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Circular Economy and Reverse Logistics : An End-of-life Resource Recovery Decision-making Assistant

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THESIS

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Presented by

Yohannes Admassu Alamerew

Thesis Director : **Daniel Brissaud**

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in the doctorial school of **IMEP-2**

Circular Economy and Reverse Logistics: An End-of-life Resource Recovery Decision Making Assistant

Thesis publicly defended on **June 3, 2020,** before the jury composed of :

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THÈSE

Pour obtenir le grade de

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Spécialité : **GI : Génie Industriel : Conception et Production**

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Preface

This Ph.D. thesis started in November 2016, at Grenoble Institute of Engineering, as part of the European Circular Economy Innovative Training Network (Circ€uit). The Circ€uit project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 721909. The project partners consist of:

http://www.itncircuit.eu/

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Abstract

The Circular Economy (CE) is perceived as one of the main instruments to achieve sustainable development goals (SDGs). Even though companies are showing increasing interest to transform their businesses towards a circular economy model, they are experiencing difficulties due to a lack of tools and indicators to assess circularity strategies and to measure the performance of reverse logistics systems. There are limited studies on the assessment of CE strategies of a product, supply chain, and service at the micro-level. The main objective of this Ph.D. thesis is to propose tools and indicators to evaluate circularity strategies and measure the performance of reverse logistics.

The study begins with identifying decision-making factors and indicators. Afterward, modelling of the reverse logistics system is accomplished to understand the complex interaction among decision variables. Then circular economy assessment tools and indicators have been developed to assist companies in the decision-making process. A case study with multiple companies is performed to examine, validate and demonstrate the applicability of the proposed tools and indicators.

The main contributions of this Ph.D. thesis include:

- a taxonomy of decision-making factors and circular economy indicators for reverse logistics,
- a system dynamics model to represent the complex system of reverse logistics system in order to understand the interaction among decision variables,
- a circular economy indicator for reverse logistics to measure the performance of products within the reverse logistics system,
- a circular economy tool to evaluate the potential environmental and economic benefits of transforming a firm into a circular business,
- a circular economy assessment tool to evaluate circularity strategies of end-of-life products, and
- a systematic analysis of the interplay among the building blocks of CE including reverse supply chain, business model, product and service design, product and service use, policy and end-of-life (EoL) recovery in circular economy research.

The findings of this Ph.D. work assist industrial practitioners in decision-making on the management of post-used products. The contributions of this Ph.D. thesis deemed to support the transition towards a more sustainable circular economy.

Résumé

L'économie circulaire (EC) est considérée comme l'une des principales stratégies permettant d'atteindre les objectifs de développement durable (ODD). Cependant, les entreprises rencontrent des difficultés dans la mise en place de l'économie circulaire. Elles doivent faire face à des défis au niveau des modèles économiques, la mise en place d'outils et indicateurs. Ces derniers visent à évaluer les stratégies de circularité et de mesurer les performances des systèmes de logistique inverse. Il existe peu d'études sur l'évaluation de ces stratégies au niveau d'un produit, d'une chaîne d'approvisionnement ou d'un service. L'objectif principal de cette thèse de doctorat consiste à proposer des outils permettant d'évaluer les stratégies de circularité et de mesurer les performances du processus de logistique inverse.

L'étude commence par l'identification des facteurs et des indicateurs de circularité nécessaires pour la prise de décision. Ensuite, la modélisation du système de logistique inverse est réalisée pour comprendre l'interaction complexe entre les variables de décision. Ainsi, outils et des indicateurs d'évaluation de l'économie circulaire ont été mis au point pour aider les entreprises à prendre des décisions. Enfin, une étude de cas avec plusieurs sociétés est réalisée pour examiner, valider et démontrer la pertienence du modèle, des outils et des indicateurs proposés.

Les principales contributions de cette thèse incluent :

- une taxonomie des variables décisionnelles et des indicateurs d'économie circulaire pour la logistique inverse,
- un modèle de dynamique de systèmes pour tenir compte de la complexité du processus de logistique inverse afin de comprendre l'interaction entre les variables de décision en fin de vie,
- un indicateur d'économie circulaire pour la logistique inverse qui mesure la performance des produits dans le système de logistique inverse,
- des outils méthode d'évaluation de l'économie circulaire pour évaluer les avantages environnementaux et économiques potentiels de la transformation des activités d'une entreprise vers l'économie circulaire,
- un outil d'évaluation de l'économie circulaire pour évaluer les stratégies de circularité des produits en fin de vie, et
- une analyse systématique de l'interaction entre diverses disciplines, y compris la chaîne d'approvisionnement inverse et le modèle économique de l'entreprise ; la conception de produits et services ; l'utilisation des produits et services ; les stratégies des processus de traitements de fin de vie dans le domaine de la recherche sur l'économie circulaire.

Les résultats de cette thèse aident les industriels à prendre des décisions en matière de gestion des produits après leur phase d'utilisation. Les contributions de cette étude soutiennent la transition vers des stratégies d'économie circulaire plus durables.

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Abbreviations

CE: Circular Economy

Circ€uit: European Circular Economy Innovative Training Network

EMF: Ellen MacArthur Foundation

EoL: End-of-life

EPR: Extended Producer Responsibility

EU: European Union

EVBs: Electric Vehicle Batteries

ICoR: International Conference on Remanufacturing

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

LCE: Life Cycle Engineering

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

OEMs: Original Equipment Manufacturers

PRM: Product Recovery Management

PRS: Product Recovery Strategy

PRO: Product Recovery Options

RG: Research Gap

RO: Research Objective

RQ: Research Question

RL: Reverse Logistics

SDGs: Sustainable Development Goals

SPC: Sustainable Production and Consumption

UNEP: United Nations Environmental Programme

UN DESA: United Nations Department of Economic and Social Affairs

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1. Introduction

This chapter introduces the Ph.D. thesis. Section 1.1 presents the concept of circular economy. Section 1.2 explains the motivation that leads to the proposition of this PhD thesis. The research objectives and research questions are formulated in Section 1.3. The research foundation of this research is presented in Section 1.4. Section 1.5 describes the research approach used for this study. The positioning of the thesis and structure of the manuscript is described in Section 1.6 and Section 1.7 respectively.

1.1. Towards building a "New Economy": The circular economy

An expanding population coupled with the growing economic growth endangered the consumption of all finite resources on our planet. The world's population continues to grow at an alarming rate, expected to hit 11 billion in 2100. During the 20th century alone, the world's population grows dramatically jumping from 1 billion in 1900 to more than 6 billion in 2000 (Haub, 1995). Today, the United Nations Department of Economic and Social Affairs (UN DESA) estimates that the world's population numbered nearly 7.7 billion in 2019 and is expected to increase further to 8.5 billion in 2030 and 9.7 billion in 2050, and 10.9 billion in 2100 (UN DESA, 2019). As a result of our "throwaway society", natural resources are being depleted at an accelerating rate (Fig. 1). The demand for resources has quadrupled in the past 50 years and is expected to double the current level by 2050 (Allwood et al., 2011).

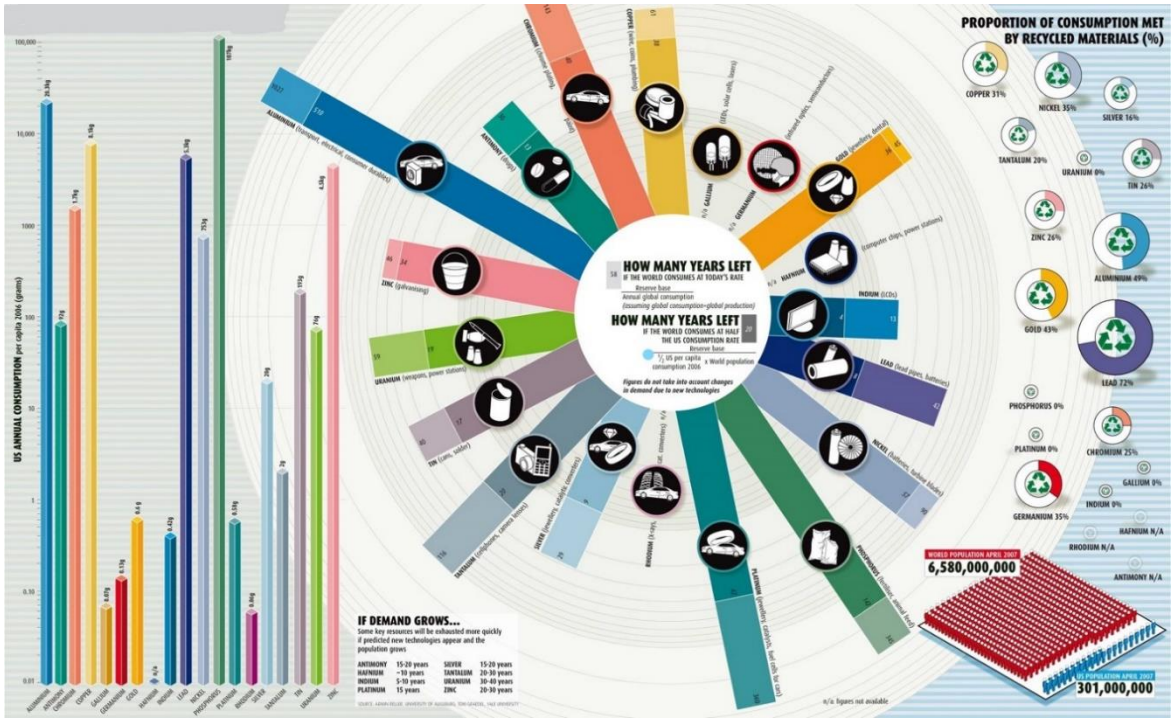

Figure 1: How long resources will last ? (New Scientist 2007)

Resource and impact decoupling from economic growth is needed to promote sustainable use of available resources (UNEP, 2019). According to (UNEP, 2017) report, roughly €2 trillion would be poured into the global economy every year if resource efficiency was boosted. One potential alternative that could address these problems is the concept of circular economy (CE). CE promotes the reduction of production and consumption levels and recovery of post-used products. A circular economy (CE) is "one that is restorative and regenerative by design, and which aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles" (Fig. 2) (EMF, 2015).

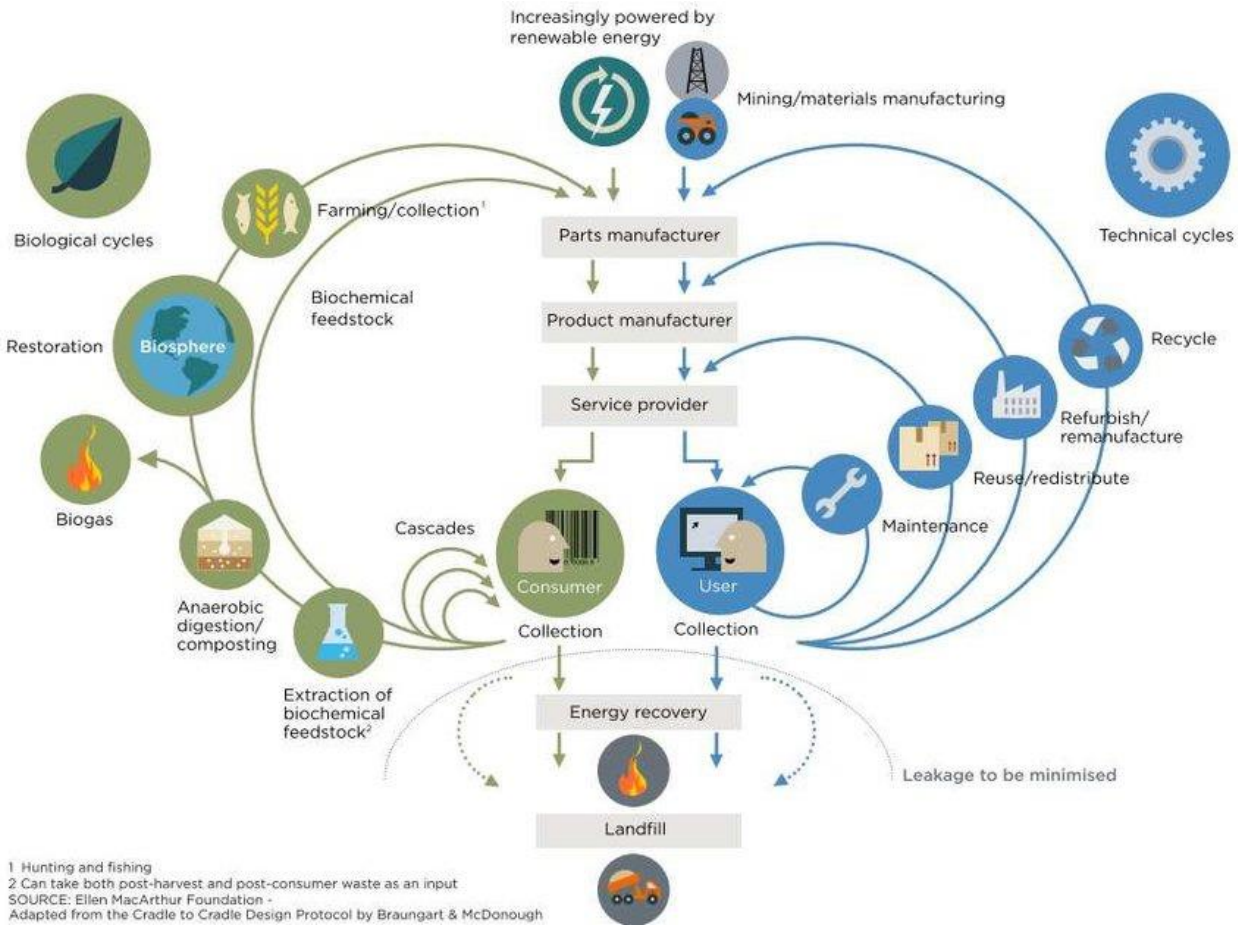

Figure 2: Circular economy flows (EMF, 2015)

CE aims to close the flow of resources by keeping products, components, and materials at their highest value through the application of circularity strategies such as repair, remanufacture, recondition, remanufacture and recycling (Bocken et al., 2017). The goal is to retain more of the value of material, energy and labour input that goes into the products to create a system that allows for long life, sharing and resource recovery.

Instead of linear flows of resources through the economy, the circular economy promotes circular flows to reduce environmental impacts and maximize resource efficiency as a strategy for sustainability (Suarez-Eiroa et al., 2019). The application of circular economy principles facilitates the potential to meet sustainable development goals (SDGs) (Korhonen et al., 2018; Saidani et al., 2018). CE mainly aims to meet economic prosperity, while maintaining environmental quality and social equity to create a sustainable world for future generations (Kirchherr et al., 2017). Transforming the production and consumption behaviour based on CE principles is the core to move towards a more sustainable development (Brissaud and Zwolinski, 2017; Di Maio and Rem, 2015). These targets are in line with SDGs, especially with the industrial and innovation aspects of SDG 9, and sustainable production and consumption of SDG 12. The circular economy practices offer everlasting benefits in the form of job creation and reduction of CO_2 emissions (Fig. 3).

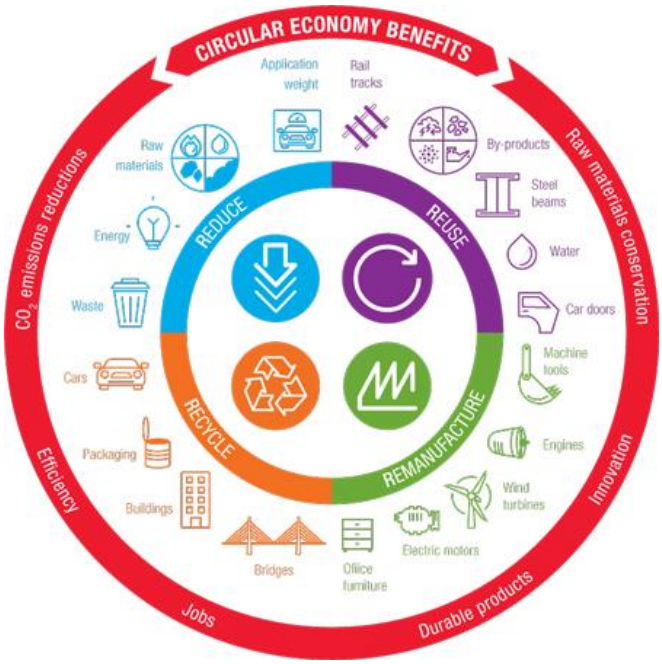

Figure 3: Benefits of the circular economy (UNCTAD)

Our most spread linear "Take, Produce, Consume and Dispose" economy is no longer sustainable, which waste large amount of embedded materials, energy, and labour. The CE is a new way organizing the relation between markets, customers and natural resources to transform from the old "take-make-dispose" economic model to the one which is regenerative by design to retain more of the value of materials, energy, and labour inputs that goes to products (EMF, 2015). Our vision is that engineering science must tackle circular economy by giving rules for implementation in order to accelerate the transition.

1.2. Motivation and challenges

This section describes the motivation for why it is worth to study this Ph.D. thesis. The first section briefly describes why this Ph.D. study is focused on the application of the CE by describing the main challenges. Then, the main challenges and motivation that initiated this study towards the need for assessment/evaluation tools and indicators are presented.

1.2.1. What are the challenges for the implementation of circular economy?

The concept of circular economy has gained popularity among researchers, business community and policy-makers (Rizos et al., 2016). Companies are increasingly informed of the opportunities promised by CE and have shown significant interest to apply CE practices (EMF, 2015; Geissdoerfer et al., 2017). It is also noted that implementation of CE principles facilitates the goals of sustainable development (Saidani et al., 2018).

Based on the literature on CE theory and policy, there are two main directions to implement CE principles: (i) a systematic economy-wide implementation and (ii) implementation with a focus on a group of sectors, products, materials, and resources (Kalmykova et al., 2018). Systematic economy-wide implementation of CE can be carried out at three levels of intervention: micro (product, company or single consumer level); meso (eco-industrial parks); and macro (cities, provinces, and regions) (Ghisellini et al., 2016; Su et al., 2013). Su et al., (2013), classified the current CE practices into four main areas: product, consumption, waste management and other areas (Table 1).

Table 1: Structure of CE practices (Su et al., 2013)

	Micro (single object)	Meso (symbiosis association)	Macro (city, province, state)
Production area (primary, secondary, and tertiary industry)	Cleaner production Eco-design	Eco-industrial park Eco-agricultural system	Network of eco-industrial park
Consumption area	Green purchase and consumption	Eco-living park	Renting service
Waste management area	Product/resource recovery	Waste trade market Renewable resources Industrial park	Regional circular industry
Other support	Policies and laws; NGOs		

The second CE implementation approach targets a group of products, materials, and resources (Kalmykova et al., 2018). The EU embraced an action plan to step up Europe's transition towards a CE model through measures to "close the loop" of product lifecycles. The action plan identifies five priority sectors along the supply chain including critical raw materials, construction and demolition, food waste, biomass and bio-based materials (European Comission, 2015).

Implementation of circular economy principles has economic, environmental and societal benefits. However, there are several challenges that impede the implementation of CE principles. Some of these challenges are lack of advanced technology, efficient supply chain system, standard performance evaluation system, reliable information, financial resources, technical skills, and poor enforceability of legislation (Rizos et al., 2016; Su et al., 2013).

Technology is one of the key factors that facilitate the successful application of CE principles. The implementation of CE principles requires the development of advanced technologies as well as updating of facilities (incl. equipment change) for recovery of retired products (Su et al., 2013). But the development of technologies and the changing of equipment costs a large amount of money and are time-consuming. On the other hand, Rizos et al., (2016) identified that a lack of technical know-how (gap in employee skills and lack of knowledgeable people) affects the implementation of CE.

CE requires tools and indicators help to assess CE practices at different measurement levels. Various tools and indicators are used due to the diverse areas of application and intervention levels of CE, and distinct characteristics of companies, industries or regions (Su et al., 2013). Heshmati, (2017) noted the different sets of methods, tools and indicators have to be proposed based on the application approaches and heterogeneity of companies, industries, and regions. Furthermore, the lack of effective legislation and support from governmental authorities poses a barrier to the application of circular economy principles (Rizos et al., 2016).

Companies have shown significant interest to engage in reverse logistics activities (Govindan et al., 2015). However, there have been challenges on the implementation, performance analysis and assessment of system change due to limited studies that approached the concept of CE with a focus on reverse logistics at a micro-level.

In a recent article, Govindan and Hasanagic (2018) identified difficulties that impede the application of the circular economy principles in the reverse supply chain activities. Some barriers in organizations include lack of a standardized system for measuring the performance CE in the supply chain; design challenges for recovering EoL products; lack of accurate information for post used products etc. Similarly, Sundin and Dunbäck, (2013) presented the main challenges in the remanufacturing of automotive parts along the

reverse supply chain. This study stressed that companies are mainly concerned with handling, transportation and storing of cores in addition to other challenges.

Another important challenge is the lack of an efficient supply chain system/reverse supply chain system (Rizos et al., 2016). For instance, absence of "green" suppliers for an input that will be used in the production process of products/services. From the demand side, there is a misconception from customers about the quality of product is perceived to be lower than the traditional product.

Moreover, Sangwan (2017) stressed that there is few research on the identification of decision criteria and performance evaluation for reverse logistics. This study identifies decision factors along with the activities of reverse logistics: collection, testing and sorting, and product recovery.

In order to conclude, with this concern, this Ph.D. thesis explores about evaluation of circularity strategies and measuring the performance of reverse logistics in order to support the transition towards the circular economy model.

1.2.2. Why assessment of CE practices in companies/businesses?

Recently, companies are taking significant steps to implement environmental friendly activities that support sustainable development by adopting the circular economy model (Akdoğan and Coşkun, 2012; Elia et al., 2017; Saidani et al., 2017). However, assessment of CE practices is not yet common in businesses (Sassanelli et al., 2019).

Although companies are showing increasing interest to transform their business into a circular economy model, there is limited study on the evaluation of circularity strategies of a product, supply chain, and service at the micro-level (Elia et al., 2017; Geng et al., 2012; Linder et al., 2017). Elia et al., (2017) proposed a reference framework to assist the evaluation phase. The framework has four levels: "the processes to monitor, the actions involved, the requirements to satisfy and the possible application levels of a CE strategy". Moreover, Elia et al., (2017), stressed that current research on evalution tools and indicators for measuring implementation of circularity scenarios is starting off, especially at the micro-level.

Similarly, Saidani et al., (2018) identified 55 sets of CE indicators and developed a taxonomy in 10 categories. The classification criteria include circularity strategies, levels of CE implementation, performance, degree of transversality, etc. In this study, 20 micro-level indicators are explored. Even though, many of these indicators are still under development and still in the pilot phase (Saidani et al., 2018; Walker et al., 2018).

Due to the lack of measurement tools and indicators, there are few successful examples that demonstrate the performance of CE practices (Asif, 2017). Performance is defined as the achievement of a given task measured with respect to a known standard of accuracy, completeness, cost, and speed. Performance measures help to give a vital sign for a company by quantifying how well the organization achieves a specific goal (Glavan, 2012). In a recent paper by Saidani et al., (2017), a framework to measure the circular economy performance level of a product is proposed based on the analysis of four building blocks of CE.

Based on the author's knowledge, there is hardly any indicator that measures the performance of a reverse supply chain for a typical product. Furthermore, there is a limited study on the assessment and evaluation of product circularity strategies. To fill in this research gap, Saidani et al., (2017), developed a holistic framework to measure product circularity performance. Also, the paper points out that current assessment methods lack systemic vision and operational considerations. Some of these methods assess environmental benefits of circularity strategies Amaya et al., (2010), measure the circularity of a product on material level Ellen MacArthur Foundation and Granta Design, (2015), assess the product/service of a company Evans and Bocken, (2013), and assess the resource duration through an indicator (Franklin-johnson et al., 2016).

Companies have faced difficulties to transform their business from a linear into a circular economic model due to lack of tools and indicators to evaluate the performance of CE practices (Saidani et al., 2018). In this regard, several authors suggested the importance to develop effective tools and indicators to support the transition from linear to a circular economy model (Di Maio and Rem, 2015; Elia et al., 2017; Saidani et al., 2018; Sassanelli et al., 2019).

This is, therefore, new tools and indicators are required to support industrial practitioners/decision-makers to measure, evaluate and assess circular economy practices as well as to examine the effects of CE adoption (Elia et al., 2017; Genovese et al., 2017; Saidani et al., 2018; Sangwan, 2017).

The main focus of this Ph.D. thesis is to study CE evaluation methods, tools and indicators to measure, assess and evaluate circular economy practices within the context of product recovery strategies with a focus on remanufacturing and a reverse logistics system at a micro-level.

Considering the aforementioned challenges, the following section identifies the research objective of this manuscript and the resulting research questions which are tackled in this Ph.D. manuscript.

1.3. Research questions

1.3.1. Research gaps and objectives

Based on literature review and expert feedback from academic researchers and industry practitioners, key research problems are identified that led to the proposal of research questions that are investigated in this Ph.D. thesis. In order to tackle the problem effectively, the main research question is divided into three sub-questions.

The main aim of this Ph.D. thesis is to develop an end-of-life decision-making tools and indicators to support companies to evaluate circularity strategies and measure the performance of reverse logistics. Based on the aforementioned research background the following main research question (RQ) is formulated:

Main RQ: **How to evaluate circularity strategies and measure the performance of reverse logistics?**

In order to effectively tackle this main research question, this Ph.D. thesis is divided into three main parts (Part #1, Part #2 and Part #3). Each part of the thesis has its own research gap, research objective and research questions to answer the global research question i.e. the main research question formulated the above paragraph. Fig. 4 depicts the research gaps, research questions, and contributions with respect to the main parts/sections of the Ph.D. thesis.

As briefly described at the beginning of this section, the main research question: "**How to evaluate circularity strategies and measure the performance of reverse logistics?**" has been formulated. To meet the aim this thesis, the main research question is divided into three research questions to systematically solve the main problem at hand. Based on this reasoning, the following three sub research questions are formulated and presented below.

Research question under Part #1 (Section #1)

RQ #1: What are the most important key decision factors and indicators that should be considered in the evaluation of circularity strategies and measurement the performance of reverse logistics?

There is limited research on decision variables (decision factors) and indicators in reverse supply chian in the context of circular economy (Alamerew and Brissaud, 2017; Doyle et al., 2012; Goodall et al., 2014; Saidani et al., 2018; Sangwan, 2017). This RQ aims to identify key decision variables and indicators used to evaluate circularity strategies and performance of reverse logistics. The research will identify decision factors/variables and indicators which are used as input in the evaluation process with respect to the relevant technical, economic, environmental, business and social criteria. Also, the most important factors which are pertinent to consider in the decision-making process are accentuated.

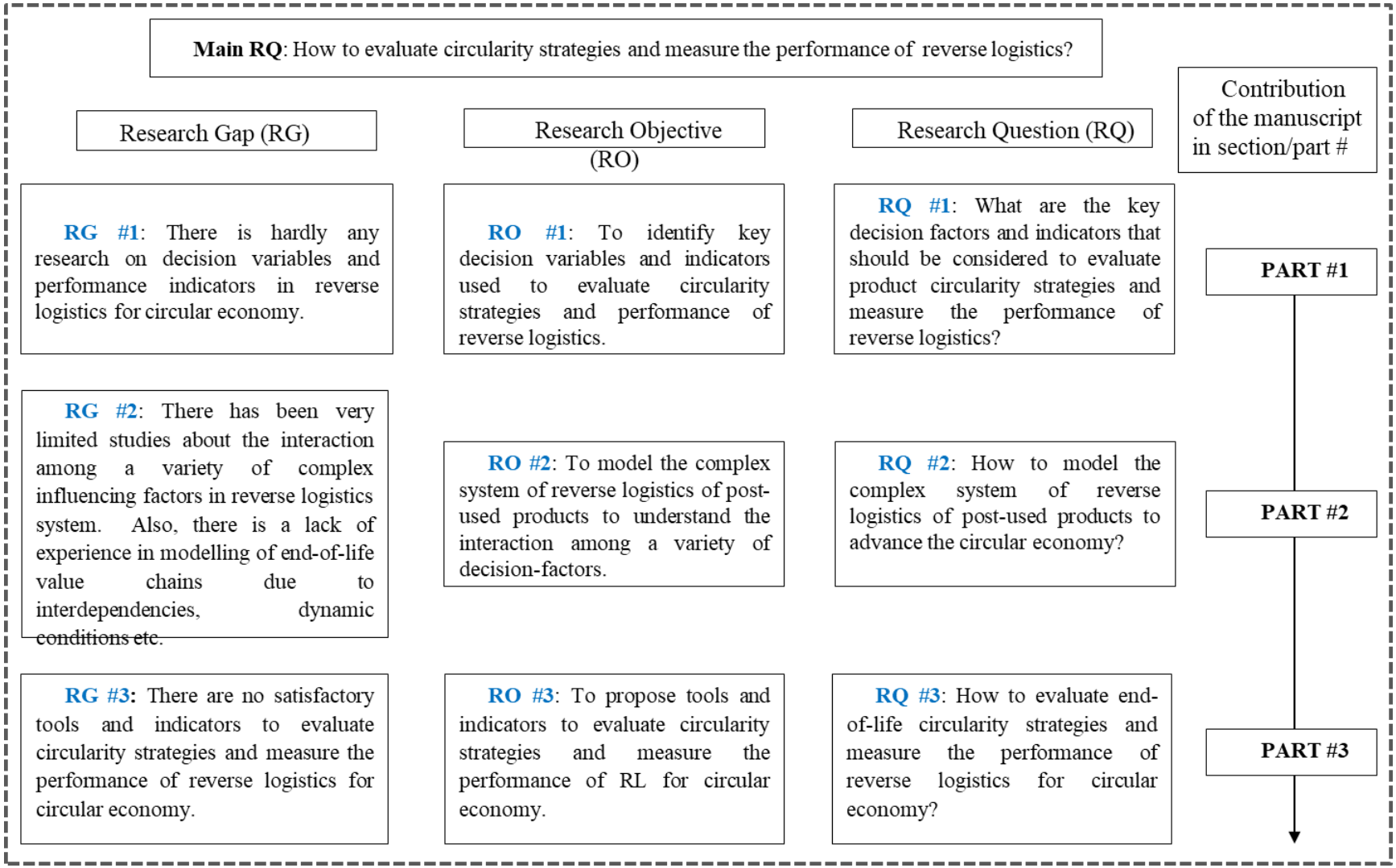

Figure 4: Research gaps, research objectives, and research questions of the Ph.D. thesis

Research question under Part #2 (Section #2)

RQ #2: How to model the complex system of reverse logistics of post-used products to advance in the circular economy?

Regarding the assessment of circular practices in companies, there is a research gap on system analysis of circularity strategies. There is a lack of study that shows the interaction among complex influencing factors in the assessment of circular scenarios (Zhang, 2019). Also, there is a lack of experience in modelling of EoL value chains due to interdependencies, dynamic conditions, innovation etcetera (Brissaud and Zwolinski, 2017; Sakao and Brambila-Macias, 2018; Zhang et al., 2004).

This sub-question aims to model the complex system of reverse logistics of post-used products to understand the interaction among a variety of influencing decision variables. The objective is to model the end-of-life value chains in order to evaluate alternative circularity strategies to choose the appropriate option for a typical product in the end-of-life decision-making process to enable the coming age of the circular economy.

Research question under Part #3 (Section #3)

RQ 3: How to evaluate EoL circularity strategies and measure the performance of reverse logistics for circular economy?

Recently, CE evaluation tools have been developed for managing the transition towards more CE practices (Geng et al., 2013). Assessment of circular practices is crucial to pinpoint areas of improvement in order to move towards a more CE model (Saidani et al., 2017). However, there are limited studies about decision-making tools and indicators to evaluate circularity strategies and measure the performance of reverse logistics for the circular economy (Elia et al., 2017; Geng et al., 2012; Linder et al., 2017; Saidani et al., 2018).

Due to the lack of measurement tools and indicators, there are few successful examples that demonstrate the performance of CE practices (Asif, 2017). New tools, methods and indicators are required to support a company is in making the transition from ‘linear’ to ‘circular’ models (Elia et al., 2017; Genovese et al., 2017; Saidani et al., 2018; Sangwan, 2017). This research question (under part #3) aims to propose tools and indicators to assess circularity strategies and measure the performance of reverse logistics for the circular economy. The former helps to identify the suitable circularity strategy considering product characteristics, end-of-life processes, and business models.

1.4. Research foundations

This section explains the theory of the importance of research initiatives in each of the fields that have been integrated and form the basis of this Ph.D. thesis work. It is the theoretical basis for the research conducted in this thesis. The research areas of life cycle engineering, product recovery management, and reverse logistics are presented in the following sections.

1.4.1. Life cycle engineering

Life cycle engineering (LCE) is a promising approach that comprises a variety of different methods with a consideration of economic, environmental and societal aspects. A broad definition of life cycle engineering is given by (Jeswiet and Szekeres, 2014) as "engineering activities which include the application of technological and scientific principles to manufacturing products with the goal of protecting the environment, conserving resources, encouraging economic progress, keeping in mind social concerns, and the need for sustainability while optimizing the product life cycle and minimizing pollution and waste." In the life cycle engineering domain, a number of generic tools, methods, and techniques have been proposed to support the decision-making process that can be used at any stage of the product life cycle. Life cycle assessment (LCA), life cycle costing (LCC) are one of the main tools positioned under the roof of LCE that can be applied for life cycle evaluation (Michael et al, 2017; Pecas et al., 2016; Umeda et al., 2012).

Life cycle assessment

Life cycle assessment (LCA) is a methodology to analyse and evaluate the environmental burdens of a product, process, activity or system by identifying and quantifying the elementary flows across the life cycle of products/services (Jeswiet and Szekeres, 2014). This approach allows for product comparison in the decision-making process. The objective of the method is to identify changes that can lead to effect environmental improvements and overall cost savings. As shown in Fig. 5, LCA process consists of four distinct stages which include: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results. A short description of the four phases is presented below (Curran, 2006).

- Goal and scope definition: This step enable to define and describe the product, process or system and to characterize the boundaries and environmental effects to be examined for the assessment.
- Inventory analysis: This phase identifies and quantifies the elementary flow associated with the life cycle of the product/service
- Impact assessment: This step seeks to establish a connection between the product, process or system, and its potential environmental impact.

- Interpretation: This phase attempts to evaluate the life cycle inventory study and impact assessment results in order to select the preferred scenario. Furthermore, the soundness and robustness of the result and assumptions made to generate the results during the evaluation process are evaluated.

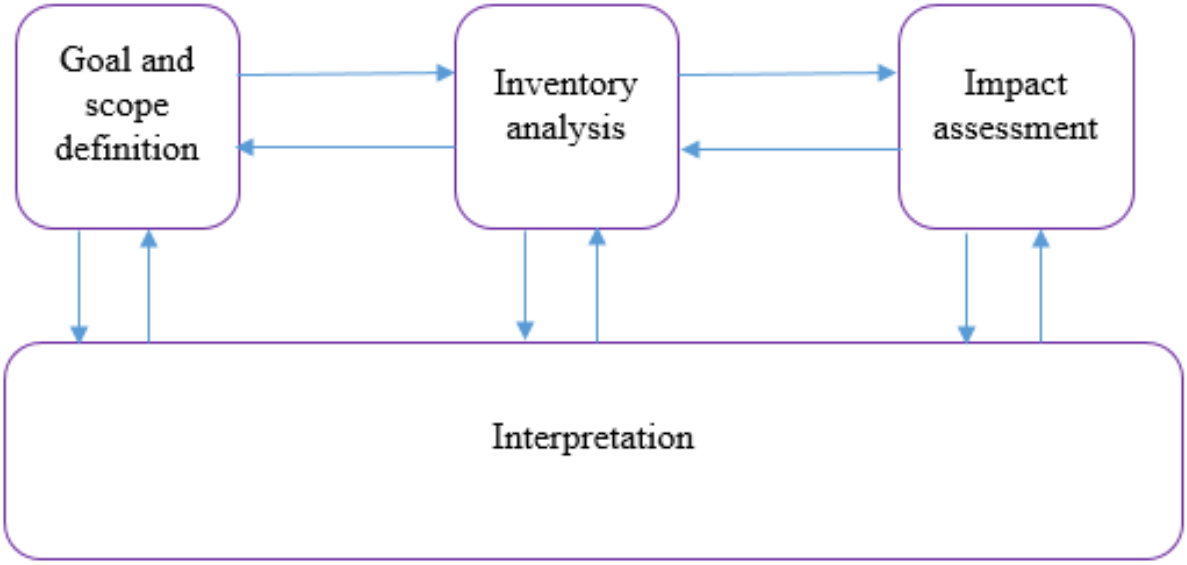

Figure 5: Life cycle assessment framework

Life cycle costing

Life cycle costing (LCC) is an approach to assess costs linked with the life cycle of a product/service in order to compare potential alternatives to assist users in the decision-making process. LCC aims at comparing life cycle costs of alternative products, processes or systems and identifying win-win situations once it is combined with LCA and Social-LCA (Lichtenvort et al., 2008).

In general, LCC consists of four main components which include: goal and scope definition, information gathering, interpretation and identification of hotspots and sensitivity analysis and discussion. Even though, during analysis the aforementioned phases can vary from case to case. The results of LCC effectively support the decision-making process if relevant reliable data is available (Gluch and Baumann, 2004; Lichtenvort et al., 2008).

1.4.2. Reverse logistics

Reverse logistics (RL) is one of the great enablers for sustainable production and consumption (Sangwan, 2017). There is a growing interest in reverse logistics (RL) from scholars and industries due to the increasing environmental problems, future legislation, increased return of post-used products etcetera (Govindan and Soleimani, 2016). According to Rogers and Tibben-Lembke, (1999), "reverse logistics is the process of planning, implementing and controlling the backward flow of raw materials, in-process inventory, packaging and finished goods, from a manufacturing, distribution, or use point, to a point of recovery or point of proper disposal". Reverse logistics includes three main activities: collection, inspection and sorting, and product recovery and redistribution (Sangwan, 2017). The development of an efficient reverse logistics system is pertinent for the recovery of end-of-life products (Govindan and Soleimani, 2016). The implementation of efficient reverse logistics systems represents as an enabler for an effective transition from a linear to a circular economy model (Ellen MacArthur Foundation and Granta Design, 2015; Gnoni et al., 2018; Lieder and Rashid, 2016). Fig. 6 depicts the forward and reverse supply chain.

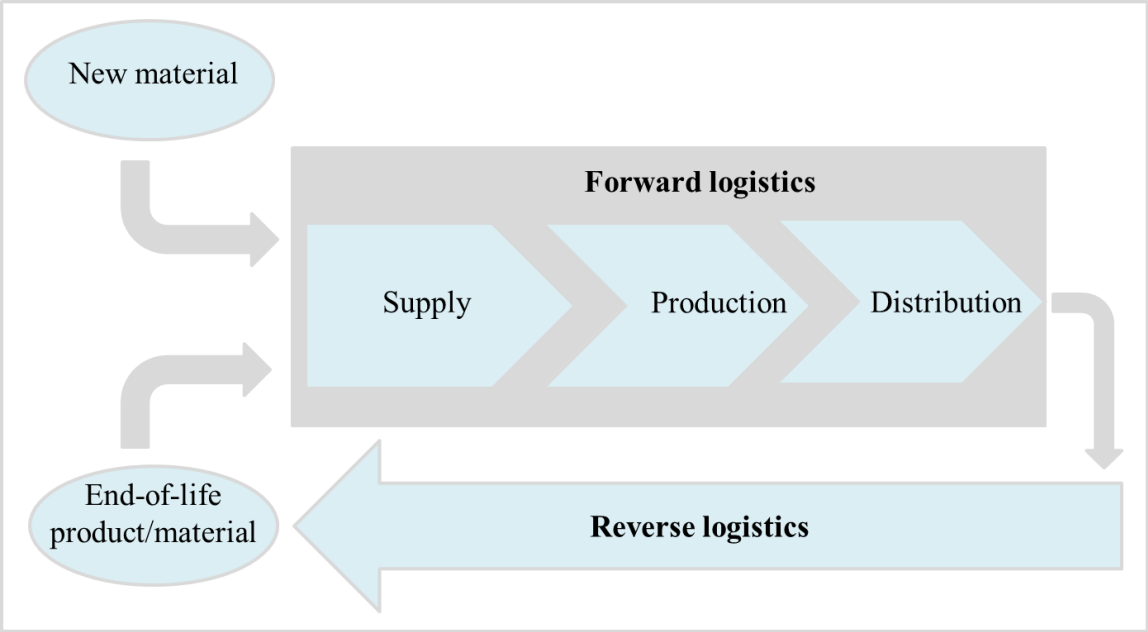

Figure 6: Forward and reverse logistics (Andrade et al., 2013)

Collection

The collection of post-used products is one of the most crucial parts of reverse logistics. It is the process of retrieving retired products and transporting them to a location where the recovery of products takes place (Pokharel and Mutha, 2009; Sangwan, 2017; Webster and Mitra, 2007). The efficiency of collecting EoL products depends on the collection activity and method of collection. Product collection activity of reverse

logistics could follow a centralized or decentralized system (Webster and Mitra, 2007). This activity may include an incentive to maximize the number of return products. Collection of worn-out products can be performed by the original equipment manufacturers, retailers or third-party logistics providers.

Sorting and testing

To determine the re-usability of a product, collected post-used products are inspected and sorted. Inspection and sorting processes could be performed in centralized and decentralized locations. A centralized facility minimizes the cost of labour and testing equipment (Sangwan, 2017). While decentralized facilities are used for low-cost testing processes such as machine refurbishing (Thierry et al., 1995).

1.4.3. Product recovery management

Product Recovery Management (PRM) is the management of all used and discarded products, components, and materials to recover as much of the economic and ecological value as possible thereby reducing the quantity of discarded waste (Thierry et al., 1995). The implementation of extended producer responsibility (EPR) in new governmental legislation and the growing environmental and economic concern, demand original equipment manufacturers (OEMs) to take care of their products after they have been discarded by the consumer (Hosseinzadeh and Roghanian, 2012). Product recovery management aims to close the loop throughout the product life cycle (Krikke et al., 1998). In recent years, product recovery (product circularity) has become increasingly important in transitioning to a circular economy model (Alamerew and Brissaud, 2017).

Product circularity strategies

An EoL option is considered as a product circularity strategy if it fulfils three main criteria: collection of retired products, reprocessing of a recovered product and redistribution of the processed product (Thierry et al., 1995). End-of-life product circularity strategies include remanufacture, repair, recondition, cannibalization, refurbish and recycle (Jawahir and Bradley, 2016; Thierry et al., 1995). All these end-of-life options are distinct from one another and selecting the best suitable product recovery option should take several factors into consideration (Kumar et al., 2007). According to Stewart and Ijomah, (2011), the selection of product circularity strategies depends on the type of product and the quality level it is returned in. The end-of-life stage in this work refers to the point in time when the product reaches the last stage of existence or at the end of useful life with reference to the first user of the product.

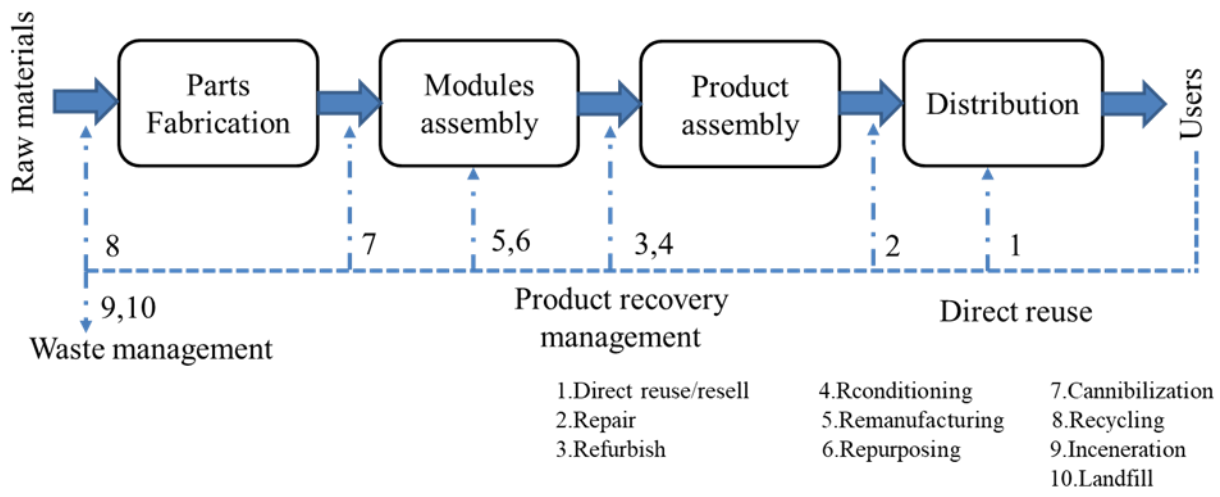

Figure 7: List of circularity strategies (modified after (Thierry et al., 1995))

Repair

Repair is an activity of returning a used product into "working order" (Krikke, 1998) by fixing and replacing specified faults in a product using service parts at the location where the product is being used (Rose, 2000). The quality of repaired products is typically less than the refurbished, reconditioned and remanufactured products. Repaired products issued a warranty less than those of newly manufactured products that cover the whole product or replaced components (King et al., 2006).

Even though repair is the most logical approach to close material loops (King et al., 2006), OEM's hindered the implementation of the strategy by refusing to sell spare parts to independent repaired shops, failed to provide information on how to repair failed products as well as by remotely deactivating the device when outside party attempts to make a repair in order to gain competitive advantage.

Repurposing

Repurposing is an emergent circularity strategy where discarded products are recovered and used in a new product that has a different purpose and application compared to the original product (Bauer et al., 2017). For instance, repurposed electric vehicle batteries could be reused for different applications such as energy storage for renewables of solar panel and wind farms, residential and public back up power system, distribution grids, and energy storage for the electric heater (Bowler et al., 2015; Richa et al., 2014).

Reconditioning

Reconditioning is the process of rebuilding and replacing failed components of a recovered product resulting in the product being returned to a acceptable working condition which may be less than the original product specification (Ijomah, 2002; Paterson et al., 2017). The resultant product receives a warranty inferior to newly remanufactured product and higher than products that have been repaired. Reconditioning involves greater labour content than repaired products but lower than remanufacturing (King et al., 2006).

Refurbishing

Refurbishing involves returning products to a specific quality level, usually less than that of a new product. Compared to refurbished products, reconditioned product has gone through extensive testing and repair than refurbished products.

Remanufacturing

Remanufacturing is an emergent product end-of-life strategy Stewart and Ijomah, (2011) for boosting resource efficiency and achieving the circular economy (Umeda et al., 2017). Remanufacturing is defined as "a process of returning a used product to at least original equipment manufacturer (OEM) performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent" (Ijomah, 2002). Compared to repaired and reconditioned products, remanufacturing involves greater labour content that gives a higher rate of product performance (King et al., 2006).

Cannibalization

Cannibalization is an activity of recovering usable parts of a discarded products and components that can be used for repair, reconditioning and remanufacturing of other return products. In cannibalization, selective disassembly and inspection are accomplished to recover potentially reusable parts while the remaining product component is recycled/landfilled (Krikke, 1998). Compared to the first three product recovery options, cannibalization retrieves only a small proportion of products (Thierry et al., 1995).

Recycling

Recycling is an activity where discarded materials are collected, processed and converted into new raw materials (Jawahir and Bradley, 2016; Paterson et al., 2017). Compared to other product recovery strategies, in the case of recycling the identity and functionality of the original product or component and the energy used to create the pre-recycled product are totally lost (Krikke, 1998). Also, additional energy is needed to transform recovered material into new products (King et al., 2006).

1.5. Research approach

This section describes the proposed research approach of the Ph.D. project. It begins with an overview and description of the main parts of this research. Then a detailed explanation is presented on the research approach formulated and why this approach is chosen for the study.

A research process is a stepwise formulation of a set of activities to perform in order to achieve the objective of a researcher in a logical framework. It consists of a series of steps to effectively conduct the research work (Sahu, 2013). The research process started with defining the research area, followed by an in-depth literature review to fully understand the subject area of the study and sharpen (formulate) the research questions. This Ph.D. thesis is framed into three main parts/sections. Fig. 8 shows the main parts of this Ph.D. thesis. First, the identification of decision factors or variables and indicators is accomplished. Then modelling of the reverse logistics system is undertaken. Finally, decision-making tools and indicators are developed. These steps are sometimes iterative to improve the results based on the experience gained during the research period.

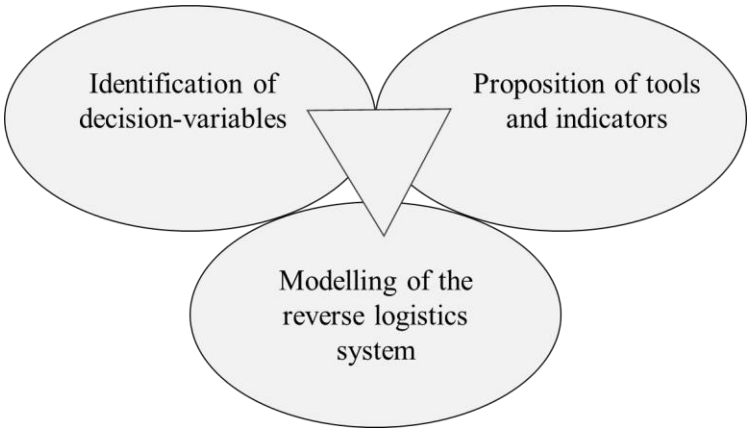

Figure 8: Main parts of the Ph.D. process

Due to the nature of the study, in this Ph.D. work, a multi-methodological research approach was chosen in order to tackle the research gaps effectively. Such a multi-methodological approach has been used in various studies. For instance,

- Saidani, (2018) in his Ph.D. thesis used a multi-methodological approach from various disciplines such as material flow analysis, life cycle assessment, industrial case studies, multi-criteria optimization, hybrid top-down and bottom-up approach, cognitive mapping and system dynamics to develop indicators and tools applied to the heavy vehicle industry.

- Idjis, (2015) used in his Ph.D. thesis three modelling methods: cognitive mapping, system dynamics, and systems for complex organizational systems' modelling methods to represent the dynamics of recovery of post-used electric vehicle batteries.

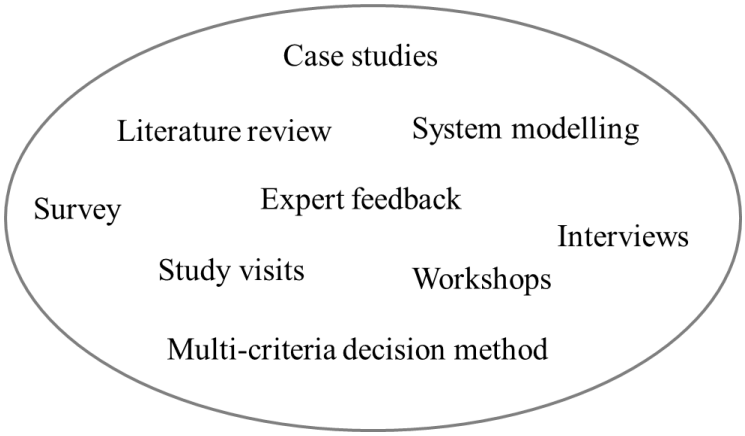

Figure 9: Research methods used in the study

The research methods used in this Ph.D. study (Fig. 9) are listed below:

- An in-depth literature review to fully understand the subject area of the study and sharpen (formulate) the research questions,
- Study visits to companies to deeply explore the research gaps in the study theme,
- A multi-criteria decision methodology to develop tool to evaluate EoL product recovery strategies,
- A system dynamic modelling approach to systematically model the complex system of a reverse logistics system,
- An online survey is used to collect data regarding recovery approaches from academia and industrial practitioners, and
- A case study approach to validate/test the proposed tools and indicators.

This study applied case studies with various companies to compare the proposed model with current industry practice, and to validate models and tools developed in this Ph.D. thesis. The case study companies are situated in European countries such as France, Sweden, Denmark, and Belgium. A case study method is an in-depth study of a situation especially useful for testing theoretical models, tools and methods by using them in real-world situations to understand specific cases and ensure a more holistic approach to research. By understanding the actual practice in an industry, this study has the potential to assist companies to select a suitable circularity strategy appropriate for the product for their unique position that fits with the company's product.

1.6. Structure of the manuscript

In the previous sections, an introduction about circular economy and reverse logistics; motivations and challenges that led to this research work; key research questions and research objectives of this thesis; contributions of the present research and theoretical background have been presented. In this section, the overall structure of the Ph.D. thesis is presented including, the outline of the manuscript; summary of articles contributed to the thesis and their connection to the research questions. Fig. 10 depicts the overall structure of this Ph.D. manuscript.

1.6.1. Outline of the thesis

A Ph.D. dissertation could be written in 'traditional: simple', 'traditional: complex', 'topic-based' and 'compilation of research articles' formats (Paltridge, 2001). This thesis is written based on a "compilation of research articles" to effectively present the Ph.D. work. The structure of this Ph.D. thesis constitutes introduction and background of the study; a compilation of four research articles; and discussion and conclusion and future research directions.

In this Ph.D. thesis is a compilation of four articles. Each of the research articles have their own introduction, literature review, method, results, discussion and conclusion. Even though the thesis is based on a compilation of publications, a clarification concerning how the articles are interrelated is presented and discussed in this section.

This Ph.D. thesis framed into three main parts: identification of key end-of-life decision variables/factors and indicators; modelling of the reverse logistics system; and development of evaluation tools and circularity-indicator for reverse logistics. This thesis frame is shown in Fig. 10. A brief description of each part is discussed below.

Part #1: To identify key end-of-life decision variables/factors and indicators

This section identifies EoL decision factors from environmental, economic, societal, legislative, technical and business aspects; identifying relevant indicators to measure circularity scenarios and pointing out the EoL decision-making methods. The decision variables/factors and indicators are used as input to the model the reverse logistics system (In part 2) and to develop circularity indicator and assessment tools (In part 3).

Part #2: To model the reverse logistics system

In this section modelling of the reverse logistics system is accomplished to understand the interaction among various decision factors. In addition, the interplay among the building blocks of circular economy.

Part #3: To propose circularity strategies evaluation tools and circularity-indicator for reverse logistics

In this section development of end-of-life circularity evaluation tools and a circular economy indicator to measure the performance of reverse logistics is presented to aid businesses in decision-making.

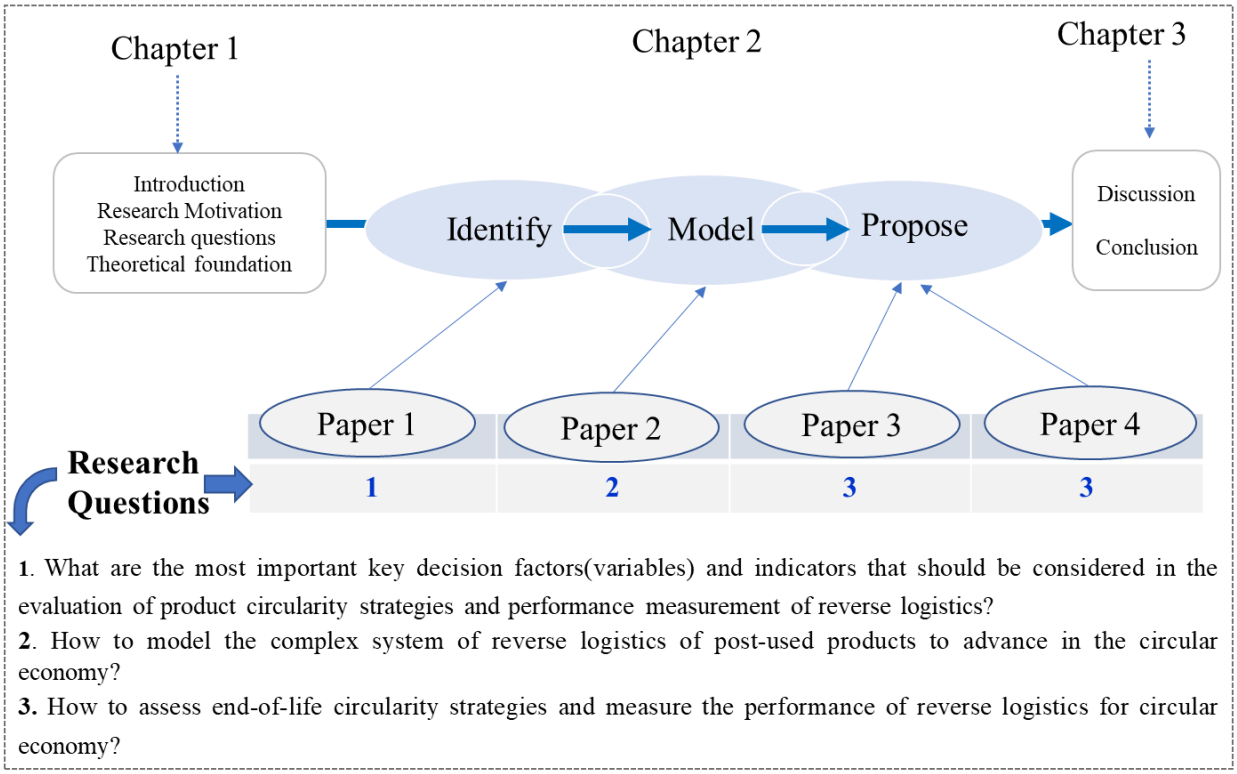

Figure 10: Structure of the Ph.D. thesis

1.6.2. Summary of publications

A total of four journal articles and two conference papers have been produced during this Ph.D. project. Table 2 presents a list of articles contributing to this thesis. The following section provides a short description of the four journal articles.

Paper #1: Circular economy assessment tool for end-of-life product recovery strategies

In this article, end-of-life decision-making factors from environmental, economic, societal, legislative, technical and business aspects, and a list of indicators are identified. The study involves experts from academics and the remanufacturing industry. Moreover, an assessment tool for circularity strategies at a strategic level is proposed.

Paper #2: Modelling reverse logistics through systems dynamics for realizing the transition towards circular economy

In this study, the complex system of reverse logistics is modelled to explore these dynamics using environmental, societal, and economic aspects from a reverse supply chain perspective. A system dynamics (SD) approach is used to model the dynamics of cost, revenue, and strategic and regulatory decisions. In addition, the interplay among the building blocks of circular economy research is discussed. Moreover, the main enablers and challenges for the circularity of electric vehicle batteries are identified. This paper is based on a case study of electric vehicle batteries (EVBs) from 5 companies located in France.

Paper III: Circular economy indicator for reverse logistics: Measuring the performance of reverse supply chain

In this article, a "Circular Economy Indicator for Reverse Logistics (CEI-RL)" is proposed for measuring the performance of reverse supply chain in a company. CEI-RL aims to assess the performance of reverse logistics with respect to the principles of CE in three dimensions: collection, sorting and testing, and product recovery. This tool is expected to help industrial practitioners to make better and informed decisions about the performance of reverse supply chain in a company.

Paper IV: A multi-criteria evaluation method of potential product level circularity

In this study, a circularity strategy evaluation method is proposed to evaluate potential circularity scenarios of products and, added service in re(manufacturing) firms based on a multi-criteria decision-making approach. The method assesses circularity scenarios including the initial business of the company (traditional business or remanufacturing (reman); advanced reman businesses (target reman businesses, multiple/mixed reuse scenarios plus service offerings) and future reman scenarios. This study involves a case study with companies who would like to transform traditional business models into a circular economy model.

Table 2: Articles contributed for this Ph.D. thesis

Thesis section	Title of the article	Type of publication	Status
Part 1	Alamerew, Y.A., Brissaud, D., 2018. Circular economy assessment tool for end of life product recovery strategies. J. Remanufacturing.	Journal article Journal of Remanufacturing (Paper #1)	Published
Part 1	Alamerew, Y.A., Brissaud, D., 2017. Evaluation of Remanufacturing for Product Recovery : Multi-criteria Decision Tool for End-of-Life Selection Strategy, in: 3rd International Conference on Remanufacturing. Linköping, Sweden.	Conference paper International Conference on Remanufacturing	Published Presented
Part 2	Alamerew, Y.A., Brissaud, D., 2020. Modelling Reverse Supply Chain through System Dynamics for Realizing the Transition towards the Circular Economy: A Case Study on Electric Vehicle Batteries.	Journal article Journal of Cleaner Production (Paper #2)	Published
Part 2	Alamerew, Y.A., Brissaud, D., 2018. Modelling and Assessment of Product Recovery Strategies through Systems Dynamics, in Procedia CIRP. pp. 822–826.	Conference paper CIRP Life Cycle Engineering	Published Presented
Part 3	Alamerew, Y.A., Brissaud, D., 2020. Circular Economy Indicator for Reverse Logistics (CEI-RL) : Measuring the Performance of Reverse Logistics in Companies. Journal of Cleaner Production.	Journal article Journal of Cleaner Production (Paper #3)	In progress!
Part 3	Alamerew Y.A., Kambanou M.L., Sakao T., Brissaud D., 2020. A multi-criteria evaluation method of potential product level circularity.	Journal article Journal of Sustainability (Paper #4)	To be Submitted before Ph.D. defence!

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2. Results

2.1. PART I - Identify: Identifying decision-making factors and indicators

In this section the first part of the Ph.D. thesis is presented. Part I identifies a list of indicators and end-of-life decision-making factors from environmental, economic, societal, legislative, technical and business aspects. The results of this research will be used as an input for modelling of the reverse logistics system and proposition of decision-making tools and indicators.

Table 3: Summary of paper #1

Title	**Circular Economy Assessment Tool for End-of-life Product Recovery Strategies**
Published in	Alamerew, Y.A., Brissaud, D., 2018. Circular economy assessment tool for end of life product recovery strategies. J. Remanufacturing. Journal of Remanufacturing. https://doi.org/10.1007/s13243-019-00069-4
Keywords	Circular Economy; Remanufacturing; End-of-life strategy; Product recovery; Multi-criteria decision methodology
Abstract	Circular Economy (CE) aims to maintain the value of products, components, materials, and resources in the economy for as long as possible. Current end of life (EoL) product circularity decision-making methods are focused on technical and economic factors neglecting other crucial areas such as legislative pressure and customer demand, which are pertinent in the decision-making process. This paper presents a decision-making method to evaluate end of life product circularity alternatives at a strategic level. A Product Recovery Multi-Criteria Decision Tool (PR-MCDT) is proposed to evaluate product circularity strategies from an integrated point of view, i.e. by simultaneously taking into account technical, economic, environmental, business, and societal aspects. The paper also identifies key end of life decision-making factors to assess product recovery strategies. An illustrative example is presented and discussed to show the applicability of the tool for the selection of product recovery options. A PR-MCDT is used at the senior/middle management level to ensure strategic decisions, which then promote the success of the company.

2.1.1. Introduction

The global crisis in resource scarcity, population growth, and climate change impacts are placing pressure to ditch the traditional "Make-Use-Dispose" economic model and adopt "make, use, return" as our collective mantra by joining the circular economy. The circular economy moves away from the traditional "take-make-dispose" economic model to one that is regenerative by design (Fellner et al., 2017). The main aim of the circular economy is considered to meet economic prosperity while maintaining environmental quality and social equity to create a sustainable world for future generations (Kirchherr et al., 2017).

Circular economy aims to facilitate an effective flow of resources, keeping products, components and materials at their highest value at all times through the extension of product life times by repair, recondition and remanufacture as well as closing of resource cycles - through recycling and related strategies (Bocken et al., 2017). Despite being proven to be both economically and environmentally beneficial, there are few successful examples, due to lack of analysis methods and tools that can assess different aspects of circular systems (Asif et al., 2012).

Product recovery has become increasingly important towards transitioning to a circular economy (Alamerew and Brissaud, 2018). Product recovery management aims to close the loop throughout the product life cycle 26. The implementation of extended producer responsibility (EPR) in new governmental legislation, together with the growing environmental and economic concern, demands that original equipment manufacturers (OEMs) to take care of their products after they have been discarded by the consumer (Hosseinzadeh and Roghanian, 2012; Sundin, 2004).

Product recovery management (PRM) is the management of all used and discarded products, components, and materials to recover as much of the economic and ecological value as possible thereby reducing the quantity of discarded waste (Thierry et al., 1995). End of life product recovery strategies include remanufacture, repair, recondition, cannibalization, refurbish and recycle (Jawahir and Bradley, 2016; Thierry et al., 1995). All these end of life options are distinct from one another and selecting the best suitable product recovery option should take several factors into consideration (Kumar et al., 2007). End of life in this work refers to the point in time when the product no longer satisfies the last user.

Current end of life product recovery decision-making approaches are centred on economic and technical factors (Stewart and Ijomah, 2011) neglecting other equally influential aspects which are pertinent in the decision-making process such as market demand, social trends and legislative pressure. Additionally, there is lack of a holistic approach that uses an inclusive methodology to assess and evaluate recovery strategies from an integrated point of view i.e. by taking into account technical, economic, environmental, business

and societal aspects simultaneously. The aim of this paper is to identify EoL decision-making factors and incorporate them into a holistic methodology to evaluate EoL product recovery strategies. The viability of a recovery strategy is evaluated against the relevant technical, economic, environmental, business and social criteria.

The rest of the paper is organized as follows. Section 2.2.2 presents the literature review on EoL decision making approaches and strategic evaluation of recovery strategies. In section 2.2.3 the research methodology used to answer the research questions is described. In section 2.2.4 the multi-criteria decision-making approach is discussed, and key decision-making factors used to assess the feasibility of recovery strategies are presented. Subsequently in section 2.2.5, the application of the method on a case is discussed. Finally, conclusions are drawn by summarizing the main findings of the study.

2.2.2. Literature Review

2.2.2.1. End-of-life product recovery decision methods

The literature survey shows that there is a wide range of EoL decision making methods which employ various approaches. Due to the variation of drivers and interested parties, a holistic decision approach is required. End-of-life decision-making needs to use a holistic approach to evaluate EoL strategies from various perspectives including environmental, economic, societal, business, technical, market and legislative aspects (Ravi et al., 2005; Ziout et al., 2014).

The term end-of-life in this research work is referred when the product no longer satisfies the last user of the product at end-of-use. Therefore, it is referred on the last user of the product and the product fails to satisfy the end user. But there are many researchers who define the term in reference to the first user of the product that makes some strategies like reuse and minor repair to be considered as end-of-life strategies. An EoL option is considered as a Product Recovery Strategy (PRS), if fulfils three main criteria's: collection of used products, reprocessing of a recovered product and redistribution of the processed product (Thierry et al., 1995). End-of-life product recovery strategies include remanufacture, repair, recondition, Repurpose, cannibalization, refurbish, upgrading and recycle (Jawahir and Bradley, 2016; Thierry et al., 1995). Even though, this is not an exhaustive list of PRS and some of the strategies overlap with each other. End of life decision-making approaches are comprehensively grouped into three main categories; optimization methods, multi-criteria decision methodology and empirical method.

Optimization methods

The decision of mathematical optimization methods uses optimization problems for choosing a suitable product recovery option for a typical product. Optimization methods are completely focused on cost and economic benefit while it lacks the ability to consider other unquantifiable factors (Doyle et al., 2012; Goodall et al., 2014). Papers that employ mathematical models, mixed integer programming models and numerical models hold a significant majority in the EoL decision making process (Stewart and Ijomah, 2011). Furthermore, due to the complexity of mathematical models and the requirement of too many input parameters, it is found to be difficult for industries to effectively and efficiently use the proposed EoL decision-making tools.

Multi-criteria decision methodology (MCDM)

These multi-criteria methods have benefits due to the technical aspect and structure by simultaneously analysing quantitative and qualitative factors. MCDM also takes the preference of the user/decision-maker in the decision-making process (Bufardi et al., 2004, 2003).

Empirical methods

In this method the decision for the appropriate product recovery option is made based on knowledge and experience gained from analysing successful cases of product recovery (Shih et al., 2006). Table 4 presents end of life decision making methods in each category with the description of the usefulness of the method.

Table 4: End-of-life decision making methods

Decision-making method	Description
Multi objective optimization decision methodology (King et al., 2006)	Mathematical multi-objective optimization model to identify optimal product recovery solution
Stochastic dynamic programming model (Krikke et al., 1998)	Mathematical optimization approach that sets conditional EoL option for a sub-assembly based on technical, legal and economic aspects
Multi criteria matrix using AHP (Iakovou et al., 2009)	MCDM approach: each component is assigned ranking of EoL option
Multi criteria for product EoL selection (Bufardi et al., 2003)	MCDM: ranking of EoL option is implemented for each component in a product
Remanufacturing product profile design tool (REPRO2) (Gehin et al., 2008)	Empirical approach of eleven product profiles to to design product accordingly
Case based reasoning (CBR) (Shih et al., 2006)	Empirical approach for suggesting EoL option for a product as a whole

2.2.2.2. Strategic decision for selection of potential recovery strategies

Strategic decisions within EoL product recovery assess the feasibility of recovery strategies for the business. Strategic evaluation is critical to ensure strategic decisions, which then promote success of the company (Diaz and Marsillac, 2017). Strategic decision of EoL products could be made prior to implementing a product recovery business; at the periodic stages to view whether it is having the desired effect on the business and at conceptual design phase particularly when they invested interests in business scenario such as product service system (Goodall et al., 2014). Several studies have focused on evaluating product recovery alternatives at strategic level. Table 5 presents EoL evaluation tools for a product at strategic level.

The literature survey shows that there is lack of a holistic approach that uses an inclusive methodology to assess and evaluate recovery strategies from an integrated point of view i.e. by taking into account technical, economic, environmental, business and societal aspects simultaneously. The research objective of this paper is therefore to answer the following questions:

- ✓ Which key factors should be considered in the evaluation of product recovery strategies with respect to the relevant technical, economic, environmental, business and social criteria?
- ✓ How to assess product circularity strategies holistically by analysing the different types of factors?

Table 5: EoL decision tools for evaluation of products (after Goodall et al., 2014)

Decision Tool	Economic	Environmental	Social
Product EoL decision making methodology (Pochampally and Gupta, 2012)	x	x	0
Product EoL strategy selection algorithm Using case base reasoning (Ghazalli and Murata, 2011)	xx	x	0
Deployment model for part reuse in customised design of remanufactured products [7]	xx	0	0
A custom-built decision tool called Repro2 to product suitability based on product profiles (Gehin et al., 2008)	x	x	x
Product Life Cycle Extension Techniques Selection (PLEATS) model (Dunmade, 2004)	x	x	x
Product EoL Strategy Selection algorism using fuzzy Logic and Bayesian updating (Pochampally and Gupta, 2012)	x	x	x
Extension of the End of Life Design Advisor (ELDA) Using a neutral networking model (Chen, Jahau Lewis, 2003)	xx	0	0

2.2.3. Research Methodology

The development process of product recovery multi-criteria decision tool (PR-MCDT) consists of three main phases; initial tool development based on literature, confrontation of the proposed tool to academics and industry practitioners, and final tool development. The development process of the tool is presented in Fig. 11. Subsequently, an explanation of each tool development phases is presented.

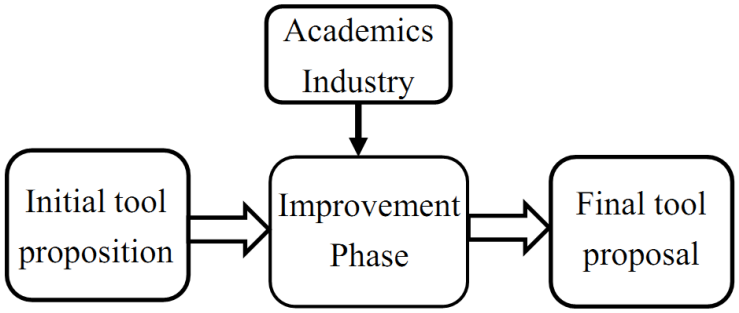

Figure 11: Graphical depiction of the research methodology

2.2.3.1. Initial tool development

A literature review is made to evaluate and analyse the available literature in the research area of EoL decision-making methods. The databases of Google Scholar, Science Direct, university's library Uni-Search & ISI web of Science is used to gather and access relevant articles. The terms "End-of-Life Decision-making", "Circular Economy", and "Product Recovery Management" are used as keywords. Further information concerning product end-of-life decision making is gathered from reviewing corporate documents, marketing and publicity documentation, organization documentation and others. There are some renowned works on the research area of Product Recovery Management (PRM). Reading articles primarily related to End-of-Life product recovery decision making approaches had a significant role in this research work. The emphasis was given to understand end-of-life decision making approaches at strategic level.

A comprehensive literature review was undertaken to identify key end of life decision-making factors that used to evaluate product recovery strategies. Firstly, an exhaustive list of factors was presented and then the decision-making factors were sorted into main categories by the authors. Afterwards, factors from each category were evaluated based on literature review and expertise from G-SCOP laboratory. Based on the analysis, key decision-making factors were identified in regard to technical, economic, business, environmental and societal aspects and the most important factors were incorporated into decision making criteria. Based on findings from literature and feedback from expertise, the most important factors pertinent to consider in the decision-making process were accentuated.

The multi-criteria decision-making approach has been chosen as methodology to evaluate EoL product recovery strategies at strategic level. An iterative and multi-level procedure is used for selecting an appropriate multi-criteria decision-making methodology. The decision-making approach considers business, technical, legislative, market, economic, environmental and societal factors which will be integrated into the evaluation process.

2.2.3.2. Improvement of the initial tool

The initial product recovery multi-criteria decision tool (PR-MCDT) was presented at the international conference on remanufacturing - ICoR-2017 [1]. The venue was chosen to allow many members of sustainability community, both from industry and academia, to reflect on the proposed tool. Verbal feedbacks were obtained and taken into consideration to improve the proposition. Table 6 presents a list of reviews along with their observations at ICoR 2017.

Table 6: List of reviewer's positions along with their comments at ICoR 2017

Reviewer	Position	Comments from reviewers
A	Director of The Centre for Sustainable Design & Academician at the University of the Creative arts based in UK.	The term end of life should be defined well with reference to which type of user (first user/last user) is considered in the proposed tool.
B	Academics from Linköping University, Sweden whose academic interest includes circular economy and product recovery	Quests how the tool is easily applied and implemented in a recovery company
C	Representative from recovery company based in Belgium and Denmark	Highlights end of life decision factors

2.2.3.3. Final tool development

The proposed tool was revised and improved based on the suggestions from the ICoR-2017 audience. Hence, the final version of the tool is presented as a contribution to the knowledge of this research. The following section presents the result and discusses the outcome of the research.

2.2.4. Result

2.2.4.1. Multi-criteria decision tool

A Product Recovery Multi-Criteria Decision Tool (PR-MCDT) is proposed for assessing product circularity strategies of a product at the end of its life. The six basic steps that grid the approach are as follows: (1) selection of potential end of life strategies, (2) scoping of end of life strategies, (3) selection of relevant indicators, (4) assessment of end of life strategies, (5) analysis and evaluation of end of life strategies, (6) refinement of strategies and final evaluation. Fig. 12 shows the main steps of the multi-criteria decision tool.

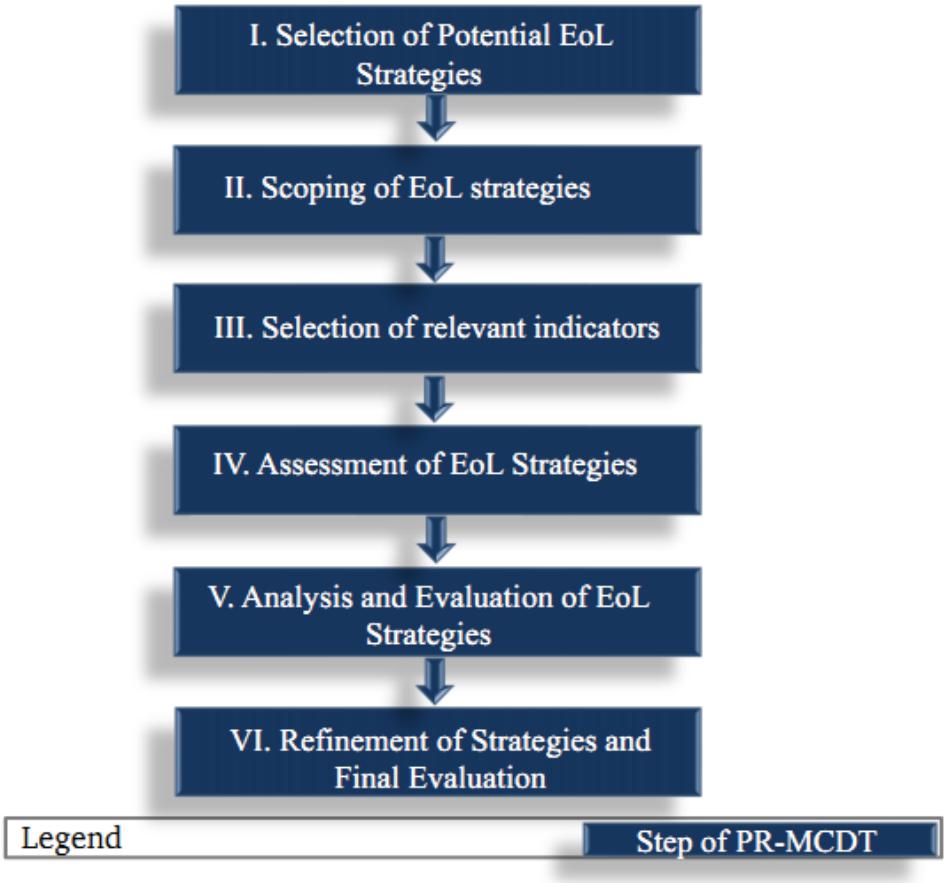

Figure 12: Multicriteria decision tool (MCDT)

MCDT is capable to consider product EoL selection holistically from an integrated point of view i.e. by simultaneously taking into account environmental, technical, economic, societal and business criteria. The main benefit of this methodology comprises, the decision maker has the opportunity to consider key decision factors such as legislation, new technologies and market demand in the end of life product recovery decision-making process. The decision-making approach also takes into account the preferences of the user

in the evaluation process of end of life strategies. A brief description of each step of the tool is presented below.

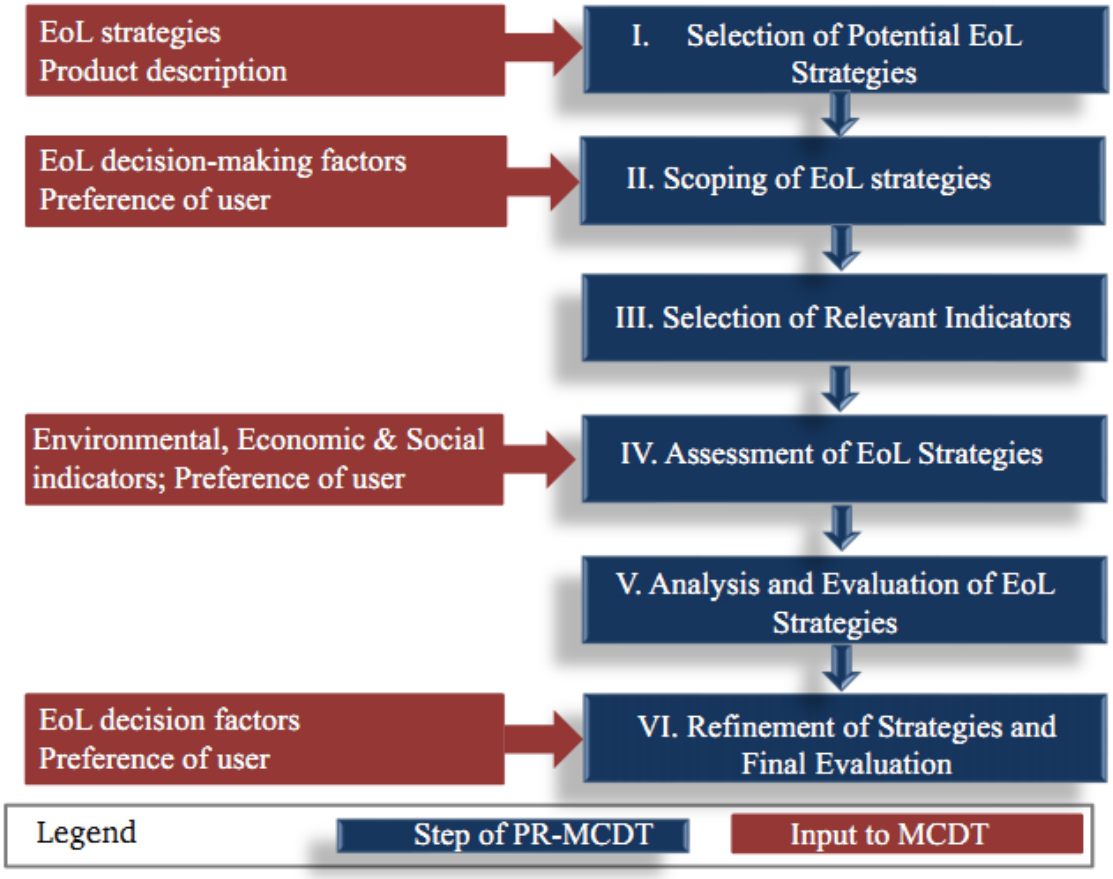

Figure 13: MCDT input

I. Selection of potential end-of-life strategies

The definition of product recovery EoL strategies, constitutes the description of the product and associated potential EoL options. In this first step of MCDT approach, the decision-maker identifies potential EoL product recovery strategies and is unlimited by any constraints. The inputs to first step of MCDT are a list of product recovery strategies and the description of the product under study. The outcome of the stage of the process is a list of potential EoL strategies for a typical product.

Product recovery EoL options include Repair, Recondition, Remanufacture, Cannibalization, Refurbish and Recycle. Except recycle, they are strategies that re-create a product similar to the initial one in order to prolong its life. If it is not possible to re-create, the recycle strategy is defined to recover the material the components of the products are made of. The strategies that transform the product in a different product like upcycle, upgrade and repurpose are out of the scope of the study. Table 7 presents a summary of main

product recovery strategies. An EoL option is considered as a product recovery strategy, if it fulfils three main criteria: collection of used products, reprocessing of a recovered product and redistribution of the processed product (Bufardi et al., 2004).

A potential product recovery EoL strategy is a possible candidate for evaluation and comparison during the decision-making process (Roy, 1996). In multicriteria decision literatures, the list of potential candidate strategies are generally called alternatives or actions (Lee et al., 2001). A functional description of the product is decisive for the recovery company to be able to achieve high level EoL treatment. The description of the product provides relevant information regarding the characteristics of the product as well as its functional use by the consumer (Sundin, 2004).

Based on work in (He et al., 2006; Ijomah, 2002; Jawahir and Bradley, 2016; Kiritsis et al., 2003; Krikke et al., 1998; Paterson et al., 2017; Pochampally and Gupta, 2012; Rose, 2000), Table 7 outlines the following end-of-life product recovery options.

Table 7: Definition of product recovery strategies

Remanufacture is an end of life product recovery strategy whereby used products are restored to the original equipment manufacturer (OEM) standard and receive a warranty at least equal to a newly manufactured product.
Recondition involves returning the quality of a product to a satisfactory state level (typically less than a virgin standard/new product) giving the resultant product a warranty less than of a newly manufactured equivalent.
Refurbishing involves returning products to a specific quality level, usually less than that of a new product. Reconditioned product has gone through extensive testing and repair than refurbished products.
Cannibalization is an activity of recovering parts from returned products. Recovered parts are used in repair, refurbishing, reconditioning and remanufacturing of other products.
Repair is an activity of returning a used product in to “working order” by fixing/replacing specified faults in a product using service parts.
Recycle is an activity where discarded materials are collected, processed and used in the production of new materials or products.

II. Scoping of end-of-life strategies

After defining potential EoL strategies, this step gives the decision maker an opportunity to take a look of defined product recovery strategies against a set of feasibility criteria for the refinement of viable EoL recovery alternatives. The purpose of step 2 is to eliminate non-conforming scenarios during initial steps

decision-making process based on various constraining influences such as technological, business, legislative and societal aspects that influence the feasibility of a particular EoL strategy.

The screening process of the EoL strategies is mainly qualitative. The selected EoL options from the screening process will be considered in the following steps of the decision-making process. The selection of a potential EoL product recovery option should be based on the information available related to the activity and experience of the decision-maker (Kiritsis et al., 2003). EoL decision-making factors and preference of the user are inputs for step 2 of the decision tool. A list of feasible strategies is the outcome at this stage of the decision-making process.

Table 8 shows a list of decision-making factors used in refinement of potential EoL strategies. Detailed explanation of how the list was created is presented in section 2.2.4.2. Based on findings from literature and feedback from expertise from academia and industry practitioners, the most important decision factors (factors written in bold letters) pertinent to consider in the decision-making process were accentuated.

Table 8: Categorization of EoL decision making factors

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

III. Selection of relevant indicators

The implementation of EoL strategy to recover a product at its end-of-life has environmental, economic and societal impacts. These impacts are measured by appropriate indicators to formulate a judgement on the selection of the best compromise for EoL strategies. The selection of relevant indicators may be accomplished from a predefined list where the decision-maker decides based on the EoL situation or develop his/her own individual indicators (Bufardi et al., 2004; Lamvik et al., 2002). Table 9 shows a list of indicators. According to (Bufardi et al., 2004), the following criteria should be specified to decide EoL situation:-

- Direction of preference: the direction of preference can be either maximization or minimization.
- Scale of measurement: the criteria can be measured on different scales depending on the availability of data and can be measured qualitatively or quantitatively.
- Unit of measurement: the criterion can be measured in different units depending on the nature of data.

Table 9: List of indicators

List of Indicators (I)	Name	Unit	Goal
Environmental (I_1)	EoL impact indicator	Eco-indicator points (Pt)	Minimizing
	CO_2 emissions	Kg	Minimizing
	SO_2 emissions	Kg	Minimizing
	Energy consumption	KWh	Minimizing
Economic (I_2)	Net recoverable value	Euro	Maximizing
	Logistic cost (Collection and transport cost)	Euro	Minimizing
	Disassembly cost	Euro	Minimizing
	Product cost (What is paid for: incineration, recycle, landfill, etc	Euro	Minimizing
Societal (I_3)	Number of employees to perform the scenario	Integer number	Maximizing
	Exposure to hazardous materials (Exposure of employees to hazardous materials in all operations)	Qualitative Scale: 5-Very important, 4-Important, 3-medium, 2-low, 1-very low	Minimizing

IV. Assessment of end-of-life strategies

Once the end of life indicators and potential product recovery strategies are selected, the next step will be an evaluation of each EoL strategies with respect to the defined indicators. Potential EoL alternatives (Alt 1, Alt 2, Alt 3 …Alt N) with respect to the evaluation indicators (I1, I2, I3 …IN) are presented in table 10 (Bufardi et al., 2004). After completing evaluation of strategies, strategies with a very bad (lowest) score is eliminated. End of life options which do not fail to have a worst value on any indicator are considered on the second evaluation (Lee et al., 2001).

Table 10: Table of evaluations

	Indicator 1 I_1	Indicator 2 I_2	Indicator 3 I_3	… Indicator n In
EoL alternative 1 Alt 1	(Alt 1, I_1)	(Alt 1, I_2)	(Alt 1, I_3)	(Alt 1, In)
EoL alternative 2 Alt 2	(Alt 2, I_1)	(Alt 2, I_2)	(Alt 2, I_3)	(Alt 2, In)
EoL alternative 3 Alt 3	(Alt 3, I_1)	(Alt 3, I_2)	(Alt 3, I_3)	(Alt 3, In)
EoL alternative 4 Alt 4	(Alt 4, I_1)	(Alt 4, I_2)	(Alt 4, I_3)	(Alt 4, In)

The definition of some of the indicators for each dimension and how they are calculated is presented below.

- **Economic indicator (I1):**

Net Recoverable Value (NRV)

Repair value = Value of component – Repair cost – Miscellaneous cost
Recondition value = Value of component – Recondition cost – Miscellaneous cost
Remanufacture value = Value of component – Remanufacture cost – Miscellaneous cost
Miscellaneous cost = Collection cost + Processing cost

Economic value = Value of component – Processing cost – Miscellaneous cost

Net recoverable value = EoL Economic Value – Disassembly cost
Disassembly cost = (Labour to disassemble product × Labour rate) + Tooling costs + Material costs + Overhead costs

Disassembly cost

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

- **Environmental indicator (I2):**

End of Life impact on the Environment (EOLI)

The end of life impact (EOLI) of a product can be computed during end of life retirement by eco-indicator (Pre Consultants, 2000):

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

Where:

N_T = total number of materials in the product
IE_i = end of life impact of material i
W_i = weight of material i (kg)

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

n= number of materials in component i

The eco-indicator values can be regarded as dimensionless figures. As a name eco-indicator is expressed in eco-indicator points (pt). In eco-indicator lists usually milli-indicator point (mPt) is used which is one-thousandth of a Pt. The end of life impact of a material for a specific strategy can be refereed from eco-indicator table (Lee et al., 2001) .A positive point implies impact imposed on the environment while a negative impact infers impact which is avoided (Lamvik et al., 2002).

- **Social indicator(I3)**

Exposure to hazardous materials: - This indicator measures the exposure of employees to hazardous materials in all operations. It can be measured in a qualitative scale (5-very important; 4-important, 3-medium, 2-low, 1-very low). The goal is to minimize the exposure of employees to hazardous materials.

Number of employees: - It refers to the number of employees necessary to perform all operations associated with the scenario. It includes logistics, processing, disassembly etc. The goal is to maximize the number of employees for societal benefit.

V. Analysis and evaluation of end-of-life strategies

This step involves the ranking of EoL strategies based on the information retrieved from step 2 and the selected environmental, economic and social indicators in Step 3. The information and data gathered from each step is critically evaluated to select the most appropriate EoL treatment strategy. Due to the wide range of different multicriteria decision-making approaches, the choice of an appropriate method should be given

great attention. It is critical for the decision maker to understand the problem, the feasible alternatives, conflicts between the criteria and level of uncertainty of the data before carrying out the choice to every multicriteria decision-making situation (Bufardi et al., 2004).

VI. Refinement of end-of-life strategies and final evaluation

Once the analysis and ranking of potential EoL strategies is completed, further detail analysis should be applied by the decision maker to understand the consequences of selecting the best suitable strategy as a final solution. A critical evaluation of the potential best feasible product recovery strategy should be done against a set of criteria presented in Table 8. This step may result in acknowledgement of the candidate strategy as a final solution or may lead to a new iteration of the approach. In case, the user found the result to be unsatisfactory, then the next EoL option is considered and evaluated in the same way as the previous candidate. Alternatively, the procedure will be repeated by considering a new set of EoL strategies and/or a new family of indicators (Goodall et al., 2014; Lamvik et al., 2002).

2.2.4.2. End-of-life decision-making factors

Findings from literature show that economic and environmental decision making factors are widely used to assess the viability of circularity strategies while neglecting other equally important factors such as legislation and societal factors (Doyle et al., 2012; Luglietti et al., 2014). Social decision-making factors are most valuable to provide feasibility analysis of adopting a recovery strategy at strategic level. Furthermore, there is lack of a holistic approach for analysing and evaluating different types of factors simultaneously.

Based upon a comprehensive literature review and feedback from expertise in the subject domain, key end of life decision-making factors used to assess the feasibility of product recovery options were identified and presented (see Table 8). The decision-making factors are categorized into business, technical, economic, environmental, legal and societal aspects.

2.2.6. Case study

To exemplify the application of product recovery multi-criteria decision tool (PR-MCDT), an illustrative example of an automotive engine is carried out to show how the approach can be used. At the end of life, an engine can follow different routes that have its own consequences from economic, environmental, societal and business point of view. In this specific case, a light fiat engine, is considered with the evaluation of its main components (cylinder block, cylinder head, pistons, connecting rods, crankshaft, Flywheel, Camshaft & Turbo) to simplify the complexity of the problem. The section is featured to follow the process defined in Fig. 12.

Step I: Selection of potential end-of-life strategies

The first step in this approach is to define the constitution of a set of potential EoL product recovery strategies. The selection of potential end-of-life strategies depends on the type of product and the associated product recovery option. In this specific case study, three potential end-of-life product recovery strategies are extracted from Table 7.

Table 11: List of potential product recovery strategies

List of Alternatives	Recovery Strategy
Alt 1	Reusing the product with minor service (Disassembly, cleaning, polishing)
Alt 2	Remanufacturing
Alt 3	Recycle

Step II: Scoping of EoL strategies

In this step, potential EoL strategies are evaluated against list of criteria categorized in to legislative, technical, business and societal aspects which is presented in Table 8. Non-conforming scenarios will be eliminated from the list while the remaining ones will be evaluated in the following steps. The selection of relevant EoL strategies depends on the preferences of the user (recovery company), the objective of the problem, experience of the user and constraints from social, market, legislation and technology. It is assumed that potential EoL alternatives of the automotive engine fairly satisfies those requirements. In general, few EoL strategies are interesting for the decision maker from a list of potential recovery options.

Step III: Selection of relevant indicator

Indicators from each dimension is selected to evaluate potential EoL alternatives. In this case study, societal indicator (exposure to hazardous materials), environmental (carbon footprint), and economic indicator (total revenue) is used.

Table 12: List of selected indicators

List of indicators	Name	Unit	Goal
Environmental	Carbon footprint	Kg. CO2	Minimize
Economic	Total revenue	Euro	Maximize
Societal	Exposure to hazardous materials	Quantitative scale 5. very important; 4-important, 3-medium, 2-low, 1-very low	Minimize

Step IV: Assessment of end-of-life strategies

The evaluation of the EoL strategies with respect to the indicators is presented in Table 13 (Luglietti et al., 2014). The total revenue for realizing a recovery strategy is calculated by subtracting all costs incurred for implementing a recovery alternative from the revenue of selling the product/material. Based on the evaluation of the potential EoL strategies with the relevant indicators, the decision-maker can eliminate potential options which have very low result.

Table 13: Economic evaluation of EoL strategies

Indicator 1 (Economic)	EoL Alt. 1 Reuse	EoL Alt. 2 Remanufacture	EoL Alt. 3 Recycle
Revenue selling materials (£)			108.46
Steel			5.74
Cast iron			34.85
Aluminium			68.44
Revenue of Selling Engine (£)	162.00	2562.00	
Operating costs	43.47	263.46	158.20
Energy Consumption	3.91	24.85	3.50
Workforce costs	39.56	238.60	154.71
Total Revenue (£)	568.53	2298.54	-49.75

Table 14: Environmental evaluation of EoL strategies

Indicator 2 (Environmental)	EoL Alt. 1 Reuse	EoL Alt. 2 Remanufacture	EoL Alt. 3 Recycle
Kg CO2 eq. treatment process	561	10920	502
Kg CO2 eq. recycling process			337154
Kg CO2 eq. avoided remanufacturing	28978	72446	
Kg CO2 eq. avoided raw material extraction	640719	640719	640410
Benefit	-669137	-702245	-302754

Table 15: Social evaluation of EoL strategies

Indicator 3 (Societal)	Reuse	Remanufacture	Recycle
Exposure to hazardous materials (Quantitative scale 5. very important; 4-important, 3-medium, 2-low, 1-very low)	2	3	4

Step V: Analysis and evaluation of end-of-life strategies

In this case study, it appears that remanufacturing has better environmental and economic benefit over reuse and recycling strategies. In terms of societal benefit, reuse strategy imposes less risk to the exposure of hazardous materials over remanufacturing and recycling strategies while remanufacturing imposes medium risk to exposer of hazardous material over employees. Even though, remanufacturing (EoL alternative 2) is the best compromise EoL strategy from an integrated point considering environmental, economic & societal indicators.

Table 16: Table of evaluation of EoL strategies

Indicator	EoL Alt. 2 Remanufacture	EoL Alt. 1 Reuse	EoL Alt. 3 Recycle
Economic Total Revenue (£)	2298.54	568.53	-49.75
Environmental Benefit (Kg CO2)	-702245	-669137	-302754
Societal - Exposure to hazardous materials (Quantitative scale 5. very important; 4-important, 3-medium, 2-low, 1-very low)	3	2	4

Step VI: Refinement of strategies and final evaluation

Before taking the final decision, EoL alternative 2 (Remanufacturing) should be examined in more detail following step II. Even if from a technical point of view, if remanufacturing of the automotive engine is possible, further investigation should be made to examine the selected strategy with list of pertinent decision-making factors like market demand and compliance with legislation. If it is realized that a the selected EoL option is unsatisfactory, another EoL option should be analysed again based on the ranking of the evaluation or the evaluation process is repeated with a consideration of alternative EoL strategies.

2.2.7. Conclusion

In this paper, we proposed a general product recovery multi-criteria decision tool (PR-MCDT) to evaluate product circularity strategies at strategic level. The decision-making tool uses a holistic approach, under several often-conflicting criteria, to assess the feasibility of recovery options with respect to relevant business, legal, environmental, social and economic factors and by taking in-to account the preferences of the decision maker. Based on the analysis of literature and feedback form expertise, decision-making factors were also identified in regard to technical, economic, business, environmental and societal aspect. The paper also highlighted key decision-making criteria pertinent to consider in the decision-making process.

The paper dealt with important aspects related to the proposed approach such as definition of EoL strategies, selection of relevant indicators and exploitation of results. The proposed decision-making tool was also applied to an automotive engine case to illustrate the applicability of the approach. The results show that, remanufacturing is a feasible EoL option compared with repair and recycling strategies.

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2.2. PART II - Model: Modelling of the reverse logistics system

In this section, the second main part of this Ph.D. thesis is presented. A modelling of the reverse logistics system is accomplished through system dynamics modelling approach. The list of decision-making factors identified in the previous section (Part I) are used as input to model the system described in this chapter.

Table 17: Summary of paper #2

Title	**Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries**
Published in	Alamerew, Y.A., Brissaud, D., 2020. Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2020.120025
Keywords	Circular economy, Reverse supply chain, Remanufacturing, System dynamics (SD), Electric vehicle battery (EVB), Repurposing
Abstract	Circular economy (CE) is increasingly recognized as an issue of critical importance for companies, academics, practitioners, policymakers, and society as a whole. A successful transition from the current, linear economic model towards a resource-efficient circular economy model requires a shared understanding of the interplay among the building blocks of circular economy and the interaction among various decision factors. This research aims to explore these dynamics using environmental, societal, and economic aspects from a reverse supply chain perspective. This paper presents a model to represent the complex system of reverse logistics to recover post-used products at their end-of-life (EoL) stage. A system dynamics (SD) approach is used to model the dynamics of cost, revenue, and strategic and regulatory decisions. In addition, the interplay among the main pillars of circular economy research is explored through a case study of electric vehicle batteries (EVBs). Moreover, the main enablers and challenges for recovery of end-of-life batteries are presented. The findings show the importance of a shared understanding to achieve a successful transition towards a resource-efficient and circular economy model. Furthermore, reuse strategies such as remanufacturing and repurposing present a huge market potential for the recovery of electric vehicle batteries in the near future.

2.2.1. Introduction

In the last few years, the concept of Circular Economy (CE) has attracted the attention of researchers, practitioners and policymakers. Instead of linear flows of materials and products through the economy, CE promotes circular flows to reduce environmental impacts and maximize resource efficiency as a strategy for sustainability. It aims to meet economic prosperity, while maintaining environmental quality and social equity to create sustainable world for future generations (Kirchherr et al., 2017). The implementation of circular economy principles is critical in meeting sustainable development goals (Korhonen et al., 2018; Saidani et al., 2018).

The successful implementation of CE principles depends on combined leveraging of building blocks of CE including reverse supply chain, product/service design, business models, end-of-life (EoL) recovery, product/service use and policy (EMF, 2015). The development of an efficient reverse logistics system is pertinent for recovery of EoL products (Govindan and Soleimani, 2016). In order to effectively plan recovery of post-used products: product designers, policy makers, researchers and decision makers need to improve their shared understanding of the interplay among the main pillars of CE and the interaction among various decision factors. This includes information about dynamically related legal, economic, social, business, and environmental aspects (Brissaud and Zwolinski, 2017; Wahl and Baxter, 2008). Sharing common understanding among various areas of research leads to a better understanding of the problem and enables solving of complex problems in reality (Sakao and Brambila-Macias, 2018). Fig. 14 shows the main building blocks of circular economy and various influencing factors within a system. The arrows show that there is a complex interaction among the building blocks of CE and related factors within a system.

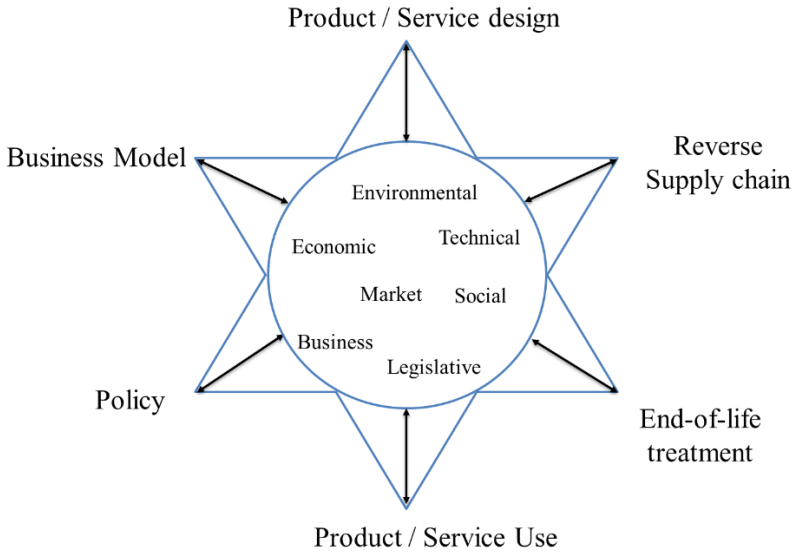

Figure 14: Interplay between diverse disciplines in the circular economy

Also, it is very crucial to develop an optimal reverse supply chain under multi-level supply chain scenario. The development of optimal multi-level supply chain has a great importance for an efficient recovery of post used products. Among the recent studies on multilevel supply chain: Gharaei et al., (2019b) proposed a multi-product, multi buyer mathematical model of the supply chain under vendor managed inventory with consignment agreement; Shekarabi et al., (2018) developed a model for a multi-product, multi-wholesaler, multi-level, and integrated supply chain under shortage and limited warehouse space; Gharaei et al., (2019a) proposed an economic production quantity (EPQ) model of replenishment designed to minimize the total inventory cost and maximize the profit, simultaneously.

Electric vehicles have been widely used due to their significant energy and environmental benefits and have shown a good alternative for conventional gasoline vehicles with their no emission of local pollutants. More than 11 million electric batteries are expected to be sold by 2020 (L. Li et al., 2018). The battery of an electric vehicle takes 40% of added value due to high expense for the cost of production. Electric vehicle batteries deemed to be unsuitable to meet the standard of electric vehicles due to their degenerative nature (Kampker et al., 2016). In order to meet the performance and safety of electric vehicles, batteries are replaced when the capacity has reached 80% of its capacity but can still be used for further applications.

At the EoL phase, an electric vehicle battery (EVB) could be remanufactured, repurposed, reused, and recycled. These recovery operations are mostly implemented in small and medium size enterprises (SMEs). Often SMEs do not have enough knowledge and capacity to evaluate the effectiveness of circularity strategies and their respective business models (Slotina and Dace, 2016). More importantly, EVB is a fast-evolving technology and may face disruptive innovations including improved performance, which affects the stability of a recovery business. In this regard, a shared understanding of the interplay among building blocks of CE such as business, reverse supply chain, policy, use, design and EoL recovery is crucial for the transformation towards circular production. Lack of such information can hinder the advancement of circular economy in the management of EVBs.

Circularity strategies include remanufacturing, re-use, repair, refurbishing, and reconditioning. In addition, materials and energy could be recovered by recycle and incineration strategies (Alamerew and Brissaud, 2018). The paper also notes the importance of emerging EoL circularity strategies for SMEs, such as upgrading and repurposing. These emerging strategies transform post-used products into like-new products that will be used for a different purpose and function (Bauer et al., 2017).

Several authors have studied the recovery process of post-used EVBs. Li et al. (2018) investigated the cost of supply chain for remanufacturing of EVBs at the enterprise level while Kampker et al. (2016) analysed

the current and future challenges of remanufacturing EVBs. Ramoni and Zhang, (2013), presented end-of-life options for recovering EVBs. But there has been no previous study in this area that presents the interaction among a variety of influencing factors including economic, societal, managerial, regulatory, and environmental factors for recovery of post-used EVBs.

Considering the growing challenge of waste from EVBs, the research objective of this paper is therefore to address practically the following research questions:

- How to model the complex system of reverse logistics for post-used products to advance circular economy perspective and for the case of electric vehicle battery recovery system?
- Which factors influence the dynamics of decision on circularity/recovery of electric vehicle batteries?
- What are the enablers to advance circularity of electric vehicle batteries and the existing main challenges?

This research aims to understand the synergetic interaction among diverse disciplines and the variety of influencing factors including economic, societal, managerial, regulatory, and environmental factors for the case study of EVBs.

The paper is structured as follows. Section 2.2.2 presents the main insights about circular economy, transdisciplinary research, EoL circularity strategies, reverse supply chain, and system dynamics. In section 2.2.3, the research framework of the study is presented. Section 2.2.4 presents the main results of research on the case study of electric vehicle batteries. Finally, conclusions are drawn by summarizing the main findings of the study and pointing out future research directions.

2.2.2. Literature review

2.2.2.1. Circular economy

An Industrial Economy (IE) can follow a linear economy, circular economy or performance economy model. Circular Economy (CE) aims to maintain the value of products, components, materials and resources in the economy for the longest time possible. CE business models falls into two categories: those that extend product life times by reuse, repair, repurpose, refurbish, recondition, upgrade, retrofit, and remanufacture; and those that close resource cycles – through recycling strategy (Bocken et al., 2017; Stahel, 2016). Management of EoL products plays an important role in the action plan for a circular economy (Alamerew and Brissaud, 2017). Adopting circular economy is expected to have considerable benefits in reducing waste volume, reduction of raw material imports and a boost for economic growth (Fellner et al., 2017). In

December 2015, the European Commission adopted an ambitious circular economy package to support EU's transition to a circular economy (European Commission, 2015).

2.2.2.2. Transdisciplinary research

The complexity of the circular economy concept raises a number of practical challenges that require experts from diverse disciplines. It requires close collaboration between academics and non-academics "transdisciplinary research approach" for knowledge production in research and decision-making in practice (Popa et al., 2015; Sauve et al., 2016). Transdisciplinary research approach enables mutual learning between scientists and external stakeholders (Jahn et al., 2012). Definitions regarding multidisciplinary, interdisciplinary and transdisciplinary are often confusing and are clarified in Table 18.

Table 18: Definition of transdisciplinary, multidisciplinary and interdisciplinary research (Sakao and Brambila-Macias, 2018)

Multidisciplinary research	Constitutes more than one discipline where each discipline makes its own contribution while researchers may share research approaches to solve a common problem.
Interdisciplinary research	Researchers from different disciplines come together and share information, data and tools to solve a common problem that is beyond their disciplinary boundary.
Transdisciplinary research	Problem solving for "real world" where academics and nonacademic stakeholders temporarily collaborate in order to make creative and innovative solution.

2.2.2.3. Electric vehicle batteries (EVBs)

The transport sector has shown lower sustainability performance (Karaeen et al., 2017). Recently, electric vehicles (EVs) play an important role in the transition towards a more sustainable transport sector. The rapid development of EV drives the rise in EV battery's production (Zou et al., 2013). EVB is a complex multiple material product which is expected to last 5 to 8 years of service life for the EV application.

With the growing number of retired EVBs, and increasing market share of EVs, a greater volume of post-used batteries will likely to enter the waste stream in the near future (Winslow et al., 2018). There is a lack of awareness of the complexities in the battery industry, including the chemistry, applications, EoL treatments, risks, and legislation (Green, 2017).

Many scholars studied the recovery of post-used EVBs and the effects of various decision factors on the recovery system. (Green, 2017), studied the influence of legislation in reuse and recycling of EVBs, while Li et al., (2018) established a dynamic game model to address the problem and simulate EoL electric battery multi-channel recycling system. Jiao and Evans, (2016), explored business models of different EV stakeholders that facilitate battery reuse for second-life applications. Zhu et al., (2017) established a mathematical model to study the effect of the remaining life cycle on the economy of spent EVBs for second use application as backup power for communication base station. The results show that the economy is influenced by the remaining cycle life for new energy application scene and its effect is weaker than calendar life and purchase price compared to high temperature and one or two types of electricity scenes.

2.2.2.3.1. End-of-life electric vehicle battery recovery strategies

At its end-of-life phase, an EVBs can be recovered through applying various circularity strategies such as reuse, remanufacturing, repurposing, and recycling (Gaines, 2012; Wolfs, 2010). EoL in this paper refers to the point in time when the battery gets removed from the vehicle regardless of its condition in which the product no longer satisfies the first user. A description of circularity scenarios for recovering an EoL EVB is presented in the following section. Fig. 15 shows the circularity strategies used to recover post-used EVBs.

Reuse

EVs could reach their EOL phase before the battery reaches 80% of its capacity due to early vehicle failure or crash. In such scenarios, the battery can be reused as a replacement battery for vehicles with the same brand (Richa et al., 2014; Winslow et al., 2018). However, the reliability and compatibility of spent batteries is the main concern for reuse applications (Burke, 2009).

Repurposing

Repurposing is an emergent circularity strategy where discarded products are recovered and used in a new product that has a different purpose and application compared to the original product (Bauer et al., 2017). End-of-life EVB could be reused for different applications such as energy storage for renewables of solar panel and wind farms, residential and public back up power systems, distribution grids, and energy storage for the electric heater (Bowler et al., 2015; Richa et al., 2014). For instance, repurposed EVBs can be used as backup power for telecommunication base stations (Zhu et al., 2017). Each of these repurposing applications requires their own design, development and manufacturing activities (Foster et al., 2014).

Remanufacturing

Remanufacturing is an industrial process whereby used products are restored to the original equipment manufacturer (OEM) standard and receive a warranty at least equal to a newly manufactured product (Ijomah, 2002; Rose, 2000; Sundin, 2004). Due to different application requirements and considerations, the second use of spent batteries might not be the optimal recovery scenario. Remanufacturing of EVBs deemed to be an optimal solution in the near future. Remanufacturing of EVB involves partial disassembly, replacement of substandard cells and reassembly of the battery (Foster et al., 2014). EVBs components, including cells and periphery modules, are suitable for remanufacturing process (Kampker et al., 2016). Also, the economic viability of remanufactured EVBs components depends on future spare part price (Rohr et al., 2017). According to Foster et al., (2014), cost-benefit analysis shows that remanufacturing of batteries is economically feasible saving up to 40% over new battery use.

Recycling

Recycling is an activity where discarded materials are collected, processed and used in the production of new materials or products (Ijomah, 2002; Jawahir and Bradley, 2016). Recycling is a popular strategy for recovering valuable materials, such as cobalt and lithium, from end-of-life EVBs (Winslow et al., 2018). Post-used EVBs could be recycled by the battery manufacturer, automotive manufacturer, retailer, and third-party recycler. The European Union has a well-established recycling infrastructure.

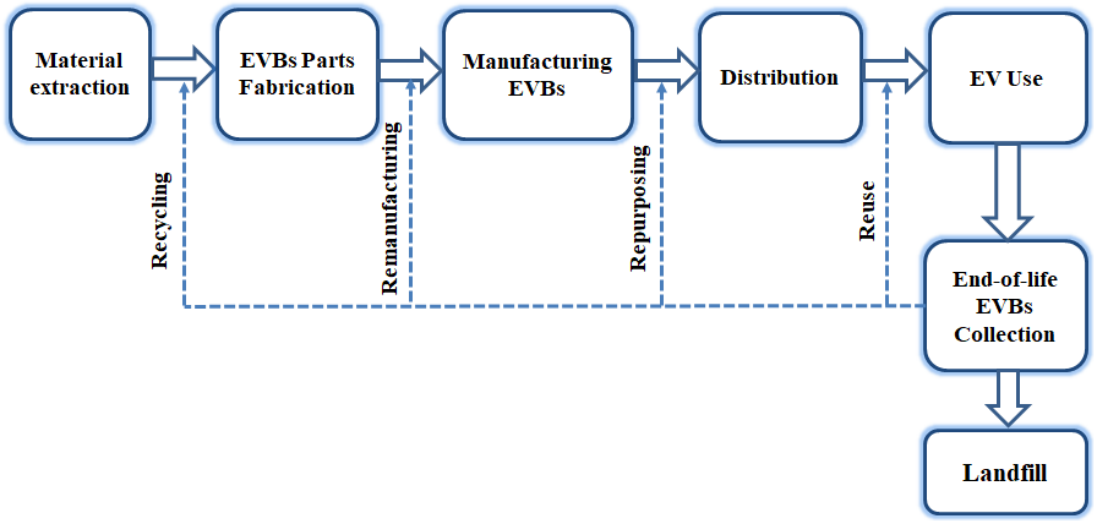

Figure 15: Circularity strategies for retired batteries

2.2.2.4. Systems dynamics

System Dynamics (SD) is an effective methodology to analyse and assess the dynamic nature of large-scale complex systems. The field developed originally in the 1950s by Professor Jay Forrester at the Massachusetts Institute of Technology. Currently, SD is widely used for improvement in strategy development, policy design and decision-making in and across complex, dynamic domains by academics, large companies, consulting agencies and government organizations (Martinez-Moyanoa and Richardsonc, 2013; Sterman, 2002).

Recently, there are several works of literature on system dynamics modelling of EoL product circularity strategies. Poles, (2013) developed an SD model to evaluate system improvement strategies of a remanufacturing scenario. The result shows that efficiency in the remanufacturing process with a higher remanufacturing capacity is achieved by a higher return rate and lower lead time. In another study, Farel et al., (2013) applied a system dynamics approach to analyse cost and benefit analysis of future EoL vehicle glazing recycling in France. This study identifies that a recycling network would increase income and reduce processing cost. (Guan et al., (2011), applied a combination of geographic information system (GIS) and system dynamics (SD) modelling system to assess and model economy, resource and environment systems. Golroudbary and Zahraee, (2015), constructed a simulation model for optimizing the recycling and collection of waste material across the supply chain. Qingli et al., (2008) examined the long-term behaviour of a single product reverse supply chain with remanufacturing and simulated the inventory variation and bullwhip effect based on SD methodology. This study shows that a remanufacturing scenario improves market share and reuse ratio while reducing the bullwhip effect of the closed-loop supply chain.

EoL product management is a complex system, which often involves sophisticated interactions and multiple feedbacks among a number of related economic, regulatory, lifestyle and societal factors (Alamerew and Brissaud, 2018). Management of EoL products requires a comprehensive approach to analyse the interaction among various system components that utilizes flows, feedback loops, auxiliary variables, and stocks to assess the dynamic nature of large-scale complex system.

2.2.2.5. Multi-level supply chain

The study of multi-level supply chain regarding reverse supply chain plays an important role for an effective and efficient recovery of post-used products. There are several studies on the research area of multi-level supply chain. Gharaei et al., (2019b) proposed a multi-product, multi-buyer mathematical model of the supply chain under vendor managed inventory with consignment agreement. The model used a novel approach for supply chain design and optimization that involves multi-product and multi-buyer under penalty, green and quality control policies and a vendor managed inventory with consignment agreement

for optimal batching size. In another study, Shekarabi et al., (2018) developed a model for a multi-product, multi-wholesaler, multi-level, and integrated supply chain under shortage and limited warehouse space. The model aims to define an optimum number of lots and the optimum lot volumes in order to minimize the total cost of the supply chain. Gharaei et al., (2019a) proposed an economic production quantity (EPQ) model of replenishment designed to minimize the total inventory cost and maximize the profit, simultaneously. The study aims to optimize the lot sizing of replenishments.

2.2.3. Methodology

This study applies three main steps to formalize the results: identification of system variables, modelling of the system and analysis of each sub-system. Fig. 16, shows a graphical representation of the methodology used in this study.

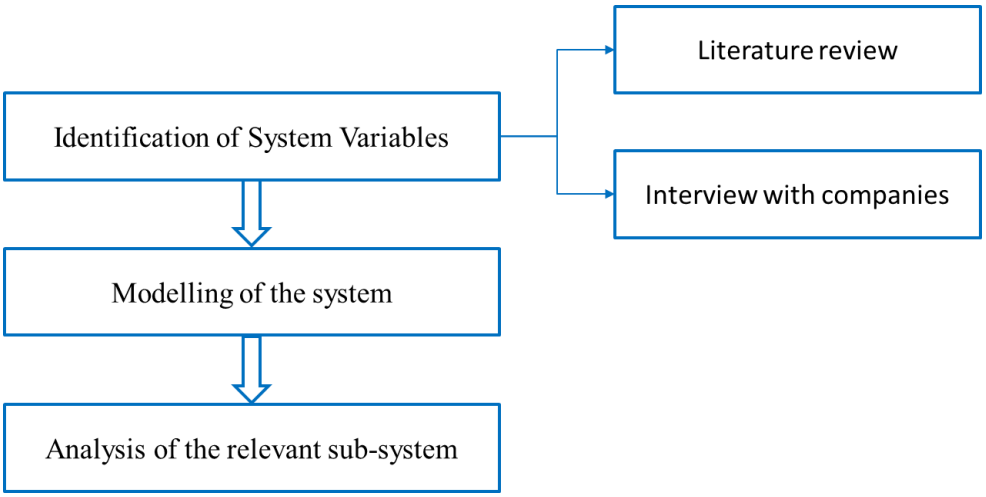

Figure 16: Schematic representation of the methodology

2.2.3.1. Identification of system variables

2.2.3.1.1. Literature review

A review of literature was made to deeply understand the state of the art on the recovery of EoL electric vehicle batteries and to identify enablers that facilitate effective recovery of post-used EV batteries. Reviewing literature also helps to identify key system variables covering environmental, legal, economic, and social aspects from various areas of research including design, reverse supply chain, business models, EoL recovery, and user perspective. Those key factors were used as input to model the interaction among various decision factors in regard to cost, revenue, and strategic and regulatory decision categories.

2.2.3.1.2. Interview with companies

Interview with companies from various stakeholders is accomplished in order to validate the findings obtained from a literature review in Step 1. Interviews were used to formalize and improve the developed model. Participants of the interview are from various stakeholders which increased the reliability of data and enriched the source of information. The data for this research was obtained from a semi-structured interview. Mostly, interviewees were company managers and each interview took between half an hour to one hour.

The companies involved in the case study are involved in the design, recycling, re-use, and repurposing applications (Table 19). The companies were selected based on their active involvement in the recovery chain of EVBs. In addition, the companies have networks with various stakeholders including first users, manufacturers, and customers. Also, scholars from business, reverse supply chain, recovery strategies management, policy, and consumer/user perspectives participated in developing and improving the model in a workshop.

The case study companies were eminently involved in developing the model including identifying decision factors; formulating the interaction among decision factors; and identifying key pertinent decision-making factors from the model. In addition, they are involved in identifying the main enablers and challenges for the recovery of EVBs.

In developing the SD model, the case study companies were firstly participated in identifying variables in building the model. The interview participants identified decision factors from their experience and from a list of variables collected from the previous study by (Alamerew and Brissaud, 2018). Then, the interviewees were involved in revising, improving, and validating the proposed model. The proposed model is improved following recommendations and suggestions from the case study companies. Also, the companies involved to identify the main enablers and challenges to recover EVBs through interviews by filling in the interview guide which is followed by a discussion.

The interview consortium is composed of three small and medium size (SMEs) companies, so-called Companies A, B and C who are involved in the EVB recovery business; research and development (R&D) company (Company D) that design batteries for electric vehicles; and a big company that creates waste of electric batteries (Company E). All these companies are mainly operating and situated in France.

Company A collects post-used EVBs from its key partners and installs into electric heaters that will be sold to customers. The company also provides service including battery maintenance and transportation as well

as collection and analysis of the data collected during use phase. In addition, the company works in close collaboration with OEMs and a recycling company.

Company B repurposes post-used EVBs in a modular battery system designed for small and medium series. The batteries could be used for mobile charging stations and forklift trucks.

Company C has been involved in recycling business of EVBs for over 30 years. The company recycles retired EVBs obtained from numerous international sources. It recovers 9 metals (aluminium, cobalt, copper, iron, lithium, nickel, platinum, neodymium and titanium) and feeds back them into the European Economy. Besides recycling of EVBs, it is also involved in consultation activity on waste import/export, collection of European industrial batteries, sorting and quality control of EVBs.

Company D is a high-tech R&D company that designs equipment for energy including batteries for electric vehicles. It is certainly one of the biggest companies in France performing this business.

Company E uses electric bikes for its business. At the EoL stage, post-used batteries are replaced by new ones. The stock of post-used batteries is given to company A.

Table 19: Summary of companies involved in the case study

Company	Role as a stakeholder	Country	Business model
Company A	Battery user	France	Selling of smart heaters including repurposed/reused EVBs
Company B	Battery user	France	Selling of reused/repurposed EVBs to forklift truck manufacturers
Company C	Battery recycler	France	Selling of recovered materials after recycling of EVBs
Company D	Battery designer	France	Service provider (Design projects)
Company E	Post-used battery supplier	France	-

2.2.3.2. Modelling technique of the product recovery system

This study applies a System Dynamics (SD) modelling approach to model the interplay among areas of research in the CE including design, business model, reverse supply chain, product/service use, policy, and EoL recovery. It also studies the interaction among various decision-making factors such as socio-economic and legislative factors in EVB recovery systems. VENSIM software package is used to design SD diagram. The stock and flow diagram to study the benefit of remanufacturing EVBs is modelled by SD approach. The diagram is developed using a cost-benefit analysis. The data used in the model were collected from (Idjis, 2015).

2.2.3.3. Analysis of the relevant subsystems

The dynamics of EoL EV battery recovery system is analysed from three main perspectives: dynamics of cost, revenue, and strategic and regulatory decisions for the recovery of EVBs. These three system perspectives were selected from literature reviews inspired by Chen et al., (2015) and Farel et al., (2013). Those have been identified and modelled using system dynamics software VENSIM DSS.

The causal loop diagram is firstly developed from a literature review with respect to three main perspectives. Then, the developed model is tested with companies for validation. The model is improved based on the suggestion from the case study companies. Each diagram is built by following 5 main steps (step 1: define the theme; step 2: place the variables and identify the focus variable; step 3: determine the causality and the feedbacks; Step 4: determine the polarity, and step 5: refine the model).

2.2.4. Results and discussion

In this section, first, modelling of remanufacturing of EVBs and the dynamics of strategic and regulatory decisions are presented. Then the interplay among the building blocks of circular economy research is discussed. Finally, the main enablers and challenges for recovery of EVBs are presented.

The stock and flow diagram to represent the remanufacturing activity for remanufacturing of EVBs in France is presented in Fig 17. The gross benefit of remanufacturing is formulated based on a cost-benefit analysis on SD modelling. Cost of remanufacturing EVBs is influenced by treatment cost (32 €/KWh), transportation cost (10 €/KWh), and fixed cost (60 €/KWh). The remanufactured battery price is assumed to be 60% of the original battery price. The price of a new battery started with a price of 800 €/KWh with 10% reduction per year. Available volume of EoL batteries is assumed to be 10000 with 10% increment per year. The cost data were collected from a research paper (Idjis, 2015).

The model is simulated for 20 years period (Fig. 18, Fig 19 and Fig 20). The graphs show the gross benefit of remanufacturing, remanufacturing margin, and price for remanufactured and new EVBs. The first scenario (simulation 1) represents remanufacturing under current conditions. On the second scenario (Simulation 2), it is assumed that the current logistic system is optimized as it should be in future. In this scenario, the collection and transportation costs are assumed to be half of the current cost. This leads to the increment of remanufacturing benefit for the industry. Also, it is assumed that the price of a remanufactured battery is 40% less than that of a new one. The model demonstrates the cost-benefit analysis of remanufacturing of EVBs that could be the strategy to tackle the accumulation of waste in the near future.

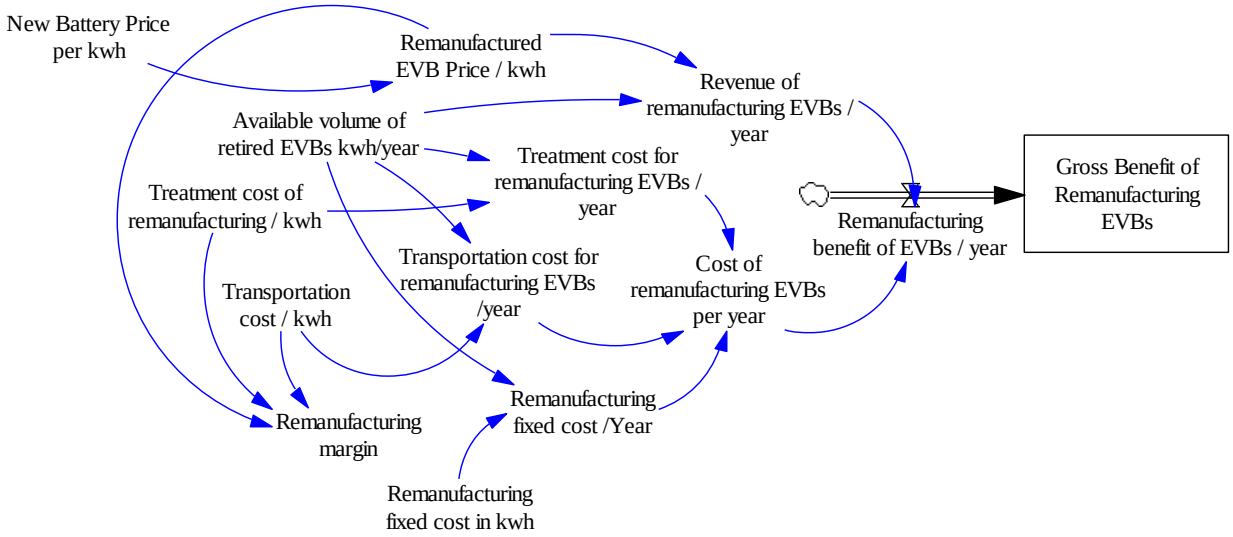

Figure 17: Proposition of a general model for remanufacturing of spent batteries

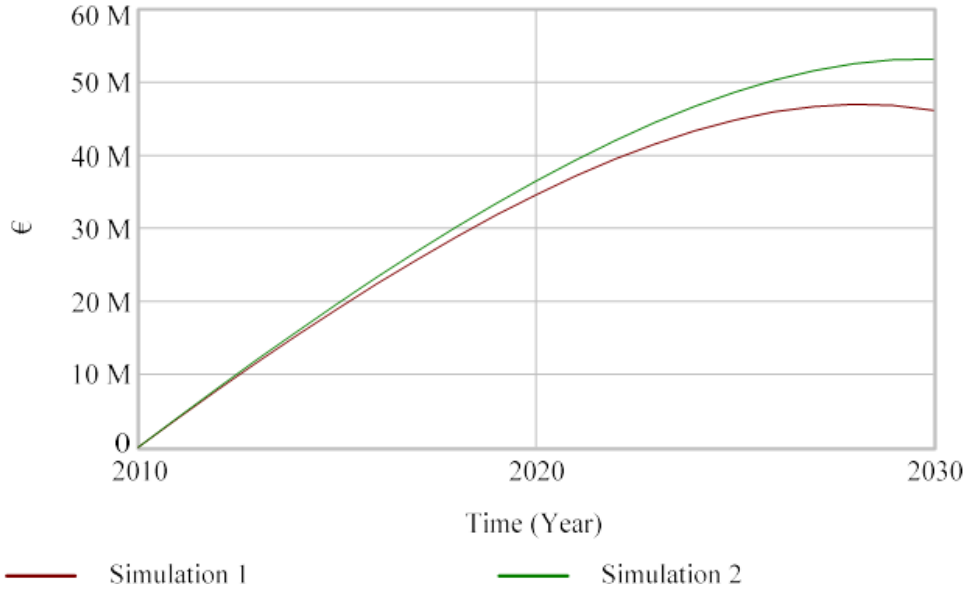

Figure 18: Simulation result for benefit of remanufacturing

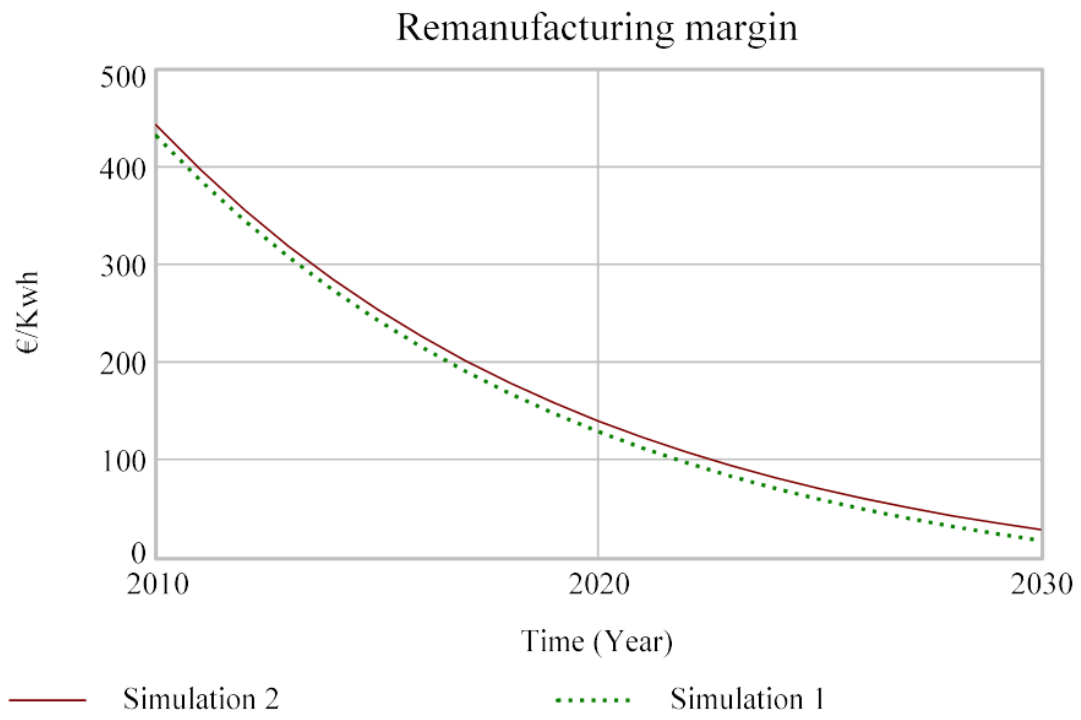

Figure 19: Simulation result of remanufacturing margin

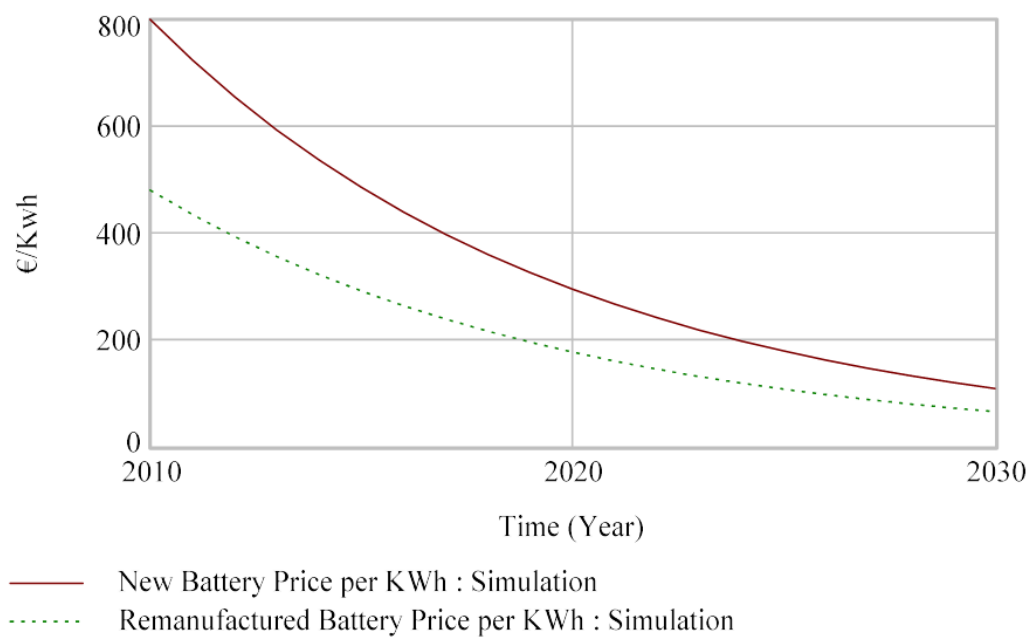

Figure 20: Simulation result of remanufacturing and new battery price

System dynamic modelling approach is used to represent the interaction among various decision factors in each sub-system. Each sub-system establishes its own network and the influence of one factor upon another is represented in a diagram. Representation by using a causal loop diagram (CLD) shows how connections to a system give rise to system behaviour and the potential impacts of modifying the connections. The CLD diagrams are presented from section 2.2.4.1 to section 2.2.4.3. The interaction among decision factors in each sub-system: dynamics of cost; the dynamics of revenue; and the dynamics of strategic and regulatory decisions on the recovery of EVBs is presented in the following sections.

2.2.4.1. Dynamics of cost decisions in EVB recovery management system

The recovery cost of EVBs depends on various decision factors including collection, storage, transportation, sales/EoL EVB, and treatment cost. At the EoL phase, EVBs could be recovered through circularity strategies such as repurposing, remanufacturing and recycling. Fig. 21 represents the causal loop diagram on the dynamics of cost in EVB recovery system. A plus "+" sign on the CLD shows a positive relation while a minus "-" sign shows inverse relation between decision factors.

The use of innovative and new business models influences the recovery cost of EVBs. Company A is involved in repurposing of post-used EVBs for 2nd life applications. The company receives huge number of post-used batteries from its industrial partners such as Company E for free and install those batteries into electric heaters for second life application. In addition to selling repurposed electric heaters, the company provides service to customers and collects usage history of repurposed batteries. When the repurposed battery reaches at the end of 2nd use phase, then the company (Company A) either sells or gives for free to a third-party recycling company, Company C, based on the market price of recovered materials.

In EVBs recovery system, the collection cost, transportation cost, and battery return rate affect the profitability of a recovery business. As shown on the causal loop diagram, establishing an optimal recovery system through a well-established network (optimized logistics) helps to decrease the cost of recovery. Furthermore, if the recovery process is optimized by selecting an optimal circularity strategy such as remanufacturing, re-use, recycling, and repurposing, the total cost of recovery would significantly decrease. This could be achieved through standardized battery labelling and/or battery registry which would reduce battery sorting, testing times and costs related to the dismantling of the battery packs and modules. Also, it helps to identify the battery chemistry. Interestingly, one of the main economic potential in the recovery of EVB is the availability of cores. Having an efficient supply chain to collect end-of-life EVBs would benefit the recovery system.

The design of battery packs influences the recovery cost of EVBs. For instance, the design of modular and interminable battery packs enables the replacement of defective or outdated battery cells, which in turn allows for additional cost-saving and prolongation of battery life (Kampker et al., 2016). Also, an innovative design of batteries to bypass weak cells would reduce the recovery cost. In addition, electric vehicle design by itself has an influence on the EVB recovery to be able to integrate remanufactured batteries. This gives a high level of freedom for the integration of remanufactured batteries into the product. In this regard, standardization of battery configurations plays a paramount role in the recovery of EVBs.

To sum up, recovery EVBs will become economically viable with the gradual improvement of technology, environmental performance, and recovery process. This requires collaboration and work of academics and non-academics from various areas of research.

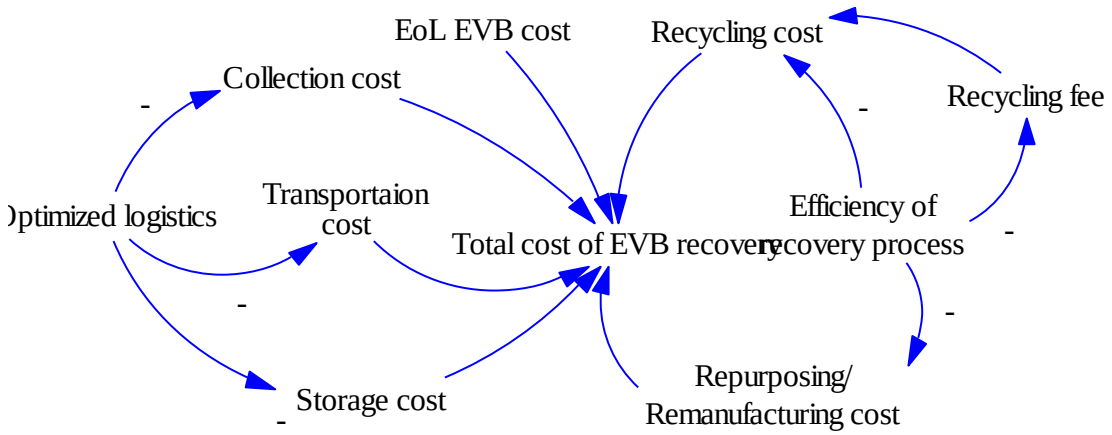

Figure 21: Dynamics of cost in EVB recovery system

2.2.4.2. Dynamics of revenue in EVB recovery management system

Recently, there is a growing market for 2nd use application of EoL batteries due to the rising number of EoL electric vehicle batteries. However, there is a lack of research on the revenue potential of the recovery business for SMEs. Although the market is still emerging and untapped, stakeholders are reluctant to start the recovery business due to market uncertainty. In this regard, mapping the dynamics of revenue helps to understand the interaction among various decision-factors and their influence on the profitability of a recovery business.

The revenue of EVB recovery could be earned by recovering post-used EVBs through the implementation of circularity strategies such as re-use, remanufacturing, repurposing, and recycling. Also, revenue could be gained by providing service to customers during the 2nd life cycle of the product. Recovered products and materials are supplied to a secondary market.

Based on the results of a case study, Company A earns revenue by selling repurposed electric heaters, providing service to customers, and selling EoL spent batteries to a recycling company (Company C) when the product reaches at the end of 2nd life. Company B generates revenue by packing modular batteries for different applications such as forklift trucks based on energy requirements, while Company C sells recycled materials. Fig. 22, demonstrates the cause and effect diagram of variables influencing the revenue of recovered EVB product.

As shown in the CLD, Fig. 22, the revenue of recovered EVB products/materials is influenced by the demand for recovered product and material, availability of enough stock in the market (quantity of recovered product/material in the market), availability of sufficient core for recovery, price of recovered product and material, and price for new product and material. Results from the case study show that the revenue of EVB recovery business is highly influenced by the availability of sufficient EoL EV battery stock for recovery, price of recovered product/material, and demand for recovered product/material from customers. This is supported by the results of Zhu et al., (2017) where the economy of post-used EVB highly depends on the purchase price and calendar life of post-used EVBs.

The demand for a recovered product/material is influenced by the level of customer satisfaction. In addition, the price difference between recovered product and new product influences the revenue of the business since consumer preference is skewed by cost. Even though, the result of the case study "Company A" shows that customers are still willing to buy costlier recovered products.

In addition, the availability of enough stock in the market has a positive influence on the revenue of a recovered product/material. Also, it is highly influenced by the supply of post-used EVBs. This, in turn, depends on the cost-effective and optimal reverse supply chain system. The revenue from a recycled EVB could also be influenced by the motivation of industries to use recycled materials and the price difference between recycled material and extracted material. This is an interesting opportunity for recycling companies since the cost of virgin raw materials is expensive in the primary market.

As depicted in Fig. 22 demand for recycled material has a positive influence due to several incentives such as motivation for reducing environmental impact and motivation for raw material cost reduction. Environmental impact studies on the assessment of EVBs show that CO2 and SO2 emissions from the production of battery material take the biggest proportion of EV emissions (Gaines, 2012).

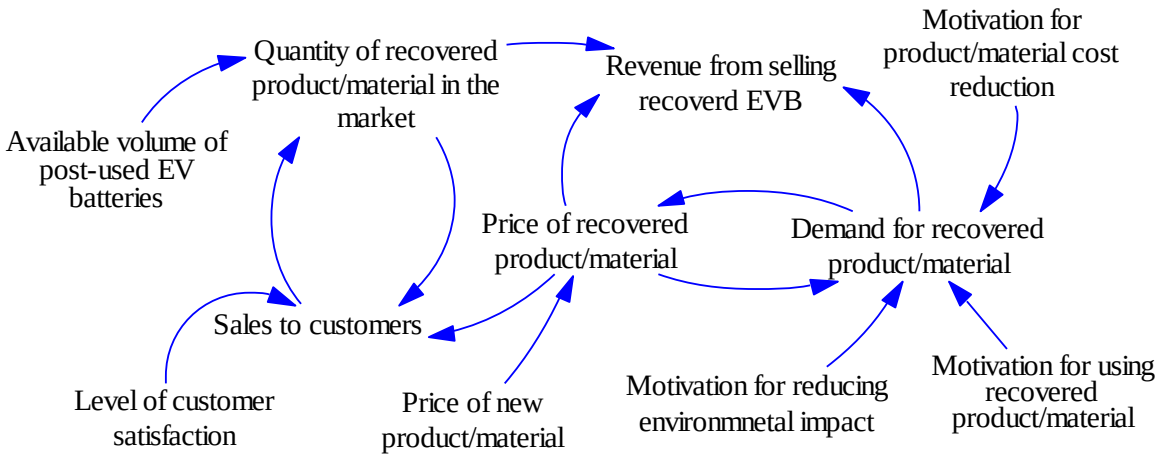

Figure 22: Dynamics of revenue in EVB recovery

2.2.4.3. Dynamics of strategic and regulatory decisions in EVB recovery management system

Strategic and regulatory decisions for EVB recovery are influenced by various factors such as regulations on EVBs, demand for a recovered EVB product/material, and motivation for reducing environmental impact. Fig. 23 depicts the dynamics of strategic and regulatory decisions in EVB recovery management system.

The European Union (EU) introduced EoL battery directive in 2006 that acquires manufacturers to take responsibility for the collection and recycling of post-used batteries. It sets a minimum recycling target of 50% by average weight (EU Directive 2013/56/, 2013). Recently, the EU had identified that the directive will be revised in the following aspects to improve the recovery of EVBs. The new EU directive is expected to define a new collection and recycling target including the level of recycling, recycling efficiency and degree of recycled content. This will improve the recovery of EVBs which leads to lower dependency on primary materials while reducing the environmental impact (Fig. 23).

In addition, the previous directive hinders the implementation of other circularity strategies such as repurposing of EVBs that could have a better environmental and economic benefit. With the growing market demand for EVs, there is a huge advancement in the technological development of EVBs. Even though, such advancement in technological innovation of EVBs is hindered by inappropriate and slow-changing legislation. In order to solve those challenges periodical amendment of the battery directive is a necessity.

Moreover, the increasing demand for recovered EVB products/materials, such as repurposed EVBs for stationary energy storage applications, has motivated SMEs enterprises to start a recovery business. However, a lack of legal definition of these emerging circularity strategies causes a big problem for

businesses wishing to get involved in recovery business (Green, 2017). In this line, regulation after the second/third life of EVBs regarding who is responsible for the EoL battery under extended producer responsibility (EPR) is expected to be revised the upcoming battery directive.

As shown in the CLD diagram in Fig. 23, high demand for recovered EVB product/material due to new market opportunities, legal obligation to recover EVBs, and motivation for reducing environmental impact have a positive influence for original equipment manufacturers (OEMs) and third-party recovery companies to get involved in recovery businesses.

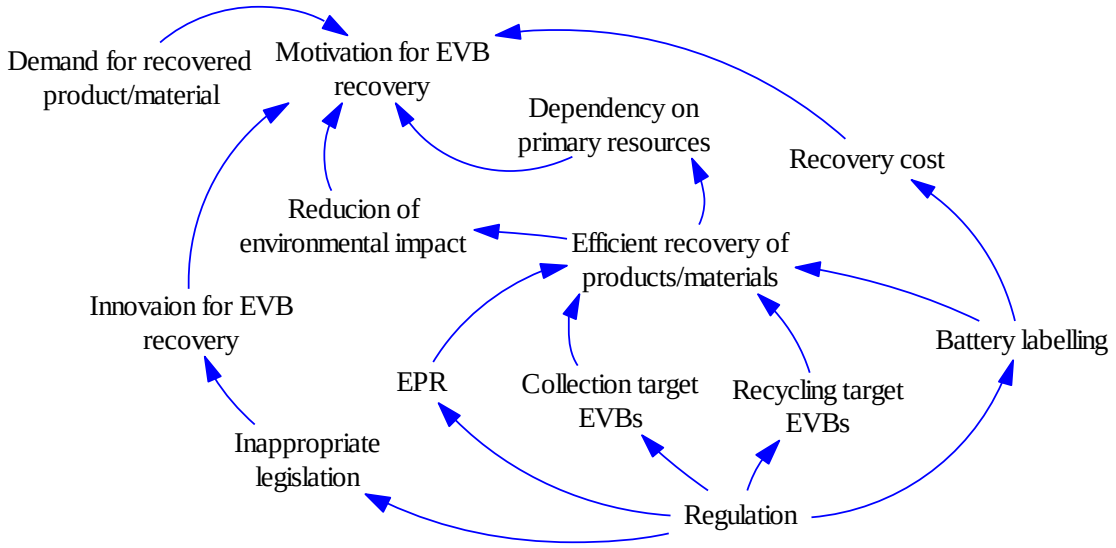

Figure 23: Dynamics of strategic and regulatory decisions in EVB recovery system

2.2.4.4. Interplay between diverse disciplines in circular economy research: a case study on electric vehicle batteries

The concept of circular economy is based on six main building blocks: reverse supply chain, business models, policy, product/service use, EoL recovery and product/service design. Due to the complexity of circular systems, transdisciplinary research approach is decisive in order to tackle current challenges facing in this world. In this line, understanding the interplay among diverse areas of circular economy research is crucial for the successful implementation of CE principles. In order to meet the action plan of CE, it is imperative to build shared understanding among the main pillars as well as to create collaborative environment among various stakeholders. Fig. 24, depicts the interplay among building blocks of CE to solve a typical problem.

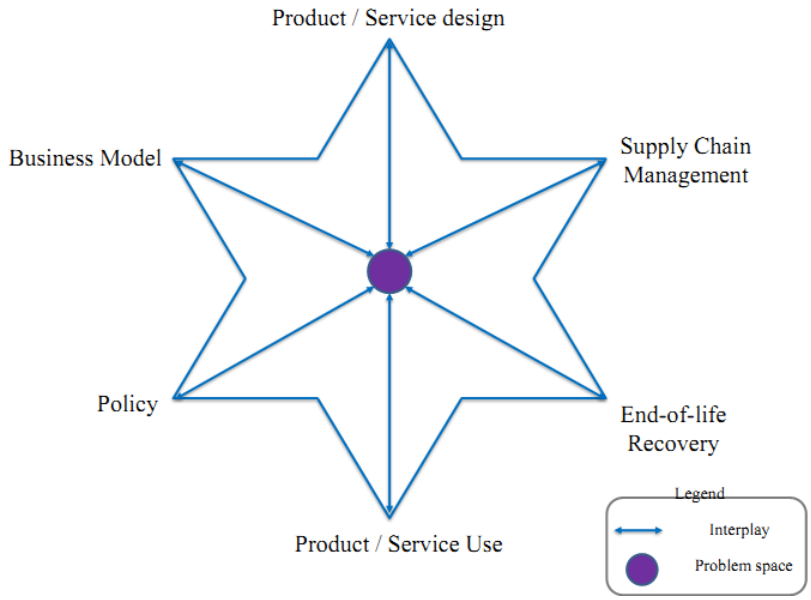

Figure 24: Interplay among the building blocks of CE research

A diagram representing the interaction between main pillars of CE and product circularity strategies to recover post-used EVBs is shown in Fig. 25. When the EVB reaches at its EoL stage, it could be re-used for the same application and function, repurposed for a different application and function, remanufactured and/or recycled. In the following sections, the interplay among diverse areas of CE research is discussed.

2.2.4.4.1. Business model

This study points out that innovation of new business models is crucial to build a successful recovery company for EVBs. For SMEs such as Company A and Company B, repurposing of EVBs give rise to innovative new business model opportunities. For instance, Company A has small cost for running its business by repurposing spent EV batteries. This company receives post-used batteries from various sources, including a local Company E which supplies around 20,000 batteries per year free of charge. Also, Company E benefits from reducing storage costs by giving away spent batteries to company A. Besides selling electric heaters to customers, Company A provides maintenance for failed batteries and collects data to study the usage history of the battery. Throughout life cycle of the product, the company maintains the ownership of the battery.

Company A applies an “innovative design” approach to install post-used EV batteries into electric heaters which will be used to store electric energy during off-pick hours. Installation of EV batteries into electric heaters requires “innovative design” since batteries are sensitive to high temperature environment. This solution reduces the electricity bill for customers by using the energy stored from the battery during peak

hours. This demonstrates an example of the interplay among building blocks of CE i.e. design, business model and reverse logistics.

When the repurposed battery by Company A loses a substantial amount of its energy capacity and reaches at its end of 2nd use phase, then the company either sells or gives for free to a third-party recycler, Company C, based on the market price of recovered materials. To sum up, the partnership between Company A, Company C and Company E serves as a catalyst for new business model innovation. Interdependency and collaboration among these companies is also important to facilitate recovery of spent batteries and to capture the value of post-used product.

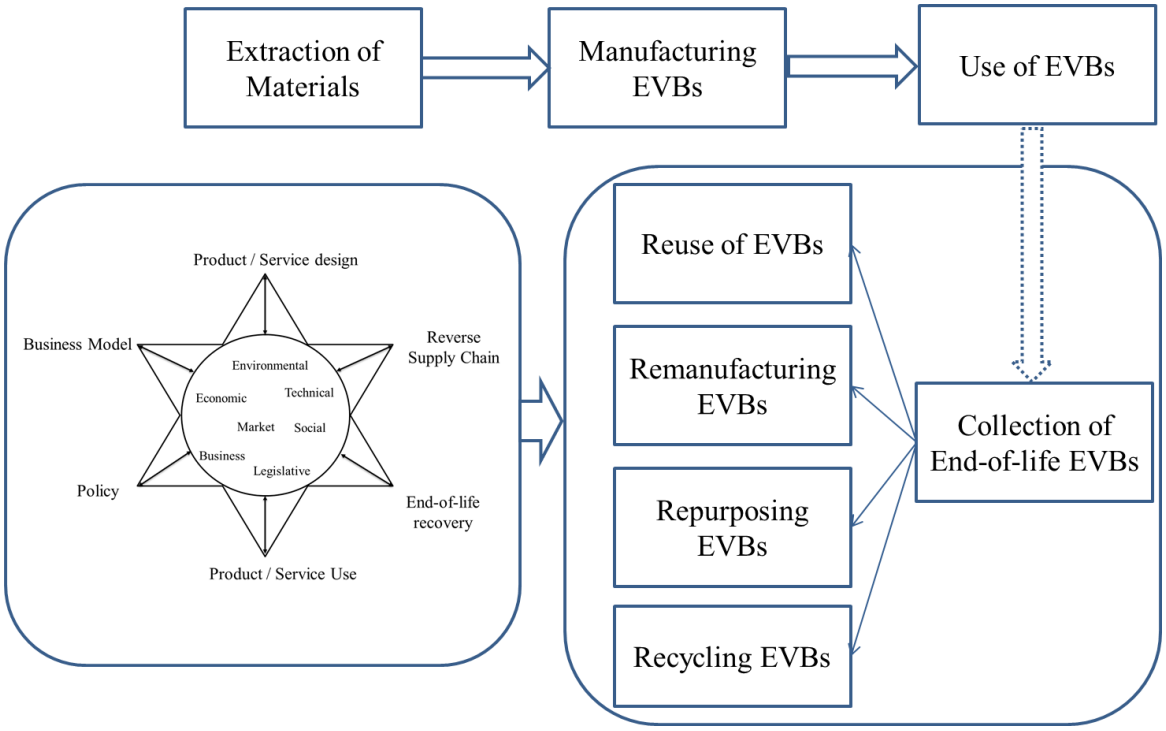

Figure 25: Depiction of the interaction between main pillars of CE and circularity strategies

2.2.4.4.2. Design

Design of EVBs for disassembly is helpful for companies to easily recover the product through various circularity strategies. Results from the case study suggest that designing EVBs for disassembly would ease the reuse, repurposing, remanufacturing and recycling processes. Furthermore, providing dedicated information about the disassembly process would help companies involved in recovery business. Moreover, it is crucial to influence the first design of batteries to bypass weak cells or modules to effectively transmit energy during the second use phase of batteries. Faster innovation cycle coupled with disruptive character of EVBs gives a high degree of freedom for design for second life.

In addition, standardization of battery components reduces the high cost and poor quality for separation and sorting of post-used EVBs. Standardization of battery configurations and specifications would increase the reuse potential of EV batteries. This will help cells from different sources to be tasted and repacked in compatible groups for their reuse. In the absence of material standardization, product labelling would enable recyclers to sort before recycling and would help consumers determine where to put unwanted items. The findings show that, design plays an important role for an effective and efficient recovery of products.

2.2.4.4.3. Policy

Recently, the increasing technological development of batteries and of the growing second use applications of EVBs fosters new market opportunities. However, the amendment of legislation that provides the necessary control is moving extremely slowly which results in hindering technological innovation and potential use of batteries for second use application through remanufacturing and reuse strategies. For instance, the regulation of extended producer responsibility is not clear when the battery enters its second life phase. In this line, there is no clear definition on who is responsible for handling the battery after performing repurposing and remanufacturing activities. In addition, rules for the second life application of batteries is not yet developed (Drabik and Rizos, 2018). In the European Union (EU), regulations are mainly focused on the collection and recycling of post-used EVBs. The result shows that policy plays a crucial role in the development of new business models and the recovery of EoL products.

2.2.4.4.4. Reverse supply chain

An efficient reverse supply chain system is pivotal for the adoption of circular economy principles. Even though supply chain is not theoretically circular, transforming the higher entropy EoL products to a lower entropy use aligns with the principles of circular production (Genovese et al., 2017). An efficient reverse supply chain helps to collect EoL products with the low cost and environmental impact for recovery though circularity strategies.

2.2.4.4.5. Product/Service use

Based on the results of the case study, access to the history of EVB during the first use phase (such as use temperature, charge/discharge, and aging) is important for efficient recovery of post-used batteries for latter applications. Company A provides affordable electric heaters for customers that reduce their electricity bills. Similarly, Company B offers packed batteries for forklift trucks based on their energy requirements. Throughout the 2nd life-phase of the product, the companies are responsible for offering service and taking care of the product until the end-of-2nd-life phase. Both Company A and Company B collect data during the second use phase to improve their service that would benefit customers.

2.2.4.4.6. Recovery

In order to meet the aimed target to implement CE principles, understanding the interplay among the building blocks of CE is a necessity. The results of the case study show that there is an interaction among the main pillars of CE including business models, design, use, reverse supply chain, EoL recovery, and policy. The recovery of EoL products serves as a catalyst for design and new business model innovation. In addition, it serves as leverage to link various areas of CE research.

2.2.4.5. Enablers and main challenges for circularity of EVB recovery

This section highlights the main enablers and challenges for recovery of EVBs. Some of the main enablers for an effective recovery of EVBs are new and innovative business models for reuse, remanufacturing and second use applications; design of an efficient reverse supply chain system for the recovery of EoL products; standardization of battery components, modules and cells; design of batteries for ease of disassembly; access for the usage history of the battery; new timely policies following the advancement of EVB recovery; and development of advanced technologies for recycling and remanufacturing of EV batteries. Table 20 presents the main enablers which facilitate circularity of EVBs across each pillars of circular economy. These results are extracted from the interviews with the representatives of case study companies.

Table 20: Summary of enablers that facilitate circularity of EVBs

Business model	• Reuse of EVBs for second use applications • Repurposing of EVBs for different applications and purposes • Battery ownership throughout the product life cycle • Providing service such as leasing EVBs • Inter-industry partnerships
Supply chain	• Design for reverse logistics • Integrating advanced technology in supply chain management
Design	• Designing new concepts of EVBs • Design for disassembly • Dedicated disassembly information for repurposing of batteries • Standardization of product and component designs
User	• Access to the history of 1st use (temperature of use, charge/discharge, aging etc.)
Recovery	• Development of advanced technologies for the recovery of EoL batteries • Efficient reverse supply chain system for spent batteries • New and innovative business models • Influence on 1st design of the battery
Policy	• Policy support for battery second use • Amending legislations that hider technological innovations and new business models • Rules for second use applications electric vehicle batteries

End-of-life EVBs has a huge potential for various second use applications. Even though, there are challenges that hinder the recovery of EVBs. The first main concern is the safety of retired battery. If a spent battery is improperly handled, it may explode. The storage of post-used EVBs must be performed in a secured place. In addition, disassembly of EVBs has to be accomplished in a well-ventilated area in order to prevent any potential exposure to toxic gases (Winslow et al., 2018). The second concern is to assert the economic feasibility of using recovered batteries for second use applications. Furthermore, the lack of sufficient information about the performance of retired batteries and new market opportunities for second use applications, hinder companies to start recovery business (Burke, 2009). Moreover, due to a lack of regulation it is difficult to provide a product warranty to recovered EVB for second use applications (Burke, 2009).

With regard to the concept of reverse logistic, an interesting future research topic could be to investigate maintenance modelling for the case of reverse logistics system by referring to the research work of Duan et al., (2018) on selective maintenance scheduling under scholastic maintenance quality with multiple maintenance actions. Furthermore, future research work needs to be conducted on a reward-driven system for reverse logistics systems. This approach could be referred from the study by Gharaei et al., (2015) on the optimization of single machine scheduling in the rewards-driven system.

2.2.5. Conclusion

The result of this paper shows the need for a shared understanding of the interplay among the building blocks of CE including business models, reverse supply chain, policy, product/service use, EoL recovery, and product/service design for a successful transition to a resource-efficient and circular economy model.

In addition, this study analyses the major interactions among decision-making factors from economic, environmental, and societal aspects. Modelling of decision-making variables is accomplished in order to present the dynamics of cost, revenue, strategic and regulatory decisions based on the principles of system dynamics methodology.

Furthermore, a case study on electric vehicle battery applications based on a study of companies in the value chain is presented and discussed. Moreover, the main enablers and challenges for circularity of EVBs with respect to the building blocks of circular economy is presented.

More research needs to be conducted on standardization of EVB components and materials. Standardization will increase second use application and material recovery of spent batteries. In addition, more research needs to be conducted on the design of batteries for second life; smart and efficient logistics, and emergent EVB circularity strategies.

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2.3. PART III - PROPOSE: CE tools and indicators

This section is composed of two research articles. The first article proposes a circular economy performance indicator for a reverse logistics system, and the second article presents a method to evaluate various CE scenarios. Each article is described in section 2.3.1. and section 2.3.2. respectively.

2.3.1. Proposition of a circular economy performance indicator for reverse logistics

Table 21: Summary of paper #3

Title	**Circular economy indicator for reverse logistics (CEI-RL) : Measuring the performance of reverse logistics in companies**
To be Submitted	Journal of Cleaner Production (In progress)
Keywords	Circularity indicators; Circular performance; Reverse logistics; Remanufacturing; Circular economy
Abstract	In the last decade, the circular economy (CE) model has gained popularity among researchers, practitioners, decision-makers and policy makers. It has been playing an important role to achieve the sustainability development goals (SDGs). Recently, a wide range of CE indicators has been proposed to measure circular economy progress at various implementation scales. Although there are more than 60 indicators proposed to assess CE, there is no effective measurement indicator that evaluate the performance of a company towards the transition from the traditional linear to circular economy across the reverse supply chain. In this regard, companies have difficulties to transform their business to circular economic model due to lack of indicators to measure the performance of CE practices. This research paper aims to address this gap and has developed a "Circular Economy Indicator for Reverse Logistics (CEI-RL)" to measure the performance of reverse supply chain in a company. The research process of this paper constitutes: a detailed literature review about circularity indicators; identification of key performance factors (KPFs); proposition of CE indicator for reverse logistics, and case study to test the proposed indicator in remanufacturing companies. CEI-RL aims to evaluate the performance of reverse supply chain with respect to the 'circular economy' principles, in three dimensions: collection, testing and sorting, and product recovery. This tool is expected to help managers/decision-makers of a company to measure the performance of reverse logistics system and to identify new opportunities to improve the system.

2.3.1.1. Introduction

In the last few years, the concept of circular economy (CE) has become an issue of critical importance for researchers, practitioners, decision-makers, policymakers, businesses and industries. The implementation of circular economy principles is critical in meeting sustainable development goals (Korhonen et al., 2018; Saidani et al., 2018). Transforming the production and consumption behaviour based on CE principles is the core to move towards a more sustainable development (Brissaud and Zwolinski, 2017; Di Maio and Rem, 2015).

The circular economy moves away from the conventional linear economy approach which utilizes "Make-Use-Dispose" economic model to one that is regenerative by design (EMF, 2015; Fellner et al., 2017). Instead of linear flows of materials and products through the economy, the CE promotes circular flows to reduce environmental impacts and maximize resource efficiency as a strategy for sustainability. It aims to meet economic prosperity, while maintaining environmental quality and social equity to create sustainable world for future generations (Kirchherr et al., 2017).

Currently, companies are taking significant steps to implement environmental friendly activities that support sustainable development by adopting the circular economy model (Akdoğan and Coşkun, 2012). The successful implementation of circular economy models relies on combined leveraging of main pillars including reverse supply chain management, product/service design, business models, end-of-life treatment, product/service use and policy (EMF, 2015). In this regard, reverse logistics is one of the great enablers for a sustainable production and consumption (Sangwan, 2017). It has attracted the attention of both academics and practitioners due to the increasing concern of environmental problems and legislative pressure (Govindan et al., 2015; Stewart and Ijomah, 2011). The implementation of efficient reverse logistics systems represents as an enabler for an effective transition from the traditional linear economic model to a circular economy model (Ellen MacArthur Foundation and Granta Design, 2015; Gnoni et al., 2018; Lieder and Rashid, 2016). Fig. 26 depicts the forward and reverse supply chain.

In this regard, it is very crucial to determine the performance of in the context of a circular economy, thus allowing businesses to assess their advancement from linear to circular economy model. Due to lack of measurement tools, methods and performance indicators, there are few successful examples that demonstrate the performance of CE practices (Asif, 2017). In this regard, companies have faced difficulties to transform their business to circular economic model due to lack of methods, tools and indicators to evaluate the performance of CE practices.

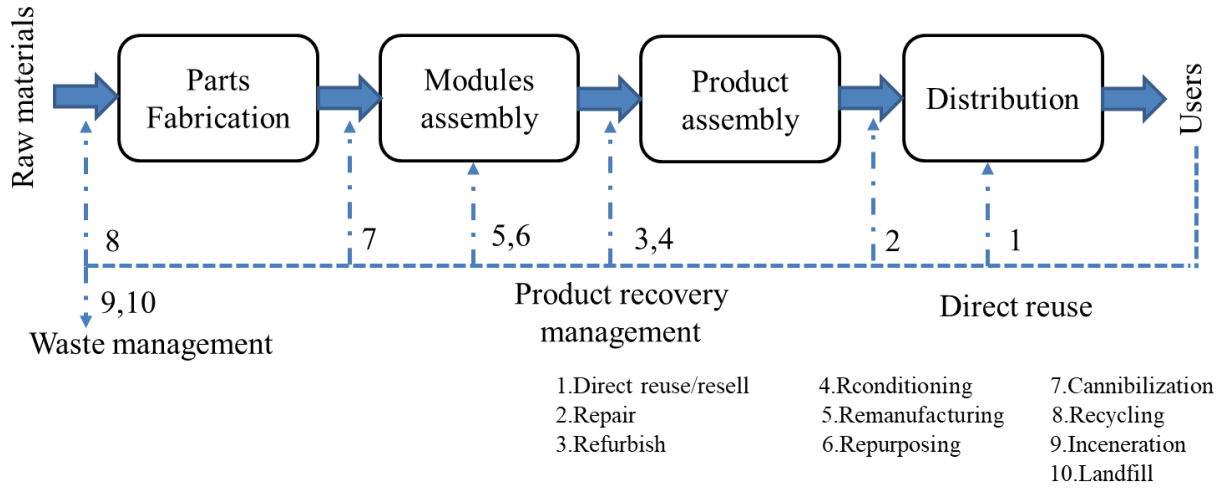


Figure 26: Integrated supply chain (modified after (Thierry et al., 1995))

Even though, the concept of CE and its application is widely explored, there are few studies focused at a micro level to evaluate the circularity of a product, supply chain and/or service (Elia et al., 2017; Huysman et al., 2017; Parchomenko et al., 2019; Saidani et al., 2017). Some literatures presented their research on circular economy indicators. Saidani et al. (2018) presented a taxonomy of C-indicators in which more than 55 set of indicators are identified. The result shows that circular economy indicators to evaluate the performance of reverse logistics is missing (Saidani et al., 2018). Elia et al., (2017) supported this argument in the recent work on critical analysis of CE assessment and indicators at micro level. Also, Saidani et al., (2017) stated that CE requires optimization of the performance of a system. Several authors suggested the importance to develop successful indicators in the move from linear to a circular economy (Di Maio and Rem, 2015; Elia et al., 2017). Current assessment methods lack systemic vision and operational considerations.

There is hardly any academic research that proposed a C-indicator to evaluate the performance of reverse supply chain of a product in companies. New C-indicators are required to measure how successful a company is in making the transition from a 'linear' to 'circular' models across the reverse logistics (Elia et al., 2017; Genovese et al., 2017; Saidani et al., 2018; Sangwan, 2017).

This research paper aims to address this gap and has developed C-indicator to measure the performance (Circularity level) of reverse supply chain of a product in a company. The proposed indicator enables industrial practitioners to measure the circularity potential of the reverse logistics system of product in a company.

The research objective of this paper is therefore to address the following research questions:

- What are the key performance factors (KPFs) or key decision-making factors (KDFs) used as an input characteristic to assess circularity performance of reverse logistics system using circularity indicators in companies?
- How to quantify the circularity performance of reverse logistics system using circularity indicators in recovery companies?

The organization of this article is prepared as follows: Section 2.3.1.2, presents a literature review about circular economy, reverse logistics, key performance factors and circularity indicators. Section 2.3.1.3 exposes the research methodology employed for this study. Results and discussion of the research is presented in section 2.3.1.4. Section 2.3.1.5 recaps the main findings of the study and opens on future research opportunities to advance further the CE implementation.

2.3.1.2. Literature review

2.3.1.2.1. The circular economy and reverse logistics

An Industrial Economy (IE) can follow a linear economy, circular economy or performance economy model. The circular economy aims to keep the value products, components, materials and resources in the economy for the longest time possible (Bocken et al., 2017; Ellen MacArthur Foundation and Granta Design, 2015).

CE business models falls into two categories: those that extend product life times by reuse, repair, repurpose, refurbish, recondition, upgrade, retrofit, and remanufacture; and those that close resource cycles – through recycling strategy (Bocken et al., 2017; Stahel, 2016). Adopting CE is expected to have considerable benefits in reducing waste volume, reduction of raw material imports and a boost for economic growth (Fellner et al., 2017).

There is a increasing interest in reverse logistics (RL) from scholars and industries due to the increasing environmental problems, future legislation, increased return of post-used products etcetera (Govindan and Soleimani, 2016; Sangwan, 2017). According to Rogers and Tibben-Lembke, (1999), “Reverse logistics is the process of planning, implementing and controlling backward flow of raw materials, in-process inventory, packaging and finished goods, from a manufacturing, distribution, or use point, to a point of recovery or point of proper disposal”. Reverse logistics includes three main activities: collection, inspection and sorting, and product recovery and redistribution (Sangwan, 2017). The development of an efficient reverse logistics system is pertinent for recovery of end-of-life products (Govindan and Soleimani, 2016).

2.3.1.2.2. Key performance factors (KPFs) / key decision factors (KDFs)

Few literatures explored in identifying key performance factors (KPFs) or Key Decision Factors (KDFs) in reverse logistics system. Sangwan identified general key performance factors in reverse logistics in three categories: collection, sorting and disassembly, and product recovery (Sangwan, 2017). Alamerew and Brissaud, (2018) presented a list of KDFs in reverse logistics. The authors categorized the decision variables into various categories including technical, business, environmental, market, legal and societal etcetera. Akdogan and Coskun, (2012) identified the drivers of RL from the producer's perspective with respect to economic, legislative and corporate citizenship aspects. In another study, Doyle et al., (2012) presented a list of end-of-life decision factors to assist successful design for recovery. Furthermore, Park and Okudan, (2017) identified and categorized sustainability indicators into five parts: environmental impact and chemical release related indicators; pollution from emission and waste related indicators; EoL management and chemical use related indicators; raw material resources and facility management related indicators; and energy and water management related indicators.

2.3.1.2.3 Circular economy indicator (CEI)

Recently, circular economy indicators have been developed for managing the transition towards more CE practices (Geng et al., 2013). Circularity indicators could be used by policy makers, decision-makers, and practitioners. Circularity indicator is a tool that helps to evaluate how well a product, service or company perform in the circular economy. According to Organisation for Economic Cooperation and Development, Development assistance Comittee (DAC), (2014), an indicator is defined as "a quantitative or qualitative factor or variable that provides a simple and reliable tool means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of an intervention".

Assessment of the performance of a reverse supply chain is crucial to identify hotspots and areas of improvement in order to move towards a more circular economy model (Saidani et al., 2017). Until now there no CE assessment indicator that measures the performance of a reverse logistics system of a product in companies (Elia et al., 2017; Saidani et al., 2017). CE paradigm could be analysed at three levels of intervention: micro (product, company or single consumer level); meso (eco-industrial parks); and macro (cities, provinces and regions) (Ghisellini et al., 2016).

This research paper focuses on CE analysis at micro level on companies evaluating the performance of the reverse logistics system. Table 22 presents a review of CE indicators at micro level that are developed in the last few years.

Table 22: Circular economy indicators at micro level

Indicator	Description	Dimension	Developer(s)
Circular Economy Index (CEI)	A new metrics system to compute the recycling rate in a sector and/or company level	Single indicator	(Di Maio and Rem, 2015)
Circular Economy Indicator Prototype (CEIP)	An article-based tool to measure the circularity of a product	Single indicator	(Cayzer et al., 2017)
Circular Economy Toolkit (CET)	A web-based tool to assess product/service for a company	Multiple indicator	University of Cambridge (Evans and Bocken, 2013)
Material Circularity Indicator (MCI)	A web-based tool to measure the circularity of product/company on material level	Single indicator	(Ellen MacArthur Foundation and Granta Design, 2015)
Circular Pathfinder (CP)	A web-based tool to identify a suitable strategy	Multiple indicator	(ResCoM, 2017)
Circular Performance Indicator	Measures the circular economy performance of plastic waste treatments	Single indicator	(Huysman et al., 2017)
Circularity Potential Indicator (CPI)	Measures the circularity potential of products	Single indicator	(Saidani et al., 2017)
Resource Duration Indicator (RDI)	Measures longevity indicator “Resource duration’’	Single indicator	(Franklin-johnson et al., 2016)
Reuse Potential Indicator (RPI)	A quantitative indicator to evaluate technical feasibility of post used products	Single indicator	(Park and Chertow, 2014)
Sustainable Circular Indicator (SCI)	An index to assess the sustainability and circularity of manufacturing companies	Single indicator	(Azevedo et al., 2017)

2.3.1.3. Methodology

The research process of this study constitutes: a detailed review of literatures; identification of key performance factors (KPFs); and development of an indicator for quantifying the performance of reverse logistics. The methodology uses an iterative process to select the input factors and build the tool. Fig. 27 shows the system diagram of the methodology used in this study.

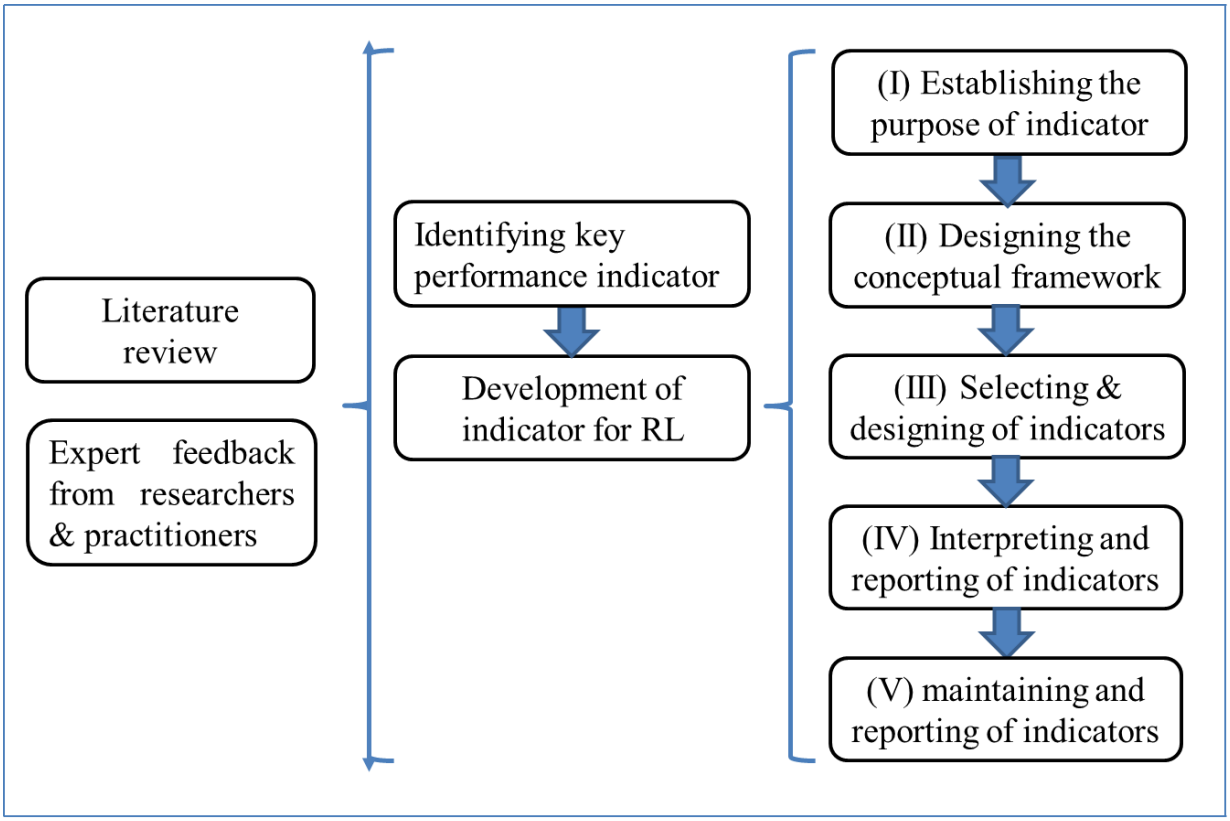


Figure 27: Depiction of the research methodology employed in this study

2.3.1.3.1. Literature review

In this study, a systematic review of literatures was carried out to deeply understand the research area of reverse logistics, circularity indicators, and decision-making factors. The databases of Google Scholar, Science Direct, university's library Uni-Search (HAL) & ISI Web of Science is used to gather and access relevant peer-reviewed journal articles and conference papers. Combination of the following terms: 'reverse logistics', 'reverse supply chain', 'circular economy', 'circularity', 'assessment', 'tool', 'evaluation', 'metric', 'indicators', 'decision-making', 'measure' is used for the database search. Moreover, further information concerning this research is gathered from reviewing publicity documentation, reports, web-pages etcetera to cover existing knowledge.

2.3.1.3.2. Identification of key performance factors (KPFs) / key decision factors (KDFs)

First, a comprehensive literature review was undertaken to identify key performance factors used as an input characteristic to assess the performance of reverse logistics using circularity indicator. Based on the results from the literature review, an extensive list of decision-factors was identified with respect to technical, economic, business, environmental and societal aspects. Then the decision factors are evaluated by expertise from academia and industry.

The most important factors which are pertinent to consider in the decision-making process were accentuated, based on the findings from literature and expertise feedback from academia and industry. The main findings of this study is presented in more detail in the research paper by (Alamerew and Brissaud, 2018). These decision factors were then sorted into three categories of reverse logistics: collection, inspection and sorting, and product recovery.

2.3.1.3.3. Proposition/development of circular economy indicator for reverse logistics (CEI-RL)

Based on the guideline proposed by Brown, (2009), a circular economy indicator for reverse logistics is developed to calculate the performance of reverse supply chain in companies. The proposed circularity indicator measures the performance of reverse logistics system with respect to collection performance of post-used products; inspection and sorting performance of retired products; and the performance of end-of-life product recovery system. The five main stages of the Brown, (2009) guidelines to develop a CE indicator includes: (i) establishing the purpose of indicator; (ii) designing the conceptual framework; (iii) selecting and designing of the indicators; (iv) interpreting and reporting of indicators; and (v) maintaining and reporting of indicators (Brown, 2009). The application of the guideline in this study is presented in Section 1.3.1.4.2 Table 27.

In the course of this study, an iterative process was used to select the input factors and develop the indicator. Participants from both academic and industry sectors were participated in order to improve the proposed framework. In the following section, the results of the study are presented and discussed.

2.3.1.3.4. Performance measurement of a reverse logistics system

Organizations need to measure the performance of their activities to evaluate their goals and objectives (Goshu and Kitaw, 2017). Performance is defined as the achievement of a given task measured with respect to a known standard of accuracy, completeness, cost and speed. Performance measures helps to give a vital sign for a company by quantifying how well the organization achieves a specific goal (Glavan, 2012). A proper set of indicators for measuring performance must be formulated in line with continuous improvement policies and business processes (Bititci et al., 2005). Goshu and Kitaw, (2017) presented a

review of literatures on the performance measures and its challenges. Shaik and Abdul-Kader, (2012) developed a performance measurement framework for RL in six performance perspectives: financial; innovation and growth; processes; stakeholder; environmental and social. The research linked the drivers of RL with performance perspectives. This research aims to evaluate the performance of a reverse supply chian with respect to the circular economy principles.

2.3.1.4. Results and discussion

2.3.1.4.1. Identifying key performance factors (KPFs) / key decision factors (KDFs)

The major activities of reverse logistics could be divided into three categories: collection, inspection and sorting, and product recovery. The following section presents key major activities of RL and decision variables in each activity.

2.3.1.4.1.1. Collection

Collection of post-used products is one of the most important part of reverse logistics. It is the process of retrieving retired products and transporting them to a location where the recovery of products takes place (Pokharel and Mutha, 2009; Sangwan, 2017; Webster and Mitra, 2007). The efficiency of collecting EoL products depends on collection activity and method of collection. Product collection activity of reverse logistics could follow centralized or decentralized system (Webster and Mitra, 2007). This activity may include an incentive to maximize the number of return products. Collection of worn-out products can be performed by original equipment manufacturer, retailers or third-party logistics provider. Table 23 presents key performance variables identified for the two main categories of collection of retired products in reverse logistics.

Table 23: KPFs for collection in RL

KPFs for collection decision			
No.	KPIs for location allocation decisions	No.	KPIs for collection method
1	Collection cost	1	Return volume
2	Processing cost	2	Operating cost
3	Customer satisfaction	3	Customer satisfaction
4	Level of social acceptability	4	Safe working environment
5	Energy use (Transportation)	5	Investment cost
		6	Customer relation

1.3.1.4.1.2. Inspection and sorting

In order to determine the re-usability of a product, collected post-used products are inspected and sorted. Inspection and sorting processes could be performed in centralized and decentralized locations. Table 24 presents key performance factors identified for inspection and sorting of EoL products in reverse logistics. The KPFs are presented with respect to facility location and disassembly categories.

Table 24: KPFs for inspection and sorting in RL

KPFs for inspection and sorting decision			
No.	KPFs for facility location	No.	KPFs for disassembly discussion
1	Testing cost	1	Disassembly cost
2	Labor cost	2	Value recovery
3	Availability of skilled labor	3	Environmental impact of processing
4	Transpiration and storage cost		
5	Return core volume		

1.3.1.4.1.3. Product recovery

Product recovery (PR) is a crucial activity of reverse logistics. PR is the management of discarded products, components, and materials to recover as much of the economic and ecological value as possible thereby reducing the quantity of discarded waste (Krikke, 1998; Thierry et al., 1995). It plays a significant role towards transitioning to a circular economy with the application of various circularity strategies (Alamerew and Brissaud, 2017). Product circularity strategies include remanufacturing, repair, reconditioning, cannibalization, refurbish and recycling. All these end-of-life options are distinct from each other and selecting the best suitable product recovery option should take several factors into consideration (Kumar et al., 2007). A brief description of circularity scenarios is presented in Table 25. Table 26 shows key decision variables identified for product recovery of end-of-life products.

Table 25: KPFs product recovery in RL

No.	KPFs
1	Market demand
2	Operating cost
3	Additional job creation
4	Consumer presumption
5	Environmental impact
6	Technical state
7	Technical feasibility
8	Safe working environment

Table 26: Description of product circularity strategies

Reuse involves the process of re-using a product if it meets sufficient quality levels (Burke, 2009; Richa et al., 2014; Winslow et al., 2018). **Repair** is an activity of returning a used product in to "working order" by fixing/replacing specified faults in a product using service parts (King et al., 2006; Krikke, 1998). **Remanufacture** is an end-of-life product circularity strategy whereby worn-out products are restored to the original equipment manufacturer (OEM) standard, and receive a warranty at least equal to a newly manufactured product (Ijomah, 2002; Rose, 2000; Sundin, 2004). **Repurposing** is an emergent circularity strategy where discarded products are recovered and used in a new product that have a different purpose and application compared to the original product (Bauer et al., 2017). **Recondition** involves returning the quality of a product to a satisfactory state level (typically less than a virgin standard/new product) giving the resultant product a warranty less than of a newly manufactured equivalent (King et al., 2006; Paterson et al., 2017). **Refurbishing** involves returning products to a specific quality level, usually less than that of a new product. Reconditioned product has gone through extensive testing and repair than refurbished products (Srivastava and Srivastava, 2006). **Cannibalization** is an activity of recovering/retrieving one or more valuable parts from returned product. Recovered parts are used in repair, refurbishing, reconditioning and remanufacturing of other products (Thierry et al., 1995). **Recycle** is an activity where discarded materials are collected, processed and used in the production of new materials or products (Jawahir and Bradley, 2016; Winslow et al., 2018).

1.3.1.4.2. Proposition of circular economy indicator for reverse logistics (CEI-RL)

In this section, the result of a circular economy indicator for reverse logistics (CEI-RL) is presented. As discussed in section 2.3.1.3.3, the indicator is built based on a guideline developed by (Brown, 2009). The guideline consists of five main steps. Table 27 presents a description of each stage of the guideline and its application in our study.

The main purpose of the proposed indicator (CEI-RL) is to assess the performance of a reverse logistics system to evaluate the CE practices in companies. The tool is structured based on the activities of reverse logistics: collection; inspection and sorting; and EoL product recovery. Initially the indicator is developed in a matrix format (Table 29), and then transformed to an excel based indicator to easily and effectively communicate the result (Fig. 28)

As presented in the result section 2.3.1.4.1, a list of qualitative decision factors is identified for each activities of reverse logistics. In order to transform the qualitative criteria into quantitative numbers, a rating system/scale is used. A semantic scale, Likert is used in this study as it is commonly used in decision-making in business research (Munshi, 2014; Nemoto and Beglar, 2014). A scoring scale from 1 to 5 is used to quantify the qualitative factors. The representation of the scoring scales is presented at the bottom of

Table 29. A weighting value is assigned for the decision factors based on the expert feedback. Summary of experts involved in the study is presented in Table 28.

Table 27: Guidelines for indicator development (Brown, 2009)

Guideline stage and description	**Application of the guideline in our study**
Step 1: Establishing the purpose of the indicator This step involves identifying the purpose of the indicator and target audience. This helps to narrow down the scope of the indicator.	The purpose of the indicator is to calculate the performance of a reverse supply chain of a product. The main target audiences are business managers in companies.
Step 2: Designing the conceptual framework In this step a theoretical framework is formulated to monitor the proposition of indicators. Conceptual framework helps to build a coherent, relevant and balanced set of indicators.	The study uses an interactive and holistic process to build the indicator aligned with the main activities of the reverse logistics system and CE practices.
Step 3: Selecting and designing the indicators This step involves selection of relevant decision factors based on criteria's such as: validity, meaningfulness, grounded in research, easily interpreted, compel interest and excite.	The selection of variables is performed based on a grounded research in RL activities. Also, it involves participation of researchers and industrial practitioners.
Step 4: Interpreting and reporting of indicators It refers to the way of reporting results in an effective way which could be easily understandable by the audience.	An excel based indicator is developed to easily report the result. A Graphical representation is made to communicate the result in an understandable way (Spider diagram).
Step 5: Maintaining and reporting of indicators This stage refers to the assessment of indicators and receiving feedback from relevant stakeholders.	This study feedback from the academia and industry is considered to improve the set of indicators.

The proposed indicator is a multi-index indicator (CEI-RL) that evaluates the performance of a reverse supply chain with respect to collection, inspection and sorting, and product recovery activities. Based on the authors knowledge, CEI-RL is the first known indicator that measures the performance of a reverse supply chain for businesses. The CEI-RL consists of 5 indexes in three main categories (collection, inspection and sorting, and product recovery): location allocation, methods of collection, facility location, disassembly and product recovery.

$$CEIRL = \mathrm{Ic}(I1 + I2) + \mathrm{IIS}(I3 + I4) + \mathrm{IPR}(I5) = I(1-5) = \sum_{d=1}^{n} Wd * S(d)\,, d = 1,2,3, \dots n$$

Where:

CEI-RL = Circular Economy Indicator for Reverse Logistics

Ic = Indicator for collection

I_{IS} = Indicator for inspection and sorting

I_{PR} = Indicator for product recovery

I_1 = Indicator for location allocation

I_2 = Indicator for collection decision

I_3 = Indicator for facility location

I_4 = Indicator for disassembly

I_5= Indicator for product recovery

W = Weighting value for decision factor d

S = Score value for decision variable d

Some of the main benefits of (CEI-RL) are:

- It helps businesses to interpret and easily compute the performance of RL with respect of CE practices. This makes companies increase their contribution to minimize the environmental challenge and pressure.
- It supports companies to identify the weak performances within the RL activities. This makes businesses to focus and improve the performance on a specific activity.
- It aids companies to assess the performance of current RL system, and evaluate an alternative opportunity aiming for a better system optimization and economic benefit. For instance, on the allocation decision of a location system (comparison between a centralized and decentralized facility); methods of collection decision (OEM Vs retailer Vs third-party logistics provider; as well as testing and inspection facility location (centralized Vs decentralized).
- The tool provides an indicator to represent environmental, economic, social and business aspects of the performance of a reverse supply chain system comprehensively.

CEI-RL is a simple and robust indicator that is easy to be calculated and interpreted. A simple indicator provides a reliable result as there is little room for alternative interpretations (Di Maio and Rem, 2015). The

strength of CEI-RL includes simplicity, ease of use, speed, and an effective tool to monitor the adoption of CE principles.

CEI-RL is a simple and robust indicator that is easy to be calculated and interpreted. A simple indicator provides a reliable result as there is little room for alternative interpretations (Di Maio and Rem, 2015). The strength of CEI-RL includes its simplicity, ease to use/implement, speed, and effective indicator to monitor the adoption of CE principles.

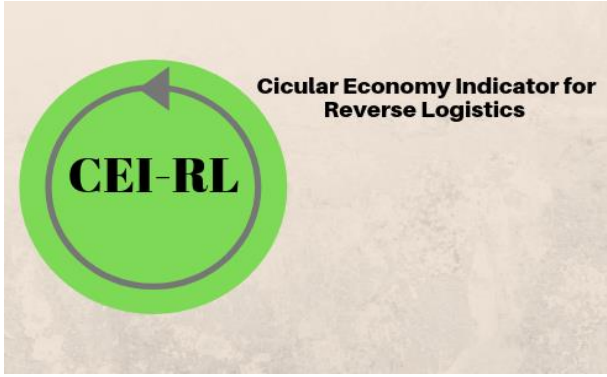
Table 28: Summary of companies involved in the study

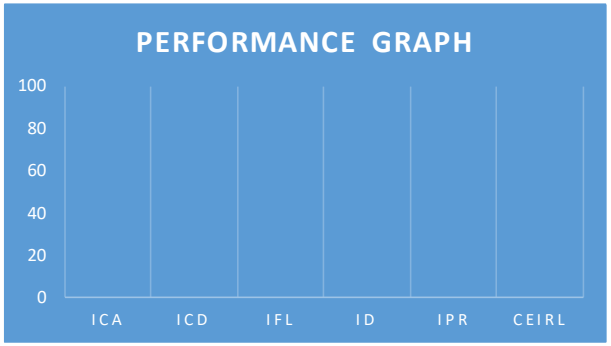
Expert	**Sector**	**Country**
Expert A	Remanufacturing of Electric vehicle batteries (EVBs)	France
Expert B	Remanufacturing of EVBs	France
Expert C	Recycling of EVBs	France
Expert D	Designer of EVBs	France
Expert E	Remanufacturing of Automotive parts	UK/Denmark
Expert F	Repair Shop	UK

Table 29: Circularity indicator matrix

Collection				Test and sorting				Product recovery	
Location allocation decisions (centralized Vs decentralized)		Methods of collection decision: (OEM Vs retailer Vs third-party logistics provider)		Facility location (Centralized Vs decentralized)		Disassembly			
KPFs	Score	KPFs	Score	KPFs	Score	KPFs	Score	KPFs	Score
Collection cost (a)		Return volume (b)		Testing cost (a)		Disassembly cost (a)		Market demand (b)	
Processing cost (a)		Operating cost (a)		Labor cost (a)		Value recovery (b)		Operating cost (a)	
Customer satisfaction (b)		Customer satisfaction (b)		Availability of skilled labor (b)		Environmental impact of processing (C)		Environmental impact (C)	
Level of social acceptability (b)		Safe working environment (b)		Transportation & storage cost (a)				Additional job creation (b)	
Energy use (C) *Transportation		Investment cost (a)		Return core volume (b)				Consumer presumption (d)	
		Customer relation (b)						Technical state (d)	
								Safe working environment (b)	
Total Score		Total Score		Total Score		Total Score		Total Score	

(a) 1-Very high; 2-High; 3-Average; 4-Low; 5 Very low
(b) 5-Very high; 4-High; 3-Average; 2-Low; 1-Very low
(C) 1-Very high impact; 2-High impact; 3-Average; 2-Low; 1-Very low
(d) 5-Very good; 4-Good; 3-Average; 2-Low; 1- Very low





Collection(c)			
Collection Allocation (CA)		Collection Decision (CD)	
KPFs	Score		
Collection cost (a)		Investment cost (a)	
Processing cost (a)		Operating cost (a)	
Customer satisfaction (b)		Customer satisfaction (b)	
Level of social acceptability (b)		Safe working environment (b)	
Energy use (C)		Return volume (b)	
		Customer relation (b)	
ICA	0	ICD	0

Inspection and Sorting (IS)			
Facility Location (FL)		Dissassembly (D)	
KPFs	Score	KPFs	Score
Testing cost (a)		Disassembly cost (a)	
Labor cost (a)		Value recovery (b)	
Transportation & storage cost(a)		Environmental impact of processing (c)	
Return core volume (b)			
Availability of skilled labor (b)			
IFL	0	ID	0

Product Recovery (PR)	
KPFs	Score
Operating cost (a)	
Market demand (b)	
Safe working environment (b)	
Job creation (b)	
Environmnetal impact (c)	
Technical state (d)	
Consumer persumption (d)	
IPR	0

(a)1-Very high; 2-High; 3-Average; 4-Low; 5 Very low
(b)5-Very high; 4-High; 3-Average; 2-Low; 1-Very low
(c)1-Very high impact; 2-High impact; 3-Average; 2-Low; 1-Very low
(d)5-Very good; 4-Good; 3-Average; 2-Low; 1- Very low

CEI-RL	0

Figure 28: Circular economy indicator for reverse logistics (Excel format)

2.3.1.5. Conclusion

Yet transitioning from a linear to a circular economy presents several challenges. The one that is tackled here is to measure CE performance of a reverse logistics system though indicators. In order to achieve the CE targets, it is very crucial for companies to measure the circularity potential of the system.

CE indicators would allow businesses to monitor the implementation of CE strategies. In this study we proposed "CEI-RL" a circularity indicator to assess the performance of reverse supply chain in companies. Moreover, the article identifies key performance factors in each activities of reverse logistics. It is expected that this indicator will help managers in businesses to make better and informed decisions to redesign their activities in reverse logistics. This indicator can be used by decision-makers/managers in companies for evaluating/measuring the performance of reverse supply chain for a typical product.

More research needs to be done to generalize the proposed circularity indicator for measuring the circularity performance of the reverse logistics system to different industrial sectors. Another interesting future work could be to measure the performance of the closed loop supply chain for a typical product. Also, more research could be conducted to propose circularity indicators based on existing company data rather than context-based assumptions.

2.3.2. A multi-criteria evaluation method of potential product level circularity strategies

Table 30: Summary of paper #4

Title	**A multi-criteria evaluation method of potential product level circularity strategies**
To be submitted	Journal of Sustainability (Submitted)
Keywords	Remanufacturing; Circularity strategies; Multi-criteria analysis; Circular Economy
Abstract	Recently, circular economy (CE) has drawn the attention of researchers, practitioners, policymakers, and business leaders. It is expected to play an important role to achieve the sustainability development goals (SDGs). A wide range of CE evaluation methods has been developed to measure progress toward CE at various implementation levels. Although, there is no effective method that assesses scenarios of transition from the traditional linear economy to a CE. This paper aims to fill this gap by proposing a "Circularity Strategy Evaluation Method" to evaluate circularity alternatives with a focus on remanufacturing. A multi-criteria approach is used to develop a method to evaluate circularity scenarios including the initial business of the company, advanced remanufacturing businesses, and future reman scenarios. An illustrative example through a case study with two companies is presented to verify the proposed method. This evaluation method aims to assist business decision makers to evaluate circularity scenarios to identify preferred strategy.

2.3.2.1. Introduction

In the last decade, the "circular economy" (CE) concept has become an issue of heightened interest for researchers, practitioners, policymakers, companies, and industries. A CE moves away from the conventional linear economy approach which utilizes a "make-use-dispose" economic model to one that is "regenerative by design" (EMF, 2015; Fellner et al., 2017). Instead of linear flows of materials and products through the economy, a CE promotes circular flows through, for example, reuse and remanufacturing, with the aim of reducing environmental impacts and maximizing resource efficiency (Suarez-Eiroa et al., 2019). A CE aims to keep the value of products, components, materials, and resources in the economy for the longest time possible and at the highest value (Bocken et al., 2017).

The implementation of CE principles and strategies can facilitate meeting some of the United Nations' Sustainable Development Goals (Korhonen et al., 2018; Saidani et al., 2018) by helping transform production and consumption behaviour (Brissaud and Zwolinski, 2017; Di Maio and Rem, 2015). A CE aims to meet economic prosperity while maintaining environmental quality and social equity (Kirchherr et al., 2017).

Currently, some companies are taking considerable steps to implement circularity strategies but widespread adoption still has not taken place (Kirchherr et al., 2018). As an outcome of companies' increased interest in implementing circularity strategies, more circular products and services are reaching the market. Research focused on the evaluation of the circularity performance of these products and services compared to their business-as-usual counterparts or other products in the same product group is just starting to take off.

More generally there is a lack of evaluation methods of CE strategies of products and services at the micro level i.e. product, company or single consumer level (Elia et al., 2017; Geng et al., 2012; Linder et al., 2017) and there are few studies that have conducted and presented evaluations of circularity strategies of a product or service (Elia et al., 2017; Huysman et al., 2017; Parchomenko et al., 2019; Saidani et al., 2017). There is need to develop a variety of methods, tools and indicators to evaluate CE strategies of products and services at the micro level which can serve different purposes for different actors and to apply them. Some examples are indicators or methods to evaluate

i) products or services (ex post) and compare to products in that product group or a reference case in order to demonstrate a positive outcome,
ii) the whole supply chain of a product/service in order to identify hotspots, and

iii) potential circularity strategies (ex post) for the same product against each other in order to help companies select the best scenario when the product reaches the end-of-life stage.

This research falls into the latter category and aims to propose a method for evaluating alternative potential circularity scenarios of a specific product in a specific company. This evaluation method will help industrial practitioners choose or select between various circularity strategies for a product.

There is a need for such evaluation methods as indicated by (Sassanelli et al., 2019) on CE assessment methods, and tools, and (Saidani et al., 2018) who created a taxonomy of CE indicators including more than 55 sets of indicators. CE assessment methods that evaluate circularity scenarios are missing. (Elia et al., 2017) supported this argument in the recent work on critical analysis of CE assessment and indicators at micro level.

The main objective of this paper is to address the following research question:

RQ: How to evaluate potential circularity strategies for a product and/or service using a decision method to help a company select a suitable strategy at EoL stage?

This research question is also broken down into two sub-questions

a. What are relevant criteria/indicators and sub-criteria/decision-making factors to be used to evaluate circularity scenarios?
b. How to formulate a decision method that incorporates the criteria and sub-criteria?

The overarching aim is to propose a circularity strategies decision-making method to evaluate circularity scenarios of products and added service in re-manufacturing firms. The method evaluates potential alternative circularity scenarios including (but not limited to) the initial or business-as-usual scenario of the company which could be a traditional sales scenario or include some form of product level circular strategy e.g. remanufacturing (reman), as well as various forms of more advanced or transformative scenarios, and future reman scenarios. Advanced scenarios could be advanced remanufacturing, (target reman businesses, multiple/mixed scenarios e.g. products included in a service (also known as product service systems) that facilitate the sequential implementation of reuse, repair and future remanufacturing scenarios. The proposed method aims to help business decision-makers of a re-manufacturing firm to select the best compromising circularity strategy with a focus on remanufacturing.

Apart from introducing the method, this work gives two examples of its application and subsequent verification.

The organization of this article is as follows: Section 2.3.2.2 presents a literature review about CE, circularity strategies, decision-making factors, and CE assessment methods. Section 2.3.2.3 exposes the research methodology employed in this study to build the circularity strategies decision-making method. The results of this paper i.e. the evaluation method is presented in section 2.3.2.4. Verification of the proposed method through case examples is presented in Section 2.3.2.5. Section 2.3.2.6 discusses and summarizes the main findings of the study and points out future research opportunities.

2.3.2.2. Literature review

2.3.2.2.1. The circular economy and product circularity strategies

The CE aims to keep products, components, materials and resources in the economy at their highest utility and value, through application of various circularity strategies (Bocken et al., 2017; Ellen MacArthur Foundation and Granta Design, 2015). Circularity strategies that extend product life include reuse, repair, refurbish, recondition, remanufacture, repurpose, cannibalization, and recycling which close resource loops (Bocken et al., 2017; Stahel, 2016).

Adopting CE is expected to have considerable benefits in reducing waste volume, raw material inputs while supporting economic growth (Fellner et al., 2017). In December 2015, the European Commission adopted an ambitious CE package to support EU's transition to a CE (European Comission, 2015). CE has also gained traction in USA, China and Australia (Ali et al., 2018).

The successful implementation of circularity strategies in businesses depends on combined leverage of the building blocks amongst others, product & service design, business models, reverse supply chain, product & service use patterns, end-of-life (EoL) recovery, and supporting policies (EMF, 2015). Reverse logistics facilitate reuse, refurbishment and remanufacturing etc of products and therefore is one of the building blocks of CE, and is an enabler for a sustainable production and consumption (Sangwan, 2017). It has attracted the attention of both academics and practitioners due to the growing concern of environmental problems and legislative pressure (Govindan et al., 2015; Stewart and Ijomah, 2011). Efficient reverse logistics system are key for an effective transition from a linear to a CE model (Ellen MacArthur Foundation and Granta Design, 2015; Gnoni et al., 2018; Lieder and Rashid, 2016).

Fig. 1 depicts a list of circularity strategies, which include:

- reuse/resell involves re-using a product if it meets sufficient quality levels (Burke, 2009; Richa et al., 2014; Winslow et al., 2018);

- repair aims to recover a used product into "working order" by fixing/replacing specified faults using service parts (King et al., 2006);
- refurbishing involves returning products to a specific quality level, usually less than that of a new product (Krikke, 1998);
- recondition involves returning the quality of a product to a satisfactory state level (typically less than a virgin standard/new product) giving the resultant product a warranty less than of a newly manufactured equivalent (King et al., 2006; Paterson et al., 2017). Reconditioned products has gone through extensive testing and repair than refurbished products (Krikke, 1998);
- remanufacturing is an EoL product circularity strategy whereby worn-out products are restored to the original equipment manufacturer (OEM) standard, and receive a warranty at least equal to a newly manufactured product (Ijomah, 2002; Rose, 2000; Sundin, 2004);
- repurposing involves using post-used products for a different purpose and application compared to the original product (Bauer et al., 2017);
- cannibalization is an activity of recovering parts from returned products. Recovered parts are used in repair, refurbishing, reconditioning and remanufacturing of other products (Alamerew and Brissaud, 2018); and
- recycling discarded materials are collected, processed and used in the production of new materials or products (Jawahir and Bradley, 2016; Winslow et al., 2018).

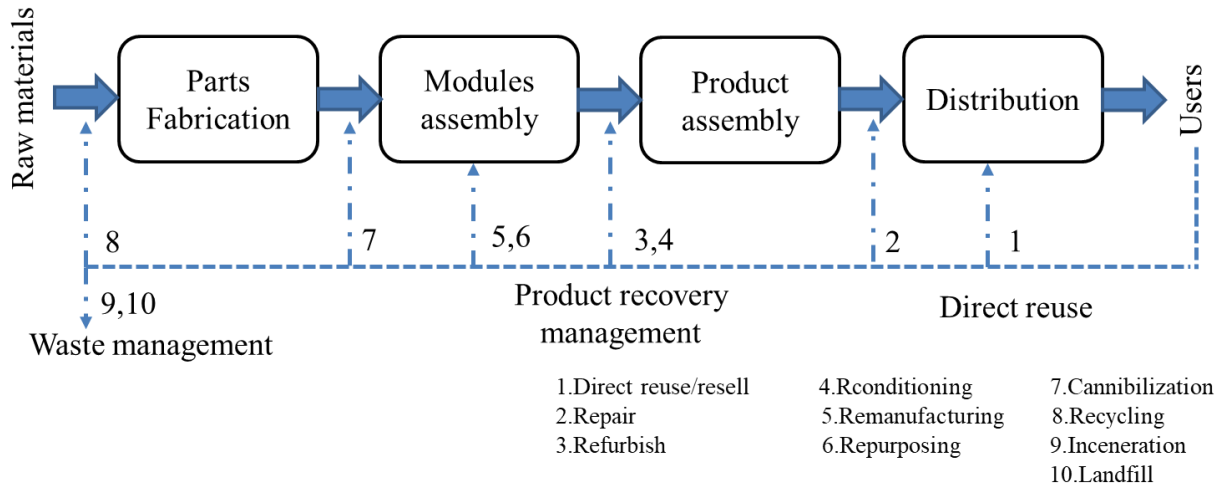


Figure 29: List of circularity scenarios (modified after (Thierry et al., 1995))

The circularity strategies terminology adopted in this article have been distinctly described in this section because overlaps do exist and there is a lack of consensus about the specifics of each strategy. End-of-life stage in this work refers to the point in time when the product reaches at the last stage of existence or in the

end of useful life with reference to the first user of the product. Also, various literatures use different terminologies for the term “circularity strategies” such as circularity measures, circularity scenarios, circularity option, circularity alternatives, EoL options, recovery strategies, and circularity strategies. In this manuscript, we use the terms circularity strategies and circularity scenarios/alternatives alternatively. Selecting a suitable circularity option should take several factors into consideration (Kumar et al., 2007; Thierry et al., 1995). Moreover, circular strategies for bio-based products and technical products generally differ. The circularity strategies described above and focused on here are the ones that aim to close technical cycles.

2.3.2.2.2. Circular economy strategies evaluation methods

Recently, CE evaluation methods have been developed for managing the implementation of circularity strategies (Geng et al., 2013). Evaluation of circularity strategies is crucial to selecting appropriate strategies but also pinpointing hotspots and areas of improvement in order to move towards a more CE (Saidani et al., 2017). Although CE evaluation methods can be developed to meet the needs of various stakeholders e.g. designers and industrial practitioners, policy makers, and consumers, the focus here as discussed in the introduction is on their use for decision-making in the business context. It the business context helps to measure how well a product, service or company perform with respect to the CE principles. The CE paradigm can be analysed at three levels of intervention: micro (product, company or single consumer level); meso (eco-industrial parks); and macro (cities, provinces and regions) (Ghisellini et al., 2016). This research paper studies CE evaluation at micro level for businesses focusing on remanufacturing strategy and added service offerings.

In recent years, there is a growing pool of academic studies that evaluate circularity strategies at a micro level (Elia et al., 2017; Saidani et al., 2017). Circularity strategies can be evaluated by optimization, MCDM or empirical method. Optimization methods are mostly focused on economic benefit while it lacks the ability to consider other unquantifiable factors (Doyle et al., 2012; Dunmade, 2004). In addition, due to the complexity of mathematical models, and their requirement of too many input parameters, it is difficult for companies to use this method effectively and efficiently. While empirical methods are based on the knowledge and experience gained from analysing successful cases rather than conventional rule-based methods (Shih et al., 2006). MCDM help decision-making in complex and interactable decision tasks (Selmi et al., 2016; Velasquez and Hester, 2013).

Table 31 presents description of CE evaluation methods. (ResCoM, 2017)developed a web-based tool (Circular Pathfinder (CP)) to identify a suitable circularity strategy focused on bio-cycles than techno cycles. Also, this tool lacks scientific validation. Similarly, (Alamerew and Brissaud, 2018) developed a

product recovery decision-making tool to evaluate CE strategies at strategic level. (Lee et al., 2014) present an End-of-life Index (EOLI) method to evaluate product performance in relation to circularity strategies based on the calculation of total cost of each end-of-life processes. The proposed index method assists designers to adopt design for EOL approach.

Table 31: Description of CE evaluation methods

Method	Description
Circular pathfinder (CP)	A web-based tool to identify a suitable strategy based on a survey of 10 product related qualitative questions. (ResCoM, 2017)
End-of-life index (EOLI)	An EoL process cost-based index to evaluate circularity strategies including remanufacturing, recycling etc (Lee et al., 2014)
Product recovery multi-criteria decision tool (PR-MCDT)	A CE evaluation tool that evaluates circularity strategies (remanufacturing, recycling, repair, and reuse) at strategic level. The strategies are evaluated according to relevant economic, business, environmental and societal indicators (Alamerew and Brissaud, 2018)
CE toolkit	A web-based tool to assess product/service throughout the entire life cycle. The proposed tool could be used by companies, distributers/retailers and consumers (Evans and Bocken, 2013)
CE assessment dashboard	A dashboard of indicators is proposed for CE strategy assessment in organizations (Pauliuk, 2018)
Circularity potential indicator (CPI)	A circularity performance indicator to measure the performance of products in the early phases of a new or re-design product development (Saidani et al., 2017)
Multicriteria matrix	A multi-criteria approach to assist decision-making for EoL management of electronic products (Iakovou et al., 2009)

2.3.2.2.3. Multi-criteria decision methods

Multi-criteria decision-making method is a tool used to select the best available scenario from a list of several potential alternatives under several criteria. The method is usually used to solve complex problem by analysing multiple criteria simultaneously (Iakovou et al., 2009). MCDM help decision-making in complex and interactable decision tasks (Selmi et al., 2016; Velasquez and Hester, 2013). Due to the complexity of circular systems, the involvement of various decision factors, and the availability of multiple scenarios, MCDM can be used to evaluate circularity strategies. Evaluation of circularity strategies needs to use a holistic approach to evaluate various decision factors from environmental, economic, societal, business, technical, market and legislative aspects. Multi-criteria decision-making methods have benefits

due to its structure by simultaneously analysing quantitative and qualitative factors. Also, MCDM also takes the preference of the user/decision-maker in the decision-making process (Alamerew and Brissaud, 2018).

Referring to Table 31, the multicriteria matrix and PR-MCDT have employed MCDM. The PR-MCDT is used to evaluate circularity strategies at strategic level. This tool helps to assess the feasibility of a recovery business or to test the performance of a recovery scenarios in order to improve a business (Alamerew and Brissaud, 2018). In addition, the multi-matrix (Iakovou et al., 2009) used multi-criteria decision-making method to evaluate EoL product and its components for recovery. This method used evaluation criteria such as the residual value, weight, ecological burden, quantity and ease of disassembly of components. In this paper a MCDM is used to evaluate circularity scenarios of a product at a tactical level i.e. traditional business scenario e.g. remanufacturing; advanced reman businesses (target reman businesses, multiple/mixed reuse scenarios and service offerings), and future reman scenarios.

2.3.2.3. Methodology

The point of departure for this research is a review of literature on the main themes related to the research question and sub-questions namely: circularity strategies for a product and/or service, and evaluation methods of circularity strategies; identification and selection of decision-making criteria as well as criteria-indicators and sub-criteria decision-making factors. These are presented in Section 2. The research process for developing the evaluation method of alternative circularity scenarios of a specific product in a specific company is depicted in Fig.2 and includes: (i) initial method selection, (ii) selection of criteria and sub-criteria, (iii) method development, and (iv) verification of the proposed method.

2.3.2.3.1. Initial method selection

A literature review was made to understand the state of the art on the evaluation of circularity strategies. As discussed in Section 2.2, circularity strategies evaluation methods often employ optimization, multi-criteria or empirical methods for decision-making. Based on the review of literature, the advantages and disadvantages for using each methods for decision-making is analysed. In this paper a multi-criteria decision-making (MCDM) approach is used to develop circularity strategies evaluation method. MCDM help decision-making in complex and interactable decision tasks (Selmi et al., 2016; Velasquez and Hester, 2013).

2.3.2.3.2. Selection of decision criteria and sub-criteria

Based upon a comprehensive literature review and feedback from experts in the subject domain, decision-making factors (decision criteria) and indicators are identified. Firstly, an exhaustive list of factors is

presented. Then the decision-making factors were sorted into various categories by the authors such as business, technical, economic, environmental, legal and societal aspects. Afterward, the list is updated following receiving expertise feedback from the industry and academia. Detailed results of this research can be accessed from (Alamerew and Brissaud, 2018).

2.3.2.3.3. Method development

Due to the complexity of circular systems, an integrated approach is required to encompass all the decision-making criteria, and to take into account both quantitative and qualitative factors. Based on the result of a comprehensive literature review, evaluation of circularity strategies can be formulated as a multicriteria decision-making problem. The multi-criteria evaluation of circularity strategies involves (I) description of the product under consideration, (II) finding potential circularity strategies, (III) identifying evaluation criterion and decision-making factors, (IV) evaluation of circularity scenarios, and (V) analysis and ranking of circularity alternatives.

In this study, MCDM is used to build the proposed method. The proposed method is first developed based on simple multi-attribute rating technique (SMART). Afterwards, the authors reduce the complexity in order to develop a practical method to effectively apply on real case studies. The authors commented on the proposed method during the development period.

2.3.2.3.4. Verification of the method

To validate the application of the proposed circularity strategies evaluation method, an illustrative example is shown based on a case study. Secondary data from two Swedish companies, so called Company A and Company B, is used to exemplify the application of the method. Company A is involved in waste management whereas Company B is a storage furniture supplier. Description of case companies is presented in section 6.

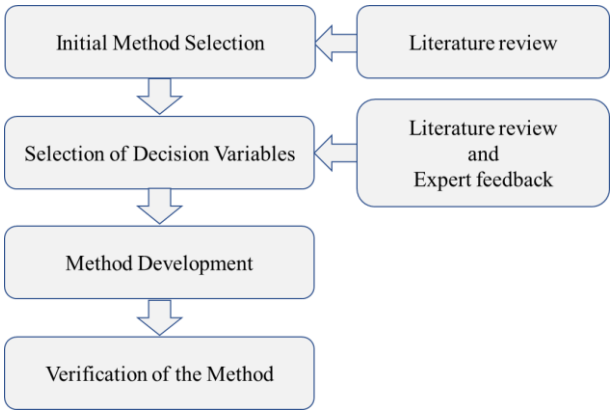


Figure 30: Graphical representation of research methodology

2.3.2.4. Results

2.3.2.4.1. Multi-criteria decision-making method description

In this section, the results of this study are presented. A "Multicriteria Evaluation Method" is proposed to evaluate alternative potential circularity strategies of a specific product in a specific company. The proposed multi-criteria decision-making method consists of 5 main steps: (I) description of the product under consideration, (II) proposing potential circularity strategies, (III) identifying evaluation criterion and decision-making factors, (IV) evaluation of circularity scenarios, and (V) analysis and ranking of circularity alternatives. The graphical representation of the method is shown in Fig. 3. In the following section each step of the evaluation method is described in detail.

I. Product characterization

This first step of the method aims to identify the main characteristics of the product under consideration. This includes information regarding type of components and materials of the product. This information will help to identify decision-making criteria, and potential circularity alternatives that are relevant to the product at hand in the next steps of the methodology (Staikos and Rahimifard, 2007).

A potential circularity strategy is a possible candidate for evaluation and comparison during the decision-making process (Roy, 1996). In multi-criteria decision-making literature, the potential candidate strategies are generally called alternatives or actions (Lamvik et al., 2002). A functional description of the product is decisive for a company to be able to efficiently recover a typical product. Description of the product provides relevant information regarding its characteristics as well as functional use by the consumer. The main output of this step is to identify factors that influence the selection of circularity scenarios including information about the product (type of the product, function, materials used … etc.), business strategy of the company, etcetera.

II. Selection of potential circularity scenarios

Based on the outputs of step 1, i.e. description of characteristics of the product, in this step potential circularity scenarios are identified. First the current business strategy of the company (business as usual) is identified from a set of circularity strategies defined in section 1.1. Then potential transformative strategy and target scenarios are selected based on the attributes of the product defined in section 4.1. This study mainly focuses on (but not limited to) remanufacturing strategy and added services. Potential circularity strategies include: the initial business of the company (traditional business or remanufacturing (reman)); advanced reman businesses (target reman businesses, multiple/mixed reuse scenarios plus service

offerings), and future reman scenarios. Also, the method can evaluate different types of reman processes (product, supply chain, business model etcetera). The main output of this step is a list of potential circularity strategies.

III. Identifying decision-making criteria and sub criteria

There are various factors which influence the recovery/re-manufacturability of post-used products (Alamerew and Brissaud, 2018; Doyle et al., 2012). Based on previous studies of this research by (Alamerew and Brissaud, 2018) a list of CE evaluation criteria/categories, decision factors/sub-criteria/sub-categories, and evaluation indicators Alamerew and Brissaud, 2018). List of decision-making factors consists of both quantitative and qualitative criteria. Selection of criteria and sub-criteria could be changed depending on analysis of the problem, the decision-maker, the availability of data and type of the product under consideration. In this study six criterions are used including environmental, economic, legislative, market and social and technical indicators.

IV. Evaluation of potential circularity strategies

After identifying the list of evaluation criteria and potential circularity strategies, the next phase of the method is to evaluate each circularity alternative against decision criteria. The main output of this step is an assessment value for each potential circularity scenarios.

A typical problem consists of a set of available circularity strategies or circularity alternatives Ai (i = 1,2, … , n). Potential circularity alternatives are evaluated against a set of criteria Cj (j = 1,2, … , m). Each criteria Cj may be broken down into Pj sub-criteria (decision-factors) Cjk (K = 1,2, … , Pj). The decision-maker is expected to evaluate potential circularity strategies with respect to each decision criteria denoted as Xij (i = 1,2, … , n j = 1,2, … , m).

The general model applied for the proposed method is:

$$\boldsymbol{M(Ai) = \sum_{j=1}^{m} \quad Wj\, Xi(j)\,, i = 1, 2,,, n} \quad \text{(Equation 1)}$$

Where Wj : weighted value of j of m criteria

$\boldsymbol{Xi(j)}$: value of i of criterion j

M(Ai) is total evaluation result for each strategy

The weighting value (Wj) is assigned based on the weight value of each criteria/sub-criteria for the evaluation decision. It depends on the type of product, the type of industry, and the perception of the

decision-maker. In this step, the decision-maker assigns the value based on the experience on the typical product/business.

Then, the evaluation score for each of the potential circularity strategies against each decision factors both for the qualitative and quantitative factors is calculated. In this step, a parameter value (5-Very high; 4-High; 3-Average; 2-Low; 1-Very low) based on scale can be assigned for the qualitative decision factors such as business, technical, societal and legal criteria. Computation of life cycle assessment (LCA) and life cycle costing (LCC) can be performed to evaluate the environmental and economic performance for the quantitative indicators respectively. These decision factors/indicators can be changed depending on the preference of the decision-maker as well as the availability of data and related factors.

Afterward, the relative weight (normalization) is conducted to allow a comparable scale for all potential circular strategies using Equation 2 and Equation 3. Depending on the typical problem, Equation 2 is used when the objective of the problem is to maximize the result and Equation 3 is used when the objective is to minimize the result.

The normalization for maximization problem, $\mathbf{N} = \frac{\boldsymbol{Xij}}{\boldsymbol{Xij\ max}}$ (Equation 2)

The normalization for minimization problem, $\mathbf{N} = \frac{\boldsymbol{Xij\ min}}{\boldsymbol{Xij}}$ (Equation 3)

Where Xij is the assigned value of Ai for the sub-criteria Cjk

Xij max; Xij min are the maximum and minimum assigned value Ai for the sub-criteria Cj respectively

Finally, the overall score of each circularity scenarios are computed based on Equation 4 and rank the circularity alternatives in descending order.

$$\boldsymbol{M(Ai) = \sum_{j=1}^{m} \quad Wj\ Xi(j)\ , i = 1, 2, , , n} \quad \text{(Equation 4)}$$

Where Wj is weighting value of the sub-criteria

$\boldsymbol{Xi(j)}$ is the value of i of criterion j

M(Ai) is total evaluation score for each strategy

V. Analysis of the result and recommendation

This step involves analysing the overall score of each circularity alternative and provide recommendation of the feasible circularity strategy from the available list of alternatives.

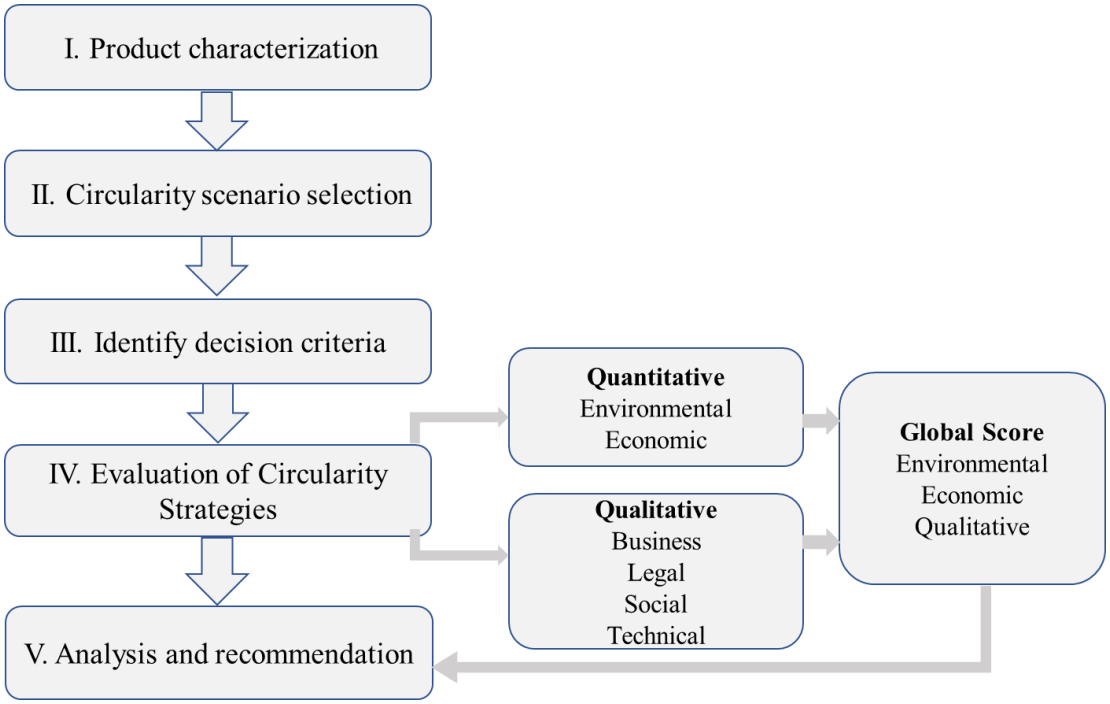


Figure 31: Depiction of the main steps of the proposed method

2.3.2.4.2. Verification of multi-criteria decision method

The proposed circularity strategies evaluation method is verified by applying an illustrative example with two case studies. Secondary data collected from two companies is used to verify the application of the proposed method to evaluate potential circularity scenarios. In the following sections, the application of the proposed method to each case study problem is presented. More details about the case study companies can be referred from (Kaddoura et al., 2019).

2.3.2.4.2.1. Case study for company A

Company A offers vacuum waste collection system for residential places, business premises, and town centers worldwide. The collection system transports the waste through an underground pipeline and sorts out into a sealed container. In addition to product planning and installation, the company provides service through maintenance, and other services. This study focuses on the inlet part of the waste collection system due to frequent failure.

In this study, three business scenarios are considered: business as usual (when the inlet breaks, the whole door is replaced); circular scenario 1 (when the inlet breaks, broken parts of the door are replaced with new parts, and parts of the door that are not broken are reused); and circular scenario 2 (when the inlet breaks,

parts of the door that are not broken are reused to make new doors). Table 32, shows a description of circularity scenarios for case study A.

The multi-criteria decision-making evaluation method has six main criteria to evaluate potential circular scenarios: environmental, economic, social, legislative, technical and business. The sub-criteria (decision factors) under each criteria are LCA, LCC, job creation opportunity, legislative pressure, technical feasibility (for instance ease of disassembly, technological compatibility etc,) and market demand respectively. Also, a weighting value of 0.15, 0.20, 0.10, 0.15, 0.20, 0.20 (based on experience from previous study on (Alamerew and Brissaud, 2018)) is assigned respectively as shown in Table 33.

Based on the outcome of the analysis, remanufacturing of the waste collection system got the highest score followed by a circular scenario and is the most suitable circularity strategy. The main results of the analysis are presented in Table 33. To read Table 33: In a line, it is a criterion and its value for every of the 3 scenarios considered (UP is the real value when it is quantitative and the value in a 1-5 scale when it is qualitative; DOWN is the same result normalized from 1 for the best score). In a column, it is a scenario studied that gives a total against all the criteria.

Some comments can be drawn for those results. First, the result would have been similar (0.65, 0.82, 0.97 respectively) when the weighting value assumed to be equal for all criteria. Second, if the analysis was performed only against environmental and economic criteria, the most circular scenario would have been the business as usual option. This has happened due to the company A's pricing system and the estimation of customers willingness to pay. Even though, the bulk selling effect of the product shows an increase in profit margin.

Table 32: Description of circularity scenarios for case study A

List of scenarios	Description
Business as usual (BAU)	The vacuum waste systems are installed based on contracts and remote control and regular maintenance is conducted during use phase. When the inlet breaks, the whole door is replaced and post used product is mostly recycled.
Transformative scenario (Circular scenario 1)	When the inlet breaks, broken parts of the door are repaired by service technicians (broken parts of the door are replaced with new parts and parts of the door that are not broken are reused).
Future scenario (Circular scenario 2) (Remanufacturing)	When the inlet breaks, parts of the door that are not broken are reused to make new doors in which the quality of the product is equivalent to a newly manufactured product.

Table 33: Evaluation of circularity scenarios for company A

		Circularity scenarios	Business as usual	Repair	Remanufacturing
Criteria	Sub criteria	Weight (W_i)			
Environmental	LCA (kg CO2 eq)	0.15	1574.90	1544.48	1514.00
Normalization (N)			0.96	0.98	1
Economic	LCC (SEK)	0.20	67060	63359	59441.8
Normalization (N)			1	0.94	0.88
Social	Job creation opportunity	0.10	4	4	5
Normalization (N)			0.8	0.8	1
Legislative	Effect of legislative pressure	0.15	5	3	1
Normalization (N)			0.2	0.33	1
Technical	Technical feasibility e.g. disassembly	0.20	2	4	5
Normalization (N)			0.4	0.8	1
Business	Market demand	0.20	3	5	5
Normalization (N)			0.6	1	1
Total (without Wi)		1.00	3.96	4.85	5.88
Overall ranking (with Wi)			0.65	0.82	0.97
(c) Parameter value: 5-Very high; 4-High; 3-Average; 2-Low; 1-Very low					

2.3.2.4.2.2. Case study for company B

Company B is a provider of storage furniture. The company supplies furniture, recycling stations, wardrobes etc. These products are sold to the customers and there is no added value on the product sold such as services.

In this study, two business scenarios are considered: business as usual (the product is sold to the customer and the customer is responsible for disposal of the product at the EOL phase), and upgrade (the product is upgraded by refreshing products' appearance). In the circular scenario the company is also in charge of administering and coordinating the upgrading process. Table 34, shows a description of circularity scenarios considered for case study B.

Compared to case study A, this case study used the same criteria and sub criteria to evaluate circularity scenarios. In this case study, a weighting value of 0.15, 0.20, 0.10, 0.15, 0.20, 0.20 (based on experience from previous study) is assigned respectively as shown in Table 5. Based on the results of the analysis as presented in Table 35, upgrading of the product is a suitable strategy. The study shows that the circular offering i.e. upgrading is a preferred strategy over the business as usual scenario.

Table 34: Description of circularity scenarios for case study B

List of scenarios	Description
Business as usual	The product is sold to the customer. The customer is responsible for disposal of the product when it reaches at its EoL phase.
Circular scenario (upgrading)	The product is upgraded by refreshing products' appearance. The company is responsible for providing the intended service.

Table 35: Evaluation of circularity scenarios for company B

		Circularity scenarios	Business as usual	Upgrade
Criteria	Sub criteria	Weight (W_i)		
Environmental	LCA ((Kg CO2 eq)	0.15	231.23	123.46
Normalization (N)			0.53	1
Economic	LCC (SEK)	0.20	1636	1798
Normalization (N)			0.90	1
Social	Job creation opportunity	0.10	2	4
Normalization (N)			0.5	1
Legislative	Effect of legislative pressure	0.15	2	3
Normalization (N)			0.66	1
Technical	Technical feasibility e.g. disassembly	0.20	2	5
Normalization (N)			0.4	1
Business	Market demand	0.20	3	4
Normalization (N)			0.75	1
Total			3.56	6.00
Overall ranking			0.63	1.00
(a) Parameter value: 5-Very high; 4-High; 3-Average; 2-Low; 1-Very low				

2.3.2.5. Discussion and conclusion

One of the challenges that impedes companies to transform their business towards a CE model is lack of methods, tools, and indicators to be able to evaluate different circularity scenarios. This paper has proposed a multi-criteria decision-making method for evaluating potential circularity strategies at the product and or service level that can be implemented after first life by the company providing the initial product.

One of the limitations of this multi-criteria decision-making tool is lack of the linkages among criteria in decision-making. Multi-criteria decision method is characterized by criteria independence without correlation (Ishizaka and Labib, 2009). Due to the complexity of circular systems, it is imperative to understand the interaction (direct or indirect dependency) among decision factors in decision-making process. In this regard, one of the future research works could be to use Analytical Network Process (ANP) to understand the inter-dependency among decision factors. Also, when assigning weighing value to criterions, it is challenging for the decision-maker to decide which of the criterion influences more and how much more for the given circularity alternatives.

Moreover, the assignment of verbal grading and its conversion into a parameter value based on a qualitative scale is subject to ambiguity during the decision-making process. In order to transform the qualitative criteria into quantitative numbers, a rating scale is used. In this study, a semantic scale, Likert is used as it is commonly used in business decision- making (Munshi, 2014; Nemoto and Beglar, 2014). A scoring scale from 1 to 5 is used to quantify the qualitative factors. Theoretically, the numerical scale/verbal grading cannot be restricted, and other scales can be used up on investigation.

The proposed method uses an integrated approach to evaluate the environmental and economic benefit of circularity strategies together with social, legislative, business and technical aspects. An illustrative example through two case studies is presented which proves that, the proposed method is simple and effective in dealing with circularity scenario evaluation problems. Compared to (Alamerew and Brissaud, 2018; ResCoM, 2017), this method evaluates circular scenarios focusing on remanufacturing and its transformative strategy that transform a product such as added service offerings.
Some of the main benefits of the proposed method are:

- It provides a list of indicators/criteria and sub criteria for businesses which help companies to prioritize the selected business,
- It identifies potential business perspectives such as advanced reman businesses (target reman businesses, multiple/mixed reuse scenarios and service offerings), and future reman scenarios,

- It gives a solution for businesses from a list of potential circularity alternatives. In addition, the method aid businesses by showing future circular product and new business opportunity,
- It helps companies to easily compare a large number of circular scenarios ex post and evaluate their circular offerings including the initial business of the company (traditional business or remanufacturing); advanced reman businesses (target reman businesses, multiple/mixed reuse scenarios and service offerings), and future reman scenarios,
- It aids companies to gain economic benefit and reduce environmental impact by evaluating their current circular strategy, and improve/transform their business model, and
- It is a simple method that can be easily used to evaluate potential circularity alternatives.

Future research

In this article, a multi-criteria evaluation method is proposed to evaluate potential circular scenarios with a focus on remanufacturing strategy. Even though, this study has made valuable contribution as an effort to fill in some of the research gaps presented in section 1, further investigations are required in the research area. One future work can be to adopt the proposed method to various types of products, services, and industrial sectors. This helps to generalize the application of the proposed method to various industrial sectors. Moreover, it could be interesting to compare and analyse the results across various industrial sectors. This aids to learn from successful experience on how one industrial sector can benefit learn from other sectors in their effort to transform to a more circular economy model.

Another important research opportunity could be to extend the proposed evaluation method to include pre-use/use phase of the product/service. This method evaluates a post-used product/service at the EoL phase. In this line, future work can be to extend the proposed method to include pre-life and use phase of the product in order to make decisions such as in design phase. Also, more research could be conducted to test the proposed method on first-hand company data. Moreover, the interaction between criteria and sub-criteria and their influence on the overall result from a system perspective should be studied in future research. One approach to address this gap could be to use Analytical Network Process (ANP).

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3. Discussion and Conclusion

In this chapter, the findings of this Ph.D. dissertation and its papers are discussed, and conclusions are drawn. First, the main contributions of this thesis are presented with respect to the objectives and research questions challenged in this thesis. Then, a detailed discussion regarding the contributions of the thesis and its impact on the implementation of CE principles is presented. Afterward, the impacts of this Ph.D. thesis for industrial practitioners, academics, policymakers, designers and users are discussed. Subsequently, the limitations of this Ph.D. study are discussed. Finally, suggestions for future research opportunities are presented.

3.1. Main contributions of the Ph.D. thesis

The main aim of this Ph.D. thesis is to develop and propose an EoL decision-making tools and indicators to evaluate circularity strategies and measure the performance of a reverse supply chain. In accordance with the objective, this Ph.D. thesis aims to answer the main research question "How to evaluate circularity strategies and measure the performance of reverse logistics?". As shown from the formulated main research question, this Ph.D. thesis has two main research themes: circularity strategies and reverse logistics. In fact, circularity strategies are one of the enablers for the recovery of post-used products and product recovery is one of the main components of reverse logistics (Sangwan, 2017).

The main outcomes of this Ph.D. thesis are (i) development of circularity strategies assessment tool at strategic level, (ii) modelling of the reverse logistics system to understand the interplay among main pillars of circular economy and of the interaction among various decision-making factors, (iii) proposition of a circular economy indicator to measure the performance of a reverse supply chain, and (iv) development of a circular economy evaluation tool for potential circularity strategies at the product level. Table 36, presents the main contributions of this Ph.D. dissertation. This thesis aimed to understand the complexity of circular economy in reverse logistics systems by systematically modelling the RL system and developing CE tools and indicators to evaluate circularity strategies and measure the performance of a reverse logistics system. The proposed tools are validated by case studies with various industries using primary and secondary data.

The proposed tools and indicators are expected to assist industrial practitioners in the management of post-used products. It helps industrial practitioners to make informed decisions on the recovery of post-used products using the proposed tools and indicators. Industrial practitioners can evaluate circularity strategies and assess the performance of a reverse supply chain within their companies. The tools and indicators proposed in this thesis have the potential to support companies to shift towards a circular economic model.

Table 36: Main contributions of this Ph.D. thesis

Research gaps (RG), Research objectives (RO), and Research questions (RQ)	Propositions and contributions
RG #1: There is hardly any research about decision factors and performance indicators on reverse supply chain for circular economy. **RO #1**: To identify key decision variables and indicators used to evaluate circularity strategies and measure the performance of reverse logistics. **RQ #1**: What are the most important key decision factors and indicators that should be considered in the evaluation of product circularity strategies and performance measurement of reverse logistics?	➢ The research identifies EoL decision-making factors from technical, economic, environmental, business, and societal aspects. Also, it presents a list of indicators to assess circularity strategies and measure the performance of reverse logistics. ➢ A product recovery decision-making tool is proposed to evaluate circularity strategies at a strategic level.
RG # 2: There has been very limited studies about the interaction among a variety of complex influencing factors in reverse logistics system. Also, there is a lack of experience in modelling of EoL value chains due to interdependencies, dynamic conditions etc. **RO #2**: To model the complex system of reverse logistics of post-used products to understand the interaction among a variety of decision-factors. **RQ #2:** How to model the complex system of reverse logistics of post-used products to advance in the circular economy?	➢ The research shows the interaction among various decision-making factors including economic, environmental, and societal factors in the reverse logistics system. Modelling of decision-making factors is accomplished with respect to the dynamics of cost, revenue, and strategic and regulatory decisions. ➢ The thesis presents the interplay among the main pillars of CE including business models, reverse supply chain, policy, product/service use, end-of-life recovery, and design for a successful transition to a resource efficient and circular economy model. ➢ The enablers and challenges for circularity of EoL products are presented for a case study of EVBs with respect to the main pillars of the circular economy.
RG # 3: There are no satisfactory tools and indicators to evaluate circularity strategies and measure the performance of reverse logistics in the circular economy. **RO #3**: To propose tools and indicators to evaluate circularity strategies and measure the performance of RL for circular economy. **RQ #3:** How to assess end-of-life circularity strategies and measure the performance of reverse logistics for circular economy?	➢ Theis thesis proposed a multi-criteria decision-making method for evaluating circularity strategies to assist companies to easily evaluate circular offerings at product level. The method provides a list of indicators/criteria for companies to prioritize the selected business and points out future circular products and new businesses. ➢ The thesis proposed a multi-index indicator (CEI-RL) that evaluates the performance of a reverse logistics system with respect to collection, inspection and sorting, and product recovery activities.

3.2. Discussion about the structure of the Ph.D. thesis and its contribution

This Ph.D. thesis is structured into three parts: (I) identification of EoL decision factors and indicators, (II) modelling of the reverse logistics system, and (III) proposition of assessment tools and indicators. It is structured into three parts in order to be able to tackle the problem systematically and to propose a successful and effective evaluation tools and indicators. These three steps are linked to each other and their output is used as an input in the following steps. First off, EoL decision factors and indicators are identified that they are used as one of the inputs in the evaluation process to the proposed tools. Secondly, modelling of the reverse logistics system is accomplished to understand the interaction among decision factors from environmental, economic and social perspectives. Finally, EoL decision-making tools and indicators are proposed considering the outcomes of the previous two steps.

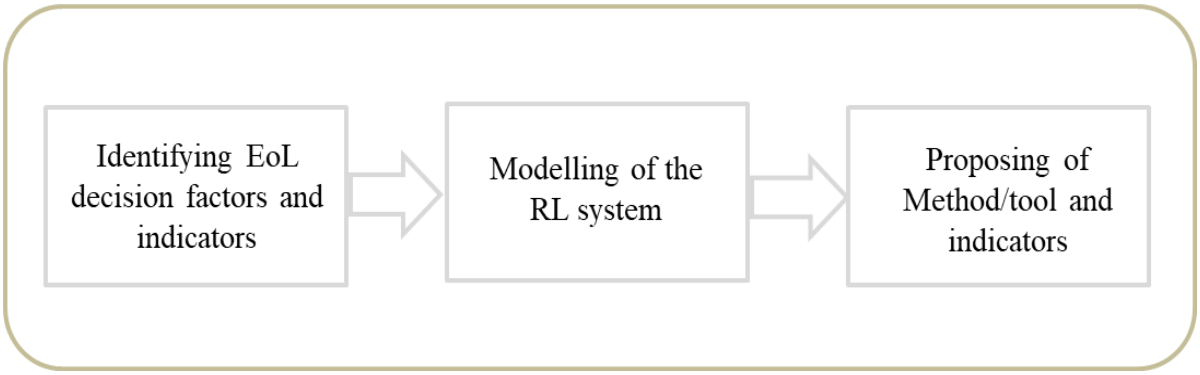

Figure 32: Main steps of the methodology

The complex nature in a circular economy raises a great deal of challenges in the decision-making process (Xu et al., 2010). Due to this complexity of circular systems, it is imperative to understand the interaction among decision factors in the decision-making process. In addition, understanding the interplay among the building blocks of CE plays a vital role in decision-making. Frequently, circular economy assessment tools evaluate environmental, economic and social aspects independently and present the overall result following various approaches such as optimization method (Zhang, 2019). This approach is challenged by system thinkers since circular systems have to be analysed by following a systemic perspective in the evaluation during the decision-making process at the strategic and tactical levels. As shown in Fig. 32, modelling of the reverse logistics system helps to tackle the aforementioned issue. In this part, modelling of the RL system is accomplished in order to understand the interaction among various decision-making factors from environmental, economic, social, business and legislative aspects. The result is used to develop decision-making tools and indicators.

3.3. Discussion about the results of the Ph.D. thesis and its contribution

Based on the analysis made following the three main steps, represented in Fig. 32, this Ph.D. thesis has contributed to four main results. The results contributed in this Ph.D. dissertation are (i) identification of decision-making factors and indicators, (ii) modelling of the reverse logistics system, (iii) circular economy for reverse logistics performance indicator, and (iv) CE evaluation tools at a strategic and tactical level. The first two results are used as a base to develop circularity strategies evaluation tool and a CE performance measurement indicator for reverse logistics.

The proposed tools and indicators are expected to help industrial practitioners in the decision-making process of EoL products, processes, and systems. These tools and indicators are expected to support companies in their transition from a linear towards a circular economy model. In addition, the contributions of this thesis expected to support academics, policymakers, designers, and users. The study is focused on the evaluation of circularity strategies and performance measurement of a reverse logistics system for technical products such as electrical and electronic, automotive and waste management products, and it does not support decisions for biological cycles. In addition, more research work has to be done to apply the proposed method, tool, and indicators to various case studies. This will help to refine the proposed tool to various product categories and to tailor them for each specific industry.

In this Ph.D. thesis, it is believed that the proposed decision-making tools and indicators help companies in decision-making processes to employ the principles of circular economy. Considering the relevance of the circular economy to meet the goals of sustainability, this research will have an important contribution to fill in some research gaps specifically in the development of decision-making tools and indicators at a micro-level. The contributions of this dissertation and its four main results will have a positive impact for the development of CE and implementation of circular economy principles. However, there are challenges that hider the implementation of CE principles such as lack of trustworthy information, inadequate leadership and management, shortage of advanced technology, and poor enforceability of legislation (Su et al., 2013).

The availability of reliable information is critical for firms to identify and select optimal circularity strategies (Geng et al., 2009; Rizos et al., 2016). Also, the amendment of legislation such as long procedures to attain certifications and labels to meet standards is required to achieve sustained growth and realization of CE. In addition, the development of advanced technology plays a paramount role in the application of CE (Su et al., 2013).

This Ph.D. dissertation has contributed by developing tools and indicators at a micro level to help companies to implement circular economy principles. But the proposition of a general decision-making tools and indicators may fail to effectively evaluate potential circularity strategies or measure the performance of a reverse supply chain. In this thesis, a full list of decision-making criterions and indicators are proposed so that decision-makers can select based on the company's product/process characteristics and condition. This may help to some extent to effectively implement CE principles. Moreover, developing company and industry specific tools will have significant influence on the application of circular economy principles.

Moreover, the proposed tools expected to have a great benefit for companies to evaluate potential circularity strategies. This will benefit companies by prioritizing businesses, showing future circular product and new business opportunities. Although there is no common understanding about the definition of circular economy and circularity strategies including reuse, repair, remanufacturing, refurbishing, reconditioning, repurposing, upgrading, and recycling. Mostly, companies use these circularity strategies interchangeably even though they have distinctively different meanings for instance remanufacturing and refurbishing. In this Ph.D. thesis and the papers, a clear definition of circularity strategies is presented in order to help industrial practitioners to understand the differences while using the decision-making tools and indicators. Even if a clear definition is given to clarify the definition of CE strategies, use of different terminologies from a scientific and companies perspective would have an impact on the implementation of the proposed tools effectively and efficiently.

The main contributions of this Ph.D. thesis in each part/section: (I) identification of EoL decision factors and indicators, (II) modelling of the reverse logistics system, and (III) proposition of assessment tools and indicators are listed as follows: -

- In part/section 1, a taxonomy of decision-making factors and circular economy indicators are presented. Research paper # 1 identifies EoL decision-making factors from technical, economic, environmental, business, and societal aspects. Also, it showed a list of indicators from environmental, economic and social categories. The decision-making factors and indicators are used as input during the development of decision-making tools to evaluate circularity scenarios as well as in proposing a circular economy indicator for quantifying the performance of a reverse supply chain of a typical product in a company. In addition, the proposed decision-factors are used to model the reverse logistics system in Paper #2 with respect to cost, revenue, and strategic and regulatory decision categories.

- In part 2, (modelling of the reverse logistics system), a system dynamic modelling approach is used to represent the complex system of reverse logistics in order to understand the interaction among a variety of decision-making variables. This is important to understand the complexity of reverse logistics system in circular economy which in turn helps to develop effective tools and indicators. The proposed models show the interaction among various decision-making factors including environmental, economic, social, and legislative factors with respect to cost, revenue, and strategic and regulatory decision categories. The proposed model is validated by companies across the value chain including designer, supplier, users and a recycling company for a case study of electric vehicle batteries.

- In addition, in paper #2, an analysis of the interplay among the building blocks of CE research is accomplished. The interplay among the main pillars of circular economy including reverse supply chain, business model, product and service design, product and service use, policy and EoL recovery is undertaken for a case study of EVBs. The results of the research show the need for a shared understanding of the interplay among pillars of the circular economy research for a successful transition to a resource-efficient and circular economy model.

- In paper #3, a circular economy indicator for reverse logistics is proposed to assess the performance of products within the reverse logistics system. The proposed indicator is expected to support companies to measure and improve their performance within the reverse logistics activities. The tool provides an indicator to represent environmental, economic, social and business aspects of the performance of a reverse logistics system comprehensively.

- In paper #4 a multi-criteria decision-making tool is proposed to evaluate potential product level circularity strategies with a focus on remanufacturing strategy. The tool identifies potential business perspectives and also points out future circular product and new business opportunities. In this line, circular economy assessment tool is also proposed to evaluate circularity strategies of end-of-life products at strategic level in paper #1. The proposed tools give a solution for businesses from a list of potential circularity alternatives.

3.4. Discussion on the implications of the Ph.D. thesis to various stakeholders

In this Ph.D. thesis, the proposed decision-making tools and indicators are expected to support companies in their move from linear to a circular economic model. It helps industrial practitioners in the decision-making of EoL products for recovery through the implementation of various circularity strategies. To achieve the aimed goal, circularity strategies evaluation tools and indicators are proposed, and their application is tested on case studies with various companies.

Besides the contribution to the industrial practitioners, this Ph.D. thesis supports academics, policymakers, designers, and users. For instance, this Ph.D. dissertation highlights the main enablers and challenges for the transition towards a circular economy model (section 2.2.4.5). In this study, recommendations are made to various stakeholders such as policymakers, designers, and users based on the results of a case study with multiple companies that are involved in the recovery business of EVBs. These suggestions aimed at fostering circularity of EVBs. Some of the recommendations include policy support for the second use of EVBs and amending legislation that hider technological innovations and new business models.

To conclude, the transition towards a resource-efficient and circular economy model requires a shared understanding of the interplay among the pillars of CE. In this thesis, a systematic analysis of the interplay among the main pillars of circular economy research is accomplished. The result of the research shows the need for a shared understanding of the interplay among pillars of the circular economy including business models, supply chain management, policy, product/service use, EoL treatment, and product/service design for a successful transition to a resource-efficient and circular economy model.

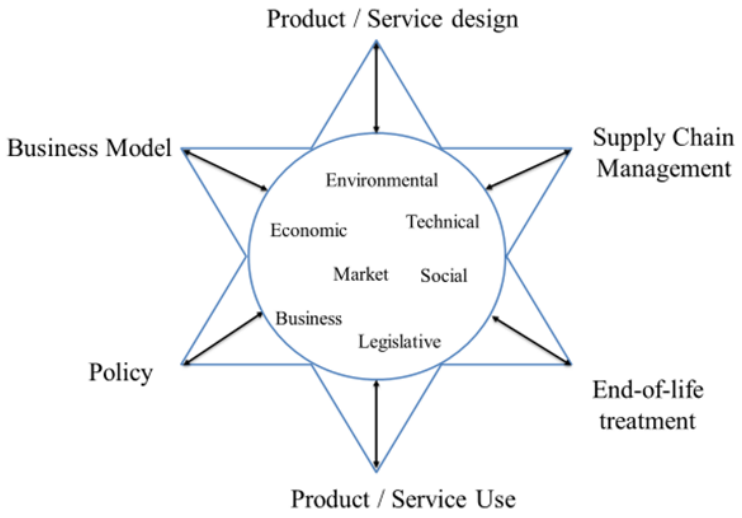

Figure 33: Interplay among the building blocks of circular economy

3.5. Perspectives and future work

In this sub-section, the limitations of this Ph.D. dissertation and research works that need additional validation steps are presented in section 3.5.1. Then future research opportunities that are promising to explore are presented in section 3.5.2.

3.5.1 Limitations and further validation

The proposed tools and indicators use an integrated approach to evaluate circularity strategies with respect to social, environmental, economic and legislative aspects. These criterions are focused on techno-cycles and therefore the proposed decision-making tools and indicators are not applicable to evaluate bio-cycles. Moreover, the proposed tools to evaluate circularity strategies at strategic and tactical levels used a multi-criteria analysis to evaluate various scenarios. One of the limitation of multi-criteria approach is its criteria independence (Ishizaka and Labib, 2009). Due to the complexity of circular systems, future research work is needed to study the correlation among criterions.

The research works of this Ph.D. thesis are validated through various case approaches including feedback from academic and industrial experts on the selection of decision-making criteria and indicators (section 2.1); and case studies with various industrial sectors such as automotive, waste management and storage furniture (section 2.2.3 and section 2.3.2). In future work, validation for the proposed research work of this thesis "circular economy indicator for reverse logistics" with a case study from companies is foreseen. Also, more case studies are suggested to the contributions of this Ph.D. thesis specifically on the product recovery decision-making tool (section 2.1) and a multi-criteria evaluation tool of potential product level circularity strategies (section 2.3.2).

As presented in chapter 1, this dissertation is structured in three parts: identification of decision-making factors, modelling of the reverse logistics system; and proposition of decision-making tools and indicators. Based on the analysis, four main results are contributed in this Ph.D. thesis including the limitations of the research on each specific part of the thesis and also future research directions are presented in each part. In the following section, suggestions for promising future research opportunities to enhance the decision-making of post-used products using tools and indicators are presented.

3.5.2 Future work

In this Ph.D. thesis a circular economy assessment tools and indicators are proposed to evaluate post-used products and measure the performance of reverse supply chain. Furthermore, modelling the dynamics of the reverse logistics system with respect to the dynamics of cost, revenue, and strategic decisions is accomplished. Even though, this study has made valuable contribution as an effort to fill in the research gaps presented in Table 36, further research directions are suggested on the following topics to facilitate the transition towards a more circular economy model.

One future research work can be the adoption and testing of the proposed tools and indicators in this Ph.D. dissertation to other types of products, services and industrial sectors. In section # 2.1, the application of a product recovery tool to evaluate circularity scenarios at strategic level is demonstrated through a case study on the automotive engine. In section # 3.3.1, a circular economy indicator for reverse logistics is proposed to measure the performance reverse logistics system. Similarly, in section # 2.3.2, a circular economy evaluation tool at a product level is applied on two case studies (vacuum waste collection system and storage furniture). Application of these proposed tools and indicators would be beneficial to generalize their use to various types of products, and services and industrial sectors.

Also, more research could be conducted to validate and improve the proposed decision-making tools on existing company data rather than second-hand data. Moreover, it could be interesting to compare and analyse the results across various industrial sectors. This aids in learning how one industrial sector can benefit from other sectors in their effort to transform into a more circular economy model from the successful experience. This helps to transform industries that are having challenges to move towards a more circular economy model.

Another important research opportunity could be to extend the proposed tools and indicators to include the life cycle of the product/system. This Ph.D. manuscript is focused on the proposition of assessment tools and indicators when the product reaches the EoL phase. In this line, future research work can be to extend the proposed tools to include the pre-life and use phase of the product. Similarly, based on the research performed in section # 3.3.1, future research topic could be to measure the performance of the closed-loop supply chain (i.e. including both the forward logistics and reverse logistics) for a typical product and added service. Furthermore, the interaction among criteria and sub-criteria and their influence on the overall result from a system perspective should be studied in future research.

3.6. Publications

Journal papers

Alamerew, Y.A, Brissaud, D., 2018. Circular economy assessment tool for end of life product recovery strategies. Journal of Remanufacturing. 9, 169-185. https://doi.org/10.1007/s13243-018-0064-8

Alamerew, Y.A., Brissaud, D., 2020. Modelling Reverse Supply Chain through System Dynamics for Realizing the Transition towards the Circular Economy: A Case Study on Electric Vehicle Batteries. Journal of Cleaner Production. 254, 1-12. https://doi.org/10.1016/j.jclepro.2020.120025

Alamerew, Y.A., Brissaud, D., 2020. Circular Economy Indicator for Reverse Logistics (CEI-RL) : Measuring the Performance of Reverse Logistics in Companies. Journal of Cleaner Production. (In progress)

Alamerew Y.A., Kambanou M.L., Sakao T., Brissaud D., A multi-criteria evaluation method of potential product level circularity strategies. Journal of Sustainability. (Submitted, In review)

Conference Papers

Alamerew, Y.A., Brissaud, D., 2017. Evaluation of Remanufacturing for Product Recovery: Multi-criteria Decision Tool for End-of-Life Selection Strategy, in: 3rd International Conference on Remanufacturing. Linköping, Sweden. (Presented)

Alamerew, Y.A., Brissaud, D., 2018. Modelling and Assessment of Product Recovery Strategies through Systems Dynamics, in Procedia CIRP. pp. 822–826. (Presented)

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