop that eliminates any extra resources input, any waste and emissions (Geissdoerfer et al., 2017). The shift from wasteful linear economic model to Circular Economic model should sustain the relation between the biosphere and the demanded, continuous economic growth.

Therefore, Circular Economy is aiming at adjusting the consumption and extraction rates along with waste elimination by minimizing the use of virgin materials become again within the biosphere boundaries (Bonciu, 2014). The core of Circular Economy is seen as the circularity of materials in a closed loop as well as, the use of raw materials in multiple phases and in different stages (Zengwei Yuan, Jun Bi, 2006). Circular Economy is seen as an alternative to linear production model which can increase economic and ecological benefits (Fern et al., 2019). It aims at leaving behind the traditional linear economy that is based on extracting natural resources for the sake of manufacturing products to be either consumed or disposed (Sassanelli et al., 2019). Moreover, the closed loop manufacturing systems are considered to be more sustainable than the traditional manufacturing methods (OECD, 2009).

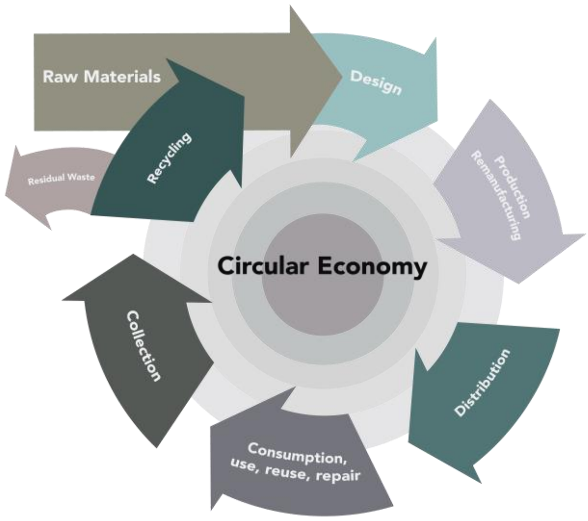

***Figure 3**. Circular Economy transition. Adapted from Bonciu (2014).*

The transition towards a resource-efficient Circular Economy is inevitable (Bonciu, 2014). The responsibility of transition into a circular system relies mainly on private business, regulators and policymakers (Geissdoerfer et al., 2017). Private businesses by taking the initiative of adopting Circular Economy concept, as well as, develop technologies that are accelerating the transition from linear to Circular mode. Regulators and policy makers by setting new standards and actions plans to implement and pave the road for a transition towards Circular Economy. In this transition, resources will no longer be obtained from the environment for the means of production (Bonciu, 2014), but rather the production process is designed in a sustainable circular way that allows the initial obtained resources used in production and turned into waste to be itself used as a resource and recycled again in the economic process allowing a longer life cycle (Fern et al., 2019; Pagoropoulos et al., 2017; Sariatli, 2017).

Furthermore, Circular Economy as a concept has gained a big fame lately on the agendas of policy makers (Geissdoerfer et al., 2017). Circular Economy is involving with different actors as policy makers (Sassanelli et al., 2019; Suárez-Eiroa, Fernández, Méndez-Martínez, & Soto-Oñate, 2019). Germany was considered the leading country in adapting Circular Economy in their national laws by 1996 (Su, Heshmati, Geng, & Yu, 2013). Then, followed by Japan in 2002, China in 2009 (Lieder & Rashid, 2016). Last, the EU's in 2015 with the Circular Economy Strategy (Geissdoerfer et al., 2017). The adoption of Circular Economy requires synergy between all parties in the supply chain (Fonseca et al., 2018). Moreover, the legalization is increasingly impacting the manufacturing industry (Rybicka, Tiwari, & Leeke, 2016).

Moreover, Circular Economy would indicate the end of the ‘‘throw away’’ societal behavior to a big extent, giving up the make, use, dispose wasteful approach of production and transit into a reuse, refurbish, recycle and other processes that allow the outputs to become the new inputs preserving their productive use and eliminate waste (Bonciu, 2014). Hence, according to Fern et al. (2019) the most common strategies for Circular economy are; minimizing inputs of resources and outputs of waste, keeping resources value as long as possible and reintegrate the products after the end of their life back into the system. The current understanding of Circular Economy and its economical applications have evolved into a bigger form that incorporates other concepts that share the closed loop idea as cradle-to-cradle and industrial ecology (Geissdoerfer et al., 2017).

Cradle-to-cradle is a sustainable philosophy that requires designers to consider each stage of product lifecycle. Starting from the design, production processes to the end of life stage (Toxopeus, De Koeijer, & Meij, 2015). The aim is to provide a modern and practical design framework that can create products and industrial systems which can sustain a long-term economic growth while maintaining a safe and waste free environment in a closed loop model (Braungart, McDonough, & Bollinger, 2007). While industrial ecology is an environmental management framework that aims at tracking and analyzing the use and flow of resources in order to succeed in developing a balance between the environment and the production processes (Duchin & Levine, 2008).The goal is to move from a linear model to a closed loop system in all kinds of production and consumption to maintain an equal ratio between the inputs and outputs to planetary (Lowe & Evans, 1995).

Therefore, cradle-to-cradle and industrial ecology concepts incorporates the closed loop idea and have a common goal which is providing the best strategies and approaches for having a sustainable economic growth that can meet the industrial expectations while maintaining safe and waste free environment. In regards to Circular Economy, there are different approaches that are developed in order to achieve resources and materials circularity to be able to attain low consumptions (Potting, Hekkert, Worrell, & Hanemaaijer, 2016). Such approaches are known as the R-strategies which are shown in the figure below.

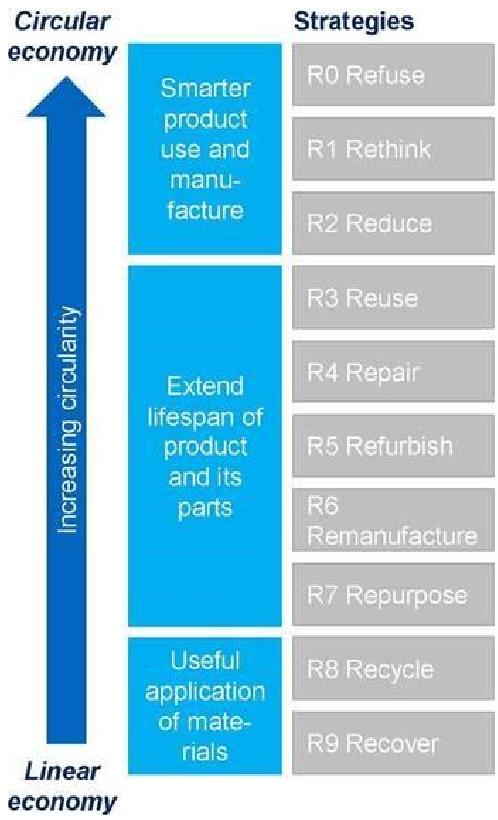

Figure 4. *The 9R strategies of circularity. Adapted from Kirchherr, Reike, and Hekkert (2017).*

The aim of this figure to present a priority order for the waste treatment methods (Kirchherr et al., 2017). All the listed strategies represent the range of circularity from high circularity to low circularity. The strategies that carry a low R number are viewed to be with a high circularity while the ones with a high R number are considered to be with low circularity. The explanation of the R strategies according to Kirchherr et al. (2017) is shown in the table next.

Table 1. *Explanation of 9R strategies of circularity according to* Kirchherr et al. (2017).

Strategy	Explanation
R0 – Refuse	To make product unnecessary through discarding its function or by offering an alternative product that can do the same function
R1 – Rethink	Make product use more intensive, like product sharing and service based models
R2 – Reduce	To minimize the use of natural resources and materials in the manufacturing of products
R3 – Reuse:	Reuse of an abandoned product that can still do its original function by a new user

R4 – Repair	Maintenance of a defective product to be used again with the same function
R5 – Refurbish	Restore an old product and bring it up to date
R6 – Remanufacture	To use parts of abandoned product in a new product with the same function
R7 – Repurpose	Use abandoned product or its parts in a new product with a new function
R8 – Recycle	Process materials to obtain the same or a lower grade quality of materials
R9 – Recover	Material incineration for recovering energy

The 9R strategies encourage smarter product manufacturing and use, It is preferable to follow the strategy of product sharing and reuse rather than the strategy that encourages extending the product life time, because the product will be used for its same function with the same or different users (Potting et al., 2016).

Circular and service based system is essential but not enough for a sustainable system, other surrounding factors like a change of lifestyle is required to achieve a long-term sustainable system (Nakajima, 2000). Also, authors argue that the main benefits from implementing Circular Economy systems appear to be more likely economic, nevertheless, the environment benefits from less pollution and the social benefits from certain assumptions like more labor jobs and less tax (Geissdoerfer et al., 2017). Therefore, in the next chapter the sustainability concept will be discussed, its dimensions, how Circular Economy is related to it and how important is it for attaining a sustainable system.

2.2 Sustainability

Sustainable development is the development that fulfil the present needs without compromising the future generations ability to fulfil their own needs (Bonciu, 2014; Fern et al., 2019). Policymakers and companies' top management are modifying their agendas and strategies because of their increasing concerns about sustainability (Geissdoerfer et al., 2017). Moreover, Circular Economy appears to have justice in terms of resource utilizations which is implicit in the concept of sustainable development (Fern et al., 2019; Geissdoerfer et al., 2017). Therefore, Circular Economy is gaining a big traction as the novel passage towards operationalizing sustainable development (Kirchherr et al., 2018). According to Korhonen, Nuur, Feldmann, and Eshetu (2018) Circular Economy is a sustainable development initiative with a focus on reducing the traditional linear model of production-consumption flow through applying circularity to materials.

Circular Economy is stated to be an economic system that is based on business models which replace the end-of-life concept with reducing or reusing or recycling of materials in order to achieve sustainable development which entails an environmental, economic and social advancements to the current and future generations (Kirchherr et al., 2017). Furthermore, sustainable development consists of three dimensions, economic, environmental and social dimensions. The three dimensions aim to reduce the environmental burden until it reaches a viable standard, maintain economic prosperity and social solidarity and synergy (Lozano, 2008).

Hence, Circular Economy is seen as the most attractive operational strategy for businesses to initiate, implement and accomplish the concept of sustainable development (Ghisellini, Cialani, & Ulgiati, 2016; Kirchherr et al., 2017; Murray et al., 2017a). Companies were able to define tangible Circular Economy strategies that encourage less use of raw material and waste production, all through technological advances, design and recovery processes (Hobson, 2016). Hence, economic benefits are achieved along with positive environmental impact. Both economic and environmental benefits are considered to fall under the umbrella of two of the dimensions of sustainable development. However, authors usually do not discuss explicitly in literature the relationship between the concept of Circular Economy and sustainable development (Geissdoerfer et al., 2017; Kirchherr et al., 2017). Moreover, most authors in literature do not review Circular Economy with a holistic view over the three dimensions of sustainable development, usually they are discussing one or two dimensions lacking the social impact which can lead to unsustainable implementation (Kirchherr et al., 2017).

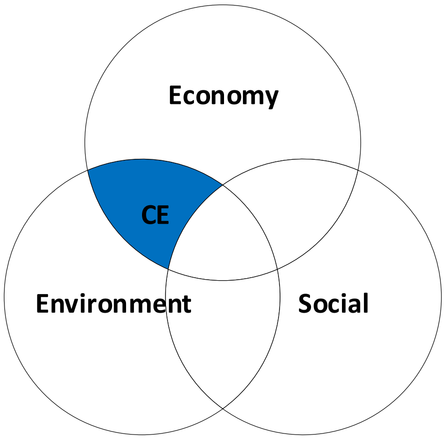

Figure 5. *CE impacting only two dimensions of sustainability. Adapted from Fern et al. (2019).*

As shown in the figure above, Circular Economy is only covering two dimensions of sustainable development leaving the social dimensions behind. According to Kirchherr et al. (2017) studying of 114 Circular Economy definitions reveals the following; almost half of the Circular Economy definitions reviewed and studies aim towards economic prosperity followed by environmental improvement in almost one third the definitions, while social impact is only mentioned and discussed in nearly one fifth of the definitions. According to Sauvé et al. (2016) most scientific literature shows and supports that Circular Economy covers both economic and environmental dimensions of sustainable development. Also, it is argued that the discussion of Circular Economy and its relation to sustainable development is usually carried in two different ways (Fern et al., 2019). Some authors address the Circular Economy and sustainable development while considering social impact within (Kirchherr et al., 2017; Murray et al., 2017a). On the contrary, other authors address the Circular Economy goal towards sustainable development only from economic and ecological point of view (Geissdoerfer et al., 2017; Sauvé et al., 2016). Therefore, the focus is mainly on the environmental performance change and improvement when addressing Circular Economy systems, there is no clear understanding of the social benefits behind Circular Economy that can contribute to the human well-being (Geissdoerfer et al., 2017).

However, Kirchherr et al. (2017) and Murray et al. (2017) suggested the importance of the inclusion of the social dimension as well, since Circular Economy is seen as tool that operationalize the sustainable development. Hence, it requires to include all the dimensions as shown in the figure below.

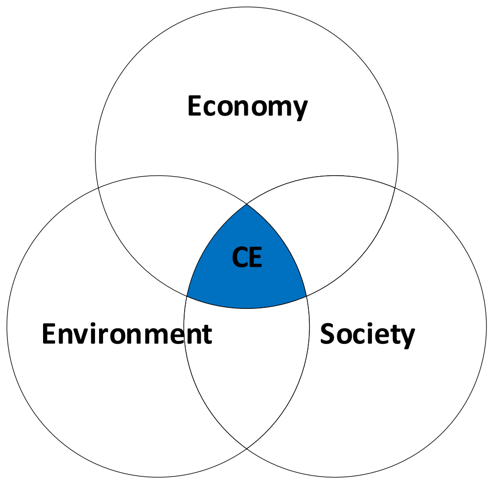

Figure 6. *CE operationalizing the sustainability concept. Adapted from Fern et al. (2019).*

As shown in the figure above, Circular Economy is covering the three dimensions and operationalizing the concept of sustainable development. According to Kirchherr et al. (2017), Circular Economy should ideally aim to a full sustainable development. From economic perspective through strengthen and protecting the economy. From environmental perspective through maintaining and protecting the environment while transitioning to better resource efficiency and low carbon footprint. Last from social perspective through strengthen the society, provide a better well-being and/or offer jobs.

According to Lozano (2008) any development that is able to balance the three dimensions is considered sustainable on the long term and ignoring any of the dimensions will lead to a failure in the whole development process. A lack of consumer awareness along with skeptical culture of companies are considered from the main barriers to Circular Economy adoption (Kirchherr et al., 2018). According to Jesus and Mendonça (2018) social awareness, sensitivity to environmental problems and shifting consumer preferences from ownership to service based model are the social and cultural drivers for Circular Economy adoption. Hence, considering the social dimensions is essential for a quicker adoption of Circular Economy while contributing to sustainability.

Moreover, developing and demonstrating new circular business models together with the end-user while taking in consideration their needs can help educating the consumers about the Circular Economy business models and solve different social barriers like resistance behavior and business routines (Jesus & Mendonça, 2018). In addition, social sustainability is seen as a perspective of social acceptance, it implies to the person's well-being as well (Assefa & Frostell, 2007). However, many issues such as high unemployment, social vulnerability and poverty trap prevented high societal expectations from being achieved (Geissdoerfer et al., 2017).

Therefore, there is a close relationship between Circular Economy and Sustainable development, however, its role remains unclear under sustainable development framework (Fern et al., 2019). What distinguishes Circular Economy from sustainable development is that Circular Economy is a tool for addressing some of the causes behind the problems that sustainable development aim to solve (Fern et al., 2019; Geissdoerfer et al., 2017). Hence, Circular Economy is a tool for reaching sustainable developments targets. However, technology advancements and innovations is important for Circular Economy to achieve sustainable development target which will be discussed in the next chapter.

3. TECHNOLOGY DEVELOPMENT AND CIRCULAR ECONOMY ASSESSMENT

3.1 Technology Development

The need for effective technologies advancements is as important as the need for a new business models that can contribute to closing the loops and ease the transition towards Circular Economy (Velis & Vrancken, 2015). There are multiple factors that have a role into facilitating or hampering the adoption of Circular Economy, such factors can be a driver, a need or a barrier or a mix of them (Jesus & Mendonça, 2018).

Technology development is one of the factors that is considered as a driver, a need and a barrier at the same time (Kinnunen & Kaksonen, 2019; Kirchherr et al., 2018). Moreover, the disinclination towards Circular Economy adoption can itself act as a barrier in the transition process from linear model to circular model (Kinnunen & Kaksonen, 2019). According to Jesus and Mendonça (2018) technical barrier is seen as the main reason behind a non-smooth transition of Circular Economy. Moreover, the potential opportunities of Circular Economy adoption are huge if the technological barrier can be overcome (Preston, 2012). Therefore, the existence of a relevant technology to a certain application in place is a necessity for the transition towards Circular Economy (Kirchherr et al., 2018; Pheifer, 2017; Shahbazi, Wiktorsson, Kurdve, Christina, & Bjelkemyr, 2016).

Furthermore, technological barriers were also outlined as a factor that limits the transformation from a linear model of take-make-dispose to a Circular model of closed loops and extended manufacturing cycle (Bechtel, Bechtel, Bojko, & Völkel, 2013). In addition, the lack of availability of technical solutions can restrain the Circular Economy adoption (Jesus & Mendonça, 2018). Hence, technology is reviewed as one of the barriers to Circular Economy due to the limited circular designs, lack of proven technologies that is already implementing Circular Economy and the limited ability to produce a high quality remanufactured products (Kirchherr et al., 2018).

However, according to Kirchherr et al. (2018) study, the technical barriers are not considered as the main bottleneck for Circular Economy transition as most literature claims. Some authors like Pheifer (2017) and Shahbazi et al. (2016) highlighted circular design as the major challenge when it comes to technical barriers for Circular Economy transition. Thus, technological advancement is not a major obstruction in the transition towards Circular Economy (Kirchherr et al., 2018).

Nevertheless, it is important to offer multiple and different technologies that can help advancing and accelerating Circular Economy because technological innovation raise the chances of having a win-win situation for achieving a better environmental quality and economic growth (Jesus & Mendonça, 2018). The rise in number of developing and existing available technologies that facilitate remanufacturing, regeneration and resource management is seen as a driver for easier Circular Economy adoption (Jesus & Mendonça, 2018).

In the process of reviewing different industries and technology streams, the role of Circular Economy in the mining industry for an instance is unclear, for that reason, technology development was reported as part of Circular Economy adoption in the mining industry with respect to the different solid materials, mine water and other waste streams (Kinnunen & Kaksonen, 2019).

Furthermore, the role of digital technologies in the transition from linear model to a circular model is vital. Nevertheless, their maturity is still in dispute (Pagoropoulos et al., 2017). However, higher recovery rates and potential better optimization are achievable through digital technologies (Reuter, 2016). As well as, linking manufacturing with digital technologies can improve material flow, inventory management optimization and communication over the whole process with different networks and stakeholders (Srai, Kumar, Graham, & Phillips, 2016).

Furthermore, information technologies are mature enough to be deployed on a large scale and support Circular Economy adoption (Lieder & Rashid, 2016). Moreover, digital technologies advance Circular Economy by supporting material tracking through taking advantage of the proper available information technologies and various data management technologies, hence, closing the material loop (Pagoropoulos et al., 2017).

However, Musango and Brent (2011) argues that the sustainable technology development process is not autonomous and needs management to be achieved. That being said, many companies acquire losses in their revenues because they start manufacturing new innovation without assessing their technologies (Clausing & Holmes, 2010). Therefore, assessing technologies is important and essential for deciding upon the benefits to be acquired by any technology. As argued by Mankins (2009) research and development departments should always consider formal technology assessment that can provide a consistent assessment besides the individual managers' opinions and experience.

Then, an effective technology management always addresses the technology assessment as the most important component for its progress (Musango & Brent, 2011). Therefore, in the next chapter technology assessment will be discussed and the current relation between Circular Economy and technology assessment.

3.2 Circular Economy Technology Assessment

For many companies, Innovative technologies are the main lead for growth; promising technologies encourage optimistic new-product business cases that seek converting the raw technology into profit (Clausing & Holmes, 2010). Also, the existence of a relevant technology to a certain application in place is a necessity for the transition towards Circular Economy (Kirchherr et al., 2018; Pheifer, 2017; Shahbazi et al., 2016). Therefore, companies are developing technologies that can achieve Circular Economy applications.

However, as discussed earlier, sustainable technology development is not autonomous and needs management. Therefore, technology assessment is important for an efficient technology development process.

Technology assessment is one of the most important and essential fields of technology management (Tran & Daim, 2008). As argued by Mankins (2009) the assessment of technologies is an important component of the effective management of technologies and any innovative technologies should be tested under certain engineering and manufacturing conditions long before it is transferred to a commercial product.

Therefore, technology assessment can create a competitive advantage for many companies by reducing risks accompanied to the development process of the technologies, provide information that support decision making in defining the track of research and development, determine the technologies to be adopted and the ones to be improved, as well as, the capital expenditure on the new technologies (Henriksen, 1997). Furthermore, technology assessment is essential for predicting the unintended implications of new invented technologies (Musango et al., 2012). Measuring the stability of new technologies and ensuring that the ones too susceptible will not go in the downstream pipe can be done through the technology assessment (Clausing & Holmes, 2010). According to Banta (2015) technology assessment is seen as a policy for examining the short and long-term consequences of developing technologies.

There are different quantitative technology assessment methods which were discussed by Clausing and Holmes (2010); Niero and Kalbar (2019); Rybicka et al. (2016). Some of the assessment tools are aimed at product level and others at technological level. However, according to Clausing & Holmes (2010) assessing technologies process development has to be done through considering a quantitative measurement of certain criteria that can be defined into:

1. Identifying all the failure modes of the developing technology
2. Define all the Critical Technology Parameters (CTPs) that control the defined failure modes. The CTPs were divided into two types; control parameters and noise parameters
3. Develop a new Latitude -operating window- where the new CTPs have been selected in order to avoid the identified failure modes
4. A conceptual design is produced while taking in consideration the new CTPs
5. Manufacturing assessment for the new technology in order to realize if there is a need to develop manufacturing tools that can fit to the technology new features if there are any. Or maybe the technology can fit with the known and normal manufacturing
6. Final Integrated technology model that overcomes all the failure modes and proves a satisfying performance under customer use conditions

In addition, considering the peer reviews along with the mentioned above criteria assures the smooth integration of new technologies to manufacturing and then to society. However, the previously mentioned assessment criteria can be considered as generic criteria that can apply to any technological development process and not necessarily to developing Circular Economy technologies. For the reason that, according to Sassanelli et al. (2019) there is a shortage in literature in the area of Circular Economy performance assessment. In terms of the methodologies that is able to consistently assess all the variables in a circular system. However, the existing literature mainly focuses on measuring or assessing a specific aspect that is related to Circular Economy. Most of the relevant literature is covering only a quantitative assessment of the material flow in the whole system, or the environmental impact of Circular Economy technologies or in some occasions covering the whole sustainability concept. Moreover, other literature focused on developing a quantitative tools that assess the industrial symbiosis of Circular Economy in certain industry like Wen and Meng (2015) or focused on developing a framework for assessing the complex value of recovered resources in Circular Economy context like Iacovidou et al. (2017) or focused on developing an assessment tool for the end of life product recovery strategies in Circular Economy like Brissaud (2019).

Nevertheless, circular Economy assessment is usually carried out by offering a certain framework or approach from an already existing approach, frameworks or a combination of different approaches and frameworks (Sassanelli et al., 2019). Therefore, a sum-up to the most common assessment methods will be shown in the table below in relation to the number of literature they were discussed in.

Table 2. *An aggregate for performance assessment methods used in common existing literature selected in that specific case. Adapted from Sassanelli et al. (2019).*

Authors	Method							
	DEA/I-O	DfX/GL	LCA/LCI/LCIA	MCDM/fuzzy methods	Em, Ex	Simula-tion/DES	MFA/MCA/MFCA	Other
Total	5	7	15	8	4	2	5	15

As shown in the table above, in the existing literature, LCA is the most common methodology used in assessing Circular Economy performance in terms of the ultimate environmental effects. Life cycle assessment is one of the common assessment methodologies for measuring the environmental sustainability of Circular Economy (Haupt & Hellweg, 2019).

Multi-criteria decision making (MCDM) is a discipline in its own right, which deals with decisions that include the best alternative choice among other potential candidates in a decision, the decision is usually based on several criteria that may be concrete or vague (Pavan & Todeschini, 2009).

Design for X or excellence, where X refers to using a proper methodology into optimizing a specific aspect of design (TL9000, 2013), it is a variable with many values which is commonly used in the industry (Luo & Hu, 2018), and mainly includes:

- Design for performance
- Design for reliability
- Design for cost
- Design for manufacturability
- Design for assembly
- Design for testing
- Design for the environment

There are different variables of design, however, in Circular Economy Design for Disassembly (DFD was used as in the case of Akinade et al. (2017). In addition, another variable that was discussed in Circular Economy was the Design for End-of-life (Lee, Lu, & Song, 2014).

Data Envelopment Analysis is a non-parametric method that can be used to measure variables in a system and measure relative efficiency by comparing it with other production scenarios that involve multiple inputs and outputs (Farrell, 1957; Sassanelli et al., 2019). While Material Flow Analysis (MFA) is a quantitative method for deciding on the flow of energy and materials through economy and identify if the flow of materials is sustainable compared to the created environmental burden. The analysis is using different material and economic information as an input/output data. It also covers the mass balance which accounts to that whatever entering the system is equal to whatever is leaving the system (Pincetl, 2012). Nevertheless, MFA is not commonly used in assessing Circular Economy performance (Sassanelli et al., 2019).

Emergy and Exergy (Em & Ex) as the two forms of Energy are representing the behavior of physical systems by the means of cumulative energy input/output methods that result in a double integration over space and time domains (Sciubba & Ulgiati, 2005). Emergy is considered the solar energy that is directly and indirectly needed for generating a flow or a storage. On the other hand, Exergy is a property of a system, it measures the utmost work that can be extracted for any system when it is going towards a thermodynamic equilibrium (Bastianoni & Marchettini, 1997).

Discrete Event Simulation (DES) is a modeling approach that is commonly used in decision support tools for logistics and supply chain management (Seay & You, 2016). Also, a Discrete Event Simulation is one in which the current state of a model changes at a random and discrete set of time points which usually leads to logical complexity because of the occurred manipulation to the units order at a certain time point (Zhang & Zhang, 2010).

According to Sassanelli et al. (2019) most of the methods mentioned in the table before were paired with other methods into forming a collective framework for assessment. In the table below, each method will be linked to the literature references were they were used for assessing Circular Economy performance.

Table 3. *Circular Economy assessment methodologies in literature. Adapted from Sassanelli et al. (2019).*

Method	References
DEA/I-O	(Expósito & Velasco, 2018; Mardani, Zavadskas, Streimikiene, Jusoh, & Khoshnoudi, 2017; Motevali Haghighi, Torabi, & Ghasemi, 2016; Pagotto & Halog, 2016; Park, Egilmez, & Kucukvar, 2016)
DfX/GL	(Akinade et al., 2017; Favi, Germani, Luzi, Mandolini, & Marconi, 2017; Grimaud, Perry, & Laratte, 2017; Issa, Pigosso, McAloone, & Rozenfeld, 2015; Lee et al., 2014; Oliveira, França, & Rangel, 2018; Santini et al., 2010).
LCA/LCI/LCIA	(Angelis-Dimakis, Alexandratou, & Balzarini, 2016; Biganzoli, Rigamonti, & Grosso, 2018; Eastwood & Haapala, 2015; Fregonara, Giordano, Ferrando, & Pattono, 2017; Gbededo, Liyanage, & Garza-Reyes, 2018; Grimaud et al., 2017; Hadzic, Voca, & Golubic, 2018; Huysman, De Schaepmeester, Ragaert, Dewulf, & De Meester, 2017; Jamali-Zghal, Lacarrière, & Le Corre, 2015; Laso et al., 2018; Martin, Wetterlund, Hackl, Holmgren, & Peck, 2017; Park et al., 2016; Petit, Sablayrolles, & Yannou-Le Bris, 2018).
MCDM/fuzzy methods	(Iakovou et al., 2009; Kazancoglu, Kazancoglu, & Sagnak, 2018; Ng & Martinez Hernandez, 2016; Olugu & Wong, 2012; Petit et al., 2018; Shen, Olfat, Govindan, Khodaverdi, & Diabat, 2013; Wibowo & Grandhi, 2017; Xu, Zhang, Yeh, & Liu, 2018).
Em, Ex	(Huysman et al., 2017; Jamali-Zghal et al., 2015; Pan et al., 2016).
Simulation/DES	(Gbededo et al., 2018; Sénéchal, 2017).
MFA/MCA/MFCA	(Franklin-Johnson, Figge, & Canning, 2016; Voskamp et al., 2017).

Other	(Akanbi et al., 2018; Fregonara et al., 2017).

Though there are multiple circularity performance assessment approaches, yet, they are not commonly used in companies (Sassanelli et al., 2019). In addition, there is no explicit and obvious qualitative assessment tool or approach to the developing Circular Economy technologies in the existing literature. Such assessment that can identify technologies circularity strategy, sustainability impact and readiness. Therefore, the gap is clear in this area of research field.

In any case, technology maturity and readiness is important for in assessing technologies. Therefore, Technology readiness level tool will be discussed in the next chapter as a common tool for assessing different technologies in their developing phase.

3.3 Technology Readiness Levels

TRLs are used in the qualification and assessment of technology proposals (Straub, 2015). It is a framework that is used in different industries to provide a measure of technology maturity from basic idea to production and commercialization (Rybicka et al., 2016).

The TRL scale was created by Stand Sadin in the late 1970s in NASA as a tool that can systematically enables the assessment of a developing technology and the ability to compare between different technologies based on their maturity (Straub, 2015). Nevertheless, technology Readiness Level (TRL) scale was developed and completely emerged on multiple stages (Mankins, 2009).

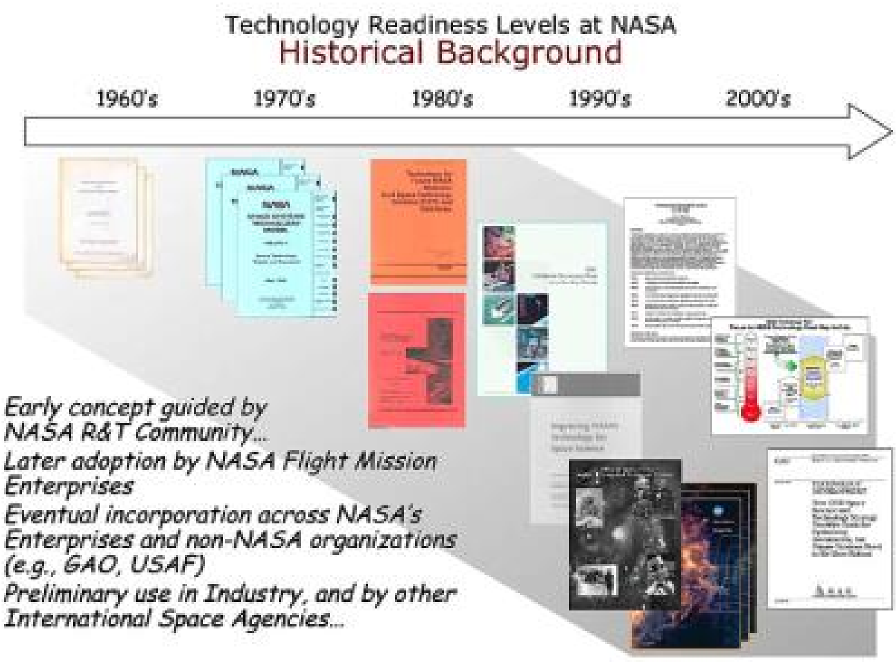

Figure 7. *Retrospective to TRA. Adapted from Mankins (2009).*

As shown in the figure above, the concept was early adopted by NASA and went through multiple development stages. The timeline that shows the historical background of TRL will be further discussed in the table below.

Table 4. *TRA history of development by Mankins (2009); Larsson, Culley and Larsson (2009); Straub (2015); Mankins (2002).*

Years	Occurring events
1960s-1970s	• The idea of TRLs started in 1960 • Idea clearly stated in a report describing the need of a technology readiness assessment tool in 1969 • Initial TRL scale invented by Stan Sadin in the late 1970s and consisted of six or seven levels
1980s-1990s	• Seven levels scale was published in July 1989 • TRL scale extended from six-seven levels to the nine levels scale commonly used today in 1989 • ‘‘Mirror documents’’ were developed in NASA in the early-to-mid 1990s to act as an integrating plan at using the TRL scale within the organization itself for managing its technology programs as well as communicating with other organizations • White paper ‘‘Technology readiness levels’’ that included a description to each technology level was published in 1995
Early 2000s	• DOD adopted the TRL scales from NASA • The TRL scale widely adopted in the world by different countries by 2005-2006

The TRL has had a great positive impact towards technology readiness assessment, and since systems are relying more on continuous development of technology in all disciplines, then its impact will significantly increase in the future of technology and systems management (Mankins, 2009).

Technology develops and matures through a series of stages, the TRLs identify these stages in nine levels where the lowest level is known as TRL 1 and the highest level is known as TRL 9 (Mitchell, 2007). The figure below illustrates the TRLs with its nine levels of technology readiness.

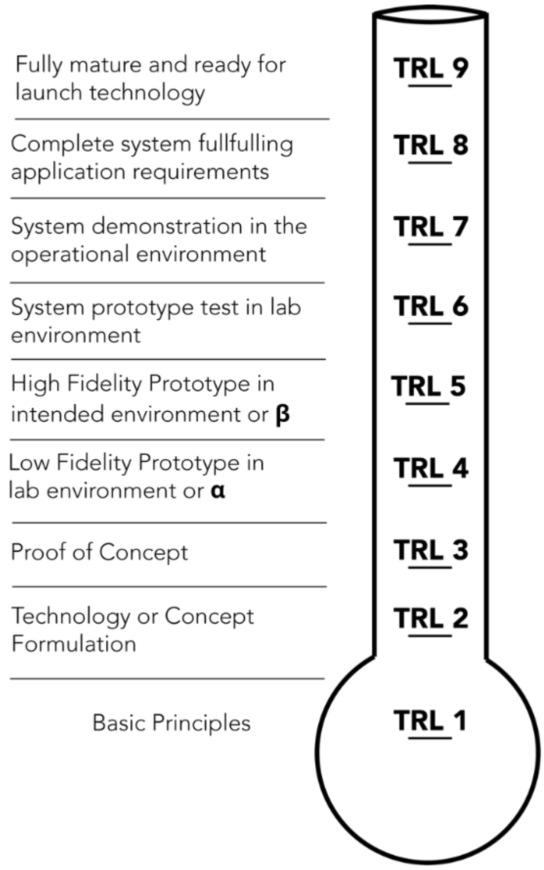

Figure 8. *Overview of TRL definitions Adapted from Mankins (2009).*

A description for each technology level was stated by Kajikawa (2014); Larsson et al. (2009); Mankins (1995); Mitchell (2007); Straub (2015). Some literature use the same description presented by NASA, some other literature paraphrase it. However, overall most technology readiness level descriptions are the same. In any case, the technology readiness levels can be described as following:

TRL 1: Basic Principles observed and reported
The basic and fundamental scientific research can be easily described along with basic principles in the core properties of the technology can be reported.

TRL 2: Concept or application formulated
Practical applications for the research or the technology developed are identified. However, the applications might be speculative. It is shifting from basic research to applied research

TRL 3: Concept or application demonstrated analytically and experimentally (needs validation and proof of concept)
Active research and development is initiated in order to validate the applications, enable the concept and assure all the analytical predications.

TRL 4: Low fidelity prototype in a laboratory environment
Where all the ‘pieces’ are integrated together creating a basic laboratory prototype which can address the intended application and solve the need required.

TRL 5: High fidelity prototype in a relevant environment (components level)
Where all the supporting elements and component-level applications are integrated with the developing basic technology and tested in an intended environment.

TRL 6: High fidelity prototype demonstrated in simulated relevant environment (system/sub-system level)
Representing an actual system/model application and demonstrating it through a high fidelity prototype that is tested in a designated environment. This level of maturation is usually triggered by the management confidence rather than the R&D requirements

TRL 7: High fidelity system prototype demonstrated in operational environment
An actual system demonstration in a similar expected operational environment in order to ensure fulfilling the need and the performance requirements.

TRL 8: Full completed system is qualified to the application requirements and regulatory standards
The final system and technology proved to work under the expected standards and conditions. By this level there should not be any more system development. Nevertheless, a new technology can be integrated to the existing system.

TRL 9: Fully mature and available system or technology is being launched and tested in a real operation
Most technologies that succeed in actual systems qualify to TRL-9. However, the final small fixes will only occur when the system is deployed in an operation. The main difference between TRL-8 and TRL-9 is operations. Where TRL-8 represent a fully complete system that is ready to be used while TRL-9 is about launching or deploying the new system in real world operation.

The technology readiness assessment objective is to qualify developing technologies to decision makers in a sense that the technologies are mature enough to be commercialized (Clausing & Holmes, 2010). Moreover, the TRL definitions were mainly made to suit the aerospace industry within the flight readiness context (Larsson et al., 2009). However, many organizations worldwide have adopted the TRLs in the use of assessing their technologies where some have modified it in order to fit their own needs and others utilized it the same way it is (Straub, 2015). Moreover, modifications have taken place to NASA’s exiting model of TRLs in order to widen its purpose and suitability for different applications (Larsson et al., 2009).

Despite the wide adoption of TRLs by various corporations, there had been many concerns regarding the credibility of the TRLs as an assessment tool indicating technology advancement (Larsson et al., 2009). The TRLs was mainly developed to assess the maturity of NASA’s hardware technologies. Furthermore, according to Larsson et al. (2009)

many sources have expressed the difficulties in applying the TRLs to assess the readiness and maturity of software based technologies.

The TRLs fails at reflecting the technology lifecycle nor the product lifecycles which contradicts to the concept of lifecycle management in a way that it does not explain what happens with the readiness if the technology become more mature (Larsson et al., 2009). Hence, the TRLs can assess technologies in the initial process of research and development and fails to assess the same technologies in the case of any future developments. Furthermore, the TRLs fails at providing a justification behind the uncertainty of any future maturation or development of the assessed technology (Mankins, 2002).

Moreover, In the case of a software that is frequently upgraded, refined or modified, the TRL would remain at the same level regardless of the new state of the software. Hence, ‘ageing’ was identified and considered as an issue (Larsson et al., 2009). In the case of multiple subsystems assessment or multiple technologies, it is hard to assess their technology maturity together, hence, decide the right level of their readiness (Mankins, 2009) or understand how individual technologies affect the whole system (Larsson et al., 2009).

TRLs does not show the riskiness of a new technology nor the research and development uncertainty which requires other tools that can help assess the risk associated with the technology under assessment (Mankins, 2009). Moreover, it does not assess the criticality of the technology, what can be substituted and what is irreplaceable (Larsson et al., 2009). Furthermore, The TRLs is based on a yes/no assessment which is seen as a subjective measure in commercial entities due to the lack of quantitative measurement (Clausing & Holmes, 2010).

Eventually, the Research and Development Degree of Difficulty is seen to be used as a complementary tool with the TRLs in order to overcome the uncertainty challenge in developing a new technology (Mankins, 2002, 2009; Straub, 2015). Moreover, in order to capture further developments and technologies diversification challenge, Larsson, Culley and Larsson (2009) have developed an extended TRL that can cover any technology improvements after TRL 9.

4. RESEARCH METHODOLOGY

This research focuses on the assessment and evaluation of developing Circular Economy technologies. Accordingly, the first research question is:

- *What is the criteria for assessing developing and sustainable Circular Economy technologies?*

Where the aim is to understand what kind of aspects do researchers and technology developers consider while assessing their Circular Economy technologies in particular. Then discuss their view on the developed framework from literature on assessing Circular Economy technologies and demonstrate their ideas over how far their technology/ies are developed using technology readiness level. As well as, understand if those technologies operationalize other essential concepts as sustainability which makes the sustainable and which circular strategy they follow. Thus, there are two sub-questions to the first research question which are:

- *How the technology advances Circular Economy and sustainability?*
- *How ready is the technology?*

Upon the answers to those sub-questions, the ability to analyze the data gathered and identify what is the criteria used by different technology developers in assessing their Circular Economy technologies, also, to conclude if this criteria does change based on the scientific field they are interested in or if there are any common findings across different scientific fields.

However, conducting this study required mapping Circular Economy technologies from different research fields while assessing their maturity and sustainability impact. To further elaborate, this thesis is aiming at realizing the technology streams that accelerates Circular Economy and advances resources efficiency. For this reason, the second research question is:

- *What are the technology catalysts that accelerate Circular Economy transition?*

Though, due to the wide range and variety of technologies, the study will be selecting researchers who are actively contributing and developing technologies in the field of Circular Economy across different industries. Hence, mapping Circular Economy technologies developed or undergoing development. In the next chapter, the design of this research will be discussed to explain how the study was conducted.

4.1 Research Design

This study is conducted as an exploratory study to answer the research questions effectively. According to Saunders, Lewis, and Adrian (2009) exploratory studies are valuable for seeking new insights, finding out what happens and assess a certain phenomenon. As discussed earlier, this research focuses on mapping Circular Economy technologies while assessing their circularity, maturity and impact on sustainability. Then, come up with common assessment criteria for developing and sustainable Circular Economy technologies. Moreover, study the relationship between the Circular Economy technologies' impact on sustainability presented and discussed in literature with the actual impact provided by the technologies developed, which justify the choice of exploratory approach in addressing this study. The nature of this research is explorative and the goal is to fill in the gap introduced in literature, as well as, investigate the presented literature that argues the poor inclusion of social dimension in Circular Economy technologies and try to introduce the reasons behind it.

The best practice for reaching the previously mentioned goal is to identify various technologies from different scientific fields and backgrounds, aiming at detecting common findings while covering wide spectrum of technologies. Hence, this type of practice requires case study research which is effective at finding more information through analyzing existing technologies in Circular Economy context. Saunders, Lewis, & Adrian (2009) argue that case study strategy can be a very worthwhile way of exploring existing theory. In addition, a well-constructed case study strategy can enable you to challenge an existing theory and also provide a source of new research questions. Also, Morris and Wood (1991) argue that the case study strategy is effective at helping the practitioner conducting the study for gaining better understanding of the context of the study. Moreover, Saunders, Lewis, and Adrian (2009); Yin (2014) discuss that case study strategy most often used in exploratory research which is evident that case study strategy was convenient choice for conducting this research.

Furthermore, the research was conducted with 7 cases as a multiple case study to facilitate a cross-analysis among the cases and reduce vulnerability. Yin (2014) argues that multiple case study are preferable than single case study. Hence, the ability of looking for common findings within the cases and generalizing it. According to Saunders, Lewis, and Adrian (2009) literature search and interviewing experts on the topic are considered as principal ways of conducting exploratory research. In this study, a search of literature on the topic is conducted as well as experts' interviews.

In the next chapter, a developed framework will be discussed. The aim is to use the framework developed in reviewing the cases studied holistically which will be discussed further next.

4.2 Developed Framework for Assessment

The purpose of this chapter is to integrate all the tools, strategies and concepts discussed in the literature before in a one connected framework that can be used as an overall view to the technologies mapped in regards to their application and circularity, their impact on sustainability and last, their maturity. The integrated framework consists of:

1. The 9R strategies
2. The 3 dimensions of sustainability
3. Technology readiness levels assessment tool

First the R strategies discussed in literature of chapter 2 will be used to identify the mapped technologies application and range of circularity as shown in the figure below, the lower the R the more circular the application to be.

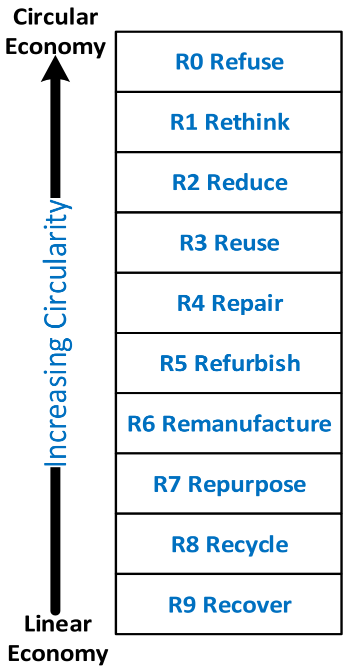

Figure 9. *9R strategies to assess technologies circularity.*

Second, analyzing the technology impact on general sustainability required assessing its impact on each separate dimension. Hence, understand if it contributes to the three dimensions collectively or it lacks one of the dimensions as discussed in literature of chapter 2. The three dimensions are shown in the next figure, the area numbered 1 and 2 are used to show later if the mapped technology is contributing to all the three dimensions or only to two dimensions leaving the social dimension behind.

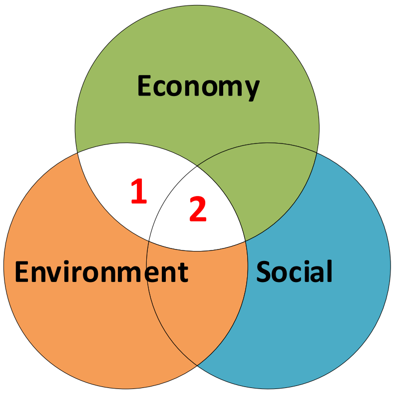

Figure 10. *The 3 Dimensions to assess technologies sustainability.*

As shown in the figure above, if the technology is located in area number 1, that means it contributes only to the environmental and the economical dimensions. While if it is located in area number 2, then it impacts the three dimensions, hence, the overall sustainability.

Last, identifying the technology maturity using the technology readiness level tool discussed in literature in chapter 3 and shown in the figure below. There is a set of structured yes/no questions for each level that aim at ensuring the fulfilment of all the requirements of the readiness level of the mapped technology as claimed by the developer. The questions to be located in the data analysis section 4.5 of this study.

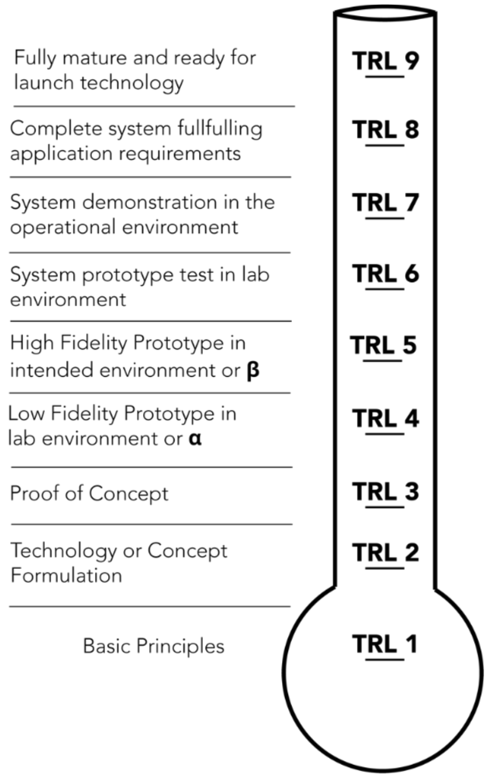

Figure 11. *TRL tool to assess technologies readiness.*

Therefore, the R strategies along with the sustainability concept and technology readiness level tool can be grouped together in one framework that can give a holistic view to the technologies mapped as an overview to different stakeholders, decision and policy makers as shown in the figure below.

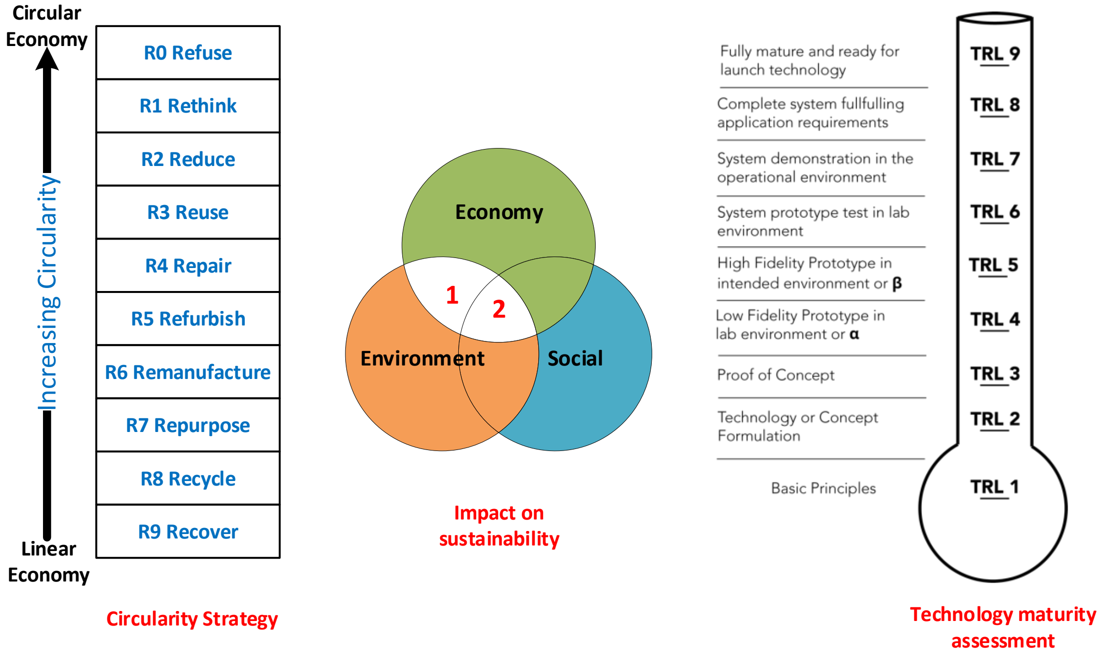

Figure 12. *Collective tools to be used as a framework for assessing developing CE technologies.*

As shown in the figure above, the framework will be used as a grouped tool for analyzing the mapped technology to identify its application, sustainability role and readiness level. The framework also contributes to the first research question of the convenient criteria for assessing developing Circular Economy technologies, which in the case of the developed framework shown above is solely based on literature.

4.3 Case Selection

This research objective is to map Circular Economy technologies, while provide an assessment criteria that can holistically assess developing Circular Economy technologies. Also, present technology catalysts that are enabling and accelerating Circular Economy. Hence, fulfilling the objective and the research questions requires identifying experts in different scientific fields with the knowledge that focus on technology development in the area of Circular Economy. The selected experts'/researchers' technologies will act as selected cases for this study. In other words, each technology mapped will act as a case study developed by a researcher and by selecting multiple cases, then multiple technologies to be mapped, assessed and analyzed.

In order to be able to meet this research objective and to answer the research questions as well, purposive sampling method will be used to select cases for further analysis. Moreover, the cases selected will serve the qualitative nature of the research where the purpose is to collect valuable information and better insight to the research conducted. According to Saunders et al. (2009) purposive sampling is mostly used in the case study research when the intention is to select cases that are informative. Furthermore, the aim is to select different cases that cover wide range of technologies backgrounds to be able to have various assessment criteria to the technologies developed as well as new inputs and insights for further improvement to the framework developed used in analyzing the cases. Hence, the strategy to be followed in purposive sampling will be heterogeneous or maximum variation sampling. According to Patton (2002) having a small sample of different cases may create variation that is considered a strength for the diverse characteristics of cases, which will allow the researcher for detecting any patterns that are likely to be of value and interest.

The process of purposive sampling was conducted as following, an initial search for Circular Economy technology developers and researchers was carried out where the information collected was about their role, their study field, latest Circular Economy activities and technologies undergoing development. Then grouping them where researchers and technology developers with the same scientific background are allocated together. Last, a criteria of selection among each group was based on the one or two researchers with the most experience in the field of Circular Economy, their area of specialization and that their latest publications was mainly about developing Circular Economy technologies. Hence, selecting one or two researchers from each group as cases to be analyzed as shown in the table below.

Table 5. *List of potential technology developers in the field of CE*

Researcher	Background	Role
Johanna Lahti	Material Science and Environmental Engineering	Senior Research Fellow. Member of Research Group: Paper Converting and Packaging
Essi Sarlin	Material Science and Environmental Engineering	Academy Postdoctoral researcher. Member of Research Group: Plastics and Elastomer Technology
Marika Kokko	Material Science and Environmental Engineering	Assistant Professor (tenure track). Member of Research Group: Bio and Circular Economy
Aino-Maija Lakaniemi	Material Science and Environmental Engineering	Assistant Professor (tenure track). Member of Research Group: Bio and Circular Economy
Jari Tuominen	Material Science and Environmental Engineering	Senior Research Fellow. Member of Research Group: Surface Engineering
Pirjo Kuula	Civil Engineering	Project Manager, Civil Engineering. Member of Research Group: Earth Constructions.
Satu Huuhka	Architecture	Senior Research Fellow. Member of Research group: Built environment in Transition
Ari Hynynen	Architecture	Professor of Architectural and Urban Research (Alvar Aalto Chair) at TUNI

Minna Lanz	Automation Technology and Mechanical Engineering	Professor, member of Research group: Manufacturing and Automation.
Suraj Panicker	Automation Technology and Mechanical Engineering	Doctoral Researcher
Sampo Tuukkanen	Medicine and Health Technology	Head of Research Group BioMediTech. Member of research group: Sensor Technology and Bio measurements (STB) and research group: Nanoscale Phenomena and Measurements (NPM)

The table above showed the potential researchers, their background and roles within Tampere University and in some cases outside the University as well. The **bolded** names as shown in the table above represent the selected researchers for interviewing and for the purpose of using their developed technologies as cases for this study. Final case selection included technologies that covered the following technology streams shown in the table below along with the researchers that contributed with their knowledge and experience to each technology stream.

Table 6. *List of the grouped technology streams and their corresponding developer*

Technology stream	Researcher(s)
Bio-Technologies	Aino-Maija Lakaniemi
Manufacturing Technologies	Suraj Panicker, Jari Tuominen
Construction Technologies	Satu Huuhka
Digital Technologies	Suraj Panicker
Material Science	Essi Sarlin

The previous mentioned technology streams are seen to cover the wide range of technologies developed by the selected researchers. Also, enable the author to evaluate and analyze the data collected to better serve the objective of this study. Moreover, as shown in the table above, some researchers are able to cover multiple technology streams as in the case of manufacturing technologies.

4.4 Data Gathering

Scientific research requires certain defined methods in order to gain a better deeper understanding and knowledge of a certain research topic. However, some methods are found to be common and applicable to different research topics. According to Yin (2013) case studies allow the researchers to use multiple research methods, both qualitative and quantitative in order to generate more data and information. Furthermore, multiple case studies approach used in conducting the research has the purpose of comparing the cases that are included (Bryman & Bell, 2015). Moreover, it allows the researcher to compare the findings from each of the cases. Hence, explore what is common among all the cases and what is unique or different.

Furthermore, the use of the combination of both qualitative methods and quantitative methods or each of them separately is beneficial for generating more information and data. According to Gummesson (1993) there are five different qualitative research methods that are considered to be the most practically used for data gathering in order to support scientific research.

- Existing material
- Questionnaires
- Qualitative interviews
- Observation
- Action science

First, existing materials refer to all kind of information that was collected and generated by someone else and it resides in books, journals, articles or any kind of publications. Second, questionnaires are used to gather qualitative and quantitative information. Questionnaires are considered as a direct data gathering method where a set of predefined questions are required to be filled out by any participant. Third, qualitative interviews are one of the most common methods of data gathering. Interviewing people to gather more accurate information, on the contrary to questionnaires, is freer to formulate questions during interviews. Fourth, observation is the method of observing a certain human behavior or phenomena in order to generate data that may not be possible and easily expressed in words. Last, action research which is the most challenging since it can contain all the research methods mentioned before. However, it requires a big involvement from the researcher to become as a change agent affecting the research taking place. Furthermore, there are pros and cons for each research method used. Hence, researchers have to consider the method or the few methods that they will use during their research in order to obtain the best quality of information for their study.

This research is conducted as a multiple case study and it has a qualitative nature, then qualitative interviews method was chosen to be the primary source of data. In qualitative research, the interview is considered to be the most widely used method (Gill, Stewart, Treasure, & Chadwick, 2008; Saunders et al., 2009). Furthermore, qualitative interviews has a less structured approach compared to quantitative research, more interest in the interviewee's point of view and it encourages the interviewee at sharing their knowledge and experiences (Bryman & Bell, 2015; Gill et al., 2008). There are several types of interviews but in qualitative research there are two main types that are relevant and commonly used; unstructured interviews and semi-structured interviews (Bryman & Bell, 2015). In this research, the author chose semi-structured interviews approach for conducting the research. In semi-structured interviews, the interviewer has an interview guide with a set of certain questions that covers the topic researched. The interview may not follow the structure designed in the interview guide and the interviewer can be flexible to ask questions by picking up on things said by the interviewees (Bryman & Bell, 2015; Patton, 2002). However, all the questions included in the interview guide should be asked one way or the other for enabling cross-case comparison. In the case of doing multiple case study research a semi-structured interviewing is preferred to ensure cross-case comparability (Yin, 2014). The interview guide had a mix of different kind of questions. According to Bryman and Bell (2015) there are 9 different kinds of questions, introducing, follow-up, probing, specifying, direct, indirect, structuring, silence and interpreting questions. Almost all of them were used in this study. However, there was a main focus on probing and interpreting questions as shown in the appendix.

Moreover, the questions were designed according to the thesis objective and research questions, later improved after the supervisor review and feedback. All the interviewees received an e-mail that discusses what the interview will be revolved around, with some generic notes to help them form some ideas and thoughts about the topics to be discussed during the interview. In order to increase the credibility over the findings concluded, the study combined primary and secondary data. Secondary data was collected from existing literature on Circular Economy technologies and their contribution towards sustainability as well as how they are assessed in terms of technology readiness. The data gathered from literature was generic, collected from articles published in various journal and were used as a reference to validate the findings in this study. In addition to the secondary data, the semi-structured interviews were used as a primary source of data to be used in this study and it was collected between June – September. Altogether, 6 qualitative interviews were held with technology developers, all interviews took place face to face at the interviewee's offices. The whole interview discussion was recorded with the interviewee's consent and similar questions were asked to all the interviewees. In the table below, the interviewee name, date and duration of interview are listed.

Table 7. *List of interviewees, their interview date and duration*

Interviewee	Date	Duration
Jari Tuominen	12.06.2019	55 minutes
Suraj Panicker	19.06.2019	58 minutes
Aino-Maija Lakaniami	26.06.2019	69 minutes
Essi Sarlin	01.07.2019	95 minutes
Satu Huuhka	23.07.2019	104 minutes

According to Saunders et al. (2009) collecting qualitative data from conducted interviews is beneficial, many recommended conducting more interviews as long as the additional data collected is providing new insights. However, at any instance if the data collected brings few insight and there become obvious data saturation then it is considered sufficient amount of interviews.

4.5 Data Analysis

The qualitative data gathered from different cases through the interviews was analyzed on multiple phases. The framework developed to review the technologies mapped will be used to analyze holistically the data into a collective final results and will allow a cross-sectional analysis as discussed later in this chapter. The framework as shown in Figure 12 consists of the R strategies model that measure the technologies circularity, followed by the three dimensions of sustainability figure, and last the Technology Readiness Level tool that assess the technologies maturity.

The identification of the technologies application and circularity level will be concluded through the R strategies model. The R strategies model was identified as an integrative model to almost all the Circular Economy applications and can measure the circularity of the technologies developed and show how far or close the technologies are to Linear or Circular Economy. The collected data from the interview transcriptions guided into identifying the different cases application and level of circularity.

Then, the three dimensions model of sustainability is used for analyzing the technologies impact on sustainability from three different perspectives. The analysis of the technologies impact on each dimension is essential for determining if the technology developed contributes to the three dimensions altogether and then operationalize the concept of sustainability, or the technology is contributing partially to the concept of sustainability by not having a positive impact on all the three dimensions. The aim of analyzing the technologies mapped using this model is to allocate them in the area 1 or 2 as shown in the figure. Hence, understand clearly where the technology is placed in regards to sustainability. The allocation process is mainly based on the interview transcriptions, the author interpretation and proper understanding of the concept, unless the technology developer gave clear and obvious evidence on each dimension which can be validates through the interview transcriptions.

Last, the Technology Readiness Level tool used for analyzing the technologies mapped readiness based on 9 levels. The analysis of technology using this tool aims at identifying the technology stage of maturity, whether it is at an early immature stage of development or it is already developed, mature and available for commercialization. The collected data was used to allocate the mapped technologies to a specific level or multiple levels based on the case in analysis. The validation of the readiness level was determined by a further qualitative yes/no questions that aimed at ensuring that the technology developer estimation of their technology readiness is fair and accurate as shown in the table below. Furthermore, interview transcriptions were used as a double check on all the answers gathered from the interviewees.

Table 8. *Qualitative questions for validating the TRL of each technology. Derived from* Mitchell (2007).

TRL	Questions associated
1	- What is the fundamental concept or motivation behind the technology developed? - Are the basic principles identified, can you describe them?
2	- What are the practical application(s) for this technology ‘this can be speculative’?

	- How those applications utilize the basic principles? - What makes this application(s) interesting to anyone?
3	- Is there any proof of concept to the key component(s) of the intended application(s)? - Needs validation achieved (in terms of circularity)?
4	- Is there a low fidelity prototype tested in a lab environment (alpha)? - Did it prove to solve the need or the problem?
5	- Is there a high fidelity prototype tested in a relevant environment (beta)? - What is the relevant environment, what is the type of end-customer? I.e. (Individual, company, community, etc.) - Is there collaboration between the end customer and the technology developer for defining all the functional and performance requirements?
6	- Is there a high fidelity prototype demonstrated in simulated relevant environment? - Does the prototype meet all the agreed upon requirements in TRL5 and has a consistent performance?
7	- Has the prototype been integrated in an operational environment -Customer's operational platform- - Has the prototype integration and operation process been considered as a success from the customer point of view?
8	- Has the system or component (s) development been completed? - Did the final system or component(s) qualified/fulfilled the application requirements? - Did the final system adhere to the regulatory standards? - Is there any other technology that may be integrated to the complete system?
9	- Did the system or component(s) operate in a real world operation successfully? - Is there any minor fixes or changes to take place?

Then, the in-depth analysis occurs for each case as discussed previously in order to answer both research question following the developed framework and serve the exploratory approach for this study. On the other hand, an overall analysis is done by the author, the aim is to compare the cases and conduct a cross-sectional analysis to identify the common findings or the unique ones through the data collected from the interviews. The analysis is done from two different perspectives. First, on a deeper level that is from the mapped technologies perspective. Second, from more of a generic level that is from the technology stream perspective. This analysis will open up new thoughts and ideas in regards to the answers of both research questions and add up a new direction especially to the first research question related to the criteria of assessing Circular Economy technologies which will serve the exploratory approach of this study.

5. MAPPED TECHNOLOGIES

This section of the research is divided based on the grouping made for selecting researchers and cases. Hence, the following division of technology streams was concluded:

- Bio-economy technologies
- Manufacturing technologies
- Construction technologies
- Digital technologies
- Material Science technologies

In this chapter, the mapped technologies, their description, circularity, readiness and sustainability impact are discussed. Most of the information presented in this chapter is based on the transcriptions of the conducted interviews.

5.1 Bio-Technologies

5.1.1 Waste Treatment with Microalgae

5.1.1.1 Description

A biological process where the purpose is utilizing photosynthetic microorganisms –microalgae- to either produce energy and/or recover resources from waste streams such as nutrients from waste waters or carbon dioxide from flue gases. The algae utilize light for growth and convert the carbon dioxide and nutrients into biomass, which can be further converted to usable products

In the case of flue gas treatment, microalgae can be integrated in a coal combustion power plant or in a pulp mill to take up the carbon dioxide, reuse it and utilize it for microalgal biomass production. However, microalgae require nutrients for growth, and therefore the same operational environment should also have some sort of a waste stream that contains nitrogen and phosphorus to enable efficient and sustainable microalgal process. The produced microalgal biomass could be used e.g. in generation of biofuels and biochemicals. Furthermore, in the case of the streams that are fed into the system are very clean, then, pharmaceuticals or human food supplement can be produced.

The development is still needed in the cultivation systems and how to make them energy and cost efficient. The current status is that it is technologically possible and it is commercially applied in production of certain human food supplements and high value cosmetic products. However, when it comes to a different or new non-commercialized algal species for a certain process, then it is about making the cultivation system suitable for that microalgal species and make it cost efficient since different algae species have different requirements for the conditions in which they grow. As an example, for large scale recovery of carbon dioxide or treatment of waste water the targeted product should be a high quantity commodity like biofuel, which generally have relatively low price. Biofuels are not produced from microalgae at the moment due to the very low price of fossil fuels. Hence, the cultivation systems need further development to become cheaper in regards for these low value products.

The cultivation systems have two main types; open systems such as raceway ponds and closed/semi closed systems known as photobioreactors. For the open systems they are considered as easy technology that is cheaper to build and relatively easy to operate. However, for the photobioreactors they are partly available technologies and commercially used by some facilities. Nevertheless, neither cultivation system is applicable to all microalgal species which then leaves a space for improvements in efficiency and system development to fit different algae species. The whole cultivation process needs to be carefully designed separately for each species and with the target product in mind.

5.1.1.2 How the technology advances Circular Economy?

The carbon dioxide released from flue gases as an exhaust of coal or wood combustion or pulp and paper mills can be utilized and used again as carbon source for the microalgae. While the nutrients like phosphorus and nitrogen can be obtained from a waste streams like waste waters from pulp and paper mill. Therefore, the technology advances Circular Economy by applying the reuse strategy, where nutrients and carbon are reused.

According to the developer:

> *''Currently there are very efficient wastewater treatment processes already in use. However, the many currently used process involve removing nitrogen from the water in the form of N2 gas and releasing it to the atmosphere which makes the water clean but does not enable recovery of nitrogen in a usable form. Instead nitrogen is turned into a very strong chemical and a lot of energy is required to get it back in a form that could be used as a fertilizer. Therefore, there is a huge amount of fossil fuels consumed for the production of fertilizers. Thus, the aim from the technology is to develop processes where nitrogen would be recovered in a form that already can be used as a fertilizer'' (A, Lakaniami, interview, June 26, 2019).*

5.1.1.3 How the technology advances sustainability?

From environmental perspective, optimizing the cultivation conditions are required for having an environmentally sustainable system, making it energy efficient as well is essential for making it environmentally sustainable.

> *''Well you also really need to think about the whole lifecycle of the process. As a microbiologist one might just like to optimize the cultivation conditions to make them as good as possible for the microalgae, but you probably would spend so*

much energy that it wouldn't actually be environmentally beneficial anymore. It would be actually worse than not treating the water at all. So you really need to consider all the pieces of the puzzle to make it environmentally sustainable and to promote circular economy and sustainability'' (A, Lakaniami, interview, June 26, 2019).

Moreover, the lower consumption of fossil fuels and the reuse of carbon dioxide will have positive contribution towards reducing the effects of climate change. Therefore, the technology has a positive impact towards the environmental dimension of sustainability.

From a social aspect it is expected to bring jobs, at least at the beginning since the processes of optimizing and operating the cultivation systems are challenging as well as the knowledge behind microbiology that makes educated personnel needed. Maybe the jobs will decrease in the future when the overall process is automated. Also, the outcome is a clean water which is good for the human health and the environment.

''Well it can bring more jobs and it's cleans the waters so it's very good for the human health. Also, probably the processes are so difficult to optimize and operate that you would need educated personnel to do that. So it cannot be just a farmer from somewhere operating the system. They would need to know a little bit about microbiology'' (A, Lakaniami, interview, June 26, 2019).

From economical perspective, there is a lot of improvements to be done in the process but treating waste waters very efficiently so nutrients are not released to the environment are very beneficial for the human health which most probably will generate a social acceptance and better economics since remediation is always expensive.

''If you are treating waste waters very efficiently so you're not releasing nutrients to the environment. Then that's good for human health and also probably for the social acceptance and also for the economics because the remediation is always expensive. So if you treat wastes and recover resources at the same time, then that's likely socially and economically a good thing'' (A, Lakaniami, interview, June 26, 2019).

5.1.1.4 How ready is the technology?

This technology is mainly dependent on the application. There is no ready-made solution for all the applications, based on what kind of carbon dioxide source, what kind of waste water and the surrounding environmental conditions as the weather. Also, the type of microalgal species to be used along with the cultivating systems to have.

''So whether you are in Finland or in Australia it determines what kind of microalgae species you can use and what kind of cultivating systems you should have. So in Finland you understand that during the winter, you cannot operate with an open pond because that will be frozen. So the microalgae would not do anything for more than half of the year. Whereas in Australia they probably could use an

open pond because of the different weather conditions" (A, Lakaniami, interview, June 26, 2019).

However, the cultivation of algae of a high value products is fully mature technology and is commercially used but not in the case where nutrients are obtained from waste water and carbon dioxide from flue gases and the aim is a circular system. Regardless, in the latter case the technology is approximately at TRL 4.

5.1.1.5 Technology overview

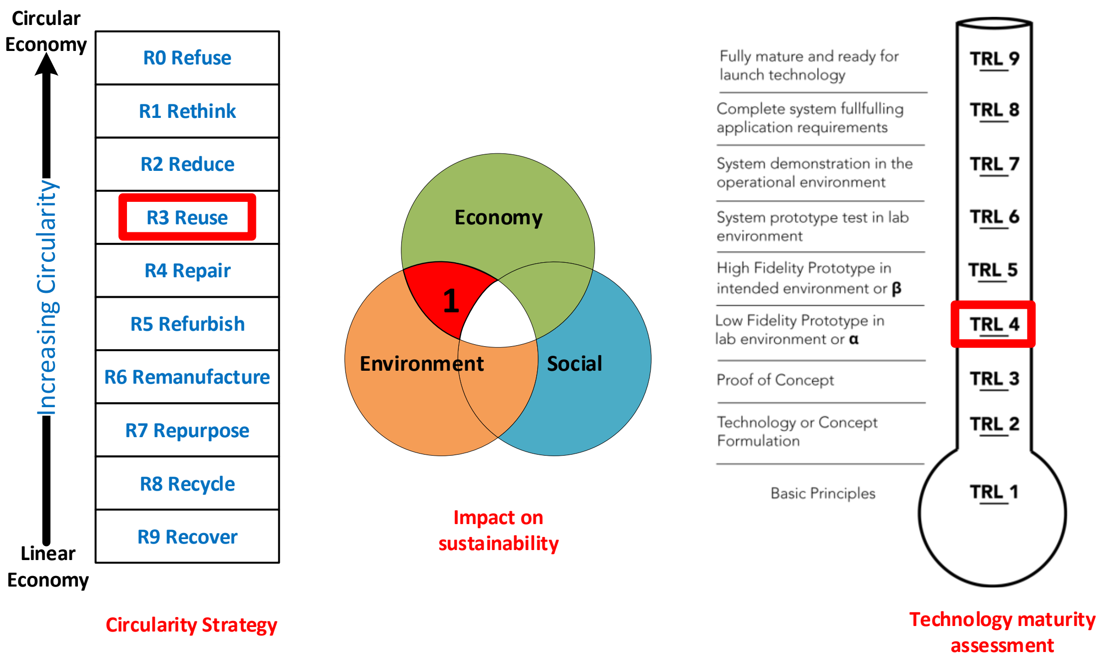

Figure 13. *Waste treatment with microalgae assessment overview.*

This technology is about carbon and nutrients reuse which reflects the level of circularity of the technology as represented in the figure above. At the moment, the technology aims at optimizing the whole cultivation processes and makes it energy efficient to ensure a positive impact on the environmental dimension. Furthermore, this technology requires experienced personnel which are expected to bring more jobs especially at the early stage of implementation, but those jobs are expected to decrease after automating the whole process. Hence, it not evident that the technology is contributing towards the social dimension on a long term. Moreover, the technology is seen to have better economics compared to other approaches like remediation which is known to be expensive, therefore, the technology is positively impacting the economic dimension of sustainability.

At the moment, the technology appears to impact the three dimensions of sustainability, however, considering the inclination of offered job opportunities that may occur in the future because of process automation eliminates its sustainable social impact. Therefore, it is only impacting two dimensions of sustainability as shown in the figure above by being placed in area numbered 1 contributing only to the environmental and economic dimensions.

Last, the technology readiness assessment tool shows that this technology is at technology readiness level four where the technology basic principles are reported, practical applications are identified, proof of concept existed and a prototype is tested in the lab.

5.1.2 Biological Metal Recovery

5.1.2.1 Description

Extraction of metals like transition and rare earth metals from low grade ores, industrial wastes and end-of-life products such as waste electronics and spent catalysts using microorganisms. The whole process is considered as an alternative to traditional mining. Hence, substituting currently existing processes of mining by utilizing different microbes that produce acidic compounds used in recovering metals and at the same time, thinking of similar systems that would be used in this approach for metal recycling.

Moreover, mines are environmentally very harmful, then instead of making a new mine to extract certain metals, recycling existing materials that contains the needed metals would be environmentally beneficial and energy efficient compared to traditional mining. Recovering gold for instance, in one ton of gold mineral there can only be ten grams of gold which is a very small ratio compared to what is mined. Then, making a huge hole in the ground and bringing a lot of rock where only a very small percentage of it is retrieved as gold while consuming a huge amount of energy is not environmentally the best practice or procedure. Furthermore, the lower the amount of metal in the rock the more energy consumed in recovering that metal. Moreover, using very traditional processes for recovering metals like pyrometallurgy can be very harmful to the environment because of using very high temperatures to recover the metals which needs a lot of energy and produces a lot of gaseous waste streams as well.

Nevertheless, using this new approach of biological metal recovery technology from waste and side streams will have an environmental negative impact, yet, it is considered environmentally better compared to traditional mining because of the use of base materials from which the metals are recycled, as well as, using microbes, which can cause less environmental harm compared to traditional mining. Hence, the technology is trying to recover metals through a new approach that has less environmental harm compared to traditional mining.

5.1.2.2 How the technology advances Circular Economy?

Recycling of transition and rare earth metals from industrial waste materials using microorganisms -biotechnology- in recovering metals. Hence, less need for extracting virgin resources and recovering the already used metals from old industrial waste, therefore, better management of natural resources.

5.1.2.3 How the technology advances Sustainability?

Addressing the environmental perspective, the technology is considered to be less harmful than the traditional mining. The ability to biologically recover metals from waste and side stream has a clear positive impact to the environment.

From the economical perspective, recovering metals from industrial waste is not economical at the moment in all cases since it needs case-specific development before it can become economically viable. However, if the processes are developed enough to recycle critical elements like rare earth elements. Then it is supposed to be economically better than recovering metals from ore deposits. Furthermore, there is no rationale behind the global metal prices and how the metal prices change. In a sense that the metal prices at some time increase and then suddenly decrease again. In this case when using waste materials the strategy of overcoming this issue to focus on recovering several different metals. Then, if the price of one metal is decreasing and the price of another metal is increasing then it can at least partly balance the losses from the first metal. However, in a mine that is not always possible, if the mine ore contains nickel, then it is the only available metal and in the case of nickel price decreasing, then there is nothing that can compensate the losses.

> *''In the case when you use waste materials, you kind of shelter yourself from this issue a little bit that you focus on recovering on many different metals. So then if the price of one metal is going down hopefully the price of the other metal is not. But in a mine you cannot do that. So if you have only nickel in your ore, you just have nickel in your ore and when the nickel price is going down it's not good for your mine'' (A, Lakaniami, interview, June 26, 2019).*

From social perspective, the technology developers argue that the technology contributes towards environmental improvement because of the availability of rare metals to the future generations, which should drive social satisfaction. Also, generate jobs in metal recycling, hence, social benefits. On the other hand, traditional mining generates a lot of jobs for the mine itself, the ore refining and all the other sorts of processes. Therefore, this technology will probably less labor intensive when recycling metals. Though nowadays almost all processes are automated but still it will probably be less labor intensive compared to traditional mining.

> *''So this would be probably less labor intensive if you recycle metals because you wouldn't need these people going below ground and bringing the rock up. Of course that's also nowadays very much automated but still it probably would be less labor intensive compared to traditional mining'' (A, Lakaniami, interview, June 26, 2019).*

5.1.2.4 How ready is the technology?

The technology is still at its early stage of development. Moreover, it is important to identify how much of certain metal you have in waste material and how much of it can actually be extracted. In most cases, it is not 100 percent but even if it reaches up to 90 percent then it is considered an acceptable percentage. However, currently, in many of the research projects it reaches up to 20 percent which is not an economically acceptable percentage yet.

Most of the technology basic principles are clear but there is some knowledge gap still in the basic principles. Hence, the technology is considered to be at TRL2 or TRL3 depending on the waste material.

5.1.2.5 Technology overview

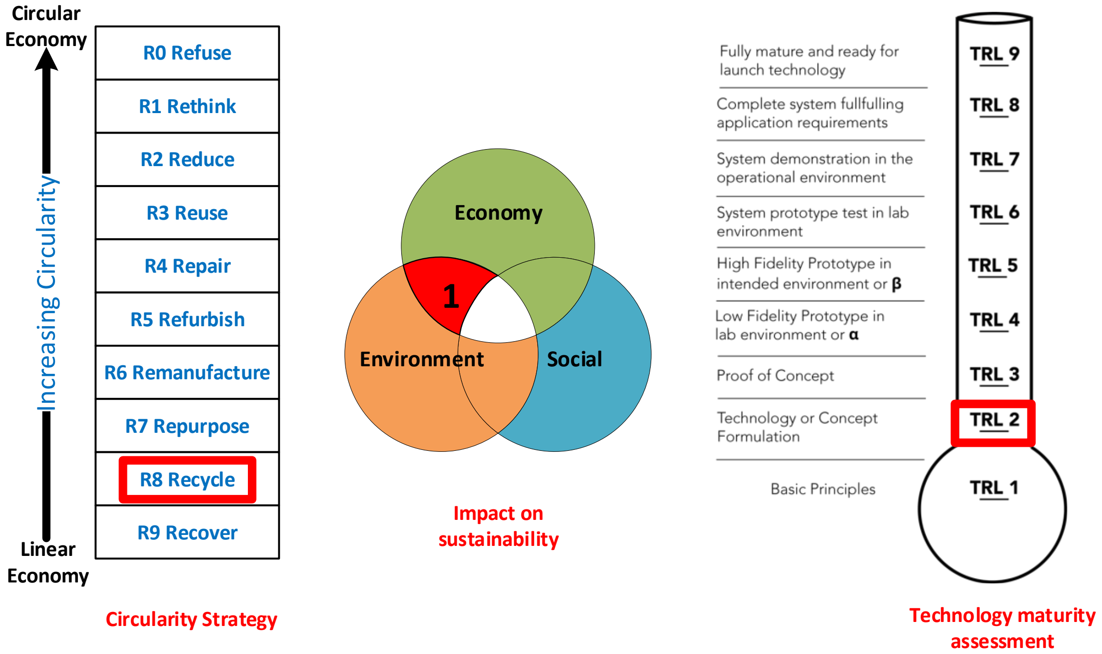

Figure 14. *Biological metal recovery assessment overview.*

This technology appears at an early stage of circularity, represented in the recycling of metals from waste industrial devices. Moreover, the technology does not provide an evident prove on its economical contribution yet. As mentioned earlier a lot of development in the processes is needed to become economically viable. However, it shows a future economic potential compared to mines when it comes to the price fluctuations of metals.

Furthermore, the technology has a clear environmental positive impact when compared to traditional mining, lower energy consumption then lower carbon footprint and better management of natural resources. On the other hand, the social impact is not positively impacted by this technology due to the lower offered labor opportunities compared to traditional mining. However, the technology developer claims that the positive environmental impact is enough for generating a social acceptance, then, impacting the social dimension. Hence, reviewing the sustainability holistically, it is clear that at the moment this technology contributes only to the economic and environmental dimensions of sustainability as shown in the red colored area numbered with 1 in the figure above.

Last, the technology readiness assessment tool shows that this technology is at technology readiness level two where the technology basic principles are reported and practical applications are identified.

5.1.3 Technology Stream Focused Findings

The findings presented next, answers the two main research questions of this study from a single case perspective. Therefore, they reflect this specific technology stream which is in this case, Bio-technologies. The findings were based on asking the technology developers from that technology stream about their thoughts and ideas when it comes to the two research questions of this study. Hence, the findings are focused and case specific compared to the generic findings included in the chapter of cross case analysis.

5.1.3.1 RQ1: What is the criteria for assessing developing and sustainable Circular Economy technologies?

To use life cycle assessment and mass balances to assess the environmental impact of the technologies. Then the economic benefit, the technology is not considered for implementation and commercialization unless it will generate more profit compared to the amount of money invested, even if it is environmentally friendly.

Then, there has to be user acceptance, so the developer has to think about the final product and validates its importance and if there will be anyone willing to buy it. For instant, food supplements cultivated on urine will not have the same user acceptance as bioplastics products used for different purposes other than food packaging.

Then, assessing the technology readiness occurs while developing the technology if the lab work is still in a 200ml tubes then it is clear to be in a very early stage of development. Usually when starting a very new process it occurs on very small scale in very simple systems, then when that small scale of system works very well, it scales up into a bigger system first then a small pilot and then a second bigger pilot. If the pilot is successful then it can be reviewed to companies to raise their interest and then it can be further developed by the companies on a commercial scale.

5.1.3.2 RQ2: What are the technology catalysts that accelerate Circular Economy transition?

The transition from linear model to circular model requires a lot of steps that mainly involves many different technologies which makes it hard to identify which technology is superior or more important when it comes to accelerating Circular Economy. Hence, there is no main one but all technologies can act as an accelerator and catalysts to Circular Economy.

5.2 Construction Technologies

5.2.1 Concrete Components Reuse

5.2.1.1 Description

The technology is about deconstructing prefabricated load-bearing wall panels or columns of buildings, or detaching beams and/or floor slab panels, process them, and then check them for quality in order to reassemble them together to form a new building, allowing concrete reuse. The technology is considered to be part of a whole system of other hardware and software technologies that are considered to be supporting technologies for achieving the best economic model. Hardware technologies are required in order to implement the technology and make it all possible while software technologies are required in a later stage to offer an online platform to connect demolishers and builders. Also, to allow information trade about the dimension of the panels and materials trade.

Supporting technologies like laser scanning for collecting data about the dimensions of the components and to document the building that will be deconstructed. Portable x-ray for checking out the quality and the location of the reinforcement bars and the steel bars. Then, deconstruction techniques on how to detach the panels using robotics chiseling or diamond saw. Also, the RFID tags to be used for identifying the panels deconstructed from the building and tracking their location in the building. Furthermore, a crane to dismantle, lift and assemble the panels.

Some of those supporting technologies are ready just to be used and there is nothing that needs to be developed about them in terms of their technological core but more about how to apply them for this particular application. Hence, using the same technologies and same applications but in a different context, more like a strategic approach of how to apply these technologies in this context to make the main technology of concrete reuse possible.

5.2.1.2 How the technology advances Circular Economy?

It has been estimated that at least one third of the Finnish construction and demolition waste would be concrete. Hence, the contribution comes in the concrete components reuse from the buildings that will be demolished and avoiding the extraction of virgin resources from the nature while reusing the resources that have already been extracted for as long as possible. Hence, providing a way to prolong the lifetime of the resources that have been extracted and manufactured into product like concrete panels.

However, it would be a primary option to actually repair the buildings before deconstructing them. On the other hand, industrial buildings or warehouses or commercial buildings tend to have a very short functional and/or economic service life and if the frame of such buildings is not worn down and there is no room for repairs or adaptive reuse of the building then dismantle, transport and reuse of concrete panels. Hence, it is considered the second best option after repairing/change of function of building.

> *''If you accept that circular economy is about avoiding the extraction of virgin resources from the nature and using the resources that have already been extracted for as long as possible so the technology provides that. The way to prolong the lifetime of the resources that have been extracted and manufactured into product, but still it would be a primary option to actually repair the buildings before we start to deconstruct them. So if there is an option that you repair the building where it is or you deconstruct it then I think you should go for repairing the building if it's possible'' (S, Huuhka, interview, July 23, 2019).*

5.2.1.3 How the technology advances Sustainability?

From environmental perspective, the environmental burden of construction is huge producing large amounts of waste and extracting virgin raw materials, sometimes transported long distances. Furthermore, the use of cement or the manufacture of cement causes more Carbon dioxide emissions than air traffic, almost three times more.

> *''Other German researchers have made LCA calculations and according to them, reusing concrete panel has a carbon footprint of 4% of the carbon footprint of a panel made from virgin materials. Hence, there is a huge environmental benefit of a 96% environmental saving potential'' (S, Huuhka, interview, July 23, 2019).*

From economic perspective, almost all the deconstruction reuse projects that have been executed in Finland, Germany, Sweden and the Netherlands were quite economical. Though, in some cases there might be some specific problems that cause large costs but normally and overall the reuse projects have been quite economical. Therefore, it has been cheaper to reuse concrete components than to use virgin materials. However, the economic aspect is still to be studied since there are ways on how to detach the components but it is expensive. Then, how it can be competitive to extracting the virgin materials because extracting the materials is cheap but to detach the panels, it requires someone to do it and labor hours are costly.

> *''The economic equation is difficult. Although I made this study about the deconstruction reuse projects that have been executed in Finland, Germany, Sweden and the Netherlands and all of them were quite economical. So in some of them you have some specific problems which caused large costs but normally they have been quite economical. So it has actually been cheaper to reuse than to use virgin materials. But even though it's been cheaper the technology is not more widespread and it's really hard to pinpoint what the reason could be if it's like distrust in reuse rather. So even if you tell somebody that you can save 30 percent of the costs they still think that maybe it's not safe. Maybe it's not healthy. I don't know if that's the reason but I think the economic side has actually been quite good in this experience'' (S, Huuhka, interview, July 23, 2019).*

From a social perspective, more manpower will be needed to identify the parts that still can be used and deconstruct or possibly repair the parts. Hence, it is more labor intensive, creating working opportunities for unemployed persons. Nevertheless, the offered jobs will require specialized knowledge, skills and expertise. Also, the technology will help solving multiple social behavioral issues by offering such work opportunities for people in shrinking communities in different countries.

> *‘’Well at least you need more manpower to refurbish the building parts so it's more labor intensive so that could create working opportunities for unemployed people and one way to look at the social implications as well, I give again an example from Germany. It's a specific example but still they have a lot of empty or almost empty buildings in the east side of Germany. So it used to be the GDR a socialistic part because people wanted to move to the west. So if the people are not doing so well in their shrinking areas so these buildings would be like valuable construction materials they could actually get some prosperity out of the fact that the buildings need to be demolished because people are no longer living there so they could produce these panels for the cities where the building happens. So now they are a problem but they could actually be a valuable resource that would create prosperity for their shrinking areas. So that would be like a social benefit for the residents who live there’’ (S, Huuhka, interview, July 23, 2019).*

5.2.1.4 How ready is the technology?

There are multiple implemented projects in the aforementioned countries. In TAU, there have not been any built prototype nor has the technology been tested. Moreover, the technology is still in an early stage of development and what have been done so far in TAU is mainly literature/theoretical studies. Furthermore, the technology is set to be at TRL2 where the fundamental concept and the developer motivation are clear. As well as, most of the technology basic principles are stated and the practical applications are set to be clear.

5.2.1.5 Technology overview

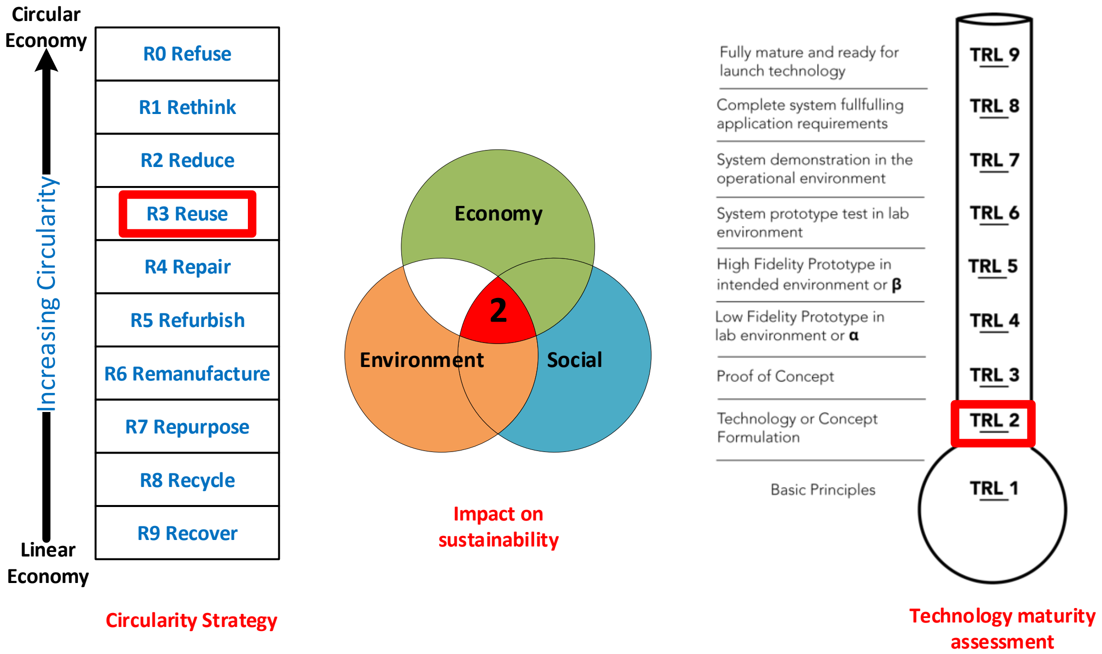

Figure 15. *Concrete components reuse assessment overview.*

This technology focuses on concrete components reuse which is represented on the circularity of the technology as shown in the figure above. The technology aims at reducing the extraction of virgin materials as well as decreasing the environmental burden by lowering the carbon footprint to ensure a positive impact on the environmental dimension. Moreover, the technology is seen to have better economics compared to traditional approach of extracting and manufacturing concrete which contributes to the economical dimension of sustainability. Furthermore, this technology will bring more labor jobs needed for identify parts to be deconstructed or repaired. Also, it shows the potential of solving some social behavioral issues in shrinking communities. Hence, contributing positively towards the social dimension.

At the moment, the technology is operationalizing the concept of sustainable development by impacting its three dimensions altogether as shown in the figure above by being placed in area numbered 2. Last, the technology readiness assessment tool shows that this technology is at technology readiness level two where the technology basic principles are reported and practical applications are identified.

5.2.2 Timber Reuse

5.2.2.1 Description

It is individual strategies that focus on increasing the lifetime and the use of timber wood through eco-design. Hence, developing strategies and design principles on how to apply the reuse approach on wood waste and deconstructed timber. The timber materials are not massive, they are lightweight with smaller dimension components which can be cut and combined easily. The process start by collecting the historical floors or planks or any other timber wood waste and organize them according to their dimensions, then store them in a certain order. Then, there will be an inventory of timber components that can be used later in constructing timber structures. Deconstructed wood tends to be smaller compared to a sound wood since its ends usually break because of the nails attached to it during construction. Then, a new design strategy can propose reusing the deconstructed shorter wood for smaller structures.

5.2.2.2 How the technology advances Circular Economy?

Timber reuse possibility because of the eco-designs thinking and strategies offered. Moreover, timber wood is currently usually burned at the end of its life cycle. In the cases of recycling, there used to be plenty of challenges because of the very limited techniques and offered structures. As a result, timber is not recycled in Finland. Hence, this approach of waste wood reuse would offer a solution to recycling challenges as well as a higher degree of circularity.

> *’’So we could think that the timber components could enter the biological cycle as well but actually you have paint on them on them or you have glue. Then it’s glued laminated timber so it's not really about natural it's more like technological cycle. In fact for the timber it’s not easy for us to enter the biological cycles. So in that way that's what I'm thinking is technological cycles for the timber components and then which is better. So would Biological cycles be better if it would be possible. I don't know. But currently I don't know if you can consider burning timber. I mean you can consider it circular in the planetary sense because forests also burn down sometimes, however, it’s less circular than if you extend the lifetime of the product’’ (S, Huuhka, interview, July 23, 2019).*

5.2.2.3 How the technology advances Sustainability?

From environmental perspective, the strategy of reusing wood will reduce the carbon emissions since wood is capable of storing carbon which slows down the carbon cycle. Also, through reduce the manufacturing of new timber. Hence, avoiding the waste of demolished timber and extending its lifetime. Though, there will be loses like the broken edges of the deconstructed timber. However, other approaches can be considered for those edges like burning them, since it can be seen as circular approach in the planetary sense as burning forests. However, burning wood is less circular than if you extend the lifetime of the product by reusing it. Hence, reusing timber is seen to be environmentally beneficial.

> ‘*’It's a bit more complicated because it's not easy to find information about the sustainability of reusing wood. I haven't been able to uncover this information so it's harder to say that there is a clear environmental benefit. But you avoid making waste so that the timber would be burned to recover energy otherwise’’ (S, Huuhka, interview, July 23, 2019).*

From economic perspective, it not evident if this approach of timber reuse is cost efficient and economically smart. The approach is totally connected to the market state and completely dependent on labor work as mentioned earlier. However, labor hours are expensive and limited in most developed countries. Hence, a lot of research is yet to be done in this area.

From social perspective, the timber remanufacture will generate job opportunities because it is more of a handiwork type of construction. The need for workers to detach the wood, pile it up, sort it and then later reuse it.

> *''For timber, well the job creation may increase because the timber can be more of handiwork type of construction so maybe there could be even more opportunities for job creation'' (S, Huuhka, interview, July 23, 2019).*

5.2.2.4 How ready is the technology?

There had been a small project for the ministry of environment in Finland about reusing timber that resulted in an inventory of the different kinds of timber structures, timber components and materials that have been used in the buildings in Finland throughout the history. Also, there was another project conducted with university students in setting new designs and strategies for reusing timber. However, there is nothing implemented yet on a commercial scale. Moreover, there are barriers for applying the reuse strategy of timber as the inconsistency of quality and quantity of the detached timber. Hence, the technology is set to bet at TRL2.

5.2.2.5 Technology overview

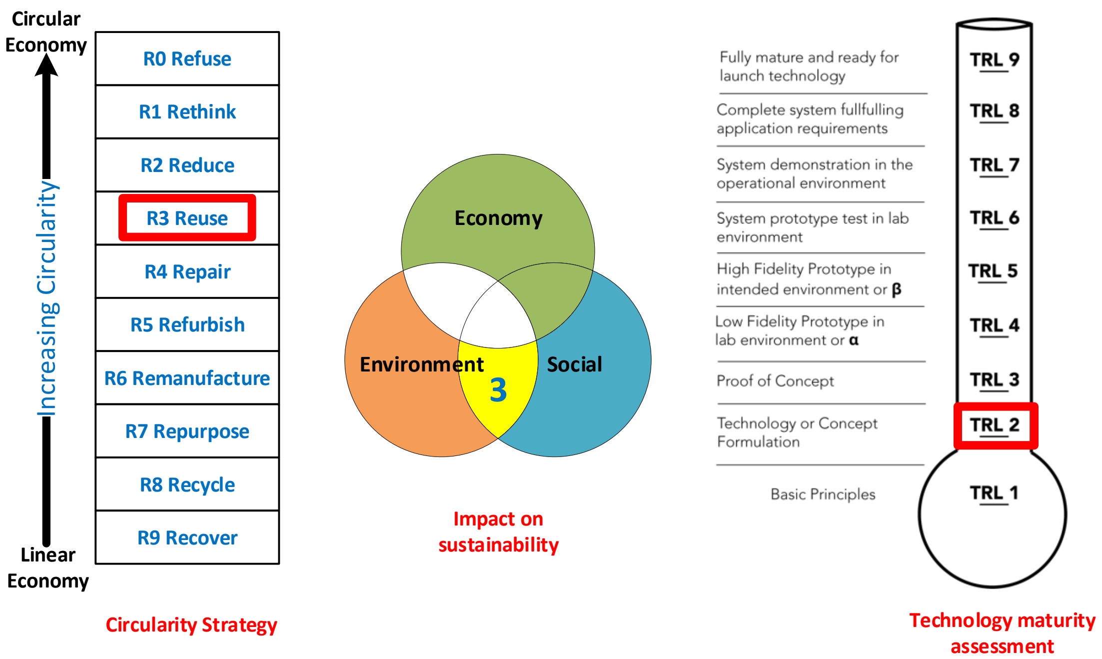

Figure 16. *Timber reuse assessment overview.*

The reuse strategy behind applying this technology falls under a moderately high level of circularity as shown in the figure above. The aim of limiting the use of natural resources and materials by extending the life cycle of timber, as well as ensuring lower carbon emissions to the surrounding environment contributes to the environmental dimension of sustainability. Moreover, the technology is labor dependent, then more offered job opportunities to the community which is a direct impact to the social dimension of sustainability. On the other hand, it is hard to prove the economic viability of this technology in the current time which does not replicate any impact to the economic dimension of sustainability. Hence, reviewing the sustainability holistically, it is clear that at the moment this technology contributes only to the social and environmental dimensions of sustainability as shown in the yellow colored area numbered with 3 in the figure above. Last, the technology readiness assessment tool shows that this technology is at technology readiness level two where the technology basic principles are reported and practical applications are identified.

5.2.3 Technology Stream Focused Findings

The findings presented next, answers the two main research questions of this study from a single case perspective. Therefore, they reflect this specific technology stream which is in this case, construction technologies. The findings were based on asking the technology developers from that technology stream about their thoughts and ideas when it comes to the two research questions of this study. Hence, the findings are focused and case specific compared to the generic findings included in the chapter of cross case analysis.

5.2.3.1 RQ1: What is the criteria for assessing developing and sustainable Circular Economy technologies?

First is to determine the circularity, to define the level of circularity that the technology meets. Then, assess the technology impact on sustainability from the environmental, the economic and the social point of view. Last technological readiness, to clarify how mature is the technology.

Life cycle assessment tool and mass balances are commonly used for assessing environmental sustainability. Then, the LCC as a tool can be used for assessing the economic dimension of sustainability. However, the social sustainability will be quite hard to design and decide on all the relevant social indicators since it is more of a qualitative, subjective assessment compared to the quantitative assessment that takes place in the other two dimensions. Nevertheless, safety is one big factor when it comes to construction technologies, which can be seen as a criteria of assessing the social dimension of construction technologies.

For technology readiness that depends if the technology is a standalone technology or part of a whole system including other technologies that together operationalize the main technology. In the latter case, then assessing the sub-technologies will result in an overall readiness for the main technology. However, in most construction technologies, if they are part of a whole system then the supporting or sub-technologies are mostly mature and will only be applied in different context to their main application to operate within the new environment set by the new technology.

5.2.3.2 RQ2: What are the technology catalysts that accelerate Circular Economy transition?

The commitment towards a transition into Circular Economy ought to incorporate different developing technologies that all contributes towards validating and implementing the concept. Furthermore, construction technologies now days are supported by other wide range of technologies. Then it is hard to decide or favor certain technologies to others. Therefore, all technologies are need for accelerating Circular Economy transition.

5.3 Digital Technologies

5.3.1 Software for Sustainable and Optimized Manufacturing

5.3.1.1 Description

It is a manufacturing software tool that focuses on achieving sustainability while considering different manufacturing processes. The tool is specifically designed to suit additive manufacturing (AM). The tool will be able to address the economic, environmental and social aspects of sustainability by monitoring various key performance indicators for the manufacturing process. For the tool to assess these sustainability metrics, it is important that different forms of knowledge that is available could be integrated. Information related to manufacturing parameters, expert knowledge, costing data, environmental emissions and social indicators are examples of data that would be collected. The idea would be to represent these different parameters, variables, and indicators in the form of a cause-effect relationship using visual representation such as graphs. The software will allow the users to make modifications to this graph to be able to identify how changing one indicator would result in changing the other ones.

Therefore, the software will have all the different key performance indicators as well as the different manufacturing processes from existing databases or from previous historical data and then bringing in the knowledge or experience of the personnel who have been working in the industry through different techniques such as analytical hierarchy process. Then, encoding these different forms of knowledge in the tool, which would perform the assessment and provide sustainability scores. Decision makers (designers, manufacturing engineers, managers) would have the freedom to make changes in the design or manufacturing parameter to analyze and predict different outcomes in terms of sustainability.

5.3.1.2 How the technology advances Circular Economy?

Resource efficiency and better resources management through simple modifications and optimization to the design or the manufacturing process parameters aiming for reaching sustainability levels can help reduce the raw materials used, hence, less materials wasted and better utilization to it.

5.3.1.3 How the technology advances sustainability?

From environmental perspective, the aim is that the tool will be able to monitor and assess the different impacts on the neighboring community of where the factories are situated in terms of emissions to air, ground and water. Then, once there is certain knowledge about the emissions, then the tool can recommend solutions or best practices to reduce it or eliminate altogether.

> *''Companies involved in manufacturing could use this software as a tool for assessing their performance and decisions in regards to sustainability. So in terms of gender sustainability I would say we can monitor and see the different impacts*

> *it has on the neighboring community of where the factories are situated and then in terms of emissions to air, ground and water, all of those things. And then the impact would be that once we know that certain emissions are going out we can implement methods to reduce it or get rid of it altogether'' (S, Panicker, interview, June 19, 2019).*

From economical perspective, the manufacturing process will be based on cost models, hence, less materials waste lead to better savings and economic feasibility. In addition, the predictability of the outcome while being flexible towards making changes to the design or manufacturing parameters drive better economics.

From social perspective, it is hard to decide how the software will impact the social dimension of sustainability since there is no hard formula that can calculate the social improvement compared to economic and environmental dimensions. The social impact assessment has been subjective and usually the results are based on surveys. Hence, understanding and identifying the existing social metrics that has been used for life cycle assessments, and work towards improving them.

> *''So the most difficult is the social sustainability because it's more based on surveys and there is no hard and fast formula which can be used. For example for economic or even for environmental dimensions you can compute these things through formulas but for the social dimension it's more based on subjective measures I would say and its indicators differs from company to company too'' (S, Panicker, interview, June 19, 2019).*

5.3.1.4 How ready is the technology?

The software is in its conception phase, it is still in an early stage of development, and mostly what has been done is literature investigations and multiple trials of introducing some of the machine learning algorithms. Therefore, mainly research work is ongoing, trying to identify different algorithms to check which one suits the best for the application.

Most of the technology basic principles and practical applications are clear. Moreover, the technology has shown interest for different customers in the industry. Hence, the technology is considered to be at TRL2.

5.3.1.5 Technology overview

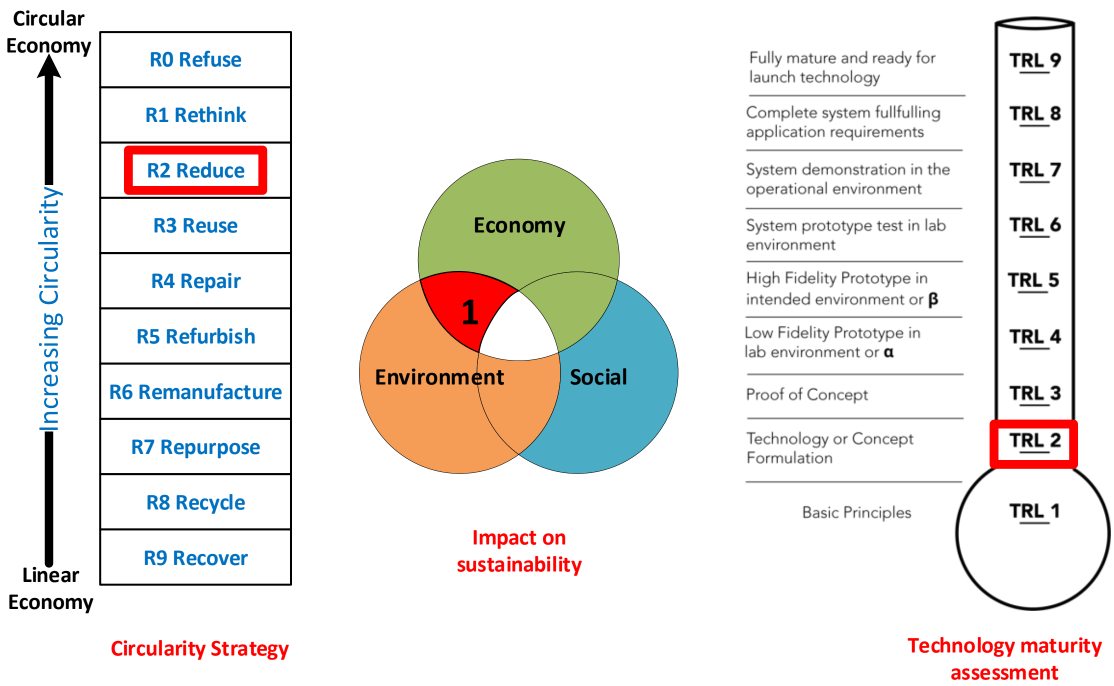

Figure 17. *Software for sustainable and optimized manufacturing assessment overview.*

The technology appears to be fulfilling the core concept of Circular Economy with a high level of circularity as shown in the figure above. The aim of reducing the use of natural resources and materials while ensuring higher manufacturing efficiency contributes to both environmental and economic dimension of sustainability. Also, the recommended solutions and practices suggested by the software will help at reducing hazardous emissions from the manufacturing process and will improve the environmental surrounding. On the other hand, it is hard to neither prove the social impact of this technology nor provide any possible future job offerings through implementing it, however, the technology developer claims that the environmental improvements should boost the social acceptance and well-being.

Hence, reviewing the sustainability holistically, it is clear that at the moment this technology contributes only to the economic and environmental dimensions of sustainability as shown in the red colored area numbered with 1 in the figure above. Last, the technology readiness assessment tool shows that this technology is at technology readiness level two where the technology basic principles are reported and practical applications are identified.

5.3.2 Technology Stream Focused Findings

The findings presented next, answers the two main research questions of this study from a single case perspective. Therefore, they reflect this specific technology stream which is in this case, Digital technologies. The findings were based on asking the technology developers from that technology stream about their thoughts and ideas when it comes to the two research questions of this study. Hence, the findings are focused and case specific compared to the generic findings included in the chapter of cross case analysis.

5.3.2.1 RQ1: What is the criteria for assessing developing sustainable Circular Economy technologies?

The technology developer argues that planning a matrix with certain targets to achieve in terms of Circular Economy will be effective for assessment. Targets like the circularity following the R strategies diagram, sustainability divided into the three dimensions and last, technology readiness. The matrix can be used to condition check all the targets it meets. For environmental aspect the condition to be checked can be LCA. For economic dimension it can be based on better economics and lower expenses. However, assessing the social dimensions is very subjective. It is hard to validate how digital technologies impact social dimension and at the same time assess their readiness since they are always updated and developed.

5.3.2.2 RQ2: What are the technology catalysts that accelerate Circular Economy transition?

Digital technologies are leading in the role of accelerating Circular Economy transition. New digital technologies like IoT, Blockchain and machine learning are carrying immense chances for Circular Economy transition. Moreover, digital technologies are supporting many industries, in some cases they are acting as sub-technologies of a whole running system which proves their importance.

5.4 Manufacturing Technologies

5.4.1 Additive Manufacturing Analytical Models

5.4.1.1 Description

Manufacturing can be classified broadly in two categories, subtractive manufacturing which is the traditional technology, and additive manufacturing which is relatively newer and disrupting technology. The study, which is currently undertaken, involves experimental work in metal additive manufacturing. The end goal of these experiments would be to develop empirical models that would provide a better understanding and representation of the additive manufacturing process. A specific type of AM process known as wire arc additive manufacturing (WAAM) is studied. WAAM is a form of direct energy deposition (DED) process wherein, the desired part is built layer on layer. The process uses an electric arc as heat source to deposit the metal wire feedstock. The system comprises of a robotic arm that has the welding torch attachment, a wire feeder, cold metal transfer power supply unit (type of welding unit), and shielding gas supply unit. The AM process allows for realization of complex geometries that would be difficult to attain with traditional manufacturing. AM can help reduce the total number of parts and sub-assemblies by replacing these as one part.

Then a greater degree of freedom, where designing and printing a CAD model that is topology optimized will have the same strength as traditionally designed parts but rather with reduced amount of raw material. The aim of remanufacturing technologies and eco-design is to design components that can be remanufactured and at the same time maintain their robustness and strength. Industrial companies use additive manufacturing as a method for remanufacturing purposes where companies have big parts like turbines or ship propeller blades that usually require to be repaired by remanufacturing. Hence, those parts can be scanned to get the whole CAD model made and then use wire arc additive manufacturing method to manufacture the broken part or component. However, to perform it effectively there should be some trial and error activities before actually printing that broken part or component in order to ensure a final good quality component.

Therefore, the aim of these analytical models is to eliminate that trial and error phase by encompassing all of those different designs, geometries, manufacturing data, the type of materials and type of process all together in order to come up with specific numbers that can be used as an input data for an efficient remanufacturing process. Moreover, optimizing the parameters of welding like the wire feed rate and the travel speed of the arc to have the best component quality as a result.

Furthermore, having straight parts or components is different from complex part with curves and angles in terms of the parameters to be set. At the present time, the approach is printing multiple prototypes based on parameter variations in a carefully planned design of experiments to ensure finding the optimum parameters. Hence, yielding the best quality output. Therefore, precious resources such as material and time are spent on activity which will not result in a commercially ready product. Hence, those analytical models will eliminate the need for this extensive prototyping.

5.4.1.2 How the technology advances Circular Economy?

It focuses on reducing material use. In traditional manufacture, in order to manufacture a certain part there will be a big block of a certain material that will be reformed to look like the desired part leaving behind many scrap and generating waste materials. In order to be able to use the generated scrap from such process, the scrap has to go through recycling which is considered as an energy intensive process because of the need to lay out a lot of energy to form it back into the original block which later can be used for another purpose. However, manufacturing the same part using different technique as wire arc additive manufacturing will allow a proper use of materials with efficiency up to 95%, reducing waste materials while maintaining the functionality of the component.

> *''So this technology is actually used for remanufacturing. However, the aim is reducing materials. So companies have big parts which are a part of turbines or parts of the ship propeller blades. So if one of them needs repair you can actually have it scanned and you get the whole CAD model made and then you can use this wire arc additive manufacturing method to manufacture the broken tail fin or whatever the component is. So that's kind of the main application which this is being used for currently. Before you start remanufacturing of the damaged part, some trial welding tests are performed to optimize the weld parameter settings. These tests take time and resources, we are trying to eliminate the trial and error tests by making a model that encompasses all of these different design geometry, part functionality, and process parameter settings and their interactions. The developed software will then be capable of providing optimized process parameters to run the wire arc additive manufacturing to remanufacture parts'' (S, Panicker, interview, June 19, 2019).*

The advancement would be into having a model which can combine all the parameters needed for a certain design and recommend what need to be fixed or changed in order to get a good weld and directly print the part without going through any trial and experimentation. Hence, saving up on wasted time and materials.

5.4.1.3 How the technology advances sustainability?

In general, there are two different opinions regarding additive manufacturing sustainability. First, additive manufacturing is more sustainable compared to conventional manufacturing process. While the other one argues that, it is not really any more sustainable than conventional manufacturing. The idea is that it depends on the system boundaries set to be used. In the case of using additive manufacturing in remanufacturing a part or component which was designed for subtractive manufacturing, then it will not be sustainable. Therefore, in order to use the full potential of additive manufacturing for improved sustainability, concepts or principles such as design for additive manufacturing need to be incorporated in the designing phase. Thus, there are developed methods such as eco-design for additive manufacturing, which is specifically designing the parts and components based on the principles that will make it convenient for later remanufacture using the additive manufacturing method. Then, following such approach would eventually result in a more sustainable product.

Therefore, it is more sustainable if it is done following the proper approach. Also, additive manufacturing has been used in national defense research, aviation and automotive industry for printing parts and components, and many companies are looking into making the transition to move into additive manufacturing to address the new targets of sustainability and bring down the costs as well. Hence, from environmental perspective, using additive manufacturing analytical models in any remanufacturing and eco design process will help reduce material usage, then less material waste and lower carbon footprint.

> *''So let's say like you have a part which is right now being manufactured traditionally where you're taking a big block and then taking out material from it to make a part. So scrap is generated. Then you have to go into recycling, and metal recycling is energy intensive process. You need to lay out a lot more of energy to get back into like the original block which can be used for something else. But the same part if we can use techniques such as design for additive manufacturing and have the functionality intact but just changing the way of manufacturing. So some of the metal AM processes such as wire arc additive manufacturing. It has material use efficiency upwards of 95 percent. So you're just using materials to print the part itself and not removing material. So that's reducing'' (S, Panicker, interview, June 19, 2019).*

While, from the economic perspective, lowering expenses due to eliminating the need of buying new components again and no expenses lost on wasted materials which make it economically smart and viable.

> *''I think that here we have the manufacturing for being more economic, it's more based on the cost models and the way of manufacturing. And then material utilization. And the other thing is more like cost perspective as in like how can we make things cheaper. Make the production cost cheaper'' (S, Panicker, interview, June 19, 2019).*

From social perspective, it is not evident if the technology will bring any more jobs, since the technology is existing and the processes of researching and optimizing parameters needs experienced personnel whom aim at having a collective model that utilize and encompasses all the material types, manufacturing process and other parameters related to designs and geometries, which does not seem to bring any more jobs at least at the current state.

5.4.1.4 How ready is the technology?

In terms of additive manufacturing technology itself, it is already existing and fully mature. It is certainly a level nine technology as it can be bought off the shelf from companies to start manufacturing or remanufacturing any parts or components. However, while printing a part there should be a manual to follow that explains how the system works but the problem is, it does not mention many details about the parameters to be maintained and optimized to get a good quality product with respect to its geometry. Hence, the improvement is in literature research to find the best practices for welding and identifying the best material properties of the weld that can achieve best materials reduction. Then, trying to have optimized parameters selection based on previous experience that sets the analytical models to be at TRL 4. The readiness level is supposed to reach level nine by the time there will be one model that gathers all the required information and parameters needed for remanufacturing any kind of part or component.

5.4.1.5 Technology overview

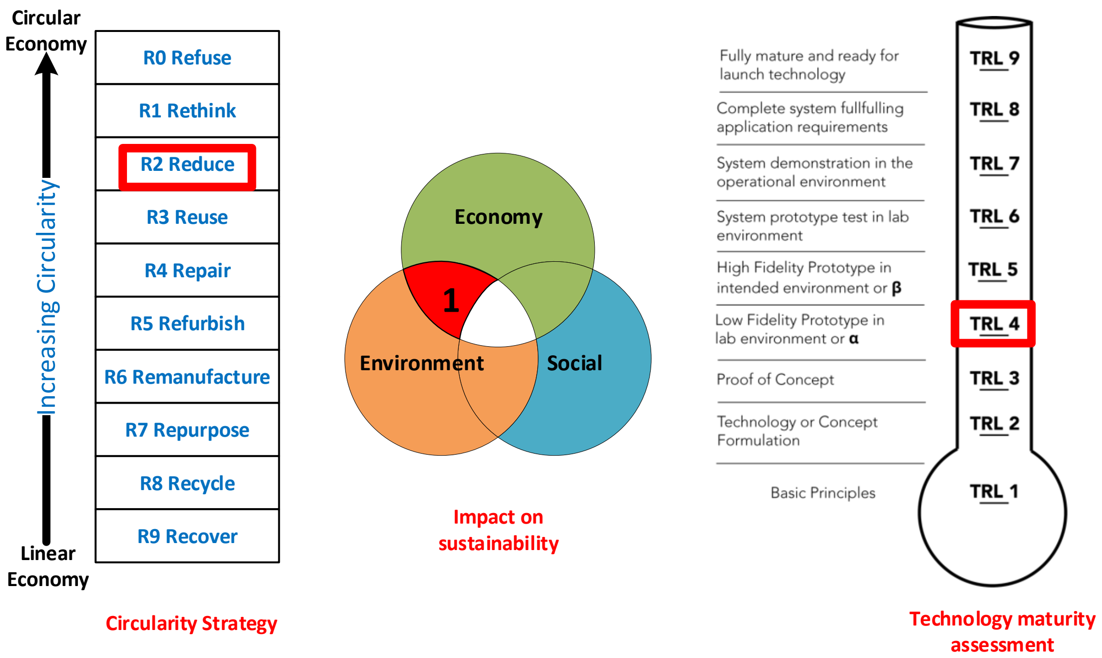

Figure 18. *Additive manufacturing analytical models assessment overview.*

The technology appears to be at high stage of Circularity as shown in the figure above, focusing on reducing the use of natural materials while maintaining the high quality of remanufacturing products compared to other traditional manufacturing methods with a percentage up to 95% as well as reduce the expenses spent on components or extra materials contributes positively to the environmental and economic dimensions of sustainability. Moreover, the collective analytical model will reduce the carbon foot print because of the best practices it will suggest for remanufacturing any component. Therefore, it will reduce material scrap which normally consume huge amount of heat and energy in order to be reused again. On the other hand, it is hard to emphasize on any positive social impact done by these analytical models nor provide any possible future job offerings through using it, however, the researcher claims that the environmental improvements should boost the social acceptance and well-being which by then impacts the social dimension of sustainability positively.

Hence, reviewing the sustainability holistically, it is clear that at the moment this technology contributes only to the economic and environmental dimensions of sustainability as shown in the red colored area numbered with 1 in the figure above. Last, the technology readiness assessment tool shows that these analytical models are at technology readiness level four where the technology basic principles are reported, practical applications are identified, proof of concept existed and last an operating prototype in a lab environment. As mentioned earlier, the readiness level is supposed to reach level nine by the time there will be one model that gathers all the required information and parameters needed for remanufacturing any kind of part or component without going through any trials.

5.4.2 Technology Stream Focused Findings

The findings presented next, answers the two main research questions of this study from a single case perspective. Therefore, they reflect this specific technology stream which is in this case, manufacturing technologies. The findings were based on asking the technology developers from that technology stream about their thoughts and ideas when it comes to the two research questions of this study. Hence, the findings are focused and case specific compared to the generic findings included in the chapter of cross case analysis.

5.4.2.1 RQ1: What is the criteria for assessing developing sustainable Circular Economy technologies?

Main focus would be on assessing the sustainability. If the technology is not sustainable then it does not fit to the concept of Circular Economy. Moreover, it is important to link the environmental impact of manufacturing technologies with the social life through using the outcomes from the environmental assessment and link it to how it affects the people related. That somehow lower emissions can be considered as social benefits. Then, instead of using the traditional approach of having surveys conducted in factories there should be defined and previously agreed social indicators -like health or safety- by different organizations that can be monitored. Then, focus and seek to meet the standards of those indicators. Moreover, other focused point in the criteria would be the cost impact of the new technology and how it advances the economic growth and drives lower expenses.

Furthermore, assessing the technology readiness, to start with the basic principles and then building a prototype for testing following the TRL steps. Then applying this technique to be customized for Circular Economy to meet any of its R strategies of Circularity.

5.4.2.2 RQ2: What are the technology catalysts that accelerate Circular Economy transition?

Manufacturing technologies that focus on products eco-designs are seen as accelerating technology catalysts to Circular Economy transition. However, there are many enabling sub-technologies to those two main technology streams but looking form a holistic point of view then sustainable manufacturing is a leading technology stream in regards to Circular Economy contribution.

5.5 Material Science Technologies

5.5.1 Composites Recycling Process Optimization

5.5.1.1 Description

It is a process technology that concentrates on composites recycling through optimizing the process parameters of the composites recycling system. The technology itself is mature and serves the manufacturing industry. However, the idea is about optimizing the parameters that are used for recycling. There are two main recycling technologies for composites, mechanical and thermal. Both recycling technologies can be used for plastics and composites.

Focusing on mechanical recycling, at the beginning there should be a clear understanding of what kind of raw material should be fed to the system and its size, if it is a big part like a huge blade of wind turbine then it has to be sorted somehow into smaller parts that the system would be able to grind. Then the grinding speed, understanding if there are different speeds on the crushing tool then what is the wear rate of the tool versus the output material rate versus the energy consumed. Then, the concept behind mechanical recycling is to crush the part to get more and more fine particles. Therefore, the technology contributes through offering a developed equation that is case specific and can use different input data, combine it and give the specific optimum speed for the grinding process. Hence, optimizing the whole recycling process.

Nevertheless, the use of recycled materials is limited to certain products that do not feature the safety factor within. To elaborate more, products designers have interest now days in the idea of the material being recycled over and over by the end of its life time. However, critical products like the wind turbine blades or plane wings and other products will not be manufactured from recycled materials or repaired for safety reasons. Hence, not all the recycled end products are suitable for that approach of design from the safety point of view. On the other hand, there are certain designs for products that has no safety issues like the wine cooler which is made of recycled material and can be later recycled. Furthermore, different products like bathtubs and light covers that are made of recycled materials and do not have safety issue. Hence, product designs are important factor in optimizing the overall recycling process of transforming one thing into another new form.

5.5.1.2 How the technology advances Circular Economy?

The technology advances Circular Economy by applying the recycling strategy where recycling composite materials from wind turbines and aeronautic parts. Mainly parts that have a long life time and their new design changes frequently due to the fast technological advancements taking place. Hence, reusing or repairing the old parts is not feasible like wind turbine blades where the old blades are considered much smaller than the blades developed and used now days. Moreover, aeronautics parts have to meet certain safety standards which will not make recycled components and parts attractive enough to be used. Then, optimizing the whole process to be efficient enough for recycling different parts into a new material that can be used later for making less critical products.

5.5.1.3 How the technology advances Sustainability?

The process optimization gives a realistic understanding to the cost of the overall process and assists at minimizing it. The costs in mechanical recycling is generated mainly from the electricity and power used. Then, optimizing the process will lead to minimizing the amount of power usage which leads to better economics and an energy efficient process. Hence cost reductions and environmental improvements are interrelated. Moreover, the positive consumer behavior of buying recycled products that are not dependent on safety or health related matters is seen as environmental benefits because of the resources use efficiency. Hence from economic and environmental perspectives, the technology is viable and impacts both dimensions positively.

> *''We are doing the process optimization. So what it gives actually is a realistic understanding on what is the cost of the process and it helps to minimize it. Of course from the environmental point of view, understanding the different variables in the process and then being able to minimize it is important. In terms of the costs, it also means that we are decreasing or minimizing the environmental aspect of the process because most of the costs for example in the mechanical recycling comes from the electricity that we are using and if we can minimize the cost of that it means that we are minimizing the amount and then we have the environmental aspect. So it's more like cost environment and which are very interrelated'' (E, Sarlin, interview, July 1, 2019).*

From social perspective, there was no clear indication on how this technology can contribute or affect the social benefits in regards to offering job opportunities or improved well-being, since some recycled products are just used for their functionality and measuring their impact on social life is not tangible. However, the technology developer argues that social acceptance on the design of the final recycled products is considered as a social benefit as well as the technology itself since it contributes to the concept of better future of the Circular Economy.

> *''We don't concentrate on the social aspect. A little bit on the design side and there the social aspect has been involving. Where the general public is giving opinions on the design. The idea was that there are designers of both students and professional designers and they design some products and then the general public is asked for opinion, rating and commenting on these products and then some products are developed further'' (E, Sarlin, interview, July 1, 2019).*

5.5.1.4 How ready is the technology?

It is a previously existing and mature technology, the further development took place in the developed equation that can be used for optimizing the whole recycling process. The equation is already formed and been used in different projects. The developed equation has been validated from the energy consumption point of view, a meter that was plugged between the recycling machine and the power source - while considering the wear of the tools used - can measure the difference in energy consumption before and after the process optimization. Then, the mechanical recycling technology is at level nine on the technology readiness scale, the further development in optimizing the whole recycling process is already existing and in practical industrial use, hence, the overall readiness of this technology is considered to be at TRL 9.

5.5.1.5 Technology overview

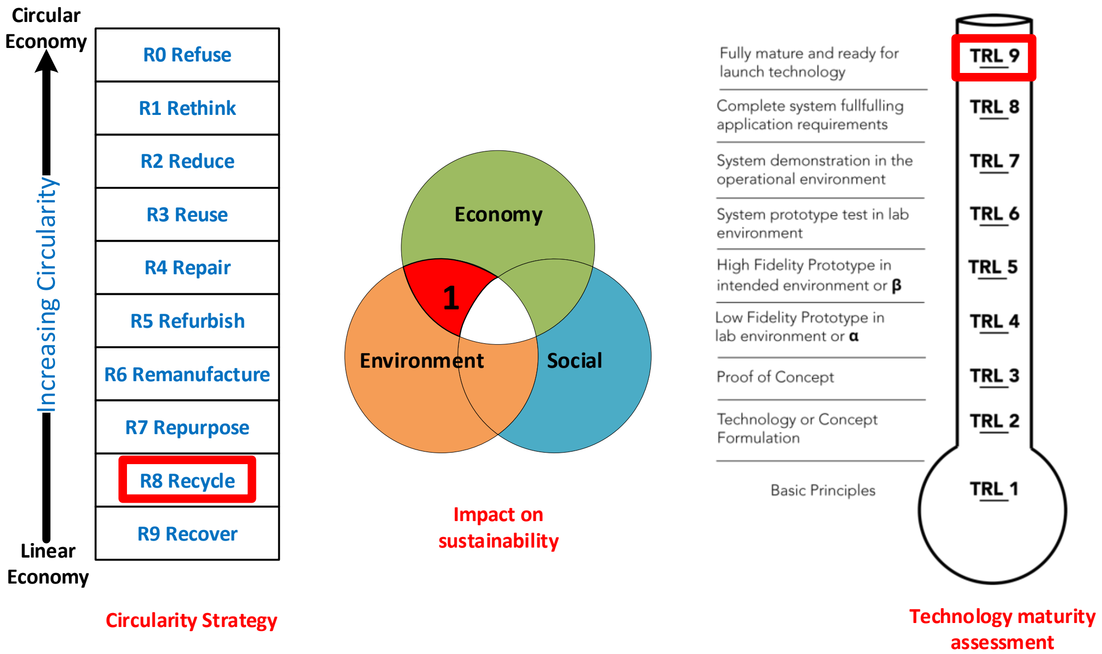

Figure 19. *Composites recycling process optimization assessment overview.*

The mechanical recycling technology appears to be at a very early stage of circularity as shown in the figure above, focusing on recycling of composite components into new commodity products. The process optimization will reduce the running costs and energy consumption as well as improve the resources management through limiting the extraction of virgin materials used in manufacturing products that can be manufactured through recycling composite materials. Moreover, the technology does not contribute with any clear social benefits. However, the technology developer claims that the environmental improvements should improve the social well-being.

Hence, reviewing the sustainability holistically, it is clear that at the moment this technology contributes only to the economic and environmental dimensions of sustainability as shown in the red colored area numbered with 1 in the figure above. Last, the technology readiness assessment tool shows that this technology with the later optimized processes is at technology readiness level nine where the technology basic principles are reported, practical applications are identified, proof of concept existed, a prototype is tested in the lab as well as, a high fidelity prototype is demonstrated in a simulated relevant environment to the operational one, the high fidelity prototype has been integrated in an operational environment successfully and fulfilled the required application while adhering to the regulatory standards. Furthermore and as mentioned earlier, the further improvement that took place was related to optimizing the process of recycling though developing an equation that can take different inputs and results with the optimum parameters for the recycling process. Regardless, the technology is considered ready and fully mature.

5.5.2 Technology Stream Focused Findings

The findings presented next, answers the two main research questions of this study from a single case perspective. Therefore, they reflect this specific technology stream which is in this case, material science technologies. The findings were based on asking the technology developers from that technology stream about their thoughts and ideas when it comes to the two research questions of this study. Hence, the findings are focused and case specific compared to the generic findings included in the chapter of cross case analysis.

5.5.2.1 RQ1: What is the criteria for assessing developing sustainable Circular Economy technologies?

The initial focus should be on sustainability as the man criteria because if the technology is not sustainable then it is a deal breaker. Afterwards the technical readiness of the technology which is directly linked to the economical state because it can be argued that the technology is not yet ready but it can be further developed to become more economical. Therefore, environmental impact laws or the environmental dimension should always be assessed first, usually using the lifecycle analysis for comparison. Then, the economical dimension to be assessed while developing the technology. Last, assessing the technical readiness is based on if the technology at a certain stage of development is economically feasible or not, based on that, then it is decided to proceed for further development in order to be available for commercialization. Therefore, in practice the economical assessment is the most important aspect in terms of sustainability and assessment criteria.

5.5.2.2 RQ2: What are the technology catalysts that accelerate Circular Economy transition?

It is a team play of many technologies that end up into a new product or a new strategy that adopts the Circular Economy. The contribution towards Circular Economy activities should include several and different streams of developed technologies and not only one. However, the leading and popular technology stream at the moment is seen to be Biotechnologies where the use of bio-based resources is the core. Such technology stream has accelerated a lot lately that makes it distinguished and significant at the moment. Then, manufacturing technology stream and nanotechnology streams comes afterwards.

6. CROSS CASE ANALYSIS

In this chapter, two different cross case analysis will be conducted from two different perspectives. First analysis will be demonstrating the common findings from the mapped technologies perspective, using the preliminary designed assessment criteria. The second analysis will be presenting the new identified assessment criteria and evaluation methods from the technologies stream perspective. In addition, reviewing the technology streams opinions and thoughts in terms of the old preliminary designed assessment criteria of this thesis.

6.1 Mapped Technologies Perspective

In the table next, the technologies mapped will be listed while presenting their assessment from circularity, sustainability and technological readiness point of view. Technologies circularity is explained using the R strategies, technologies are listed in descending order from highest circularity -first technology- to the lowest circularity, which is the last technology in the table. Then, technologies sustainability demonstrate the dimensions that the mapped technology only contributes to, while technologies readiness is explained by determining the readiness level using the TRL tool.

Table 9. *Technologies mapped and their assessment.*

Technologies mapped	Assessment		
	Circularity, R-strategies	3 Dimensions	TRL
Additive manufacturing analytical models	R2. Reduce	Economic & Environmental	4
Software for sustainable and optimized manufacturing	R2. Reduce	Economic & Environmental	2
Concrete components reuse	R3. Reuse	Economic, Environmental & Social	2
Timber reuse	R3. Reuse	Environmental & Social	2
Waste treatment with Microalgae	R3. Reuse	Economic & Environmental	4
Composites recycling process optimization	R8. Recycle	Economic & Environmental	9

Biological Metal recovery	R8. Recycle	Economic & Environmental	2

As shown in the table above, it is found that:

- Most technologies with high circularity are low on readiness level, which may indicate the early stage of development of many Circular Economy technologies now days. However, there is one technology mapped that has a relatively better level of readiness compared to the other technologies with similar high circularity, but still it does not argue the general low readiness of Circular Economy technologies mapped.
- The most developed and mature technology -composites recycling process optimization- offers recycling as a strategy of circularity which is considered of a lower importance to other circularity strategies like reuse and reduce.
- Most mapped technologies where lacking the inclusion of the social dimension of sustainability. Hence, social benefits are ignored while developing the technologies and most focus is on economic benefits and environmental improvements.
- There is one technology -concrete components reuse- that is impacting the three dimensions of sustainability. Hence, operationalizing the concept of Circular Economy as discussed in literature.
- Only timber reuse technology lacks to impact the economic dimension because the technology developer could not assure if the technology implementation is seen to be economically feasible.

The above findings were a result of assessing the mapped technologies using the predefined criteria and framework. However, while conducting the assessment there were some common and odd findings between technology developers. Also, the technology developers had their own views and feedback in regards to the assessment criteria and evaluation methods. The common and odd findings across technology developers, as well as their opinions and feedback will be discussed next:

- It was common that there was an unclear understanding and confusion to the different R strategies.
- It was common when it comes to sustainability assessment, many technology developers would connect the environmental benefits to social benefits and claim impacting both dimensions. It was also common that the economic dimension has the highest priority, it is the deal breaker to further develop any technologies.
- It was common by all technology developers that social dimension is overlooked. Not necessarily to be deliberately overlooked, but few argue the lack of awareness to its importance.
- One technology developer argued that the TRL tool has some limitations when it comes to further development. To further explain, the technology developer was wondering about, what will be the TRL of a fully mature technology that goes

through frequent development. Will the TRL be extended to new levels or the technology will stay at the same TRL.

- It was common between few technology developers to be familiar with the steps of technology development as shown in the TRL model but not with the model itself.
- One technology developer argues that being more flexible and less strict in following the levels of the TRL model can be more effective in allowing the researchers to learn and bridge some obstacles while developing their technologies.

6.2 Technology Stream Perspective

In this chapter, technology streams determine the criteria for assessing Circular Economy technologies, each technology stream has its own separate criteria for assessment. Nevertheless, most technology streams identified the following as the main common criteria to be examined and assessed;

- Sustainability
- Circularity of technology
- Technological readiness

Furthermore, each technology stream has introduced different evaluation methods for each criterion. Then, to combine all the findings of the five technology streams, a cross-case analysis is conducted in order to better demonstrate the commonalities and differences between the technology streams assessment criteria and their evaluation methods. Therefore, Table 8 and Table 9 are made. Table 8 is covering the first criterion; sustainability from its three dimensions, each with its own evaluation methods as following;

- Environmental as LCA, mass balances, energy consumption or lower emissions
- Economic as LCC, profitability or lower expenses
- Social as user acceptance, health, safety

In the evaluation methods section in the table below, there is one slot titled with ‘‘not specified’’ since in some cases one of the criterion is identified to be essential for assessment but without mentioning or discussing any evaluation methods or tools to reflect on.

Table 10. *First assessment criterion with its evaluation tools across each technology stream.*

Technology streams	Sustainability										
	Environmental				Economic			Social			
	LCA	Mass balances	Energy consumption / Lower emissions	Not specified	LCC	Profitability / lower expenses	Not specified	User acceptance	Health	Improved safety	Not specified
Bio	✓	✓				✓		✓			
Construction	✓	✓			✓					✓	
Digital	✓					✓					✓
Manufacturing			✓			✓			✓	✓	
Material science	✓		✓				✓			✓	

As shown in the table above, it is common across most technology streams that:

- LCA is the most common evaluation tool for assessing the environmental dimension of sustainability as presented in the literature review of (Sassanelli et al., 2019) and in chapter three.
- Profitability or lowering the expenses is the most common evaluation aspect for assessing economic dimension of sustainability
- Improved safety is the most common evaluation indicator for assessing the social dimension of sustainability

Furthermore, the following can be concluded form the table as well:

- Mass balances and energy consumption are equally considered as the second best evaluation method for assessing environmental dimension
- From the construction technology stream perspective, LCC is considered to be an effective evaluation tool for the economic dimension.
- Material science technology stream emphasized on the economic dimension to be the deal breaker for developing any technology. However, there was not any specified evaluation tool or method for assessing the economic dimension
- User acceptance is considered to be an important factor at impacting the social dimension from the Bio-technology stream perspective. Since bio-based products are sensitive when it comes to their functionality or final use. Hence, the products compliance with social preferences is important.
- From manufacturing technology stream perspective, health and improved safety are the two main evaluation indicators for assessing the social dimension. The choices were driven from the hard environment of the manufacturing industry where workers safety and health state is a major concern.
- Digital technology stream emphasized on the importance of assessing the social dimension of sustainability. However, it argued that it is very subjective. Hence, there was not any specified evaluation tool or method for assessing the social dimension

Then, Table 9 is covering the second and third criterion. Each criterion with its own evaluation methods as following;

- Technological readiness as TRL, scientific order of technology development, commercialized product, mature sub-technologies, economic feasibility
- Circularity as 9R strategies, Ellen Macarthur Circular Economy system diagram

In the evaluation methods section in the table below, there is one slot titled with ‘‘not specified’’ since in some cases one of the criterion is identified to be essential for assessment but without mentioning any evaluation methods or tools to reflect on.

Table 11. *Second and third assessment Criterion with their evaluation approaches across each technology stream.*

Technology streams	Technological readiness						Circularity		
	TRL	Scientific order of technology development	Commercialized product	Mature sub-technologies	Economic feasibility	Not Specified	9R strategies	Ellen Macarthur Circular Economy System diagram	Not specified
Bio		✓							✓
Construction				✓				✓	
Digital	✓						✓		
Manufacturing	✓						✓		
Material science			✓		✓				✓

As shown in the table above, it is common across most technology streams that:

- TRL is the most common evaluation tool for assessing the readiness of technologies
- 9R strategies are the most common evaluation method for assessing and describing technologies circularity

Furthermore, the following can be concluded from the table as well:

- From the perspective of Bio-technologies, following the regular scientific order of developing any technology is fairly enough for assessing its readiness. The scientific order was considered to start with a small scale system, then a bigger scale system, then a small pilot, then a big pilot and in case of industrial interest by companies then, it can be further developed for commercialization purpose. On the other hand, there was not any specific evaluation tool or method for assessing the technology circularity. Nevertheless, the importance of assessing circularity was highlighted.
- Material science technology stream perspective, consider having an economic feasible technology that can offer a commercialized product is the best evaluation indicator for assessing the readiness of technologies. Therefore, technologies are viewed from economic and commercial aspects, if the technology is economical feasible and commercially successful then it is a mature and ready. However, from the technology stream perspective there was not any specific evaluation tool or method for assessing the technology circularity. Nevertheless, the importance of assessing circularity was highlighted.
- From the construction technology stream perspective, it is argued that there are many supporting and enabling technologies to any construction technology. Therefore, assessing the whole system maturity of construction technology is based on the maturity of its sub-technologies. Furthermore, assessing the technology circularity can be performed using Ellen Macarthur Circular Economy system diagram.

7. CONCLUSIONS

In this chapter, this research is summed up and concluded. The first section summarizes the findings to the research questions and present if the objective of this study was achieved by the work conducted in this research or not. The second section discusses the contribution and the implications of this research to the existing literature while the third section discusses the contribution and implications of this research to the management of companies. Last section identifies the constraints and the validity of the data in this research. Also, suggest new areas to investigate for future research.

7.1 Meeting the Objective

This study has an objective of mapping Circular Economy technologies within Tampere University while providing the policy and decision makers with an assessment criteria that allow them to holistically assess developing Circular Economy technologies. Also, present technology catalysts that are enabling and accelerating Circular Economy. Therefore, gaining knowledge about technology catalysts that accelerate Circular Economy required conducting a multiple case study on different developing Circular Economy technologies from different technology streams. Investigating the cases was done through gathering data from interviews and literature as a secondary source of data.

There are two main research questions to this thesis. First research question was: *What is the criteria for assessing developing and sustainable Circular Economy technologies?* To answer these questions, the framework developed in this study in chapter 4.2 was used to analyze the single cases within each technology stream. The analysis covered three perspectives, circularity, sustainability and technological readiness to answer the sub-questions to the first research question:

- *How the technology advances Circular Economy and sustainability?*
- *How ready is the technology?*

The three perspectives were the main assessment criteria chosen by the researcher of this study. However, it was only used for the purpose of conducting the study and initiating a room of improvements, modification or changes. Therefore, the question was answered separately in each technology stream. In addition, a cross case analysis was conducted in chapter 6 to identify the new criteria and evaluation methods, as well as, detect the commonalities across technology streams. The findings summary is, most technology streams follow the same criteria chosen by the research but decided on different or similar evaluation method for each criterion. Therefore the assessment criteria would be:

- Circularity using the 9R strategies models
- Sustainability using LCA, profitability and improved safety
- Readiness using TRL

Nevertheless, through analysis there was recommendation on improving some of the evaluation methods, as having an extended TRL to meet the future developments of mature technologies.

Second research question was: *What are the technology catalysts that accelerate Circular Economy transition?* Answering this question required covering wide range of different technologies that act themselves as a catalyst to Circular Economy, and then analyze their answers to the same question to generate more information and detect commonalities within. This research question was answered separately in each technology stream by analyzing single cases within the technology stream in chapter 5. Then, identifying the common technology catalysts across technology streams which was conducted in the cross case analysis in chapter 6. As a summary, most technology streams argue that all type of technologies act as a catalyst and equally contribute towards accelerating Circular Economy. However, digital technologies, manufacturing technologies and bio-technologies have been highlighted as the leading technologies in accelerating the transition towards Circular economy.

Therefore, the explorative nature of this study was able to generate answers and findings in regards to the two research questions. Hence, fulfilling the objective of this study. However, the link between technology development and Circular Economy may need further investigation in order to further argue the findings of this study.

7.2 Theoretical Implications

This study focused on technology catalysts and assessment of Circular Economy technologies. Both focuses were found lacking in the existing literature where there was not much offered information regarding technology catalysts that accelerates Circular Economy nor the criteria of assessing Circular Economy technologies. Therefore, this study develops knowledge and contributes to the collective literature of this study, represented in, sustainable Circular Economy and technology development and assessment.

This study contributes to the academic literature of technology development and assessment in defining the best criteria to assess developing Circular Economy technologies in a qualitative manner. The literature does not explicitly cover any assessment criteria for Circular Economy technologies in their development phase. Rather, assess the performance of currently existing CE technologies, as argued by Sassanelli et al. (2019) that covers most of Circular Economy assessments through a literature review.

Therefore, the assessment of the cases based on their circularity, sustainability impact and technological readiness covered three different perspectives at addressing holistically Circular Economy technologies. In addition, opened a space of improvement and modifications that revealed the common assessment criteria and evaluation tools or methods for assessing Circular Economy technologies across five technology streams.

In the academic literature of sustainable Circular Economy, it was clear in many cases that, the inclusion of social benefits and considering the social dimension while developing Circular Economy technologies was absent. The analysis identifies that environmental improvements are always linked to social benefits, accordingly, impacting the social dimension. However, it is argued that ideally, the inclusion of the social dimensions separately is essential and should not be overlooked. Therefore, this study supports the literature that argues that Circular Economy does not contribute explicitly to the social dimension of sustainability (Murray et al., 2017b), and disagrees with the literature that acknowledge the importance of the inclusion of social dimension (Geissdoerfer et al., 2017). Furthermore, such finding agrees with (Sassanelli et al., 2019): that existing literature has a strong orientation towards the environmental dimension of sustainability, either alone or combined with economic one.

One of the common findings across all technology streams in this study matched with the evaluation method commonly used in assessing the environmental dimension of sustainability in the existing literature. Life Cycle Assessment (LCA) is considered the best tool for assessing the environmental impact linked to all the stages of product life as argued in the collective literature review made on assessing the performance of Circular Economy technologies (Sassanelli et al., 2019).

Moreover, the cross case analysis was beneficial in identifying other important results which contribute to the academic literature of technology development and assessment. It was found that there is a direct and strong relation between technology circularity and technology readiness. Most technologies with high circularity has a low readiness level which indicate that Circular Economy technologies with reduce or reuse strategies require a lot of developments or still immature compared to recycling technologies. This result contradicts to the arguments made in literature that the high strategies of Circularity as reduce and reuse are more effective in increasing material efficiency compared to recycling (Reh, 2013; Stahel, 2013). Which indicates that there is a gap between what the technology developers in the field of Circular Economy are focusing on and what is convenient for an effective and sustainable economic growth when it comes to resource management and material efficiency.

7.3 Managerial Implications

The transition towards Circular Economy and the new standards of sustainability that are set to be met, require the existence of different tools that can assist managers and company key players in decision making towards any developing Circular Economy technology. Therefore, the assessment criteria developed through the cross case analysis in this study will help the managers to form an idea about any developing technology as it covers technology circularity, sustainability and readiness, and upon which can be used as a tool to assist them in their decisions. In addition, it can be deployed within the R&D department to be used as a reference when developing any Circular Economy technology.

On the other hand, the developed assessment criteria can be used by decision and policy makers to determine on Circular Economy technologies in their development phase. The decision can help them decide to further proceed in developing the technologies that can fulfill their designed road map and strategies towards an effective and sustainable economic growth.

The findings of this study discussed technology catalysts that accelerate Circular Economy, as well as, the assessment criteria of Circular Economy technologies. The findings indicate that technologies with high circularity appear to be low on their readiness. On the other hand, technologies with low circularity have high readiness. Nevertheless, reduce and reuse strategies of circularity are considered to be very effective in terms of profitability and resources efficiency. Therefore, managers should consider their development plans to be focused more on technologies with high circularity.

The confusion in theory of whether Circular Economy contributes to the social dimension of sustainability or not appears to be an issue that needs to be tackled while developing technologies. In this study, the Circular Economy contribution to sustainability appears to be limited only two Economic and Environmental dimensions of sustainability. Therefore, in the beginning of technology development, managers should be in a close contact with the technology developers to make sure that technology developers can view the business perspective when developing their technologies. Also, make sure that their focus is not only directed to economic and environmental benefits, but social benefits as well. In addition, it was surprising to identify through cases analysis that the poor inclusion of social dimension is blamed on the key players in the field of Circular Economy, or in other situation, there would be a claim of social benefits based on the environmental improvements done by the developing technology. Therefore, managers are supposed to consider the differences between the environmental and social benefits.

7.4 Limitations of this Study

To ensure the validity of this study, a framework for technology analysis was created by conducting a literature review that covered all the theoretical areas under research. However, the framework included some assessment tools that was chosen by the researcher as a reference to conduct the study which shows limitations on the effectiveness of the selected tools. Moreover, there is a possibility of missing important details of the theoretical research areas which shows some limitations to this study validation.

Furthermore, the technologies mapped in this study covers different technological fields that made it hard for the author in many cases to understand the technicalities behind the technology described which may poses some limitations on the reliability of the data gathered. However, the interviewees were able to review the study to ensure a clear and correct description to their technologies.

The framework developed was conducted on the purposed of assessing and analyzing the cases in a qualitative approach. Also, the framework used to analyze the cases in the same pattern and sequence in order to later be able to conduct a cross case analysis to the selected cases. At the same time the selected cases were based on purposive sampling strategy to serve the objective of the study. Therefore, using case study as a research design, the case selection strategy and the patterned approach of analyzing cases may implicate the generalizability of this study. Nevertheless, the findings of this study can be considered as the beginning for further in-depth studies in assessing developing and sustainable Circular Economy technologies.

Using TRL tool in assessing technology readiness had a limiting aspect of not covering the technology dynamics over time. It was hard to realize how technological changes over time may affect technology readiness and overview. Thus, the framework used for assessing the selected cases in this study seemed to have an instantaneous overview to the technology mapped.

The identified main criteria that was a result of conducting this study for assessing developing Circular Economy technologies was similar to the predetermined criteria used as a reference for assessing the selected cases. That may indicate that interviewees were influenced and biased towards the predetermined criteria. However, the evaluation and assessment methods for each criterion was varying and changing from technology stream to another when compared to the original predetermined assessment tools used in this study.

This study was conducted on 7 different cases that covered different technology streams and were not stream focused. The results of this study were somehow generalized since they were based on the 7 cases analysis to determine on the assessment criteria of developing and sustainable Circular Economy technologies and technology catalysts. Therefore, it not evident that the findings of this study are the best criteria for assessing CE technologies or determine upon which technology streams act as catalysts for accelerating Circular Economy transition.

7.5 Future Research

This thesis focused on studying seven Circular Economy technologies and tried to cover as many technology streams as possible. However, there is still a big room of improvement and development in studying the most convenient assessment criteria for each technology streams by investigating more technologies for each technology stream and apply more intensive analysis.

Moreover, this study claims that Circular Economy lacks the inclusion of social dimension based on assessing the dimensions from one indicator which is future employment opportunities. However, researching, studying and determining on more social indicators to be used in assessing the selected cases can add more in-depth to study and may have a change effect on the existing finding.

The assessment of the selected cases was qualitative. However, it was clear the importance of different quantitative tools in assessing the technologies in terms of their sustainability. Especially when it comes to the economic and environmental dimensions.

Therefore, inclusion of quantitative tools to the study will add another perspective to the assessment of technologies, though it will require expertise and knowledge on using those tools and will consume more time.

REFERENCES

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Davila Delgado, M., Bilal, M., & Bello, S. A. (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling*, *129*, 175–186. https://doi.org/10.1016/J.RESCONREC.2017.10.026

Akinade, O. O., Oyedele, L. O., Ajayi, S. O., Bilal, M., Alaka, H. A., Owolabi, H. A., … Kadiri, K. O. (2017). Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. *Waste Management*, *60*, 3–13. https://doi.org/10.1016/J.WASMAN.2016.08.017

Angelis-Dimakis, A., Alexandratou, A., & Balzarini, A. (2016). Value chain upgrading in a textile dyeing industry. *Journal of Cleaner Production*, *138*, 237–247. https://doi.org/10.1016/J.JCLEPRO.2016.02.137

Assefa, G. Ã., & Frostell, B. (2007). Social sustainability and social acceptance in technology assessment : A case study of energy technologies. *Technology in Society*, *29*, 63–78. https://doi.org/10.1016/j.techsoc.2006.10.007

Banta, D. (2009). What is technology assessment ? *International Journal of Technology Assessment in Health Care*, *25*, 7–9. https://doi.org/10.1017/S0266462309090333

Bastianoni, S., & Marchettini, N. (1997). Emergy/exergy ratio as a measure of the level of organization of systems. *Ecological Modelling*, *99*(1), 33–40. https://doi.org/10.1016/S0304-3800(96)01920-5

Bechtel, N., Bechtel, N., Bojko, R., & Völkel, R. (2013). Be in the Loop : Circular Economy & Strategic Sustainable Development Be in the Loop : Circular Economy & Strategic Sustainable Development, *Independen*, 58. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:bth-1942

Biganzoli, L., Rigamonti, L., & Grosso, M. (2018). Intermediate Bulk Containers Re-use in the Circular Economy: An LCA Evaluation. *Procedia CIRP*, *69*, 827–832. https://doi.org/10.1016/J.PROCIR.2017.11.010

Bonciu, F. (2014). The European Economy : from a linear to a circular economy. Rom. J. Eur. Aff. 14. Retrieved from http://rjea.ier.ro/sites/rjea.ier.ro/files/articole/RJEA_2014_vol14_no4_art5.pdf

Braungart, M., McDonough, W., & Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design. *Journal of Cleaner Production*, *15*(13–14), 1337–1348. https://doi.org/10.1016/J.JCLEPRO.2006.08.003

Brissaud, D. (2019). Circular economy assessment tool for end of life product recovery strategies. *Journal of Remanufacturing*, (3), 169–185. Retrieved from https://doi.org/10.1007/s13243-018-0064-8

Bryman, A., & Bell, E. (2015). *Business Research Methods* (Fourth). Oxford : Oxford University Press 2015.

Clausing, D., & Holmes, M. (2010). Technology Readiness. *Research-Technology Management*, *53*(4), 52–59. Retrieved from https://doi.org/10.1080/08956308.2010.11657640

Drucker, P. F. (2005). Managing oneself. *Harvard Business Review*, *83*(1), 100–109. https://doi.org/10.4324/9781315250601-24

Duchin, F., & Levine, S. H. (2008). Industrial Ecology. *Encyclopedia of Ecology*, 1968–1975. https://doi.org/10.1016/B978-008045405-4.00627-3

Eastwood, M. D., & Haapala, K. R. (2015). A unit process model based methodology to assist product sustainability assessment during design for manufacturing. *Journal of Cleaner Production*, *108*, 54–64. https://doi.org/10.1016/J.JCLEPRO.2015.08.105

Expósito, A., & Velasco, F. (2018). Municipal solid-waste recycling market and the European 2020 Horizon Strategy: A regional efficiency analysis in Spain. *Journal of Cleaner Production*, *172*, 938–948. https://doi.org/10.1016/J.JCLEPRO.2017.10.221

Farrell, M. J. (1957). The Measurement of Productive Efficiency. *Journal of the Royal Statistical Society: Series A (General)*, *120*(3), 253–281. https://doi.org/10.2307/2343100

Favi, C., Germani, M., Luzi, A., Mandolini, M., & Marconi, M. (2017). A design for EoL approach and metrics to favour closed-loop scenarios for products. *International Journal of Sustainable Engineering*, *10*(3), 136–146. https://doi.org/10.1080/19397038.2016.1270369

Fern, E., Gonzalo, M., & Soto-o, D. (2019). Operational principles of circular economy for sustainable development : Linking theory and practice. *Journal of Cleaner Production*, *214*, 952–961. https://doi.org/10.1016/j.jclepro.2018.12.271

Fonseca, L. M., Domingues, P., Martins, F. F., & Zimon, D. (2018). Assessment of Circular Economy within Portuguese Organizations. *Sustainability*, *10(7)*, 2521. https://doi.org/10.3390/su10072521

Franklin-Johnson, E., Figge, F., & Canning, L. (2016). Resource duration as a managerial indicator for Circular Economy performance. *Journal of Cleaner Production*, *133*, 589–598. https://doi.org/10.1016/J.JCLEPRO.2016.05.023

Fregonara, E., Giordano, R., Ferrando, D. G., & Pattono, S. (2017). Economic-Environmental Indicators to Support Investment Decisions: A Focus on the Buildings' End-of-Life Stage. *Buildings*, *7*(3), 65. https://doi.org/10.3390/buildings7030065

Gbededo, M. A., Liyanage, K., & Garza-Reyes, J. A. (2018). Towards a Life Cycle Sustainability Analysis: A systematic review of approaches to sustainable manufacturing. *Journal of Cleaner Production*, *184*, 1002–1015. https://doi.org/10.1016/J.JCLEPRO.2018.02.310

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Jan, E. (2017). The Circular Economy e A new sustainability paradigm ? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy : the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research : interviews and focus groups. *British Dental Journal*, *204*(6), 291. https://doi.org/10.1038/bdj.2008.192

Grimaud, G., Perry, N., & Laratte, B. (2017). Decision Support Methodology for Designing Sustainable Recycling Process Based on ETV Standards. *Procedia Manufacturing*, *7*, 72–78. https://doi.org/10.1016/J.PROMFG.2016.12.020

Grubler, A. (1998). *Technology and Global Change*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781316036471

Hadzic, A., Voca, N., & Golubic, S. (2018). Life-cycle assessment of solid-waste management in city of Zagreb, Croatia. *Journal of Material Cycles and Waste Management*, *20*(2), 1286–1298. https://doi.org/10.1007/s10163-017-0693-2

Haupt, M., & Hellweg, S. (2019). Measuring the environmental sustainability of a circular economy. *Environmental and Sustainability Indicators*. https://doi.org/10.1016/j.indic.2019.100005

Henriksen, A. D. P. (1997). A technology assessment primer for management of technology. *International Journal of Technology Management*, *13*(5–6), 615–638. https://doi.org/10.1504/ijtm.1997.001681

Hobson, K. (2016). Closing the loop or squaring the circle ? Locating generative spaces for the circular economy. *Progress in Human Geography*, *40*(1), 88–104. https://doi.org/10.1177/0309132514566342

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., & De Meester, S. (2017). Performance indicators for a circular economy: A case study on post-industrial plastic waste. *Resources, Conservation and Recycling*, *120*, 46–54. https://doi.org/10.1016/J.RESCONREC.2017.01.013

Iacovidou, E., Millward-hopkins, J., Busch, J., Purnell, P., Velis, C. A., Hahladakis, J. N., … Brown, A. (2017). A pathway to circular economy : Developing a conceptual framework for complex value assessment of resources recovered from waste. *Journal of Cleaner Production*, *168*, 1279–1288. https://doi.org/10.1016/j.jclepro.2017.09.002

Iakovou, E., Moussiopoulos, N., Xanthopoulos, A., Achillas, C., Michailidis, N., Chatzipanagioti, M., … Kikis, V. (2009). A methodological framework for end-of-life management of electronic products. *Resources, Conservation and Recycling*, *53*(6), 329–339. https://doi.org/10.1016/J.RESCONREC.2009.02.001

Issa, I. I., Pigosso, D. C. A., McAloone, T. C., & Rozenfeld, H. (2015). Leading product-related environmental performance indicators: a selection guide and database. *Journal of Cleaner Production*, *108*, 321–330. https://doi.org/10.1016/J.JCLEPRO.2015.06.088

Jamali-Zghal, N., Lacarrière, B., & Le Corre, O. (2015). Metallurgical recycling processes: Sustainability ratios and environmental performance assessment. *Resources, Conservation and Recycling*, *97*, 66–75.

https://doi.org/10.1016/J.RESCONREC.2015.02.010

Jesus, A. De, & Mendonça, S. (2018). Lost in Transition ? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. *Ecological Economics*, *145*(August 2017), 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001

Kajikawa, Y. (2014). Multi-level perspectives with technology readiness measures for aviation innovation. *Sustainability Science*, *8*(1), 87–101. https://doi.org/10.1007/s11625-012-0187-z

Kazancoglu, Y., Kazancoglu, I., & Sagnak, M. (2018). A new holistic conceptual framework for green supply chain management performance assessment based on circular economy. *Journal of Cleaner Production*, *195*, 1282–1299. https://doi.org/10.1016/J.JCLEPRO.2018.06.015

Kinnunen, H., & Kaksonen, A. H. (2019). Towards circular economy in mining : Opportunities and bottlenecks for tailings valorization. *Journal of Cleaner Production*, *228*, 153–160. https://doi.org/10.1016/j.jclepro.2019.04.171

Kirchherr, J., Piscicelli, L., Bour, R., Huibrechtse-truijens, A., Hekkert, M., Kostense-smit, E., & Muller, J. (2018). Barriers to the Circular Economy : Evidence From the European Union (EU). *Ecological Economics*, *150*(April), 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy : An analysis of 114 de fi nitions. *Resources , Conservation & Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Korhonen, J., Nuur, C., Feldmann, A., & Eshetu, S. (2018). Circular economy as an essentially contested concept. *Journal of Cleaner Production*, *175*, 544–552. https://doi.org/10.1016/j.jclepro.2017.12.111

Larsson, A., Culley, S. J., & Larsson, T. C. (2009). A methodology for evaluating Technology Readiness during product development. *In International Conference on Engineering Design: 24/08/2009-27/08/2009 (Vol. 3, Pp. 157-168). Design Research Society*.

Laso, J., García-Herrero, I., Margallo, M., Vázquez-Rowe, I., Fullana, P., Bala, A., … Aldaco, R. (2018). Finding an economic and environmental balance in value chains based on circular economy thinking: An eco-efficiency methodology applied to the fish canning industry. *Resources, Conservation and Recycling*, *133*, 428–437. https://doi.org/10.1016/J.RESCONREC.2018.02.004

Lee, H. M., Lu, W. F., & Song, B. (2014). A framework for assessing product End-Of-Life performance: reviewing the state of the art and proposing an innovative approach using an End-of-Life Index. *Journal of Cleaner Production*, *66*, 355–371. https://doi.org/10.1016/J.JCLEPRO.2013.11.001

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation : a comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lowe, E. A., & Evans, L. K. (1995). Industrial ecology and industrial ecosystems. *Journal of Cleaner Production*, *3*(1–2), 47–53. https://doi.org/10.1016/0959-6526(95)00045-G

Lozano, R. (2008). Envisioning sustainability three-dimensionally. *Journal of Cleaner Production*, *16*, 1838–1846. https://doi.org/10.1016/j.jclepro.2008.02.008

Luo, X., & Hu, R. (2018). Chip packaging: Encapsulation of nitride LEDs. *Nitride Semiconductor Light-Emitting Diodes (LEDs)*, 491–528. https://doi.org/10.1016/B978-0-08-101942-9.00015-0

Mankins, J. C. (1995). Technology readiness levels. *White Paper*, *April*, *6*.

Mankins, J. C. (2002). Approaches to strategic research and technology (R&T) analysis and road mapping. *Acta Astronautica*, *51*(1–9), 3–21.

Mankins, J. C. (2009). Technology readiness assessments : A retrospective. *Acta Astronautica*, *65*(9–10), 1216–1223. https://doi.org/10.1016/j.actaastro.2009.03.058

Mardani, A., Zavadskas, E. K., Streimikiene, D., Jusoh, A., & Khoshnoudi, M. (2017). A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency. *Renewable and Sustainable Energy Reviews*, *70*, 1298–1322. https://doi.org/10.1016/J.RSER.2016.12.030

Martin, M., Wetterlund, E., Hackl, R., Holmgren, K. M., & Peck, P. (2017). Assessing the aggregated environmental benefits from by-product and utility synergies in the Swedish biofuel industry. *Biofuels*, 1–16. https://doi.org/10.1080/17597269.2017.1387752

Mitchell, J. A. (2007). Measuring the Maturity of a Technology : Guidance on Assigning a TRL (No. SAND2007-6733). *Sandia National Laboratories*.

Morris, T., & Wood, S. (1991). Testing the Survey Method: Continuity and Change in British Industrial Relations. *Work, Employment & Society*, *5*(2), 259–282.

Motevali Haghighi, S., Torabi, S. A., & Ghasemi, R. (2016). An integrated approach for performance evaluation in sustainable supply chain networks (with a case study). *Journal of Cleaner Production*, *137*, 579–597. https://doi.org/10.1016/J.JCLEPRO.2016.07.119

Murray, A., Skene, K., Haynes, K., Murray, A., Skene, K., & Haynes, K. (2017a). The Circular Economy : An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369–380. https://doi.org/10.1007/s10551-015-2693-2

Murray, A., Skene, K., Haynes, K., Murray, A., Skene, K., & Haynes, K. (2017b). The Circular Economy : An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369–380. https://doi.org/10.1007/s10551-015-2693-2

Musango, J. K., & Brent, A. C. (2011). Energy for Sustainable Development A conceptual framework for energy technology sustainability assessment ☆. *Energy for Sustainable Development*, *15*(1), 84–91. https://doi.org/10.1016/j.esd.2010.10.005

Musango, J. K., Brent, A. C., Amigun, B., Pretorius, L., & Hans, M. (2012). A system dynamics approach to technology sustainability assessment : The case of biodiesel developments in South Africa. *Technovation*, *32*(11), 639–651. https://doi.org/10.1016/j.technovation.2012.06.003

Nakajima, N. (2000). A Vision of Industrial Ecology : State-of-the-Art Practices for a Circular and Service-Based Economy. *Bulletin of Science, Technology & Society*, *20*(1), 54–69.

Ng, K. S., & Martinez Hernandez, E. (2016). A systematic framework for energetic, environmental and economic (3E) assessment and design of polygeneration systems. *Chemical Engineering Research and Design*, *106*, 1–25. https://doi.org/10.1016/J.CHERD.2015.11.017

Niero, M., & Kalbar, P. P. (2019). Resources , Conservation & Recycling Coupling material circularity indicators and life cycle based indicators : A proposal to advance the assessment of circular economy strategies at the product level. *Resources, Conservation & Recycling*, *140*(July 2018), 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002

OECD. (2009). Sustainable Manufacturing and Eco-Innovation.

Oliveira, F. R. de, França, S. L. B., & Rangel, L. A. D. (2018). Challenges and opportunities in a circular economy for a local productive arrangement of furniture in Brazil. *Resources, Conservation and Recycling*, *135*, 202–209. https://doi.org/10.1016/J.RESCONREC.2017.10.031

Olugu, E. U., & Wong, K. Y. (2012). An expert fuzzy rule-based system for closed-loop supply chain performance assessment in the automotive industry. *Expert Systems with Applications*, *39*(1), 375–384. https://doi.org/10.1016/J.ESWA.2011.07.026

Pagoropoulos, A., Pigosso, D. C. A., & Mcaloone, T. C. (2017). The emergent role of digital technologies in the Circular Economy : A review. *Procedia CIRP*, *64*, 19–24. https://doi.org/10.1016/j.procir.2017.02.047

Pagotto, M., & Halog, A. (2016). Towards a Circular Economy in Australian Agri-food Industry: An Application of Input-Output Oriented Approaches for Analyzing Resource Efficiency and Competitiveness Potential. *Journal of Industrial Ecology*, *20*(5), 1176–1186. https://doi.org/10.1111/jiec.12373

Pan, H., Zhang, X., Wang, Y., Qi, Y., Wu, J., Lin, L., … Zhang, Y. (2016). Emergy evaluation of an industrial park in Sichuan Province, China: A modified emergy approach and its application. *Journal of Cleaner Production*, *135*, 105–118. https://doi.org/10.1016/J.JCLEPRO.2016.06.102

Park, Y. S., Egilmez, G., & Kucukvar, M. (2016). Emergy and end-point impact assessment of agricultural and food production in the United States: A supply chain-linked Ecologically-based Life Cycle Assessment. *Ecological Indicators*, *62*, 117–137. https://doi.org/10.1016/J.ECOLIND.2015.11.045

Patton, M. Q. (2002). *Qualitative Research & Evaluation Methods* (Third). Thousand Oaks (CA) : Sage cop. 2002.

Pavan, M., & Todeschini, R. (2009). Multicriteria Decision-Making Methods. *Comprehensive Chemometrics*, 591–629. https://doi.org/10.1016/B978-044452701-1.00038-7

Petit, G., Sablayrolles, C., & Yannou-Le Bris, G. (2018). Combining eco-social and environmental indicators to assess the sustainability performance of a food value chain: A case study. *Journal of Cleaner Production*, *191*, 135–143.

https://doi.org/10.1016/J.JCLEPRO.2018.04.156

Pheifer, A. A. G. (2017). Barriers & enables to circular business models. *White Paper. Brielle*, (April).

Pincetl, S. (2012). A living city: using urban metabolism analysis to view cities as life forms. *Metropolitan Sustainability*, 3–25. https://doi.org/10.1533/9780857096463.1.3

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2016). Circular Economy: Measuring innovation in the product chain - Policy report. *PBL Netherlands Environmental Assessment Agency*, (2544), 42.

Preston, F. (2012). *A Global Redesign ? Shaping the Circular Economy. Briefing paper. London. Chatham House.*

Reh, L. (2013). Process engineering in circular economy. *Particuology*, *11*(2), 119–133. https://doi.org/10.1016/J.PARTIC.2012.11.001

Reuter, M. A. (2016). Digitalizing the Circular Economy. *Metallurgical and Materials Transactions B*, *47*(6), 3194–3220.

Rybicka, J., Tiwari, A., & Leeke, G. A. (2016). Technology readiness level assessment of composites recycling technologies. *Journal of Cleaner Production*, *112*, 1001–1012. https://doi.org/10.1016/j.jclepro.2015.08.104

Santini, A., Herrmann, C., Passarini, F., Vassura, I., Luger, T., & Morselli, L. (2010). Assessment of Ecodesign potential in reaching new recycling targets. *Resources, Conservation and Recycling*, *54*(12), 1128–1134. https://doi.org/10.1016/J.RESCONREC.2010.03.006

Sariatli, F. (2017). Linear Economy versus Circular Economy : A comparative and analyzer study for Optimization of Economy for Sustainability. *Visegrad Journal on Bioeconomy and Sustainable Development*, (7), 31–34. https://doi.org/10.1515/vjbsd-2017-0005

Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods : A systematic literature review. *Journal of Cleaner Production*, *229*, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019

Saunders, M., Lewis, P., & Adrian, T. (2009). *Research methods for business students* (5th editio). Harlow: Prentice Hall.

Sauvé, S., Bernard, S., & Sloan, P. (2016). Environmental sciences , sustainable development and circular economy : Alternative concepts for trans-disciplinary research. *Environmental Development*, *17*, 48–56. https://doi.org/10.1016/j.envdev.2015.09.002

Sciubba, E., & Ulgiati, S. (2005). Emergy and exergy analyses: Complementary methods or irreducible ideological options? *Energy*, *30*(10), 1953–1988. https://doi.org/10.1016/J.ENERGY.2004.08.003

Seay, J. R., & You, F. (2016). Biomass supply, demand, and markets. *Biomass Supply Chains for Bioenergy and Biorefining*, 85–100. https://doi.org/10.1016/B978-1-78242-366-9.00004-6

Sénéchal, O. (2017). Research directions for integrating the triple bottom line in maintenance dashboards. *Journal of Cleaner Production*, *142*, 331–342. https://doi.org/10.1016/J.JCLEPRO.2016.07.132

Shahbazi, S., Wiktorsson, M., Kurdve, M., Christina, J., & Bjelkemyr, M. (2016). Material ef fi ciency in manufacturing : swedish evidence on potential , barriers and strategies. *Journal of Cleaner Production*, *127*, 438–450. https://doi.org/10.1016/j.jclepro.2016.03.143

Shen, L., Olfat, L., Govindan, K., Khodaverdi, R., & Diabat, A. (2013). A fuzzy multi criteria approach for evaluating green supplier's performance in green supply chain with linguistic preferences. *Resources, Conservation and Recycling*, *74*, 170–179. https://doi.org/10.1016/J.RESCONREC.2012.09.006

Srai, J. S., Kumar, M., Graham, G., & Phillips, W. (2016). Distributed manufacturing: scope, challenges and opportunities. *International Journal of Production Research*, 6917–6935. https://doi.org/10.1080/00207543.2016.1192302

Stahel, W. R. (2013). Policy for material efficiency - Sustainable taxation as a departure from the throwaway society. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(1986). https://doi.org/10.1098/rsta.2011.0567

Straub, J. (2015). In search of technology readiness level (TRL) 10. *Aerospace Science and Technology*, *46*, 312–320. https://doi.org/10.1016/j.ast.2015.07.007

Su, B., Heshmati, A., Geng, Y., & Yu, X. (2013). A review of the circular economy in China : moving from rhetoric to implementation. *Journal of Cleaner Production*, *42*, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020

Suárez-Eiroa, B., Fernández, E., Méndez-Martínez, G., & Soto-Oñate, D. (2019). Operational principles of circular economy for sustainable development: Linking theory and practice. *Journal of Cleaner Production*, *214*, 952–961. https://doi.org/10.1016/J.JCLEPRO.2018.12.271

TL9000. (2013). Design for X (DFx) Guidance Document. Retrieved from https://tl9000.org/handbooks/documents/guidance_document_design_for_XDFx_v1.3.pdf

Toxopeus, M. E., De Koeijer, B. L. A., & Meij, A. G. G. H. (2015). Cradle to cradle: Effective vision vs. Efficient practice? *Procedia CIRP*, *29*, 384–389. https://doi.org/10.1016/j.procir.2015.02.068

Tran, T. A., & Daim, T. (2008). A taxonomic review of methods and tools applied in technology assessment. *Technological Forecasting and Social Change*, *75*(9), 1396–1405. https://doi.org/10.1016/J.TECHFORE.2008.04.004

Velis, C. A., & Vrancken, K. C. (2015). Which material ownership and responsibility in a circular economy ? *Waste Management & Research*, *33*(9), 773–774. https://doi.org/10.1177/0734242X15599305

Voskamp, I. M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J. P., & Rijnaarts, H. H. M. (2017). Enhanced Performance of the Eurostat Method for Comprehensive Assessment of Urban Metabolism: A Material Flow Analysis of Amsterdam. *Journal of Industrial Ecology*, *21*(4), 887–902. https://doi.org/10.1111/jiec.12461

Weaver, P., Jansen, L., van Grootveld, G., van Spiegel, E., & Vergragt, P. (2017). *Sustainable Technology Development*. Sustainable Technology Development. Routledge. https://doi.org/10.4324/9781351283243

Wen, Z., & Meng, X. (2015). Quantitative assessment of industrial symbiosis for the promotion of circular economy : a case study of the printed circuit boards industry in China ' s Suzhou New District. *Journal of Cleaner Production*, *90*, 211–219. https://doi.org/10.1016/j.jclepro.2014.03.041

Wibowo, S., & Grandhi, S. (2017). Performance evaluation of recoverable end-of-life products in the reverse supply chain. *Proceedings - 16th IEEE/ACIS International Conference on Computer and Information Science, ICIS 2017*, 215–220. https://doi.org/10.1109/ICIS.2017.7959996

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*, 825–833. https://doi.org/10.1016/J.RSER.2016.09.123

Xu, Y., Zhang, L., Yeh, C.-H., & Liu, Y. (2018). Evaluating WEEE recycling innovation strategies with interacting sustainability-related criteria. *Journal of Cleaner Production*, *190*, 618–629. https://doi.org/10.1016/J.JCLEPRO.2018.04.078

Yin, R. K. (2014). *Case Study Research : Design and Methods* (Fifth). Los Angeles: SAGE.

Zengwei Yuan, Jun Bi, Y. M. (2006). The Circular Economy: a new development Strategy in China. *Journal of Industrial Ecology*, *10*(1–2), 4–8. Retrieved from https://doi.org/10.1162/108819806775545321

Zhang, P., & Zhang, P. (2010). Industrial control system simulation routines. *Advanced Industrial Control Technology*, 781–810. https://doi.org/10.1016/B978-1-4377-7807-6.10019-1

APPENDIX A: THE INTERVIEW STRUCTURE

Introduction part

First, start with a brief introduction about myself, and break the ice through a little discussion then introduce my research topic. Afterwards explain what the interview today will be covering as follow:

- The latest Circular Economy technology or technologies you are developing
- Learn about your experience of assessing Circular Economy technologies from technological readiness perspective
- And from sustainability perspective as well

Then, explain how the interviewee input will be so valuable for fulfilling the research questions and also developing a new assessment tool. Then, move into the question part.

Technology mapping part:

1. In your opinion, what type of technologies can act as a catalyst for enabling circular economy, and why? -Catalysts to be defined as accelerator and advancing for CE-
2. Can you tell me more about the technology developed/undergoing development?
   - Does it have a name?
   - What was your motivation for developing this particular CE technology?
   - What is its nature? If there is no clear answer then: do you consider it as a hardware, software, a chemical formula or what?
   - Is it a standalone technology or part of something else, can you tell me more about it?
   - What does the technology do in a lab environment? i.e. 9Rs
   - How do you visualize a completely developed and mature form of this technology?
   - When did you start researching and developing this technology? What was the path that led to developing this technology, were you triggered by studying/researching other technologies?
3. How the technology does advances circular economy and general sustainability?
   - How does it improve resource efficiency?
   - How does it improve environmental sustainability?
   - How does it improve social sustainability?
4. If you want this technology to be widely spread then, where it can be spread? And who can use it?

Assessment part:

1. In your opinion, what is the best criteria for assessing CE technologies?

2. What were the aspects you take into consideration to assess the technology readiness?
3. Should the social contribution of the technology be assessed as well? How?
4. In your opinion what would you add or change to the figure in order to assess CE technologies in particular and their readiness to improve resource efficiency and sustainability?
5. Or would you use another tool or method for assessing? Which tool and why?
6. Where would you place your technology readiness on the TRL figure?

Closing and snowballing:

I am done with all the question related to my research but at the moment please feel free to add anything else to the topic or express any comments. Afterwards, if you know any other researcher who is involved with CE related technologies please let me know. Then close with, thank you so much for your time, the chance of interviewing you and for your valuable information.