Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries

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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.

Keywords:

Circular Economy, Reverse Logistics, Remanufacturing, System Dynamics (SD), Electric Vehicle Battery (EVB), Repurposing

Highlights:

- ✓ There is a growing interest to study the role of reverse logistics in the circular economy
- ✓ The complex system of reverse logistics is modelled through system dynamics
- ✓ The main enablers and challenges for circularity of electric vehicle batteries are identified
- ✓ The interplay among the building blocks of circular economy research are presented

Abbreviations:

CE	Circular economy
CLD	Causal loop diagram
EU	European union
EoL	End-of-life
EV	Electric vehicle
EVB	Electric vehicle battery
SD	System dynamics
SMEs	Small and medium size enterprises

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. 1 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.

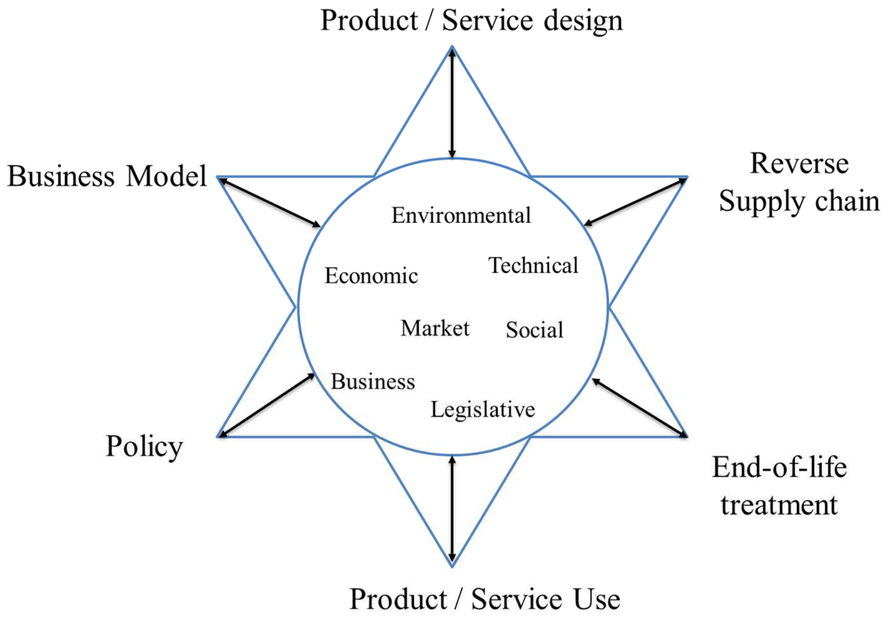

Figure 1: Interplay among the building blocks of CE

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) analyzed 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 presents the main insights about circular economy, transdisciplinary research, EoL circularity strategies, reverse supply chain, and system dynamics. In section 3, the research framework of the study is presented. Section 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. Literature Review

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, redesign 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 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; Sauvé 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 1.

Table 1: 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.

2.3 Electric Vehicle Batteries (EVB)

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.

2.3.1 End-of-life electric vehicle battery circularity 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. 2 shows the circularity strategies used to recover post-used EVBs.

2.3.1.1 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).

2.3.1.2 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).

2.3.1.3 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.

2.3.1.4 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.

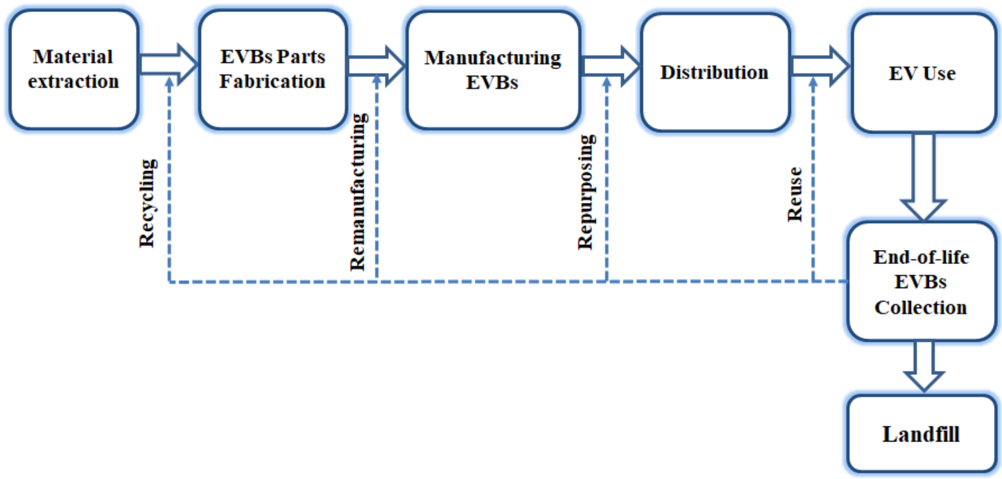

Figure 2: Circularity Strategies for retired batteries

2.4 Systems Dynamics

System Dynamics (SD) is an effective methodology to analyze 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 analyze 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 behavior 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 analyze 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.

2.5 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.

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. 3, shows a graphical representation of the methodology used in this study.

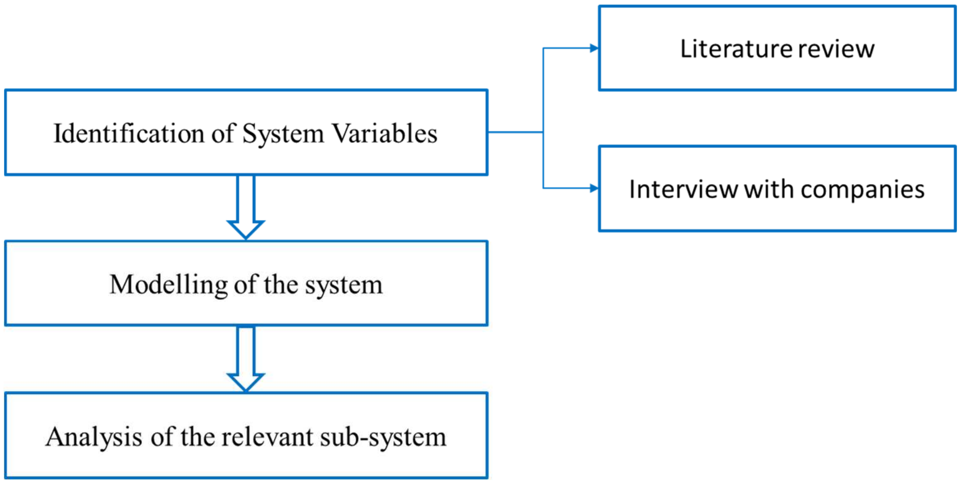

Figure 3: Schematic representation of the methodology

3.1. Identification of system variables

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.

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 2). 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.

Table 2: 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	-

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.

3.2 Modelling technique of the reverse logistics 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).

3.3 Analysis of the relevant subsystems

The dynamics of EoL EV battery recovery system is analyzed 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).

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 4. 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. 5, Fig 6 and Fig 7). 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.

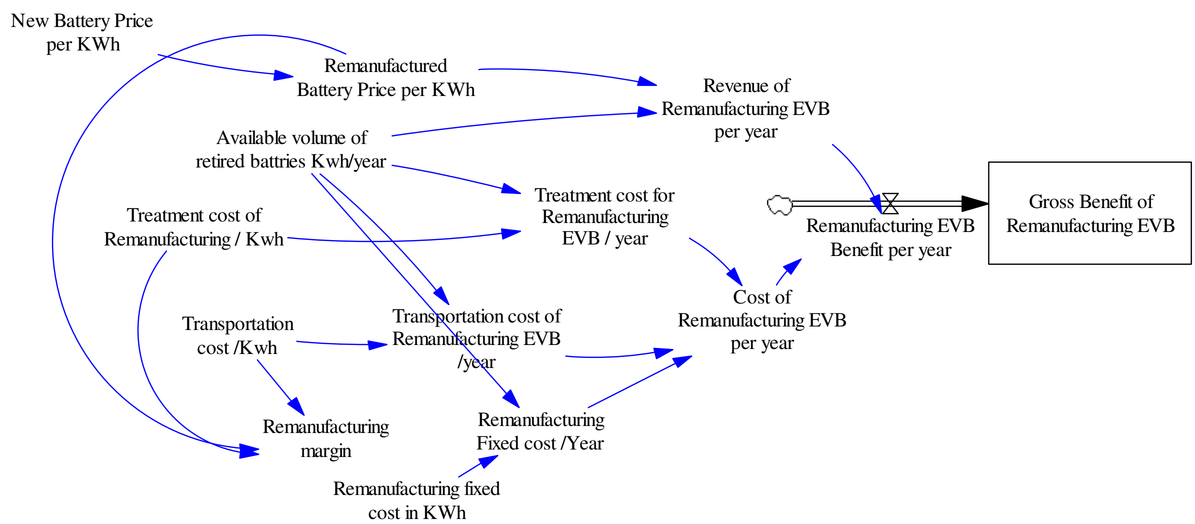

Figure 4: Proposition of a general model for recovery of spent batteries

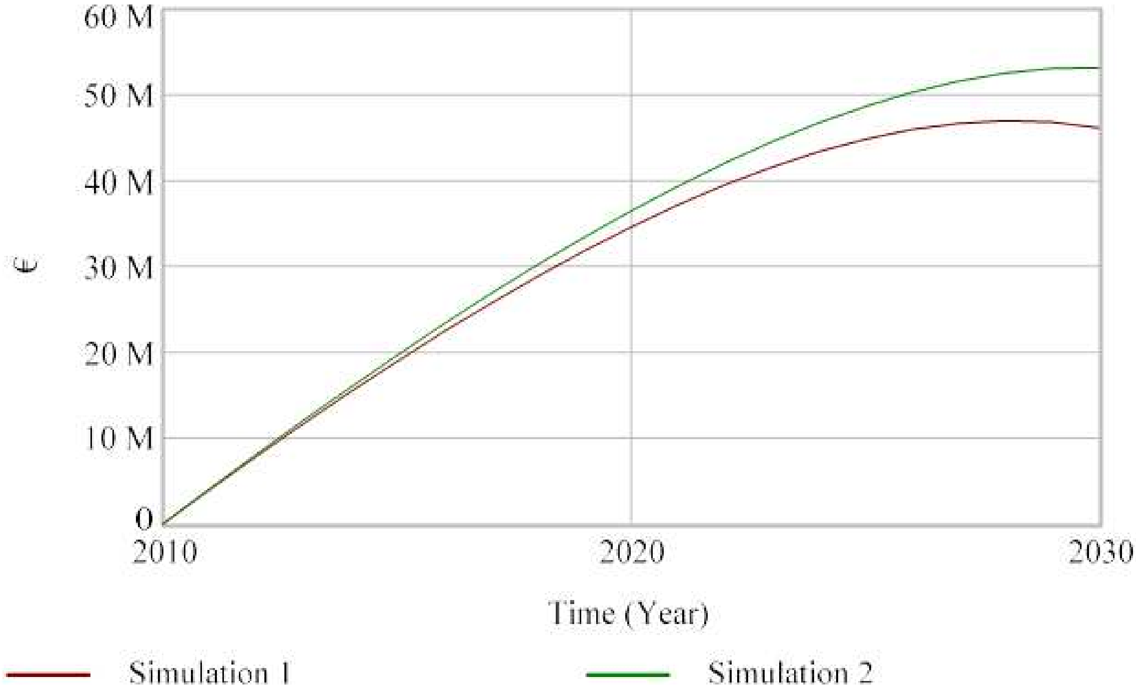

Figure 5: Simulation result for benefit of remanufacturing

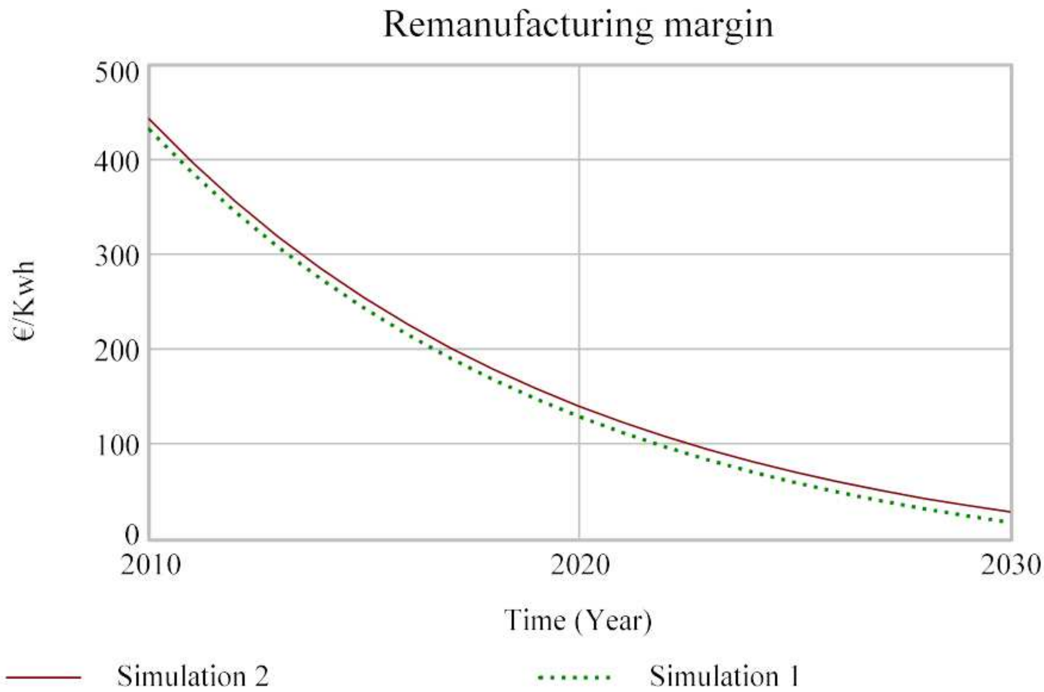

Figure 6: Simulation result of remanufacturing margin

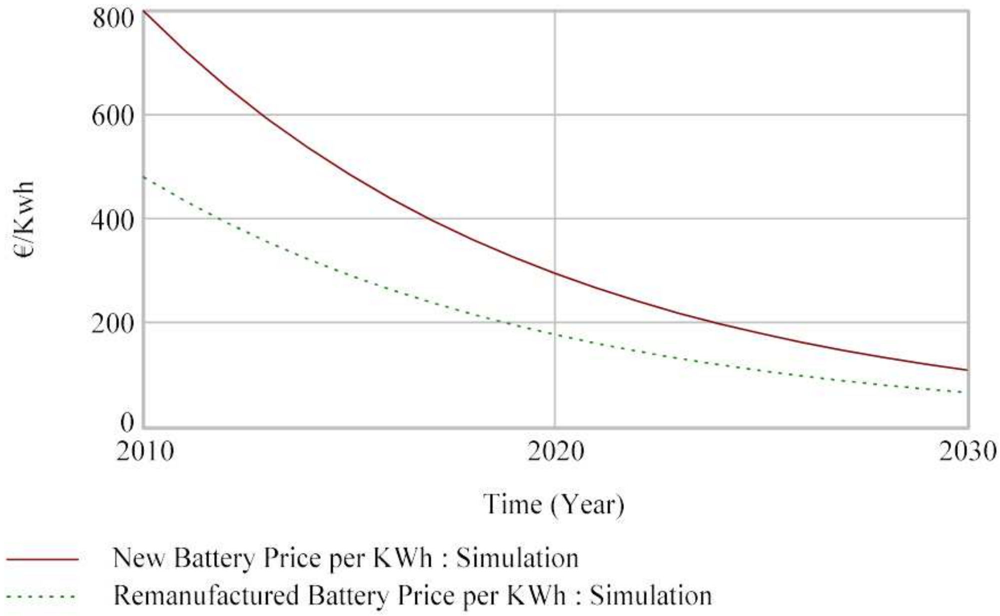

Figure 7: Simulation result of remanufacturing and new battery price

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 behavior and the potential impacts of modifying the connections. The CLD diagrams are presented from section 4.1 to section 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.

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. 8 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.

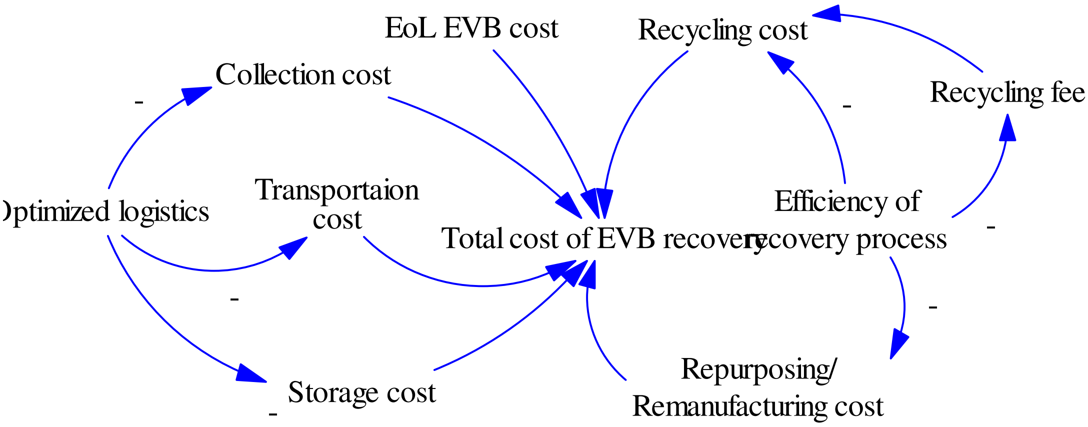

Figure 8: Dynamics of cost in EVB recovery system

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. 9, demonstrates the cause and effect diagram of variables influencing the revenue of recovered EVB product.

As shown in the CLD, Fig. 9, 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. 9 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 CO_2 and SO_2 emissions from the production of battery material take the biggest proportion of EV emissions (Gaines, 2012).

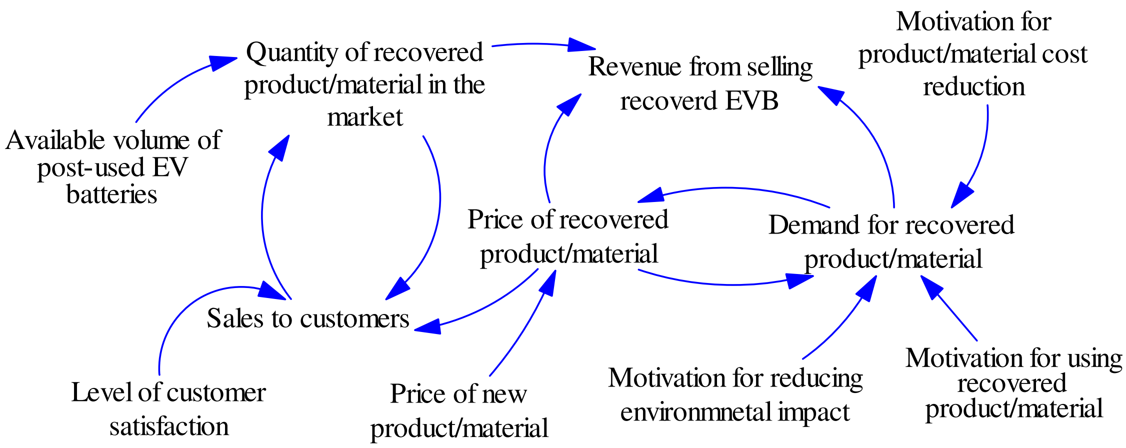

Figure 9: Dynamics of revenue in EVB recovery system

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. 10 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 10).

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. 10, 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.

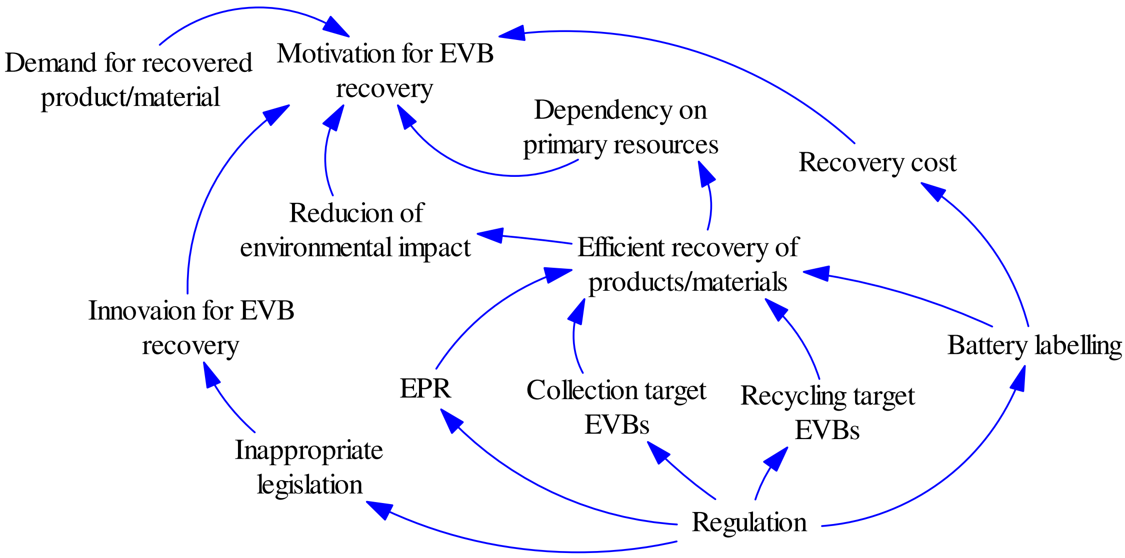

Figure 10: Dynamics of strategic and regulatory decisions in EVB recovery system

4.5 Interplay among the building blocks of 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. 11, depicts the interplay among building blocks of CE to solve a typical problem.

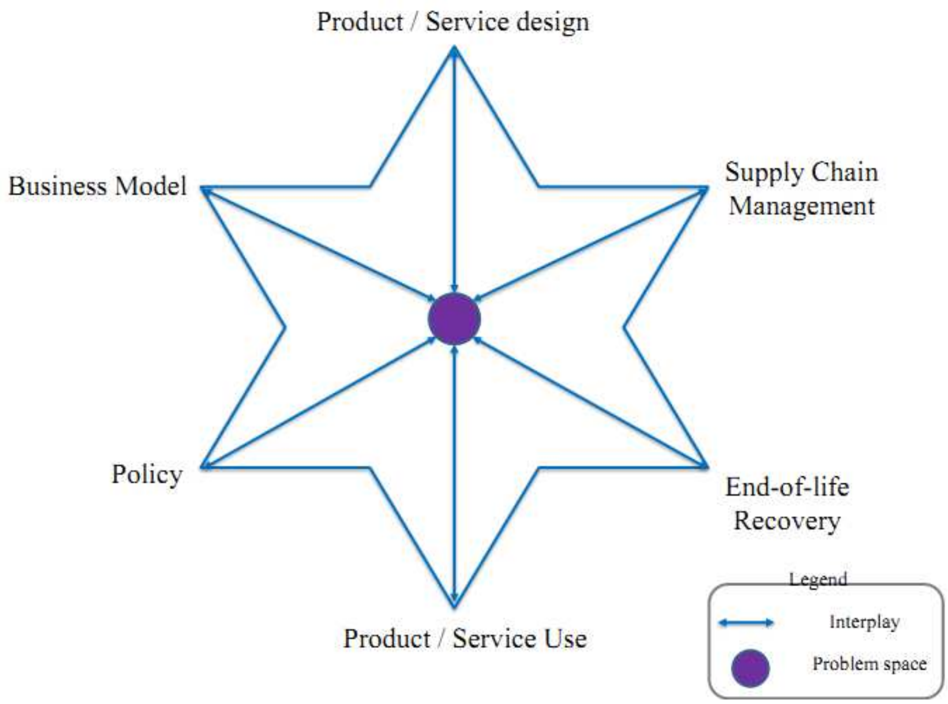

Figure 11: Interplay among the building blocks of CE research

A diagram representing the interaction between main pillars of CE and product circularity strategies to recover post-used EVBs is shown in Fig. 12. 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.

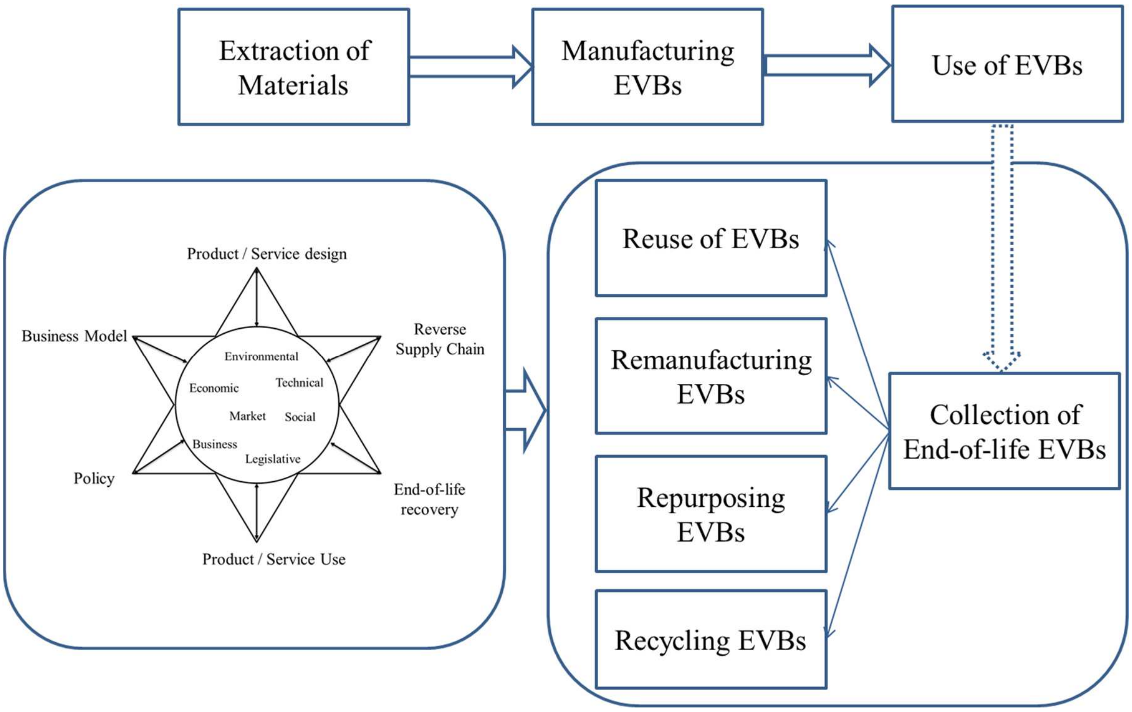

Figure 12: Depiction of the interaction between main pillars of CE and circularity strategies

4.5.1 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.

4.5.2 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 labeling 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.

4.5.3 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.

4.5.4 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.

4.5.5 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 2^{nd} life-phase of the product, the companies are responsible for offering service and taking care of the product until the end-of-2^{nd}-life phase. Both Company A and Company B collect data during the second use phase to improve their service that would benefit customers.

4.5.6 Product 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.

4.6 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 3 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 3: 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
Reverse 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 EVBs • Standardization of product and component designs
User	• Access to the history of 1^{st} 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 second use of EVBs • Amending legislations that hinder technological innovations and new business models • Rules for second use applications of EVBs

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.

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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