Addis Ababa University
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School of Mechanical & Industrial Engineering

Circular Business Model for Vehicle Lead-Acid Batteries in Ethiopia

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Declaration

I hereby declare that the work which is being presented in this thesis entitled "Circular Business Model for Vehicle Lead-Acid Batteries in Ethiopia" is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

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Abstract

The automotive battery industry is shifting towards sustainability, driven by the need for circular business models, particularly lead acid batteries (LABs). This transition presents unique challenges and opportunities for circular economy implementation. In developing countries like Ethiopia, the LAB industry faces sustainability issues and undercapacity utilization. This research aims to identify potential circular strategies, pinpoint the most influential factors affecting adopting of circular business model (CBM), and develop a CBM tailored for LABs to address sustainability challenges and promote circular practice in the automotive battery industry. The research employs a multi-faceted methodology including expert opinions, thematic analysis, hybrid Grey and Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis, and the Business Model Canvas framework. The study identifies and propose three promising circular economy strategies: repair for reuse, repurpose, and recycle which collectively provide substantial environmental and economic benefits by extending battery life, reducing resource consumption, and generating revenue. Further, the study identifies four key factors influencing the adoption of CBM for LABs by analyzing the dynamic interplay of 23 factors: lack of business model with take-back systems, high cost of handling and processing, lack of effective communication and coordination, and lack of supportive government policies. Finally, the study offers a practical roadmap for implementing circular practices by modeling identified circular strategies within the Circular Business Model Canvas framework. This research prioritizes environmental responsibility, resource efficiency, and economic viability, contributing to LAB sustainability and fostering an environmentally responsible automotive sector.

Keywords: circular strategies, sustainability, adoption factors, circular economy

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Chapter One

1. Introduction

The rapid transition towards clean energy production and use to replace fossil fuels has increased demand for batteries. Due to their great durability and low cost, lead-acid (LA) batteries have maintained their market share, while Lithium-ion (Li) batteries are a close second-most popular battery technology (Yanamandra et al., 2023). As the utilization of LA batteries increases, it is important to study their repairing, repurposing, and recycling potentials in the circular economy (CE) perspective to reduce the environmental impact, increase the sustainability and competitiveness of value chains, avoid the depletion of natural resources, and promote economic growth (Ahuja et al., 2020).

Given its capability to dissociate economic growth from resource consumption and waste generation, the circular economy is recognized by industries, scholars, and policymakers as a potential strategy to jointly increase the sustainability and competitiveness of value chains (Bressanelli et al., 2022). Unlike a linear economy, the circular economy closes the "take-make-consume-throw away" pattern by preserving the maximum utilization of products, components, and materials for as long as possible. The core principles of CE are to eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate natural ecosystems (Islam & Iyer-Raniga, 2022). While organizations must shift from a linear approach to the CE, issues such as data unavailability and integration often hinder this firm and ecosystem level transformation (Chauhan et al., 2022a). The collaboration of all stakeholders, data-driven decision-making, circular business models (Islam & Iyer-Raniga, 2022) and in-depth knowledge of designing circular business models have the potential to accelerate the transition to CE and drive and support the implementation of the circular economy (Albertsen et al., 2021; Lewandowski, 2016).

A circular business model is the logic of the firm for how it creates and captures value in a specific business (Olsson et al., 2018). The CBM developed based on recycling (closing the loop) circular strategy can reduce waste and pollution, circulate products and materials, and regenerate natural ecosystems. In addition to this circular strategy, repairing for reuse and repurposing (second life application) has the highest potential contribution to creating a more sustainable approach, increasing efficiency, and reducing greenhouse gas emissions compared to recycling (Kosai et al., 2022; Mossali et al., 2020; Schulz-Mönninghoff et al., 2021; Pagliaro & Meneguzzo, 2019; Thakur et al., 2022; Toorajipour et al., 2022, Islam & Iyer-Raniga, 2022). This thesis focuses on the development of a circular business model for repairing, repurposing, and recycling lead-acid batteries used in vehicles in Ethiopia. Ethiopia is experiencing rapid development, leading to an increasing demand for batteries. However, the country is also grappling with the challenge of effectively managing battery waste as a valuable resource. This thesis aims to provide a roadmap for developing a circular battery industry in Ethiopia that can support sustainable economic growth and environmental protection.

To develop the circular business model, a comprehensive methodology was implemented that involved the following steps:

1. In-depth examination of circular economy strategies: Expert interviews and a cost-benefit analysis were conducted to identify the most promising circular strategies for lead-acid batteries in Ethiopia.
2. Identification of adoption factors: Grey-DEMATEL analysis was used to identify the key factors that influence the adoption of circular strategies for lead-acid batteries.
3. Development of circular business model: The business model canvas framework was used to develop a circular business model for repairing, repurposing, and recycling lead-acid batteries in Ethiopia.

This approach allowed for the development of a strategic framework that is tailored to Ethiopia's specific circumstances. In conclusion this thesis provides a significant contribution to the development of a circular battery industry in Ethiopia. The findings and insights from this study have the potential to drive positive change in the Ethiopian battery industry, aligning it with circular economy principles and contributing to a more sustainable economic growth and environmentally responsible future.

1.1. Background of the study

The use of batteries in vehicles is an important part of modern-day transportation. Two of the most common types of batteries used in vehicles are Lead Acid and Lithium-Ion batteries. Lead Acid batteries are the oldest type of battery and have been used since the 19th century (Prengaman & Technologies, 2009). They are generally cheaper to manufacture and are heavier in weight.

The automotive battery manufacturing industries faces disruptions in the supply of raw materials and a global environment exposed to pollution from waste generated during the production and disposal of used batteries. In order to reduce the environmental impacts of batteries, manufacturers must take steps to ensure the safe and efficient production of their products. This includes reducing the amount of hazardous waste generated during production, and developing sustainable manufacturing processes that reduce energy consumption and emissions. Additionally, companies must focus on developing closed-loop systems and other circular economy initiatives, such as reusing, repurposing, remanufacturing, and recycling strategies, to ensure that their products are produced in a sustainable and responsible manner.

In recent years, a circular business model for these types of batteries has become increasingly popular (Chauhan et al., 2022a).. This model, also known as closed-loop recycling, involves recycling of used batteries and reusing the materials in new batteries. This process helps to reduce the amount of waste generated and also reduces the amount of energy used in the production of new batteries. Additionally, the recycled materials are often much cheaper than the virgin materials used in the production of new batteries.

Overall, the circular business model for batteries is an effective and efficient way to reduce the amount of waste generated, reduce the energy used in battery production, reduce costs associated with the production of new batteries, and capture more value of product (Ahuja et al., 2020).

1.2. Problem Statement

The implementation of a circular economy for vehicle lead-acid batteries in developing countries like Ethiopia is at an early stage, despite the presence of initiatives and projects aimed at promoting sustainable e-waste management and battery recycling. However, the lead-acid battery manufacturing and recycling industries in Ethiopia face challenges associated to industry closing and under capacity production due to factors affecting the adoption of potential circular economy strategies like insufficient collaboration among stakeholders, economic constraints, and insufficient information and data integration to track the flow of battery products and making the resulting data accessible for better resource management.

In Ethiopia there were **two** lead acid battery manufacturing industries and there are **two** lead recycling industries from end-of-life lead acid batteries. From those industries;

- One lead-acid battery manufacturing industry was closed over 10 years ago.
- One recycling industry is going to close.
- The remaining one manufacturing & one recycling industries are producing less than 50% and 10% of their production capacity respectively.

The industry owners express a belief that the closure of this industry and its undercapacity production are primarily attributed to resource shortages and a lack of competitiveness from exporters. However, data from the Ethiopian Customs Commission and Manufacturing Technology and Engineering Industry Research and Development Center indicates the presence of untapped resources within this sector.

1. According to the seven consecutive years (2016-2022 GC) data taken from **Ethiopian Customs Commission 4,389,444.89 kg** of automotive lead acid battery are imported annually in average.

2. According to the seven consecutive years (2016-2022 GC) data from Manufacturing Technology and Engineering Industry Research and Development Center, the annual production capacity of one active manufacturing industry is **1,044,000 kg** and their average production is **522,000 kg** and the annual production capacity of the two active recycling industries is **10,150,000 kg** and their average production is **1,050,000 kg**. Since the amount of lead from lead acid battery is 60%, therefore the

consumption of those one manufacturing and two recycling industries are **870,000** & **1,749,999.97 kg** end-of-life LABs respectively. **Therefore,**

There fore

- $Average\ annual\ LABs\ battery\ supply\ =\ imported\ +\ produced$

$$= \mathbf{4,911,444.89}\ \boldsymbol{kg}$$

- $Actual\ annual\ consumption\ of\ the\ three\ active\ industries\ under\ consideration\ in\ Average\ is = \mathbf{2,619,999.97}\ \boldsymbol{kg}$

The average annual supply of Lead-acid Batteries (LABs) currently available in the market is the sum of imported batteries and domestically produced batteries. This supply figure represents the quantity of LABs that are provided to consumers at the present time. The reason for considering this supply in relation to the end-of-life status of LABs is that, as customers purchase new batteries, they typically dispose of their old batteries. In other words, this calculation takes into account the number of LABs that reach the end of their operational life cycle when customers replace them with new batteries. Therefore, annual quantity of end-of-life lead acid batteries is 4,911,444.89 kg.

This analytical data indicates that the current consumption of end-of-life batteries for those three active industries are only **53.34%** of the country's available resource. This indicates that the industries have insufficient information about end-of-life LABs, have not effectively identified and collaborated with all relevant stakeholders.

3. Based on export data from **Ethiopian Customs Commission** there are **four** lead acid battery scrap exporters from Ethiopia to other neighborhood countries and they export 1,099,350kg, 126,000kg, 160,000kg, 99,980kg, and 2,179,500kg of lead acid battery scrap in 2018, 2019, 2020, 2021, and 2022 respectively.

4. On the other hand, based on five consecutive years of data collected by the Ministry of Transport and Logistics (2010-2014 E.C), 1,401,114 vehicles were registered in Ethiopia up to 2014 E.C, with an annual average of 116,305 new vehicle registrations. This suggests a demand for new or repaired lead-acid batteries within each vehicle, as they typically reach the end of their service life after three years.

One of the main contributors to this issue is that the industries are primarily employing a single circular strategy (recycling) out of the nine available strategies in a circular economy. Furthermore, they are recycling only the lead metal from end-of-life lead-acid batteries, neglecting other valuable components such as plastics from the containers and rubber. This limited circular strategy has not made them economically competitive with scrap exporters.

1.3. Research Questions

1. What are the potential circular strategies within the CBM framework for LABs that enable more value capture and contribute to a sustainable circular economy?
2. What are the most influential factors affecting the adoption of CBM for LABs?
3. How can value creation, proposition, and capture be optimized for vehicle batteries within the circular economy framework, contributing to a more sustainable, resource-efficient, and economically viable future?

1.4. Objectives

1.4.1. General objective

The general objective of this study is to develop a circular business model for lead-acid batteries that creates, proposes, and captures more value, leading to a more sustainable, resource-efficient, and economically viable future.

1.4.2. Specific objectives

- To identify potential circular strategies which can create and capture more value in the development of CBM.
- To identify the most influential factors affecting the adoption of CBM for LABs
- To develop circular business models for the identified circular strategies of vehicle lead-acid batteries (LABs) that can create, propose, and capture more value, leading to a more sustainable, resource-efficient, and economically viable future.

1.5. Scope and Limitation of the Study

1.5.1. Scope of the Study

The scope of this study is defined by its focus on the development of a circular business model pertaining to the repairing, repurposing, and recycling circular strategies specifically applied to lead-acid batteries used in vehicles in Ethiopia. In this context, the scope of the study encompasses three key aspects:

Circular Business Model Development: The primary objective of this study is to explore and establish effective circular business models that revolve around the repair, repurpose, and recycling strategies for lead-acid batteries. These models are designed to address the unique challenges and opportunities presented by the lead-acid battery industry in the Ethiopian context.

Industry Focus: The study is delimited to three active entities within the Ethiopian landscape. This includes one lead acid battery manufacturing industry and two lead metal recycling industries.

Geographical Context: The study's scope is rooted in the geographical context of Ethiopia, taking into account the distinctive factors and dynamics that pertain to the Ethiopian lead-acid battery industry. The aim is to provide insights and recommendations that are relevant and tailored to the Ethiopian market and its specific challenges and opportunities

1.5.2. Limitations of the Study

It is crucial to recognize and address the limitations of this study to provide a transparent assessment of its scope and applicability. The primary limitations of the study are as follows:

1. Limited Representation: The findings and conclusions of this study heavily rely on the perspectives and experiences of a selected group of industry experts. Despite efforts to diversify the participant pool, it is essential to acknowledge that the viewpoints and insights gathered from this specific group may not comprehensively encapsulate the entirety of the industry landscape. There may be additional perspectives and nuances not covered in this study.

2. Generalizability: The study's scope is confined to the Ethiopian context, focusing on the lead-acid battery industry within this specific geographical and industrial setting. Therefore, the findings and recommendations generated within this study may not be directly transferable to other regions or industries with distinct characteristics and dynamics.
3. Expert Opinion Basis: The study heavily relies on expert opinions and insights. While expert opinions provide valuable qualitative data, they are inherently subjective. As a result, the study's conclusions are influenced by the individual perspectives and experiences of the experts interviewed.
4. Dynamic Industry Environment: The lead-acid battery industry is subject to continuous technological advancements, market fluctuations, and regulatory changes. This study represents a snapshot of the industry at a specific point in time and may not reflect developments that occur after the data collection period.
5. Potential Bias: Despite efforts to minimize bias, researcher and participant bias may still be present in the study, affecting the interpretation of data and the development of conclusions.

By recognizing these limitations, the study aims to provide a clear understanding of its boundaries and the context within which its findings and recommendations should be considered. These limitations serve as opportunities for future research and further exploration within the field of circular business models for lead-acid batteries.

1.6. Significance of the Study

Designing circular business models (CBMs) has been highlighted as an important enabler in the transition towards CE and stimulating and fostering its implementation. The significance of this study, which focuses on the tailored development of firm-specific circular business models, is multifaceted:

Enhanced Battery Lifecycle and Value Creation: By identifying and implementing potential circular strategies such as standardized battery repair, repurposing for second-life applications, adhering to remanufacturing to restore used batteries to original equipment manufacturer specifications, and recycling non-lead battery components, this study actively extends the lifespan and utility of batteries. In doing so, it maximizes value capture, ultimately contributing to increased revenue for the firm.

Improved Sustainability and Resilience: The study plays a pivotal role in enhancing the sustainability of the firm. Through the identification and collaboration of all relevant stakeholders, it reduces the company's exposure to volatile material prices and potential supply chain disruptions, thereby fortifying its resilience.

Workforce Retention and Job Creation: This research endeavor is also poised to have a positive impact on the workforce. By facilitating activities such as battery repair, sales for second-life applications, and the recycling of various components, including lead metal and plastics, it retains existing employees and creates fresh employment opportunities in these domains.

Economic Benefit and Market Expansion: By actively engaging in circular strategies, this study promotes economic benefit. It allows businesses to capitalize on cost savings, enhanced resource efficiency, and access to new markets, ultimately expanding their economic footprint.

Customer Acquisition and Environmental Impact: In the realm of circular strategies, this study offers the potential for new customer acquisition, particularly in the repurposing segment. Furthermore, by reducing waste generation, environmental pollution, and resource consumption, the study aligns with the broader goals of environmental sustainability and waste reduction.

In summary, the significance of this study extends beyond the boundaries of the battery industry to make a substantial contribution to the larger discourse on circular economy practices, sustainable business models, and environmental responsibility.

Chapter Two

2. Literature Review

2.1. Introduction

The circular economy is an economic model that aims to optimize the use of resources, minimize waste generation, and promote sustainable development (Heath et al., 2022). It replaces the notion of "end-of-life" with a focus on restoration, transitions to the utilization of renewable energy, eliminates the use of toxic chemicals that hinder reuse and harm the environment, and strives to eradicate waste through enhanced material, product, system, and business model design.

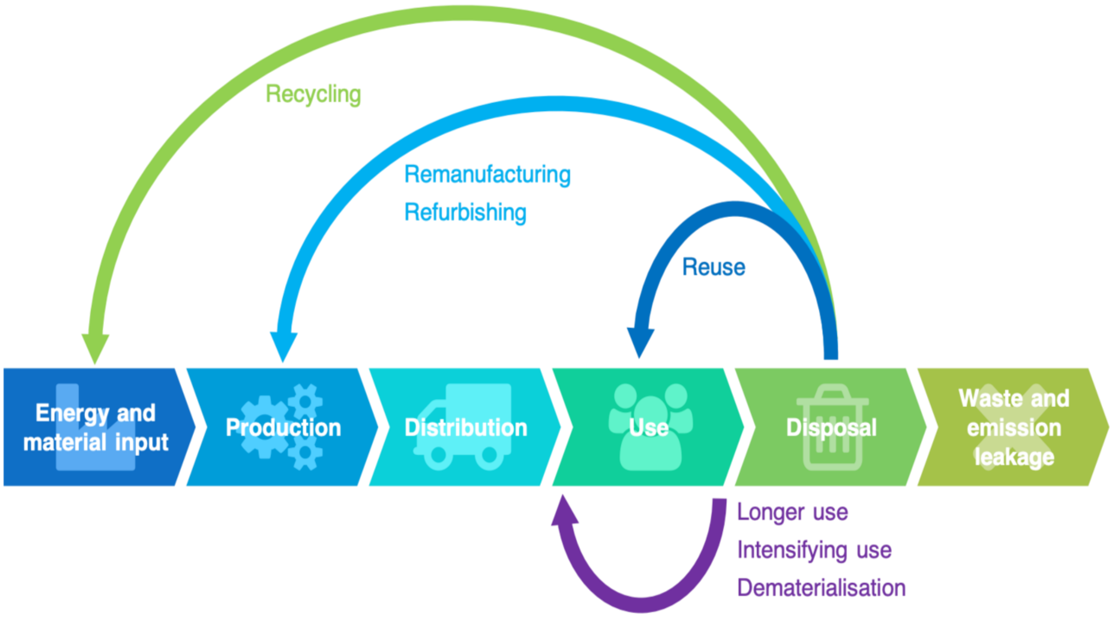


Figure 1. Illustration of circular economy (Geissdoerfer et al., 2020)

In a circular economy, resources are managed and used in a way that maximizes their value and minimizes environmental impact (Morseletto, 2020; Berg et al., 2020 & Alhawari et al., 2021). It involves designing products and systems with longevity, durability, and recyclability in mind. The goal is to keep materials and products in use for as long as possible, extract maximum value from them during their life cycle, and ensure their proper recovery and regeneration at the end of their life (Neligan et al., 2022).

Establishing a circular economy necessitates fundamental transformations across the entire value chain, encompassing product design, technology, the adoption of novel business models, and innovative approaches to conserving our natural resources (extending product lifetimes) and transforming waste into a valuable resource through recycling, fostering shifts in consumer behavior, establishing fresh norms and practices, and implementing education and financial initiatives are all vital components of this endeavor.

2.1.1. Circular economy strategies

Circular economy strategies are a set of approaches and principles aimed at transitioning from a linear, wasteful economy to a more sustainable and regenerative one (Potting et al., 2017). Here are key circular strategies in three categories associated with the circular economy:

Table 1. Circular economy strategies (Morseletto, 2020)

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

2.1.2. Circular economy of vehicle batteries

The increasing demand for electric vehicles (EVs) is putting pressure on the availability of the critical raw materials, such as lithium and cobalt, used in the manufacturing of lithium-ion batteries (Wrålsen et al., 2021a). Lead-acid batteries are also widely used in conventional internal combustion engine vehicles (ICEVs) and can have negative environmental impacts when not managed properly at the end of their life (Sloop et al., 2009; Zakiyya et al., 2018). In recent years, circular business models (CBMs) have emerged as potential solutions to address these issues.

The reviewed articles highlight that circular economy (CE) strategies for lead-acid batteries are primarily centered on recycling, a well-established approach(Chakraborty & Moniruzzaman, 2017; Jolly & Rhin, 1994; Li et al., 2019, 2020; Q. Zhang, 2013), and repairing, which is currently in development (Chakraborty & Moniruzzaman, 2017; X. Liu & Teng, 2021; Sun et al., 2020).

Recycling methods for spent lead-acid batteries involve both metallurgical and chemical processes, typically preceded by pretreatment procedures like breaking, crushing, and physical separation (Zakiyya et al., 2018)..

Typically, the electrodes of lead-acid battery equipment are made of lead and lead oxides, and the electrolyte inside the lead-acid battery is sulfuric acid solution (B. Zhang et al., 2022; X. Liu & Teng, 2021). **Repairing methods** are Deep discharge repair, Pulse repair, and Hydrotherapy.

An end-of-life lead-acid battery typically comprises four primary components: waste electrolyte (11–30%), polymeric materials (22–30%), lead alloy grids (24–30%), and lead paste (30–40%). Among these components, lead paste proves to be the most challenging to recycle. It consists of a mixture containing 50–60% PbSO4, 15–35% PbO2, 5–10% PbO/Pb(OH)2, 2–5% metallic Pb, along with small traces of impurities, such as iron, antimony, tin, and barium (Li et al., 2020).

2.2. Circular business models

The concept of circular business models (CBMs) has emerged to support businesses operationalize the CE in ways that provide social, environmental, and economic value and are considered as an important level for transitioning to a CE (Albertsen et al., 2021). Applications of circular business models, the collaboration of all stakeholders, and data-driven decision support systems are required for appropriate planning to adhere to the CE principles for LIBs (Islam & Iyer-Raniga, 2022).

Circular business model is the logic of the firm for how it creates, propose, and captures value in a specific business (Olsson et al., 2018)

1. **Value creation**: Value creation refers to the process of generating value for customers through the development and delivery of products, services, or solutions that meet their needs or solve their problems. Value creation can take many forms, such as improving efficiency, reducing costs, increasing revenue, enhancing customer experience, or creating new markets or opportunities.
2. **Value proposition**: A value proposition is a statement that defines the unique benefits or value that a product, service, or solution offers to its customers, and how it differs from competing offerings in the market. A robust value proposition plays a pivotal role in not only attracting but also retaining customers. It must be succinct, persuasive, and distinctly articulated.
3. **Value delivery**: Value delivery refers to the process of delivering the value promised by a company's value proposition to its customers. This can include activities such as production, distribution, marketing, sales, and customer service. The goal of value delivery is to ensure that customers receive the value they expect from the company's products or services.
4. **Value capture**: Value capture refers to the process of capturing a portion of the value that is created and delivered to customers by a company. This can be achieved through pricing strategies, such as setting prices based on the perceived value of the product or service, or through other means, such as licensing, franchising, or royalties. The goal of value capture is to ensure that the company is able to capture a fair share of the value it creates and deliver to its customers.

Circular business models are designed to create economic, social, and environmental value by keeping resources in use for as long as possible, maximizing the utilization of resources, and minimizing waste and pollution. One area where circular business models have gained traction is in the management of vehicle batteries (Kotak et al., 2021; Pražanová et al., 2022; Sopha et al., 2022).

Lead acid and lithium-ion batteries are critical components of electric and hybrid vehicles, but they also pose significant environmental challenges when they reach the end of their useful life. Lead acid batteries contain lead and sulfuric acid, which can be hazardous to the environment and human health if not disposed of properly (Sloop et al., 2009; Sun et al., 2020; Zakiyya et al., 2018). Lithium-ion batteries, on the other hand, contain valuable and scarce resources such as lithium, cobalt, and nickel, which are often lost in the linear model of production and disposal (Makwarimba et al., 2022; Pagliaro & Meneguzzo, 2019; Swain, 2017).

Circular business models offer a solution to these challenges by promoting the recovery, reuse, and recycling of vehicle batteries (Albertsen et al., 2021; Olsson et al., 2018; Wrålsen et al., 2021b). By doing so, these models can help to reduce the environmental impact of battery production and disposal, conserve natural resources, and create new economic opportunities.

Several circular business models have been proposed and implemented for the management of electrical vehicle batteries, including closed-loop systems (Olsson et al., 2018), second-life applications (Milani & Besharat, 2022; Van Opstal & Smeets, 2023), and leasing and take-back schemes (Wrålsen et al., 2021a).

Closed-loop systems involve the recovery and recycling of materials from end-of-life batteries to create new batteries. Second-life applications involve the reuse of batteries that are no longer suitable for vehicle use in other applications, such as stationary energy storage.

Table 2. the application of repurposed batteries (Albertsen et al., 2021)

No	Application	Actors	Comments
1	Storage of solar or wind power	Households, property owners	Small or large scale, off-grid or grid-connected
2	Peak shaving	Industries	Reducing power demand
3	EV charging	Property owners (PW), grid owners	Reducing power demand at time of charging
4	Increased grid capability and stability	Grid owners	Instead of installing larger cables, or to avoid fluctuation
5	Backup	Industries, PW	In case of electricity loss
6	Electricity trading	Electricity companies	Having a battery farm for electricity trading
7	Vehicle propulsion	Vehicle manufacturers	E.g., ferries, forklifts

Leasing and take-back schemes promote the return of batteries to manufacturers or service providers for refurbishment or recycling.

2.2.1. Types of CBMs

Circular business models are becoming increasingly important in the vehicle battery industry, particularly for electric vehicle lithium-ion batteries. Here are some types of circular business models for the vehicle battery industry based on the search results:

1. **Closed-loop recycling:** This model involves recycling the materials of the battery at the end of its life and using them to create new batteries. This model is being adopted by some vehicle manufacturers and policymakers in the EU (Albertsen et al., 2021).

2. **Product life extension**: Product life extension refers to the practice of extending the useful life of a vehicle battery beyond its initial design lifespan. This can be achieved through various strategies, such as improving the battery's durability, capacity, or efficiency, and promoting repair and refurbishment(Albertsen et al., 2021). By extending the battery's life, the circular business model can reduce waste and increase the value of the battery over its lifecycle (Olsson et al., 2018; Kirchherr et al., 2017).

3. **Product-as-a-service or Battery-as-a-service**: This model involves providing batteries as a service rather than selling them. This allows the manufacturer to retain ownership of the battery and take responsibility for its end-of-life management (Helander & Ljunggren, 2023; Shi & Hu, 2022; Tahara et al., 2020). This business model incentivizes the manufacturer to extend the lifespan of the battery, promote re-use and recovery, and ensure the battery is recycled at the end of its useful life (Bocken et al., 2016; Stahel, 2016; Wrålsen et al., 2021b).

2.2.2. Barriers, enablers, and stakeholders

Barriers

Analyzing the challenges and barriers for second life and recycling of EV LIBs from a business model perspective, they can be categorized along three aggregate dimensions: Cognitive, organizational, and technological (Olsson et al., 2018).

Cognitive barriers are related to decision makers being uncertain about how promising future business models centered on second life will be. Companies may exhibit reluctance in adopting new business models that may contradict their existing operations, as they fear potential misalignment with their long-term strategic goals.

Organizational barriers: are associated with the adjustments required to facilitate the growth and expansion of new business models. These adaptations often necessitate resources, capabilities, changes in work methods, the reconfiguration of resource and information flows, the establishment of new processes, and the restructuring of organizational structures, among other aspects.

Technological barriers are exogenous and are related to lack of standardization in design of new batteries beyond the cell level, which makes preparing them for second life and recycling costly and complex, and to the uncertainty of how they will perform after first life (with respect to capacity loss).

Barriers refer to the factors that obstructed the implementation of a Circular Economy approach for Electric Vehicle Batteries (Sopha et al., 2022). The author identifies 21 barriers with in 5 categories from 64 selected articles.

A. Technology and Infrastructure Category

- ✓ Inefficient recycling processes
- ✓ Slower development of infrastructure for collecting, sorting, dismantling, recycling, and remanufacturing centers
- ✓ Unoptimized end-of-life (EoL) paths due to inappropriate characterization, testing, and assessment, along with a lack of standards
- ✓ Absence of Vehicle Battery design considerations for EoL
- ✓ Compositional uncertainty of batteries
- ✓ Lack of standardization on EoL processes for batteries

B. Supply-chain Operations and Management Category

- ✓ Underdeveloped recovery marketplace
- ✓ Low rate of returned batteries
- ✓ Limited information sharing regarding EoL processes
- ✓ Uncertainty in supply (number and quality) and price/value of batteries
- ✓ Lack of commitment within the supply chain

- ✓ Inadequate communication and coordination
- ✓ Challenges in competitiveness

C. Economics Category

- ✓ High cost of handling, transporting, and recovering processes, labor, leading to a lack of profitability
- ✓ Absence of incentives
- ✓ Low economic value of EoL batteries
- ✓ Risks associated with investments

D. Policy and Regulations Category

- ✓ Inefficient and inadequate government policies
- ✓ Lack of safety standards for battery management

E. Social Category

- ✓ Lack of customer awareness
- ✓ Low perceived quality of recycled products

Enablers

Drivers/enablers refer to the key factors or forces that are driving the adoption and implementation of circular practices in the lifecycle of vehicle batteries. Electrical vehicle batteries standards, legal environmental responsibilities, economic incentives, extensive collaboration and alignment of the supply-chain stakeholders, and innovative business models (Sopha et al., 2022), mechanisms policy (regulations, laws, voluntary standards, and guidance which can mandate, motivate, or incentivize various stakeholders to adopt a CE for LIBs), analytical frameworks, and technologies that can inform decisions and incentivize stakeholders (Heath et al., 2022). National and international regulation and policies" followed by "Economic benefits" are considered the main drivers for developing CBMs in the LIB market (Wrålsen et al., 2021b).

A. Technology and infrastructure Category

- EOL design for VBs (design for disassembly)
- Battery modularization

- Proper status checking, diagnosing, and tracking
- Information digitalization

B. Supply-chain operations and management Category

- Information sharing and standards of information interfaces
- Extensive collaboration, cooperation, and alignment of supply-chain stakeholders (i.e., early integration in product development)
- Innovative business model such as servitization, leasing platform

C. Economics Category

- Economic incentives for recyclers, i.e., tax breaks, subsidies, economic support, and the introduction of deposit refund

D. Policy and regulations Category

- Eco-design directive
- EVB standards including compounds
- Standardization of EoL process
- Certification
- Material tax on critical elements
- Policy and legislation on information sharing
- Legal environmental responsibilities
- Regulation consistency in the global market (EP8)

E. Social Category

- Social commitment
- High customer awareness through education and training

Stakeholders

The implementation of circular business models for vehicle batteries requires collaboration between various stakeholders, including vehicle manufacturers, battery manufacturers, recyclers, and policymakers (Kurdve et al., 2019; Wrålsen et al., 2021a). Collectors and processors, Entities, Organizations, LIB or PV manufacturers, Firms that recycle or upgrade/purify, Associations, Owners of LIB and PV, and System owners (Heath et al., 2022).

2.2.3. Adoption factors of CBM for vehicle batteries

The adoption of circular business models can help to promote sustainable resource management, reduce waste and pollution, and create new economic opportunities through the collaboration of all stakeholders, and data-driven decision support systems are required for appropriate planning to adhere to the CE principles for vehicle batteries (Islam & Iyer-Raniga, 2022). The adoption factors of a circular business model for vehicle battery recycling include several key elements(Albertsen et al., 2021; Lewandowski, 2016; Tripathy et al., 2022; Urbinati et al., 2021):

1. Technological Readiness: The availability of advanced and efficient recycling technologies for vehicle batteries is a crucial factor. The development of innovative processes and infrastructure that enable safe and effective recycling plays a significant role in promoting the adoption of circular practices.
2. Regulatory Environment: Supportive regulations and policies are essential for encouraging the adoption of circular business models for vehicle battery recycling. Clear guidelines and standards can provide a framework for the industry, incentivize recycling efforts, and ensure compliance with environmental and safety requirements.
3. Economic Viability: The economic feasibility of circular business models is a vital factor for adoption. Recycling processes must be cost-effective and offer financial incentives for stakeholders involved in the value chain. This includes manufacturers, recyclers, and other relevant parties, ensuring that the circular model is economically sustainable.
4. Supply Chain Collaboration: Collaboration among stakeholders in the vehicle battery supply chain is crucial for successful adoption. This includes manufacturers, suppliers, recyclers, and policymakers. Building strong partnerships and fostering cooperation can streamline the recycling process, ensure the efficient flow of materials, and create a closed-loop system.
5. Consumer Awareness and Engagement: Educating consumers about the importance and benefits of vehicle battery recycling is key. Raising awareness regarding the environmental impact of improper disposal and the value of recycling can encourage individuals to actively participate in recycling programs, promoting the circular business model.

6. Environmental Sustainability: The growing focus on sustainability and environmental consciousness is a significant driver for circular business model adoption. Demonstrating the positive environmental impact of vehicle battery recycling, such as reducing waste, conserving resources, and minimizing carbon emissions, can encourage stakeholders to embrace circular practices.
7. Access to Funding and Investments: Adequate funding and investment opportunities are essential for the development and scaling of circular business models. Access to financial resources, including grants, subsidies, and venture capital, can support research and development efforts, infrastructure establishment, and technology implementation in vehicle battery recycling.

2.2.4. Tools and frameworks for CBM development

Analysis tools

Adopting a circular business model involves transitioning from a linear "take-make-dispose" approach to one that emphasizes resource efficiency, waste reduction, and the regeneration of materials. However, the adoption of such a model requires careful consideration of numerous factors that can either facilitate or hinder its implementation.

To identify the most influential factors affecting the adoption of a circular business model, various methods and tools can be employed. In this context, this paper presents four such techniques: the Grey-DEMATEL Method (Adegoke et al., 2022; Akter et al., 2022; de Campos et al., 2021; Gupta & Barua, 2018; Mubarik et al., 2021; Özdemir & Tüysüz, 2015; Si et al., 2018; Sivakumar et al., 2018; Tripathy et al., 2022), Analytic Hierarchy Process (AHP) (Aungkulanon et al., 2023; Islam et al., 2022), Factor Analysis (Albertsen et al., 2021; Urbinati et al., 2021; Wrålsen et al., 2021a) , and Influence Diagrams (Schulz-Mönninghoff et al., 2021; Urbinati et al., 2021). These methods provide decision-makers with systematic approaches to analyze and prioritize the multitude of factors involved in the adoption process.

1. **Grey-DEMATEL Method**: The Grey-DEMATEL method is a hybrid approach that combines the Grey System Theory (GST) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method (Soares et al., 2023). It is a multi-criteria decision-making technique that helps analyze the cause-and-effect

relationships among factors and quantifies the strength and direction of the relationships between factors and identifies the most influential ones.

2. **Analytic Hierarchy Process (AHP):** AHP is a structured decision-making method that breaks down a complex problem into a hierarchical structure and enables the comparison of factors based on their relative importance. The advantages of AHP include:

    - Structured approach: It helps in structuring the decision problem by breaking it down into a hierarchical model, making it easier to analyze and prioritize factors.
    - Stakeholder involvement: AHP allows for incorporating the preferences and judgments of different stakeholders, facilitating a more inclusive decision-making process.
    - Consistency checking: It provides a consistency check to ensure the logical and coherent assessment of factors.

3. **Factor Analysis**: Factor Analysis is a statistical method used to identify underlying dimensions or latent factors within a dataset. It helps in reducing the complexity of a large number of variables by grouping them into a smaller set of factors. The advantages of Factor Analysis include:

    - Variable reduction: It simplifies complex datasets by identifying the underlying factors that explain the variance in the observed variables, reducing the dimensionality.
    - Pattern identification: Factor Analysis can uncover hidden patterns and relationships among variables, providing insights into the influential factors.
    - Data-driven approach: It is a data-driven method that does not rely on preconceived notions or assumptions, making it suitable for exploratory analysis.

It's important to note that the choice of method ultimately depends on the specific requirements of the problem, the available data, and the preferences of the decision-makers. In comparison to these tools, the Grey-DEMATEL method stands out for its ability to handle uncertainty, vagueness, and incomplete information in complex systems. It combines the strengths of grey system theory and the DEMATEL method to provide a comprehensive analysis of direct and indirect influences among factors. It can incorporate both qualitative and quantitative data, making it versatile in various decision-making scenarios.

Advantages of Grey-DEMATEL over others:

Grey-DEMATEL has certain advantages over the other methods mentioned in the context of identifying influential factors for the adoption of a circular business model:

- ✓ Consideration of interdependencies: The adoption of a circular business model involves a complex network of factors that are interconnected and influenced by each other. Grey-DEMATEL explicitly takes into account these interdependencies by quantifying the cause-and-effect relationships between factors. This is particularly relevant when analyzing the adoption of a circular business model, as the factors involved are often interrelated and influence each other's outcomes.

- ✓ Handling uncertainty: Grey-DEMATEL is designed to handle uncertainty and vagueness in data. When dealing with the adoption of a circular business model, there might be limited or incomplete data available, or the relationships between factors may be unclear. Grey-DEMATEL can effectively handle such uncertainties by using grey numbers, which represent uncertain or partially known information. This allows for a more robust analysis in situations where data quality or availability is a concern.

- ✓ Reliability assessment: Grey-DEMATEL provides a measure of reliability for the identified influential factors. This is valuable when making decisions related to the adoption of a circular business model because it helps in assessing the robustness and validity of the identified factors. By evaluating the reliability, decision-makers can have more confidence in the results and make more informed decisions.

- ✓ Complex decision-making: The adoption of a circular business model often involves multiple stakeholders, various criteria, and a range of decision alternatives. Grey-DEMATEL can handle the complexity of such decision-making scenarios by considering the interdependencies and providing a comprehensive analysis of influential factors. It allows decision-makers to evaluate the factors from multiple perspectives and make decisions based on a more holistic understanding.

Modeling tools

Circular business modeling tools are frameworks or methodologies designed to help businesses integrate circular economy principles into their operations. These tools provide assistance in analyzing, designing, and implementing circular business models, offering valuable insights and guidance for organizations seeking to embrace the circular economy. Several tools have emerged to address the diverse needs of businesses on their journey towards sustainable and circular practices. In this context, four notable tools stand out: the Circular Business Model Canvas, the Circular Economy Model Toolkit, circular business model innovation, and the Circular Economy Value Chain Map. Each tool offers unique features and perspectives, enabling organizations to approach circular business model development from different angles. By understanding the strengths and applications of these tools, businesses can make informed decisions about the most suitable tool for their specific needs and embark on the journey towards circularity with confidence.

Lean Business Model Canvas

The Lean Business Model Canvas is a strategic tool used by startups and businesses to quickly and effectively visualize and analyze the key elements of their business model (Felin et al., 2020; Moshood et al., 2022; Razabillah et al., 2023). It consists of nine essential building blocks: customer segments, value propositions, channels, customer relationships, revenue streams, key activities, key resources, key partnerships, and cost structure. The Lean approach emphasizes the iterative and experimental nature of the business model development, encouraging continuous testing and learning to optimize resources, minimize waste, and deliver value to customers in the most efficient and effective way possible.

Circular Business Model Canvas:

The Circular Business Model Canvas is a tool used to design and analyze circular business models (Lewandowski, 2016; Pollard et al., 2023). It is based on the original Business Model Canvas but incorporates elements specific to the circular economy. The canvas consists of eleven building blocks that help entrepreneurs and organizations identify and develop circular business opportunities. These blocks include customer segments, value proposition, channels, customer relationships, key activities, key resources, key partnerships, cost structure, revenue streams take-back system and adoption factors.

Circular Economy Model Toolkit:

The Circular Economy Model Toolkit is a comprehensive set of resources and guidelines that assist organizations in transitioning to circular business models (Reigado et al., 2017). It provides step-by-step instructions, case studies, and tools to support the development of circular strategies. The toolkit covers various aspects of the circular economy, including product design, material selection, reverse logistics, and business model innovation. It aims to help businesses identify opportunities for circularity and implement them effectively.

Circular Business Model Innovation:

Circular business model innovation refers to the process of creating and implementing new business models that align with the principles of the circular economy (Linder & Williander, 2017; Pieroni et al., 2019). It involves rethinking traditional linear models (take-make-dispose) and designing models that prioritize resource efficiency, waste reduction, and value retention. Circular business model innovation often involves exploring new revenue streams, collaborative partnerships, product life extension, recycling and reusing strategies, and other circular practices. The goal is to create sustainable and profitable business models that contribute to the circular economy.

Circular Economy Value Chain Map:

The Circular Economy Value Chain Map is a tool used to visualize and understand the flow of materials, energy, and value within a circular economy system (Hua et al., 2020; Weimer et al., 2019). It helps identify opportunities for optimization, resource recovery, and value creation at different stages of the value chain. For vehicle batteries, the value chain map would depict the entire lifecycle of a battery, from raw material extraction to manufacturing, distribution, use, and end-of-life management. By analyzing the map, stakeholders can identify points where circular practices can be implemented, such as recycling and reusing battery components, extending battery life through maintenance and upgrades, or designing batteries for easier disassembly and material recovery.

Tool selection

Choosing a specialized circular business modeling tool provides several benefits, including a structured and efficient approach, access to expert knowledge, coherence in design, visualization and communication support, and adaptability for iterative design. These advantages make the Business Model Canvas a valuable resource for organizations seeking to adopt circular economy principles and develop sustainable business models. Here are the advantages of using the Business Model Canvas compared to other tools:

1. Comprehensive Overview: The Business Model Canvas provides a comprehensive and structured overview of the key elements of a business model. It allows organizations to visualize and understand the interrelationships between various components such as customer segments, value propositions, channels, and revenue streams. This holistic view helps in identifying potential gaps or areas of improvement within the business model.

2. Strategic Analysis: The Business Model Canvas facilitates strategic analysis by enabling organizations to assess the alignment of different elements of their business model. It helps in identifying potential strengths, weaknesses, opportunities, and threats. This analysis is valuable for making informed strategic decisions and developing strategies to enhance competitiveness.

3. Collaboration and Communication: The Business Model Canvas is a widely recognized and widely used tool, making it easier to collaborate and communicate business ideas within teams, across departments, and with external stakeholders. The canvas format provides a common language and visual representation that enhances understanding and facilitates effective discussions around the business model.

4. Adaptability to Different Industries: The Business Model Canvas is a flexible framework that can be applied across various industries and business types. It does not restrict its usage to startups or specific sectors, making it applicable to both new ventures and established organizations. This adaptability allows businesses from diverse domains to use the framework for business model innovation and optimization.

5. Focus on key elements and establish a clearly defined framework: The Business Model Canvas highlights the essential components of a business model, enabling organizations to prioritize their focus. By identifying and addressing these core elements, organizations can align their strategies and resources effectively.

<table>
<tr>
<td rowspan="3">Partners
• Cooperative networks
• Types of collaboration</td>
<td>Activities
• Optimising performance
• Product Design
• Lobbying
• Remanufacturing, recycling
• Technology exchange</td>
<td rowspan="3">Value Proposition
• PSS
• Circular Product
• Virtual service
• Incentives for customers in Take-Back System</td>
<td>Customer Relations
• Produce on order
• Customer vote (design)
• Social-marketing strategies and relationships with community partners in Recycling 2.0</td>
<td rowspan="3">Customer Segments
• Customer types</td>
</tr>
<tr>
<td rowspan="2">Key Resources
• Better-performing materials
• Regeneration and restoring of natural capital
• Virtualization of materials
• Retrieved Resources (products, components, materials)</td>
<td>Channels
• Virtualization</td>
</tr>
<tr>
<td>Take-Back System
• Take-back management
• Channels
• Customer relations</td>
</tr>
<tr>
<td colspan="3">Cost Structure
• Evaluation criteria
• Value of incentives for customers
• Guidelines to account the costs of material flow</td>
<td colspan="2">Revenue Streams
• Input-based
• Availability-based
• Usage-based
• Performance-based
• Value of retrieved resources</td>
</tr>
<tr>
<td colspan="5">Adoption Factors
• Organizational capabilities
• PEST factors</td>
</tr>
</table>

Figure 2**.** Circular business model canvas framework (Lewandowski, 2016)

6. Integration with Other Tools: The Business Model Canvas can be integrated with other strategic management tools and frameworks such as SWOT analysis, Porter's Five Forces, or the Balanced Scorecard. This integration enhances the overall analysis and decision-making process, providing a more comprehensive understanding of the business environment and facilitating the development of robust strategies.

2.3. Literature Summary

Circular economy strategies for lead-acid batteries are primarily centered on recycling and repairing. Recycling is a well-established approach for lead-acid batteries, and there are a number of different recycling methods available. Repairing is a newer approach, but it is gaining traction as a way to extend the lifespan of lead-acid batteries.

Circular business models

Circular business models (CBMs) are an important tool for operationalizing the circular economy in the vehicle battery industry. They are designed to create economic, social, and environmental value by keeping resources in use for as long as possible, maximizing the utilization of resources, and minimizing waste and pollution.

Advantages of Circular business models

Circular business models offer several advantages across economic, social, and environmental dimensions. Here are some key advantages (Albertsen et al., 2021; Geissdoerfer et al., 2017, 2020; Linder & Williander, 2017; Olsson et al., 2018; Wrålsen et al., 2021b):

1. **Resource Efficiency:** Circular business models prioritize the optimal use of resources, reducing the need for virgin materials. By keeping resources in use for as long as possible and minimizing waste, these models contribute to resource conservation and efficiency.
2. **Waste Reduction**: By keeping materials in circulation, circular business models minimize waste generation, diverting valuable resources from landfills and incineration. This not only reduces the environmental footprint of businesses but also conserves disposal costs.
3. **Environmental Sustainability:** Circular business models aim to minimize the environmental impact by reducing waste, pollution, and energy consumption. This approach aligns with sustainability goals and helps mitigate the negative effects of traditional linear business models on ecosystems.
4. **Economic Viability:** Circular business models can enhance economic viability by creating new revenue streams from recovered materials and reducing costs associated with waste disposal and resource procurement. This can lead to

improved profitability, increased market share, and a competitive advantage for businesses adopting circular practices.

5. **Innovation and Product Design:** Circular business models encourage innovative product design that prioritizes durability, reparability, and recyclability. This fosters a culture of innovation, driving advancements in technology and design to create more sustainable products.

6. **Extended Product Life:** Circular models promote the repair, refurbishment, and repurposing of products, leading to extended product lifecycles. This not only reduces the frequency of replacements but also contributes to lower overall environmental impact.

7. **Job Creation:** The shift toward circular business models often requires new skills and job roles, particularly in areas such as repair, remanufacturing, and recycling. This can contribute to employment opportunities and skill development within local communities.

8. **Improved Corporate Reputation:** Embracing circular practices enhances a company's reputation by showcasing a commitment to sustainability and responsible resource management. This positive image can attract environmentally conscious customers and investors.

9. **Regulatory Compliance:** Circular business models align with and often exceed regulatory requirements related to environmental protection and waste management. This helps businesses stay in compliance with evolving environmental regulations.

10. **Customer Loyalty:** Consumers increasingly value sustainable and eco-friendly products and services. Circular business models can enhance customer loyalty by meeting these preferences and demonstrating a commitment to environmental responsibility.

11. **Resilience to Supply Chain Disruptions:** Diversifying supply chains through circular practices, such as sourcing recycled materials, can enhance resilience to raw material shortages and price fluctuations, making businesses more adaptable to supply chain disruptions.

12. **Global Competitiveness:** Companies that embrace circular business models may gain a competitive edge in the global market by aligning with international sustainability standards and meeting the growing demand for environmentally friendly products and practices.

Several different CBMs have been proposed and implemented for the management of vehicle batteries, including closed-loop systems, second-life applications, and leasing and take-back schemes.

Closed-loop systems involve the recovery and recycling of materials from end-of-life batteries to create new batteries. Second-life applications involve the reuse of batteries that are no longer suitable for vehicle use in other applications, such as stationary energy storage. Leasing and take-back schemes promote the return of batteries to manufacturers or service providers for refurbishment or recycling.

Barriers:

- Technological challenges: Recycling and repairing vehicle batteries can be complex and challenging tasks, requiring specialized equipment and expertise.
- Economic challenges: Recycling and repairing vehicle batteries can be expensive, and it is not always clear who should bear the cost.
- Policy challenges: There is a lack of clear and supportive policies for circular economy strategies in the vehicle battery industry.
- Lack of awareness and understanding: Many stakeholders are not aware of or do not understand the benefits of circular economy strategies for vehicle batteries.

Enablers:

- Technological advances: New technologies are being developed that can make recycling and repairing vehicle batteries more efficient and cost-effective.
- Government support: Governments can provide financial and other incentives to support the development and implementation of circular economy strategies for vehicle batteries.
- Collaboration: Collaboration between different stakeholders, such as vehicle manufacturers, battery suppliers, recyclers, and policymakers, is essential for the successful implementation of circular economy strategies.

Stakeholders:

- Vehicle manufacturers: Vehicle manufacturers are key stakeholders in the circular economy for vehicle batteries. They are responsible for designing and producing batteries that are recyclable and repairable.
- Battery suppliers: Battery suppliers also play an important role in the circular economy for vehicle batteries. They can provide manufacturers with recycled materials and help to develop new recycling and repair technologies.
- Recyclers: Recyclers are essential for recovering and recycling materials from end-of-life vehicle batteries.
- Policymakers: Policymakers can play a vital role in promoting the circular economy for vehicle batteries by developing and implementing supportive policies and regulations.
- Consumers: Consumers also have a role to play in the circular economy for vehicle batteries. They can choose to purchase vehicles with batteries that are recyclable and repairable, and they can recycle their batteries at the end of their useful life.

Adoption factors

The adoption of circular business models (CBMs) for vehicle battery recycling is essential for promoting sustainable resource management, reducing waste and pollution, and creating new economic opportunities. Key factors that influence the adoption of CBMs for vehicle battery recycling include:

- Technological readiness: The availability of advanced and efficient recycling technologies is crucial.
- Regulatory environment: Supportive regulations and policies are essential for incentivizing adoption.
- Economic viability: Recycling processes must be cost-effective and offer financial incentives for stakeholders.
- Supply chain collaboration: Collaboration among stakeholders in the vehicle battery supply chain is crucial for success.
- Consumer awareness and engagement: Educating consumers about the importance and benefits of vehicle battery recycling is key.

- Environmental sustainability: The growing focus on sustainability and environmental consciousness is a significant driver for CBM adoption.
- Access to funding and investments: Adequate funding and investment opportunities are essential for the development and scaling of CBMs.

Here are adoption factors summarized in different literatures

Table 3 Identified adoption factors of CBM for vehicle batteries in various literature sources

Category	Adoption factors	Reference
Organizational	Lack of Business model with take-back systems (OF1)	(P. Kumar et al., 2021; Tripathy et al., 2022)
	Perceived financial benefits (OF2)	(Tripathy et al., 2022)
	Design limitations for disassembly capability (OF3)	(Shahhoseini et al., 2023; Tripathy et al., 2022)
	The capability of human resources (OF4)	(Tripathy et al., 2022)
	Lack of industrial ecology and by-product synergy (OF5)	(Tripathy et al., 2022)
	Lack top management support (OF6)	Milani & Besharat, 2022; Pan & Nguyen, 2015
	Poor Company culture (OF7)	(Albertsen et al., 2021; de Campos et al., 2021; Milani & Besharat, 2022; Pan & Nguyen, 2015; Tripathy et al., 2022)
Technological	Battery modularization (TF1)	(Islam & Iyer-Raniga, 2022; Sopha et al., 2022; Tripathy et al., 2022)
	Unavailability of efficient technologies (TF2)	(Bressanelli et al., 2021; Q. Liu et al., 2022; Rusch et al., 2022; Sopha et al., 2022)
	Limitation on Information digitalization technology (TF3)	(Sopha et al., 2022)
	Lack Proper status checking, diagnosing, and tracking technology (TF4)	(Beaudet et al., 2020; Chen et al., 2019; Islam et al., 2022; Islam & Iyer-Raniga, 2022; Kellner et al., 2019; Makwarimba et al., 2022; Milani & Besharat, 2022; Sopha et al., 2022; Tripathy et al., 2022; Yun et al., 2018)
Economical	High cost of handling, transporting, recovering process, and labor (EF1)	(Beaudet et al., 2020; Heath et al., 2022; Islam & Iyer-Raniga, 2022; Morseletto, 2020)
	Lack of incentives (EF2)	(Sopha et al., 2022)
	Low economic value of EOL VBs (EF3)	(Chirumalla et al., 2022; Government, 2013; Islam & Iyer-Raniga, 2022; Olsson et al., 2018)
	Risk on investment (EF4)	(Ahuja et al., 2020; Beaudet et al., 2020; Urbinati et al., 2021)
	Low Market demand and customer preferences (EF5)	(Garrido-Hidalgo et al., 2020; Milani & Besharat, 2022; Sopha et al., 2022; Swain, 2017; Urbinati et al., 2021)

Category	Adoption factors	Reference
Supply-chain management	Low rate of returned batteries (SCM1)	(Bianchini et al., 2019; Chauhan et al., 2022b; N. M. Kumar & Chopra, 2022; Pedone et al., 2020)
	Lack of information sharing of End-of-life process (SCM2)	(Pedone et al., 2020)
	Uncertainty in supply (number and quality), price/value of VBs (SCM3)	(Albertsen et al., 2021; Illankoon et al., 2023; Urbinati et al., 2021)
	Lack of effective communication and Supply-chain integration/coordination (SCM4)	(Bianchini et al., 2019; Cagno et al., 2021; Chirumalla et al., 2022; Milani & Besharat, 2022; Sopha et al., 2022)
	Lack of Competitiveness (SCM5)	(Bressanelli et al., 2021; Garrido-Hidalgo et al., 2020; Heath et al., 2022; Sopha et al., 2022)
Environmental	Stringent (Strict) regulations (ENF1)	(Chen et al., 2019; Gupta & Barua, 2018; Rusch et al., 2022; Scur et al., 2022; Tripathy et al., 2022)
	Lack of attention for conservation and protection of natural resources (ENF2)	(Hua et al., 2020; King & Boxall, 2019; Pregowska et al., 2022)
	Difficulties in disposing the wastes from recovered batteries (ENF3)	(Milani & Besharat, 2022)
	Inadequate infrastructure (ENF4)	(Islam et al., 2022; King & Boxall, 2019; Tripathy et al., 2022; Van Opstal & Smeets, 2023)
Political (P)	Political instability (PF1)	(Numfor et al., 2021; Wautelet, 2018)
	Lack of Supportive government policies and regulations for circular economy adoption (PF2)	(Heath et al., 2022; Hua et al., 2020; Scur et al., 2022; Sopha et al., 2022)
	Lack collaboration between public and private sectors to promote circularity (PF3)	(Beaudet et al., 2020; Marmolejo-Saucedo et al., 2021)
	Absence of international agreements and commitments on circularity (PF4)	(Chakraborty & Moniruzzaman, 2017; Heath et al., 2022; Sopha et al., 2022; Urbinati et al., 2021; Wautelet, 2018)
Socio-cultural	Lack of Customer awareness (SF1)	(Pollard et al., 2023; Shevchenko et al., 2022; Sopha et al., 2022)
	Perceived quality of the recycled products (SF2)	(Pollard et al., 2023; Shevchenko et al., 2022; Sopha et al., 2022)

Table 4 Description of Adoption Factors

Category	Adoption factors	Description
Organizational	Lack of Business model with take-back systems (OF1)	The absence of a business model that includes potential circular strategies with a system for taking back used batteries
	Perceived financial benefits (OF2)	The perceived economic advantages associated with adopting a circular business model
	Design limitations for disassembly capability (OF3)	The constraints in the design of a product that hinder its ability to be easily disassembled for maintenance, repair, or recycling purposes, and incompatibility between product components manufactured from different companies
	The capability of human resources (OF4)	lack of adequate skills, knowledge, and expertise within the workforce to effectively manage and implement circular processes.
	Lack of industrial ecology and by-product synergy (OF5)	integration of battery repairing, remanufacturing, and recycling processes with other industries to maximize resource utilization
	Lack top management support (OF6):	This refers to the lack of support from top management for the adoption of a circular economy business model.
	Poor Company culture (OF7)	Refers to an organizational environment where there is a lack of emphasis to values and norms that promote and support circularity
Technological	Battery modularization (TF1)	The limitation of design allowing batteries to be easily replaced and recycled as modular units.
	Unavailability of efficient technologies (TF2)	The absence of technologies that enable efficient remanufacturing, recycling and reprocessing of battery components.
	Limitation on Information digitalization technology (TF3)	Insufficient Digital systems and tools for managing information related to battery lifecycle and circular processes.
	Lack Proper status checking, diagnosing, and tracking technology (TF4)	The absence of technologies that enable accurate monitoring and evaluation of battery conditions and performance
Economical	High cost of handling, transporting, recovering process, and labor (EF1)	The financial implications associated with managing the processes of handling, transporting, and recovering batteries.
	Lack of incentives (EF2)	The absence of economic incentives to encourage circular practices.
	Low economic value of EOL VBs (EF3)	The limited economic worth of vehicle batteries at the end of their life-cycle.
	Risk on investment (EF4)	Refers to the financial uncertainties and potential losses associated with investing in circular business models for vehicle batteries.
	Low Market demand and customer preferences (EF5)	A low level of market demand for repaired, remanufactured, repurposed and recycled batteries.

Category	Adoption factors	Description
Supply-chain management	Low rate of returned batteries (SCM1)	The limited number of end-of-life batteries being returned for circularity.
	Lack of information sharing of End-of-life process (SCM2):	This refers to the lack of information sharing between different supply chain actors about the EOL process.
	Uncertainty in supply (number and quality), price/value of VBs (SCM3)	Unpredictability in the supply of used batteries, including concerns about their quantity, quality, and market value.
	Lack of effective communication and Supply-chain integration/coordination (SCM4)	Inadequate communication and coordination among stakeholders involved in the battery recycling supply chain.
	Lack of Competitiveness (SCM5)	The level of competition among battery companies, battery scrap exporters and their ability to sustain circular practices.
Environmental	Stringent (Strict) regulations (ENF1)	Strict and rigorous rules, laws, or guidelines that are established and enforced by governing bodies to protect and preserve the environment in the process of battery repairing, repurposing, remanufacturing, and recycling.
	Lack of attention for conservation and protection of natural resources (ENF2)	The limited emphasis on preserving and safeguarding natural resources.
	Difficulties in disposing the wastes from recovered batteries (ENF3)	Challenges in effectively managing and disposing of waste materials generated during the repair, remanufacturing, and recycling of batteries.
	Inadequate infrastructure (ENF4)	The absence of sufficient infrastructure to support the collection and processing of used batteries.
Political	Political instability (PF1)	The political volatility, or uncertainty within a region or country.
	Lack of Supportive government policies and regulations for circular economy adoption (PF2)	The limited/absence of Government policies and regulations that promote and support the adoption of circular economy practices.
	Lack collaboration between public and private sectors to promote circularity (PF3)	The lack of partnerships and collaborations between public and private entities to drive circularity initiatives
	Absence of international agreements and commitments on circularity (PF4)	Lack of International agreements and commitments that emphasize sustainability and circularity in the battery industry.
Socio-cultural	Lack of Customer awareness (SF1)	Lack of awareness of customers on the importance of battery circular economy practices.
	Perceived quality of the recycled products (SF2)	Customers' negative perceptions of the quality and reliability of repaired, repurposed, remanufactured, and recycled battery products

2.4. Research gaps

While research on circular business models (CBMs) for vehicle batteries is gaining traction, there exists an evident gap in the identification and exploration of potential strategies specifically tailored for LABs. These traditional batteries remain a crucial component in the automotive industry and require a unique approach for circularity.

The research summary addresses the gaps in our current understanding of circular business models for vehicle batteries, emphasizing the growing importance of circular economies, especially in the automotive industry. Vehicle batteries, integral to electric vehicles, play a pivotal role in the industry's sustainability. However, there's a gap in comprehending the complex interplay of organizational, technological, economic, supply chain, environmental, political, and sociocultural factors affecting the adoption of circular business models for vehicle battery repair, repurposing, and recycling.

Moreover, when delving into the specifics of circular business models, an unaddressed gap pertains to how the 11 elements of the Business Model Canvas (BMC) are integrated and adapted to meet the distinct needs of LABs. This includes exploring the intricacies of key elements like value proposition, customer segments, channels, customer relationships, revenue streams, key resources, key activities, key partners, cost structure, and the interplay between these elements to formulate effective strategies for LABs within a circular business framework.

By identifying and addressing these gaps in the literature, this research endeavors to contribute to a more comprehensive understanding of circular strategies specifically tailored to LABs while considering the shades of the Business Model Canvas elements. These insights aim to provide a holistic framework for developing effective circular business models in the context of LABs and serve as a valuable resource for both industry stakeholders and policymakers seeking sustainable solutions for battery management.

Chapter Three

3. Research Methodology and Material

3.1. Research methodology Introduction

A circular business model is the logic of the firm in which a specific company, together with partners, to create, capture, and deliver value to improve resource efficiency by extending the lifespan of products and parts, thereby realizing environmental, social, and economic benefits. This research aims to explore the barriers, enablers, stakeholders, and potential Circular Economy strategies, analyze the factors affecting the adoption of the Circular business model for vehicle batteries, and develop a circular business model. This research aims to explore potential Circular Economy strategies, analyze the factors influencing the adoption of the Circular business model for vehicle batteries, and develop a circular business model. To achieve this aim, a combination of different methods and materials was used. The following sections will describe the methodology and materials used in this research.

- **Secondary data collection and analysis**: Secondary data from different organizations were collected to quantify annually imported LABs and exported LABs scrap, to determine annual production capacity and actual production of battery manufacturing and lead recycling industries, and to quantify available fuel vehicles in the country. This helped to provide a quantitative analysis of the current state of the industry and to determine available resources in the country and utilization of recycling and manufacturing industries.
- **Literature review**: A systematic literature review was conducted to identify and analyze existing knowledge on barriers, enablers, stakeholders, circular economy strategies, adoption factors, business models, tools and frameworks related to circular economy implementation for vehicle batteries. This review encompassed scholarly articles, research papers, industry reports, and other relevant publications to provide a foundation of understanding and insights.
- **Interviews:** Interviews were conducted with 20 industry experts to examine circular economy strategies, identified from the literature review. This interview allowed to provide a qualitative analysis in the vehicle battery sector.

- **Expert opinions:** Expert opinions were sought to examine adoption factors derived from the literature and to identify the relevant adoption factors and to evaluate the initial direct relation of one adoption factor to the other factors. The insights and perspectives provided by domain experts were instrumental in ensuring the accuracy and reliability of the findings.
- **Thematic analysis:** it was used to analyze interview data collected from industry experts to identify potential circular strategies in vehicle lead acid battery industries.
- **Grey-DEMATEL approach**: The Grey-DEMATEL approach was used to analyze the most influential factors affecting the adoption of a circular business model for vehicle batteries. This helped to identify the most important factors that need to be considered in the development of a circular business model.
- **Pareto principle**: The study employed the Pareto principle (80/20 rule), where approximately 80% of effects result from 20% of critical causes. This principle was used to prioritize the vital few factors influencing the challenges and opportunities of adopting the circular business model, based on the outcome of the Grey-DEMATEL analysis.
- **Business Model Canvas framework**: The Business Model Canvas framework was used to develop a circular business model for vehicle batteries. This helped to provide a clear and concise representation of the circular business model.
- **Expert judgments**: Expert judgments were used to validate the analyzed results to ensure the accuracy and reliability of findings.

3.2. Research Design

The research flow diagram, displayed in Figure 3. , illustrates the sequential steps and methodology employed in this study.

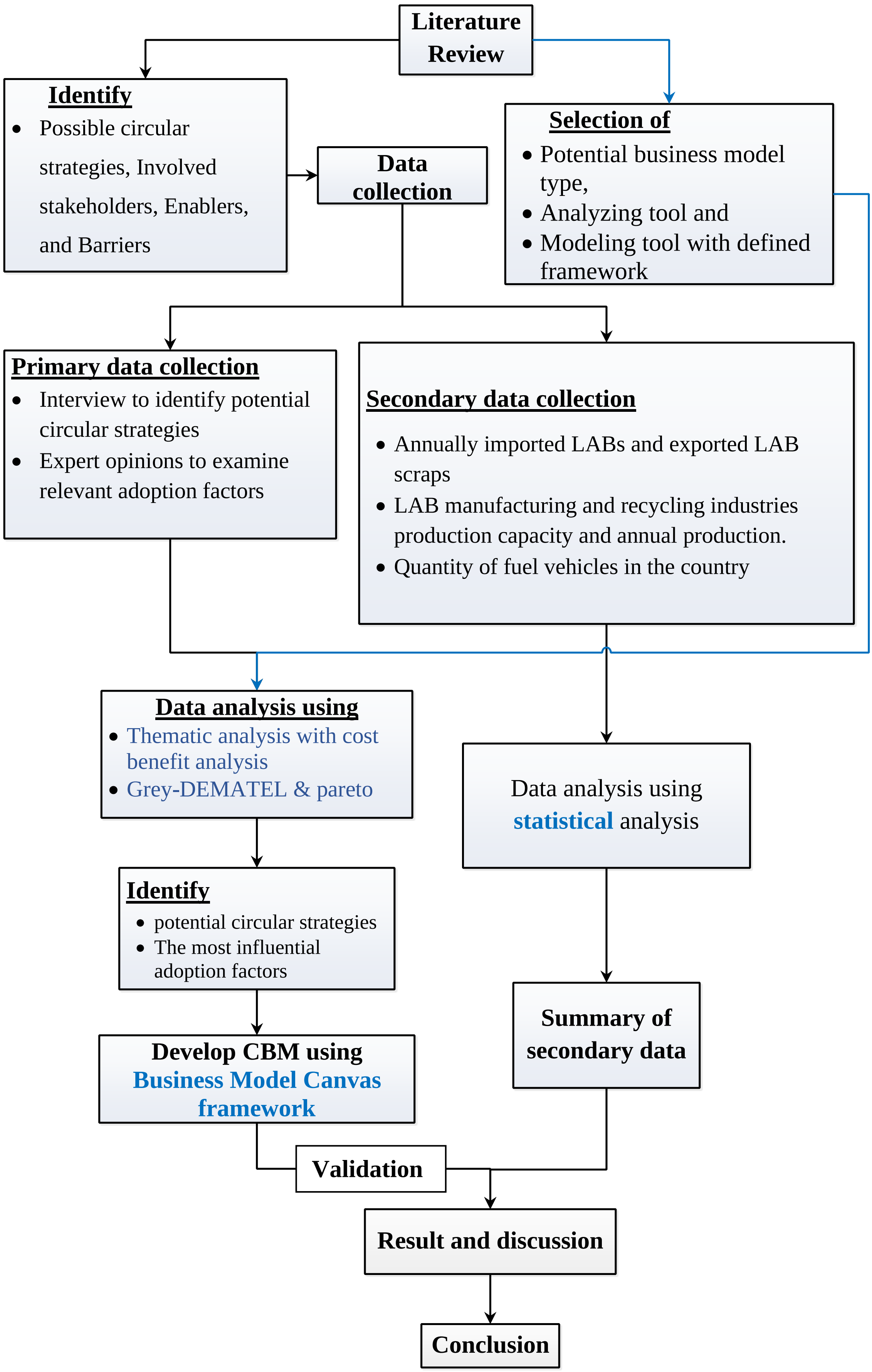


Figure 3. Research flow diagram

3.3. Study Area of Research

The study area for this research focuses on two active industries Engaged in lead recycling and vehicle lead-acid battery manufacturing industries in Ethiopia, specifically one lead recycling industry and one lead-acid battery manufacturing industry. The selection of these industries is based on the current status, it is worth noting that Ethiopia previously had two lead recycling industries from end-of-life vehicle batteries and two vehicle lead-acid battery manufacturing industries. However, currently, one of the lead recycling industries has closed down around five years ago, and the other is non-operational due to a shortage of raw materials.

The objective of this research is to identify potential circular economy (CE) strategies that can be implemented within the sector, to analyze the most influential factors influencing the adoption of circular business models (This analysis involves assessing the barriers and enablers that affect the adoption of CE practices) and subsequently develop a circular business model Using the business model canvas framework, tailored to the unique characteristics and requirements of the vehicle battery sector. This involves designing a holistic and sustainable approach that integrates circular principles into the manufacturing, use, and end-of-life stages of battery products.

3.4. Data source

The research's foundation rests on a meticulous gathering of data from both secondary and primary sources, ensuring a comprehensive and robust dataset for rigorous analysis. This section delves into the diverse array of data sources employed, highlighting the systematic approach undertaken to build a well-informed understanding of Circular Business Models (CBM) for lead-acid batteries. The exploration encompasses a thorough literature review across prominent journals and databases, supplemented by industry reports, government documents, and developmental plans. This strategic combination of secondary sources is complemented by primary data collection through interviews and expert opinions, fostering a holistic and evidence-based study. The following subsections delineate the intricacies of each data source, showcasing the methodical approach employed to enrich the research findings.

3.4.1. Secondary Data Sources - Literature Review

In order to comprehensively investigate the existing literature related to Circular Business Models (CBM) for lead-acid batteries, the study employed an extensive search strategy across a diverse range of prominent journals and reputable databases. The following journals were systematically explored:

- Journal of Cleaner Production
- Journal of Sustainability
- Journal of Resources, Conservation and Recycling
- Journal of Business Research
- International Journal of Electrochemical Science
- IEEE Transactions on Engineering Management
- World Electric Vehicle Journal
- Journal of Power Sources
- International Journal of Minerals, Metallurgy and Materials
- Journal of Industrial and Production Engineering
- Ecological Economics
- Journal of Environmental Management
- Journal of Sustainable Production and Consumption
- Journal of Industrial Ecology
- Business Strategy and the Environment

Additionally, the study accessed renowned databases for scholarly articles and research publications, including:

1. JSTOR
2. IEEE Xplore (Institute of Electrical and Electronics Engineers)
3. ScienceDirect
4. Web of Science
5. SpringerLink
6. Scopus
7. Emerald Insight

This exhaustive search aimed to encompass a wide array of perspectives and ensure a thorough exploration of the literature surrounding CBM for lead-acid batteries. Despite the comprehensive search, the study identified a gap in the existing literature, indicating a need for further research and exploration in this specific domain.

3.4.2. Secondary Data Sources - Industry Reports and Government Documents

The following data sources were utilized to collect industry reports, government documents, and developmental plans:

1. ***Ethiopian Customs Commission***: Data from the Ethiopian Customs Commission was utilized to gather information on the quantity of annually imported Lead-Acid Batteries (LABs) and exported LABs scrap. This data provided insights into the import and export trends of LABs and LABs scrap.
2. ***Manufacturing Technology and Engineering Industry Research and Development Center***: Data from this center was collected to determine the annual production capacity and actual production of the battery manufacturing and lead recycling industries. Additionally, information on the capacity of upcoming and existing Electric Vehicle (EV) assembling companies was obtained from this source.
3. ***Ministry of Transport & Logistics***: Data from the Ministry of Transport & Logistics was used to quantify the availability of fuel vehicles and fully electric vehicles (EVs) in the country. This data helped in understanding the current vehicle composition and the presence of EVs in Ethiopia.

These secondary sources contributed to the contextual understanding and quantitative analysis of the research.

3.4.3. Primary Data Sources - Interviews and Expert Opinions

Primary data was collected through interviews and group discussions with selected experts from two industries in Ethiopia. The experts were categorized into three departments: production, supply chain management, and marketing and finance. The data collection process consisted of four rounds:

- Interviews were conducted as the initial step to identify potential circular strategies.

- The first round of expert opinions involved evaluating factors identified in the literature, ranging from non-relevant to highly relevant. The focus during this stage was on assessing relevant adoption factors
- In the second round of expert opinions, the aim was to evaluate the influence of one factor on another.
- To ensure the robustness of the analysis results obtained from the research, expert judgment was then employed for validation.

3.5. Sampling Techniques and Size

The purposive sampling technique was employed to gather expert opinions for the research. Purposive sampling involves deliberately selecting individuals or experts who possess specific knowledge, expertise, or experience relevant to the research objectives. Through this sampling technique, experts were carefully chosen based on their expertise in the field, ensuring their insights would contribute valuable perspectives to the study. The purposive sampling approach allowed for a targeted and strategic selection of participants, enhancing the credibility and richness of the expert opinions collected.

Purposive sampling: is ‘used to select respondents that are most likely to yield appropriate and relevant information aligned with the research objectives and is a way of identifying and selecting cases that will use limited research resources effectively (Campbell et al., 2020). The decision to employ a purposive sampling strategy in selecting respondents was driven by the objective of obtaining significant information and perspectives regarding existing barriers, enablers (drivers), involved stakeholders, circular economy (CE) strategies, adoption factors, and the existing circular business model within the firm's circular economy. Managers and experts were targeted to ensure a comprehensive understanding of the subject matter. Accordingly, a total of 20 respondents were carefully selected from the supply chain and management, marketing and finance, and production planning and control departments of the two selected industries (all have more than seven-years’ experience).

Table 5. Number of respondents from two industries

Industry	Position	Level of education	Department			Quantity	Total
			production planning & control	marketing & finance	supply chain & management		
Industry-1 (Lead-recycling)	Manager	MSc	1	--	--	1	3
		MBA	--	1	1	2	
		BSc	--	--	--	0	
		BA	--	--	--	0	
	Expert	MSc	1	--	--	1	6
		MBA	--	1	--	1	
		BSc	2	--	1	3	
		BA	--	1	--	1	
Industry-2 (Battery- manufacturing)	Manager	MSc	1	--	--	1	3
		MBA	--	1	1	2	
		BSc	--	--	--	0	
		BA	--	--	--	0	
	Expert	MSc	2	--	1	3	8
		MBA	--	1	--	1	
		BSc	1	--	1	2	
		BA	--	1	1	2	
Total							**20**

3.6. Data collection methods

The collection of data plays a crucial role in conducting comprehensive research and obtaining valuable insights. In this study, a combination of various data collection methods was employed to gather relevant information and enhance the depth of understanding. The data collection methods utilized in this research encompassed secondary data collection, literature review, interviews, observations, expert opinions, and expert judgement.

3.6.1. Secondary data collection methods

In order to determine the availability of vehicle battery resources and the capacity for resource utilization within the battery recycling and manufacturing industries in the country, the collection of reliable data is important. This entails gathering information on the import and export of lead-acid batteries (LABs), annual production capacity and actual production of battery industries, and the quantity of fuel vehicles. To obtain this information, reliable secondary data was collected from various governmental organizations in Ethiopia through formal letters of request. Access was sought from organizations including Ethiopian customs commission, Manufacturing Technology and Engineering Industry Research and Development Center, and the Ministry of Transport & Logistics. These letters outlined the specific data needed to quantify the annual import and export of LABs, determine the production capacity and actual production of battery manufacturing and lead recycling industries, and assess the number of fuel vehicles in the country.

Literature review

The data collection method from literature employed in this research involves a systematic process of gathering relevant information from existing literature. The following steps are involved in this process:

1. **Defining Research Scope**

The scope of the literature study focused on a comprehensive exploration of Barriers, enablers, and stakeholders implicated in the implementation of circular business models, Potential circular strategies that could create and capture more value in CBM development, The most influential factors affecting the adoption of CBMs for vehicle batteries, and Existing circular business models and frameworks that create, capture, and deliver more value.

2. **Develop Search Strategy:**

To gather relevant literature, I employed a comprehensive search strategy. This involved identifying keywords and phrases including "circular business model," "Circular economy," "barriers and enablers," "stakeholders," "opportunities," "challenges," "circular strategies," "Circular value chain," "Battery life extension," "battery second life," "reuse," "repurpose," "repair," "refurbish," "remanufacture," "recycle," "value creation and capture," "adoption factors," "lead-acid and lithium-ion batteries," and "life cycle assessment."

I conducted searches in academic databases including ***JSTOR, IEEE Xplore (Institute of Electrical and Electronics Engineers), ScienceDirect, Web of Science, SpringerLink, Scopus,*** and ***Emerald Insight***, with ***Google Scholar***, and research repositories search engines. I also considered using Boolean operators to combine keywords effectively and refine the search results. Additionally, filters and limiters, such as publication date, document type, and language, were applied to further refine the search results and ensure their relevance to the research objectives.

3. **Literature Screening:**

After compiling a list of potentially relevant articles, I began the screening process. I carefully reviewed the titles and abstracts of each article to determine their relevance to my research objectives. Articles that were clearly unrelated or did not align with my research scope were excluded. This initial screening helped streamline the subsequent literature review.

4. **Review and Data Extraction:**

With a refined selection of articles, a detailed literature review was conducted, thoroughly reading each article with close attention to the methodologies, findings, and discussions related to the research objectives. Relevant data was extracted, including information on barriers, enablers, stakeholders, circular strategies, influential factors for adoption, and circular business models for LABs.

To collect and organize research papers, I utilized **Mendeley**, a reference manager and academic social network. This software facilitated the systematic recording of information, including article titles, authors, publication years, research methodologies, key findings, and other pertinent data. With Mendeley, I maintained consistency in data extraction throughout all the selected articles, ensuring accuracy and reliability in my literature review.

5. **Data Synthesis and Analysis:**

After completing the literature review and data extraction, I proceeded to synthesize the collected information. During this process, I carefully analyzed the data and identified common themes, patterns, and trends pertaining to barriers, enablers, stakeholders, circular strategies, adoption factors, and circular business models for LABs. Similar findings and data points were grouped together to facilitate analysis and interpretation.

To analyze the data, using qualitative techniques based on the nature of the collected information. For example, I used thematic analysis to identify recurring themes or statistical analysis to quantify relationships between influential factors and CBM adoption.

6. **Reporting the Findings:**

Finally, I reported the findings of my data analysis. I organized the results according to my research objectives and presented them in a clear and structured manner. I utilized tables to enhance the presentation of the data.

In my report, I provided a comprehensive discussion of the identified barriers, enablers, stakeholders, circular strategies, influential factors, and the circular business models developed for LABs. I interpreted the findings in the context of existing literature and highlighted their implications for theory and practice.

Throughout my research, I ensured proper citation of all the sources used, maintaining a consistent referencing style in my report or manuscript.

3.6.2. Primary data collection methods

Interviews

Interviews were conducted with 20 industry experts to examine potential circular economy strategies. Semi-structured interviews were conducted with the selected industry experts to gain insights into their perspectives on potential circular economy strategies and the factors that facilitate or hinder the adoption of circular business models. An interview protocol consisting of one comprehensive and open-ended questions. The interview questions were designed to align with the research objectives, and to guide the discussions and ensure consistency across interviews. The questions were designed to cover the most relevant and potentially impactful circular strategies for the vehicle battery industry and the advantages and limitations of each circular strategy.

Table 6. Framework for interviews of Circular economy strategies

SN.	Circular strategies	Description
1	Reuse	
2	Repair	
3	Repurpose	
4	Remanufacture	
5	Recycling	

Expert opinions

Expert opinions were sought to examine relevant adoption factors derived from the literature and to evaluate the initial direct relation of one factor to the other factors. It has two rounds; first round is to evaluate the relevancy and the second is to compute experts pairwise relations. The insights and perspectives provided by domain experts were instrumental in ensuring the accuracy and reliability of the findings.

Expert judgments

Expert judgments were used to validate the analyzed results to ensure the accuracy and reliability of findings.

In validating my analysis results, which encompassed the identification of potential circular strategies through thematic analysis, the assessment of adoption factors through Grey-DEMATEL, and the development of a Circular Business Model (CBM) using the Business Model Canvas (BMC) framework, I engaged experts with over seven years of experience in the field.

Their expert judgment was essential for confirming the accuracy and relevance of the analysis results. The experts, possessing extensive experience and knowledge, reviewed and provided insights into the identified circular strategies, adoption factors, and the proposed CBM.

Their feedback and assessments played a pivotal role in validating the robustness and practicality of the analysis outcomes. The incorporation of expert judgment not only fortified the credibility of the analysis but also provided a valuable perspective from industry professionals well-versed in the dynamics of circular economy strategies and business model development.

Their contributions ensured that the identified strategies and adoption factors were well-grounded and that the proposed CBM adhered to industry standards and best practices. This validation process was instrumental in affirming the quality and applicability of the analysis results, bolstering the reliability of the research findings and recommendations.

In conclusion, the involvement of experts with substantial experience in the field further solidified the integrity of the research and its capacity to make a meaningful impact in the context of the study.

3.7. Data Analysis Tools

3.7.1. Grey-DEMATEL approach with Microsoft Excel

The Grey-DEMATEL approach was used to analyze the most influential factors affecting the adoption of a circular business model for vehicle lead-acid batteries. The Grey-DEMATEL method is a hybrid approach that combines the Grey System Theory (GST) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method (Soares et al., 2023). It is a multi-criteria decision-making technique that helps analyze the cause-and-effect relationships among factors and quantifies the strength and direction of the relationships between factors and identifies the most influential ones.

Steps of the Grey-DEMATEL analysis:

- Step 1: Problem Formulation Clearly define the problem or system under analysis. Identify the factors or variables that are relevant to the problem and need to be evaluated for their influence.
- Step 2: Constructing the Grey Relational Matrix (GRM) Create a matrix representing the relationships between factors. The GRM captures the direct relationships among factors and is the basis for further analysis. The matrix can be constructed based on expert opinions.
- Step 3: Grey Relational Coefficient Calculation Calculate the grey relational coefficients that represent the degree of influence between each pair of factors. Grey relational coefficients indicate the closeness or similarity between factors based on their behavior and trends.
- Step 4: Constructing the Total Grey Relational Coefficient Matrix (TGRCM) Combine the grey relational coefficients obtained in the previous step with the direct relationships matrix to create the Total Grey Relational Coefficient Matrix. This matrix reflects both direct and indirect influences among factors.
- Step 5: Grey Total Effect (GTE) Calculation Compute the Grey Total Effect, which represents the total influence of a factor in the system. It is calculated by summing up the elements in each row of the TGRCM.
- Step 6: Grey Total Influence (GTI) Calculation Calculate the Grey Total Influence, which represents the overall influence received by a factor from other factors. It is obtained by summing up the elements in each column of the TGRCM.

- Step 7: Grey Self-Effect (GSE) Calculation Determine the Grey Self-Effect, which represents the direct influence of a factor on itself. It is calculated by summing up the diagonal elements of the TGRCM.
- Step 8: Impact Calculation Compute the Impact of a factor, which indicates its net influence in the system. It is calculated by subtracting the Grey Total Influence from the Grey Self-Effect.
- Step 9: Ranking and Interpretation Rank the factors based on their Impact values, from highest to lowest. Interpret the results to identify the most influential factors in the system. Factors with higher Impact values have a greater influence on the system. This helped to identify the most important factors that need to be considered in the development of a circular business model.

In executing the Grey-DEMATEL analysis, Microsoft Excel served as the primary tool for conducting intricate calculations. The software's robust functionality and formulaic capabilities played a crucial role in ensuring accurate and efficient computation of various parameters involved in the analysis.

3.7.2. Pareto principle

In light of the Grey-DEMATEL analysis, I employed the Pareto Principle, adhering to the notion that approximately 80% of issues stem from 20% of crucial causes (Craft & Leake, 2002), to prioritize the factors influencing the adoption of the lead-acid battery circular business model. This prioritization was achieved by calculating the cumulative percentage of the total impact, starting from the result obtained through the Grey-DEMATEL analysis.

3.7.3. Circular Business Model Canvas framework

The Circular Business Model Canvas framework is a strategic management and entrepreneurial tool used for visualizing, describing, and designing circular business models (Lewandowski, 2016; Pollard et al., 2023). It is based on the original Business Model Canvas but incorporates elements specific to the circular economy. The canvas consists of eleven elements or building blocks that help entrepreneurs and organizations identify and develop circular business opportunities. These building blocks include customer segments, value proposition, channels, customer relationships, key activities, key resources, key partnerships, cost structure, revenue streams take-back system and adoption factors. These building blocks enable the design of a business model aligned with circular economy principles. Here are the components of the Circular Business Model Canvas:

1. **Value Propositions:**
   - Circular products that enable product-life extension, product-service systems, virtualized services, and collaborative consumption.
   - Incentives and benefits offered to customers for returning used products.
2. **Customer Segments:**
   - Directly linked to the value proposition component, it represents the fit between the value proposition and customer segments.
3. **Channels**:
   - Possible virtualization of channels by selling virtualized value propositions and delivering them virtually.
   - Selling non-virtualized value propositions through virtual channels.
   - Virtual communication with customers.
4. **Customer Relationships:**
   - Production based on customer orders and preferences.
   - Social marketing strategies and relationships with community partners when implementing recycling 2.0.
5. **Revenue Streams:**
   - Generated through circular products or services.
   - Payments for availability, usage, or performance related to product-based services.
   - Revenue from the value of resources obtained from material loops.
6. **Key Resources:**
   - Selection of suppliers offering better-performing materials.
   - Virtualization of materials and resources for regenerating and restoring natural capital.
   - Resources obtained from customers or third parties meant to circulate in closed material loops.
7. **Key Activities:**

- Focus on improving performance through good housekeeping, process control, technology changes, sharing, and virtualization.
- Product design enhancements for circularity and eco-friendliness.
- Lobbying efforts.

8. Key Partnerships:

- Collaboration with partners along the value chain and supply chain that support the circular economy.

9. Cost Structure:

- Reflects financial changes made in other components of the Circular Business Model Canvas.
- Includes the value of incentives for customers.
- Requires special evaluation criteria and accounting principles.

10. Take-Back System:

- Design of a take-back management system, including channels and customer relations associated with product returns.

11. Adoption Factors:

- Organizational capabilities and external factors that support the transition to a circular business model.

3.8. Method data analysis

3.8.1. Statistical data analysis

Secondary data has been analyzed using statistical data analysis to summarize annual imported LABs, to determine annual production capacity and actual production of battery manufacturing and lead recycling industries, and to quantify available vehicles in the country.

3.8.2. Thematic analysis

Thematic analysis is a qualitative data analysis method that can be used to identify patterns and themes in interview data. It is a flexible and adaptable method that can be used to answer a wide range of research questions. In this context I were used this analysis method to identify potential circular economy strategies in vehicle LABs, which can create, deliver and capture more value. The collected interview data underwent a rigorous process of thematic analysis. This involved several steps, including:

1. **Familiarization:** The researchers familiarized themselves with the interview transcripts to gain a comprehensive understanding of the data.
2. **Initial Coding:** Initial codes were assigned to segments of the data that represented specific concepts, themes, or patterns.
3. **Collating Codes:** Similar codes were collated to form potential themes, which captured key ideas and insights present in the data.
4. **Theme Development:** Themes were refined and developed through an iterative process of reviewing and analyzing the codes within each potential theme.
5. **Review and Validation:** The developed themes were reviewed by multiple researchers to ensure accuracy and validity. Any discrepancies were resolved through discussion and consensus.
6. **Reporting:** The final themes were defined and described, supported by illustrative quotes from the interview transcripts.

- **Cost benefit analysis:** To further substantiate the economic feasibility of repairing lead-acid batteries, I conducted a comprehensive cost-benefit analysis. This analysis reinforces the economic feasibility of repairing lead-acid batteries within the circular economy framework by evaluating the costs associated with repair against the benefits reaped, emphasizing the potential financial advantages.

3.9. Reliability and validity

In this research study, I, as the sole data collector, have meticulously designed and executed the data collection method with a keen focus on both reliability and validity to ensure the accuracy, consistency, and trustworthiness of the data gathered.

3.9.1. Reliability

To guarantee the reliability of this data collection method, the following steps have been undertaken:

1. **Consistency in Data Collection Procedures:** I have standardized the process of data collection, maintaining a consistent approach for conducting interviews and surveys with all participants.
2. **Thorough Preparation:** Before commencing data collection, I have invested significant time in understanding the research objectives, refining the research questions, and preparing data collection instruments. This ensures a standardized process throughout the study.
3. **Pilot Testing:** To identify and address any potential inconsistencies or ambiguities in data collection instruments and procedures, I conducted pilot tests before the main data collection.
4. **Test-Retest Reliability:** For survey instruments, I have explored test-retest reliability. This involved administering the same survey to the same participants on two different occasions and assessing the consistency of their responses.

3.9.2. Validity

Expert judgments were used to validate the analyzed results to ensure the accuracy and reliability of findings. In validating my analysis results, which encompassed the identification of potential circular strategies through thematic analysis, the assessment of adoption factors through Grey DEMATEL, and the development of a Circular Business Model (CBM) using the Business Model Canvas (BMC) framework, I engaged experts with over seven years of experience in the field.

Their expert judgment was essential for confirming the accuracy and relevance of the analysis results. The experts, possessing extensive experience and knowledge, reviewed and provided insights into the identified circular strategies, adoption factors, and the proposed CBM.

Their feedback and assessments played a pivotal role in validating the robustness and practicality of the analysis outcomes. The incorporation of expert judgment not only fortified the credibility of the analysis but also provided a valuable perspective from industry professionals well-versed in the dynamics of circular economy strategies and business model development.

Their contributions ensured that the identified strategies and adoption factors were well-grounded and that the proposed CBM adhered to industry standards and best practices. This validation process was instrumental in affirming the quality and applicability of the analysis results, bolstering the reliability of the research findings and recommendations.

In conclusion, the involvement of experts with substantial experience in the field further solidified the integrity of the research and its capacity to make a meaningful impact in the context of the study.

3.10. Data quality management

In this section, the meticulous management of data quality is outlined to ensure the accuracy, reliability, and validity of the research findings. Data quality is fundamental to this study's credibility and significance.

Data Collection Protocols: The research employs stringent data collection protocols, encompassing structured interview guides and well-defined survey instruments. These protocols establish consistency and uniformity in data collection processes.

Data Validation: Rigorous data validation procedures are executed during data entry. These checks include range, consistency, and logic checks to identify and rectify discrepancies or errors in the collected data.

Data Cleaning: Comprehensive data cleaning is carried out prior to analysis. Irregularities, missing values, and outliers are detected and addressed to enhance data accuracy.

Participant Validation: After data collection, participants are provided with the opportunity to validate their responses, allowing them to confirm the accuracy of the recorded information. Any necessary revisions are made based on participant feedback.

Secure Data Storage: The collected data is stored securely to prevent unauthorized access and ensure participant privacy. Digital data is encrypted and password-protected to guarantee its confidentiality.

Data Transparency: Detailed documentation of the data collection process and methodology is maintained to promote transparency. This documentation includes clear explanations of data collection instruments, procedures, and any adaptations made during the research.

By implementing these data quality management practices, this research endeavors to produce reliable, credible, and valid findings that contribute to a comprehensive understanding of circular business models for lead-acid batteries in the context of the vehicle battery industry. Data quality management is an integral aspect of the research process, safeguarding the integrity and trustworthiness of the study's outcomes.

3.11. Ethical consideration

This section underscores the ethical considerations meticulously adhered to during the research, emphasizing the utmost importance of ethical principles and participant welfare in every phase of the study.

Informed Consent: Ethical research begins with informed consent. Prior to the commencement of interviews, a comprehensive informed consent process was diligently followed. This process involved providing participants with clear, detailed information about the research objectives, procedures, potential risks, and benefits. Participants were given ample time to review this information, ask questions, and make informed decisions about their involvement in the study. Their voluntary agreement was documented through formal consent forms, reaffirming their willingness to participate.

Confidentiality: The confidentiality of participant information is of paramount importance. Every participant was assured that their identity and responses would remain strictly confidential. Pseudonyms or unique identifiers were used in place of real names to protect their privacy. Any data shared during the research was stored securely, and access was limited to authorized personnel only.

Voluntary Participation: Participants were explicitly informed of their right to voluntary participation, emphasizing that they could withdraw from the research at any stage without facing any consequences. This commitment to voluntary involvement is essential to respecting the autonomy and free will of participants.

Data Security: Ensuring the security of participant data is an ethical imperative. Robust data security measures were implemented to protect the confidentiality and integrity of the information gathered. Digital data was encrypted and stored on password-protected devices and secure servers.

Debriefing: Participants were offered the opportunity for debriefing at the conclusion of their involvement in the research. This allowed them to gain insights into the broader context of the study, its goals, and the collective significance of their contributions.

Research Ethics Compliance: This study adheres to established research ethics principles and guidelines, as outlined by institutional review boards and relevant ethical codes of conduct.

Continuous Monitoring: Ethical considerations were continuously monitored and upheld throughout the research process. Any concerns, questions, or ethical issues raised by participants were addressed promptly and transparently.

By rigorously observing these ethical considerations, the research endeavors to uphold the highest standards of integrity, respect for participants' rights, and responsible research conduct. These ethical foundations ensure that the study's findings are not only academically sound but also ethically sound, contributing to the welfare and dignity of all involved.

Chapter Four

4. Data Presentation and Analysis

4.1. Introduction

In this chapter, I embark on the critical phase of this research, where I present and analyze the data collected through a combination of secondary sources, primary data collection, and expert opinions. This chapter is instrumental in bringing empirical evidence to bear on the research questions and objectives outlined in Chapter One, allowing me to shed light on the intricate dynamics of circular business models for lead-acid batteries (LABs) within the Ethiopian context.

As introduced in previous chapters, my research aims to address three primary questions. First, it seeks to identify potential circular strategies that can promote the development of Circular Business Models (CBMs) for LABs, thereby enabling greater value capture and contributing to a sustainable circular economy. Second, I delve into the critical factors that influence the adoption of these circular business models within the Ethiopian context. Lastly, I endeavor to develop a comprehensive circular business model encompassing the repair, repurpose, and recycling strategies for LABs.

To answer these questions and fulfill my objectives, I have engaged in an extensive data collection process, which includes the extraction and analysis of secondary data, primary data collected through surveys and interviews, and the synthesis of expert opinions. This chapter forms the bridge between data collection and the implications of my findings for the subject matter. It serves to provide readers with a detailed overview of the datasets I have gathered and the analytical methods I employed, offering transparency and insight into the research process.

The data presented and analyzed in this chapter will serve as the empirical foundation upon which the subsequent chapter will construct its conclusions and recommendations. You will gain a deeper understanding of the landscape of LABs in Ethiopia, the current state of circular business models in this context, and the insights of experts who are intimately familiar with the nuances of this industry. Through meticulous data presentation and rigorous analysis, this chapter endeavors to contribute significantly to the understanding of circular business models for lead-acid batteries and pave the way for more sustainable and value-driven practices in this sector.

4.2. Data Analysis

4.2.1. Secondary data analysis

Secondary data was gathered from various reputable sources to provide a comprehensive understanding of the current state of lead-acid batteries (LABs) within Ethiopia. This data collection involved accessing specific statistics and reports related to lead-acid batteries and circular business models. The following secondary data has been integrated into the research:

Secondary data sourced from the Manufacturing Technology and Engineering Industry Research and Development Center (2010-2014 E.C.) provides valuable insights into the capacity and production within the battery manufacturing and lead recycling industries in Ethiopia. The data reveals that the combined annual production capacity of these industries amounted to an impressive 11,194,000 kilograms (kg). Furthermore, the five-year average annual production during this period was approximately 1,572,000 kg. This data underscores the significance of these industries in the Ethiopian context and their contribution to the field of battery manufacturing and lead recycling. The average capacity utilization of these industries in the last five years is approximately 14.03%, indicating that they have been operating at roughly 14% of their total capacity. This level of capacity utilization can have implications for efficiency and resource utilization.

Table 7. Battery manufacturing and lead recycling industries production capacity and their last 5 years production

No	**Industry**	**Annual Production capacity kg**	**last 5 years Average annual production in kg**
1	Industry-A (manufacturer)	1,044,000	522,000
2	Industry-B (recycler)	9,650,000	1,000,000
3	Industry-C (recycler)	500,000	50,000
Total		**11,194,000**	**1,572,000**

Source: Manufacturing Technology and Engineering Industry Research and Development Center (2010-2014 E.C.)

The import of lead-acid batteries (LABs) within Ethiopia plays a crucial role in understanding the dynamics of this sector. The following data, sourced from the Ethiopian Customs Commission for the years 2016 to 2022, presents insights into the quantity of imported lead-acid batteries:

Table 8. Number of imported lead-acid batteries

Year	Quantity Pcs	Net weight kg	Unit weight (average)
2016	359181	4922223.53	13.70401978
2017	371701	5358836.47	14.41706229
2018	26403	539894.71	20.44823353
2019	473031	6284675.48	13.28596959
2020	347153	5756461.68	16.58191541
2021	335435	2932080.87	8.741129787
2022	340473	4931941.51	14.48557659
Total	**2,253,377**	**30,726,114.25**	**101.6638887**
Average	**321911**	**4389444.89**	**14.52341268**

Source: Ethiopian Customs Commission (2016-2022)

These statistics provide essential information about the scale of LAB importation within Ethiopia, which is a key factor in the broader context of battery manufacturing and lead recycling in the country. Understanding the trends and quantities involved in LAB imports is crucial for assessing the demand and consumption patterns within this industry.

Table 9. Number of Exported Scrap lead-acid batteries

Year	Export LAB scrap (Kg)
2018	1099350
2019	126000
2020	160000
2021	99980
2022	2179500
2023	500000
Total	4164830
Average	**694,138.33**

Source: Ethiopian Customs Commission, 2018-2023

The data on the export of LAB scrap signifies an essential aspect of the recycling and manufacturing industry. It demonstrates the amount of LAB scrap exported, which could be indicative of recycling and recovery activities. The resource availability for

LAB manufacturing and recycling industries is a key component in evaluating the industry's resource utilization in comparison to its capacity utilization. Understanding the export quantities and variations over the years is crucial for assessing the resource availability for repairing, repurposing recycling within Ethiopia.

Table 10. Number of Vehicles Registered in Ethiopia

Year E.C	Number of Vehicles Registered	Yearly increment of vehicles
2010	935,888	---
2011	1,071,345	135,457
2012	1,200,110	128,765
2013	1,339,005	138,895
2014	1,401,114	62,109
Average	**1,189,492**	**116,306.5**

Source: Ministry of Transport and Logistics 2010-2014 E.C

This data provides valuable insights into the number of vehicles registered in Ethiopia from 2010 to 2014 E.C. It is a key factor in assessing the demand for lead-acid batteries (LABs) in the automotive industry.

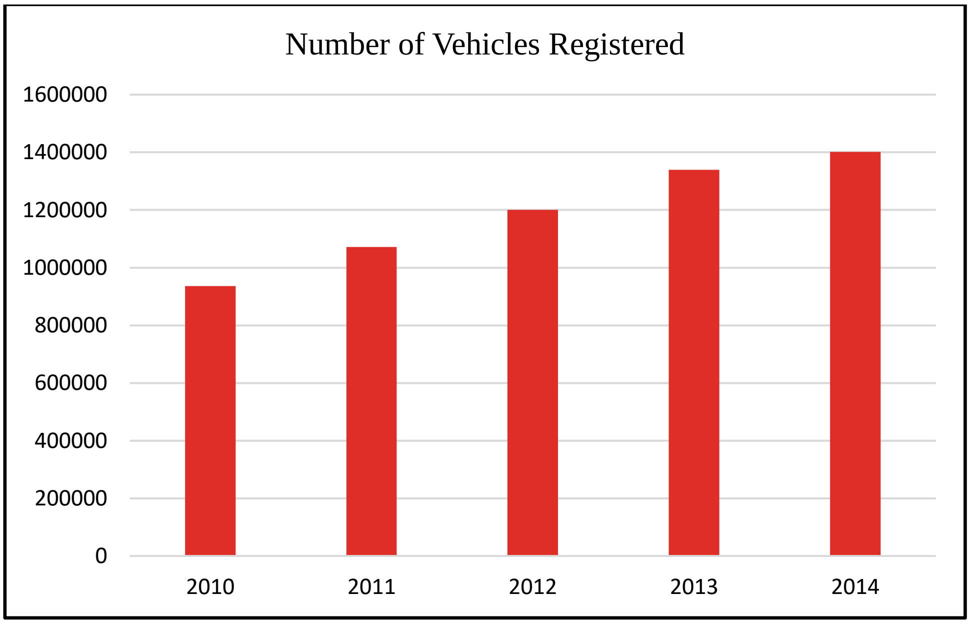


Figure 4. Growth representation of vehicles quantity in Ethiopia

The increasing trend in vehicle registrations over these years indicates a growing market for LABs. Understanding these trends is crucial for evaluating the capacity utilization of LAB manufacturing and recycling industries in response to market demand.

The average of 1,189,492 vehicles registered in a year during this period signifies a substantial and consistent market for LABs. This data is instrumental in assessing the resource availability, manufacturing capacity, and recycling capability required to meet the demands of the automotive industry. Further analysis can provide insights into the relationship between vehicle registration and the LAB industry's resource utilization and capacity.

4.2.2. Primary data analysis

For a more in-depth understanding of the Ethiopian context concerning LABs and circular business models, primary data was collected through the following methods:

Interviews data analysis

This section presents and analyzes the primary interview data collected from 20 industry experts on potential circular economy strategies for vehicle lead-acid batteries. The interviews were semi-structured and designed to elicit rich and contextualized responses from participants. Here is interview question (Within the domain of circular economy strategies, which encompass Reuse, Repair, Repurpose, Remanufacture, and Recycling, I kindly request your expert perspective on the most relevant and potentially impactful strategies for the circular economy of lead-acid batteries within the vehicle battery industry. Please examine these strategies considering nine key factors: battery chemistry and characteristics, environmental impact, economic feasibility, market demand, technological compatibility, adherence to safety and regulatory standards, resource efficiency, ease of implementation, and long-term sustainability). The collected interview data underwent a rigorous process of thematic analysis. This involved several steps, including: familiarization, initial coding, collating codes, theme development, review and validation, and reporting.

Reuse

It appears that the interview data indicates that attempting to directly reuse and repurpose lead-acid batteries without any maintenance is impractical. This is due to the fact that lead-acid batteries naturally experience wear and degradation over time, which has a negative impact on their performance and safety. Here are key reasons why reusing lead acid batteries without maintenance is not practical:

1. **Active Material Depletion:** Lead acid batteries rely on a chemical reaction between lead plates and sulfuric acid electrolyte to generate electricity. During each charge and discharge cycle, the active materials on the battery plates are consumed and gradually depleted. This depletion reduces the battery's capacity and overall performance.

2. **Plate and Grid Breakdown:** Over time, the lead plates within the battery can degrade and break down, reducing their ability to store and deliver electrical energy effectively.

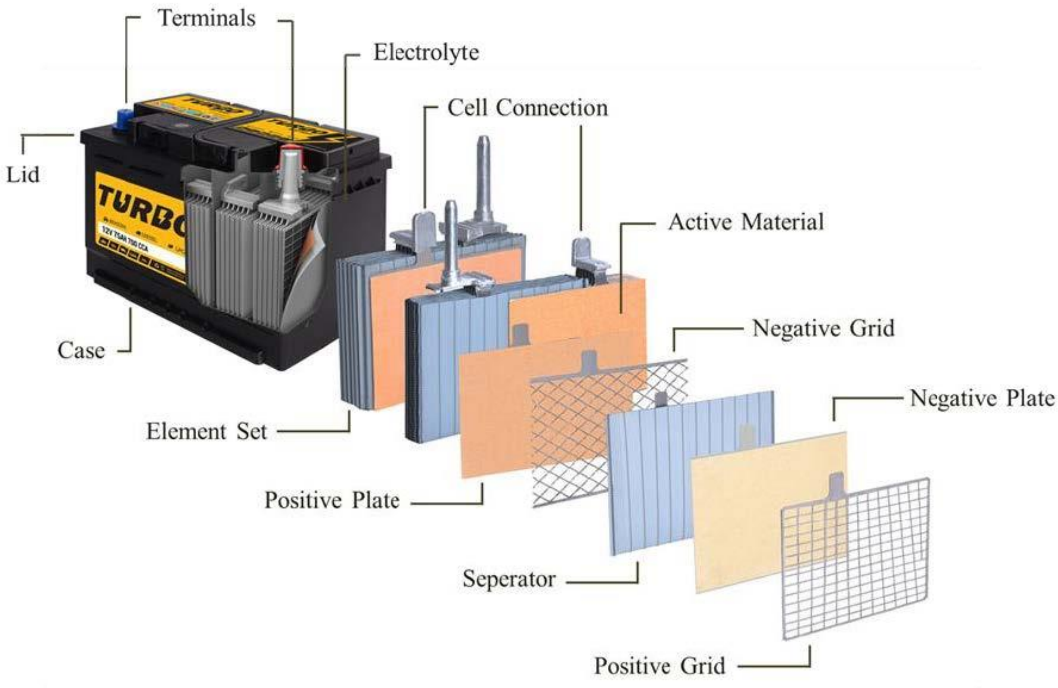


Figure 5. Vehicle Lead-acid battery components; source (Blecua de Pedro, 2021)

3. **Corrosion:** Corrosion of the lead plates and other internal components can occur, further diminishing battery performance and potentially causing shorts or leaks.

4. **Sulfation:** Sulfation is a common issue where sulfate crystals form on the battery plates, reducing their ability to react with the electrolyte and store energy.

5. **Water Loss:** Lead acid batteries require a specific electrolyte level to function correctly. Water loss, which can occur through evaporation during use, can lead to decreased performance and potential damage.

6. **Acid Stratification:** In lead acid batteries, sulfuric acid and water can separate into layers, creating an uneven distribution of electrolyte within the battery. This can lead to uneven charging and reduced capacity.

7. **Surface Charge:** Lead acid batteries can develop surface charges that make them appear fully charged even when their capacity is significantly reduced. This can lead to unreliable performance.

Conclusion: The thematic analysis of the interview data provided valuable insights into the impracticality of reusing lead-acid batteries without maintenance. Experts highlighted several factors, including active material depletion, plate and grid breakdown, corrosion, sulfation, water loss, acid stratification, and surface charge, which all contribute to reduced battery performance and safety risks. To make lead-acid batteries suitable for reuse, it is essential to do inspection, testing, and necessary repairs or maintenance.

Repair

The interviews with industry experts highlighted the significance of a repair circular economy strategy for lead-acid batteries, to extend the lifespan of batteries through repair and reuse practices. They emphasized that before examining the potentiality of repair strategy, we have to justify the scope of repair. This encompasses a combination of activities, as outlined below:

a) **Cleaning the battery terminals**: This involves removing any dirt, corrosion, or other buildup from the battery terminals. This can be done with a wire brush and some baking soda and water.
b) **Replacing the Battery Vent Caps**: involves removing the old vent caps on a lead-acid battery and installing new ones. These caps enable safe gas release during battery operation and provide access for electrolyte level maintenance.
c) **Adding distilled water to the battery cells**: Lead-acid batteries lose water over time, so it is important to add distilled water to the battery cells regularly. The water level should be above the lead plates, but it should not be so high that it covers the vents in the battery caps.
d) **Reconditioning the lead plates**: This involves removing sulfate crystals that have formed on the lead plates. Sulfate crystals can build up on the lead plates

over time, reducing the battery's capacity and performance. Reconditioning the lead plates can help to improve the battery's performance and extend its lifespan.

e) **Replacing the electrolyte**: This involves replacing the mixture of sulfuric acid and distilled water that makes up the battery's electrolyte. The electrolyte can become depleted or contaminated over time.

f) **Assembling and charging the battery**: Once you have completed any necessary repairs or maintenance, you need to reassemble the battery and charge it fully.

Below are the interview assessment results based on the repair activities mentioned above within nine factors.

1. ***Battery Chemistry and Characteristics***: In the assessment of repair activities, experts highlighted that lead-acid batteries are relatively easy to repair. This ease of repair is attributed to the accessibility and lower complexity of lead-acid battery components, making them more amenable to repair and maintenance practices.

2. ***Environmental Impact****:* The assessment results for the second factor, environmental impact, emphasize the substantial environmental benefits associated with repairing lead-acid batteries. Repairing these batteries reduces the need for manufacturing new ones, a process that can be energy-intensive and environmentally polluting. Furthermore, it contributes to a reduction in the volume of electronic waste that requires disposal. This underscores the potential of lead-acid battery repair as an environmentally responsible approach, aligning with resource conservation and reduced carbon footprint.

3. ***Economic Feasibility:*** The assessment results for the third factor, economic feasibility, underscore that repairing a lead-acid battery is a more cost-effective choice compared to replacing it with a new one. The cost of repair can vary depending on the extent of damage and the availability of skilled technicians. The potential for cost savings or profits depends on key considerations highlighted during the interviews, including:

   - ✓ ***Purchase Price of Scrap Batteries***: It depend on the current market price for scrap batteries, the condition of the batteries, and the quantity you are able to acquire at a time.

- ✓ ***Repair Costs***: Including testing, labor, materials, and equipment for repairing cost of the batteries.
- ✓ ***Operating Expenses:*** This category includes a range of operational costs, such as expenses for storage, transportation, marketing, and administrative activities.
- ✓ ***Market Price for New Batteries, Competitors, Quality of Repairs, and Warranty Policies:*** The pricing dynamics in the market for new batteries, the presence of competitors, the quality of repair services, and warranty policies, along with the level of customer service, all collectively play a pivotal role in building customer trust and fostering economic feasibility.

To further substantiate the economic feasibility of repairing lead-acid batteries, a comprehensive cost-benefit analysis was conducted:

Cost-Benefit Analysis

To further substantiate the economic feasibility of repairing lead-acid batteries, I conducted a comprehensive cost-benefit analysis. This analysis reinforces the economic feasibility of repairing lead-acid batteries within the circular economy framework by evaluating the costs associated with repair against the benefits reaped, emphasizing the potential financial advantages.

1. **Purchase Price of Scrap Batteries**:

The purchase price of scrap lead-acid batteries is influenced by current market rates and the buyer category. Prices for scrap batteries are typically quoted per kilogram, rather than per individual battery.

For this section, I collected purchase prices of scrap lead-acid batteries from various sources, including industries, collectors, and exporters. Data was gathered through interviews and direct participation in the market as a purchaser. The average price of scrap batteries per kilogram, based on data collected from four exporters, two industries, and ten collectors, is summarized in the table below.

Table 11. Average Scrap Lead-Acid Battery Prices per Kilogram in Ethiopia

Date	Source	Type of battery	Price (birr)/kg			Average price
			Min.		Max.	
June 12-15/2023	Industry 1	Automotive battery	65		70	67.5
June 19-22/2023	Industry 2	Automotive battery	65		75	70
June 26-26/2023	Exporters	Automotive battery	70		75	72.5
July 03-08/2023	Collectors	Automotive battery	Buying	50	65	57.5
			Selling	60	75	67.5
Average						67
Average purchase price, excluding the price set by collectors						**69.375**

Please note that collectors typically sell scrap batteries to exporters or industries, and their purchase price is not included in the average price calculation.

Weight of lead acid battery

To calculate the purchase price of a single lead-acid battery, it is necessary to determine the weight of the battery. The weight of a vehicle lead-acid battery depends on several factors, including:

1. **Capacity (Ah)**: The battery's capacity, measured in ampere-hours (Ah), directly affects its weight. Higher capacity batteries generally weigh more because they have more lead plates and electrolyte.

2. **Plate Thickness**: The thickness and number of lead plates within the battery impact its weight.

3. **Electrolyte Volume**: The volume of electrolyte (sulfuric acid and water solution) in the battery also contributes to its weight.

4. **Technology and Design**: Technology and Design: Advanced technologies, such as absorbed glass mat (AGM) and gel cell batteries, have different designs and can weigh more or less than traditional flooded lead-acid batteries. Flooded lead-acid (FLA) batteries are the heaviest type of lead-acid battery, while AGM batteries are the lightest. Sealed lead-acid (SLA) batteries are lighter than FLA

batteries, but not as light as AGM or gel cell batteries. Gel cell batteries are also lighter than FLA batteries, but not as light as AGM batteries.

5. **Terminal Type**: The type and material of the battery terminals (e.g., lead or lead alloy) can influence the battery's weight.
6. **Brand and group**: The weight of a lead acid battery can vary depending on the brand and groups such as Battery Council International (BCI), Deutsche Industry Norm (DIN)

To provide a practical context for understanding the weight of lead-acid batteries, I selected 12-Volt batteries with 35-Ampere-Hour (Ah) and 100-Ampere-Hour (Ah) ratings. These batteries were categorized under different industry standards, including JIS, BCI, and DIN groups. The table below summarizes the average weight of these batteries:

Table 12. Average weight of 12V, 35AH, and 100AH lead-acid car batteries.

Battery Type	**Average Weight (kg) of Battery (Group: JIS, BCI, & DIN)**	
	12V,35AH	**12V,100AH**
AGM	10.5	30.8
FLA	12.5	32.5
SLA	11.5	31.5
Average	**11.5**	**31.6**

Source: https://www.batterycouncil.org/, https://www.din.de/ and https://www.jisc.go.jp/eng/

$$purchase\ price\ for\ single\ scrap\ LAB = average\ weight \times price\ per\ kilogram$$

$$For\ 12V, 35AH\ LAB = 11.5 \times 69.375 = 797.8125\ birr$$

$$For\ 12V, 100AH\ LAB = 31.6 \times 69.375 = 2192.25\ birr$$

2. Replacing cost of Battery Vent Caps

The vent caps are designed to release hydrogen and oxygen gases that are produced when the battery recharges, preventing them from building up pressure inside the battery and they permit the checking and maintenance of water and acid levels. Most lead acid car batteries have two to six vent caps on top of the battery. The cost of Replacing Battery Vent Caps is including:

- **Cost of Required Tools and Materials:** It includes current price of new vent caps, safety goggles and gloves, pliers or a wrench, petroleum jelly, and Towel or rags.

$$Average\ Current\ vent\ cap\ price\ is\ 172.5\ birr\ per\ piece$$

$$average\ number\ of\ Vent\ Caps\ per\ battery = (2+6) \div 2 = 4\ pieces$$

$$vent\ cup\ price\ for\ one\ battery = 4 \times 172.5 = 690\ birr$$

$$Estimated\ tools\ \&\ other\ materials\ cost = 30\ birr\ for\ each\ battery$$

$$\boldsymbol{Total\ Tools\ and\ Materials\ cost} = 690 + 30 = 720\ birr$$

- **Labor Costs**: it is calculated by breakdown the salary of labors (experts) per hour and considering the time required to:
    - ✓ Disconnect the battery cable from the battery terminal.
    - ✓ Remove the old battery vent caps.
    - ✓ Clean the battery posts and vent cap threads with a wire brush.
    - ✓ Apply a thin coat of petroleum jelly to the battery posts and vent cap threads.
    - ✓ Install the New Vent Caps:

The cost and time required to replace battery vent caps in a lead-acid battery can vary depending on several factors, including the number of vent caps, the brand and quality of the vent caps, the technician's experience with the process, and any specific precautions or safety measures taken. Based on data collected from expert interviews, the process of replacing battery vent caps in a lead-acid battery typically takes an average of five minutes for the replacement of one vent cap. Since most batteries have two up to six vent caps (four in average), it takes about **20 minutes** to replace all four battery vent caps.

Based on the current salary of battery technicians, I assumed an expert salary of 12,000 birr per month, considering 26 working days with 8 hours per day (equivalent to 192 hours per month).

$$Expense\ per\ Minute\ =\ (Monthly\ Salary\ /\ Monthly\ Working\ Hours)\ /\ 60$$

$$= (12{,}000\ birr\ /\ 192\ hours)\ /\ 60$$

$$= (62.5\ birr)\ /\ 60 \approx 1.0417\ birr$$

$$Expense\ for\ 24\ minutes = 1.0417 \times 20 \approx 20.384\ birr$$

$$\boldsymbol{Total\ cost\ of\ Battery\ Vent\ Caps\ replacement\ per\ single\ battery}$$
$$\boldsymbol{= 720 + 20.384 = 740.384\ birr}$$

3. Replacing cost of electrolyte

- ✓ ***Cost of electrolyte chemical***: it is done by calculating the amount of electrolyte required to replace and multiplying by current price of electrolyte.
  - ✓ Weight of lead LABs is 60%
  - ✓ Weight of electrolyte is 38% (35% sulfuric acid and 65% distilled water)
  - ✓ Weight of others is around 2%
  - ✓ Density of electrolyte at 35% concentration of sulfuric acid is 1.259 kg/L
  - ✓ Current average price of electrolyte is 305 birr per liter

<u>For 12V,35AH battery average weight is 11.5kg</u>

$$lead\ weight = 60\%\ of\ 11.5kg = 6.9kg$$

$$electrolyte\ weight = 38\%\ of\ 11.5kg = 4.37kg$$

$$volume\ of\ electrolyte\ @35\%\ concentration\ of\ sulfuric\ acid$$
$$= 4.37kg \div 1.259\ kg/L = 3.47liter$$

$$cost\ of\ electrolyte = 3.47liter \times 305\ birr/liter = \mathbf{1{,}058.35}\ \boldsymbol{birr}$$

<u>For 12V,100AH battery (average weight is 31.6kg)</u>

$$lead\ weight = 60\%\ of\ 31.6kg = 18.96\ kg$$

$$electrolyte\ weight = 38\%\ of\ 31.6kg = 12.008\ kg$$

$$volume\ of\ electrolyte\ @35\%\ concentration\ of\ sulfuric\ acid$$
$$= 12.008\ kg \div 1.259\ kg/L = 9.538\ liter$$

$$cost\ of\ electrolyte = 9.538\ liter \times 305birr/liter = \mathbf{2{,}909.09}\ \boldsymbol{birr}$$

- ✓ ***Cost for Required Tools and Materials:*** *Safety Equipment and Materials cost**:*** including gloves, eye protection, cleaning supplies, and disposal containers costs are considered. And also, *Tools and Equipment*: Include funnels, battery hydrometers, and wrenches costs are considered. ***Estimated cost is 10 birr per battery***
- ✓ **Labor Costs:** it is calculated by breakdown the salary of labors (experts) per hour and considering the time required to:
  - Preparation for Safety
  - Cleaning and Preparation:
  - Removal of Old Electrolyte:
  - Cleaning Battery Interior:
  - Refilling with New Electrolyte:
  - Sealing Cells:
  - Charging the Battery:
  - Safety Checks and Testing:

The time it takes to replace the electrolyte in a lead-acid battery can vary depending on several factors, including the size and type of the battery, the technician's experience with the process, and any specific precautions or safety measures. Based on data collected from expert interviews, the process of replacing the electrolyte in a lead-acid battery can range from 30 minutes to a few hours, with an average duration of approximately **two** hours with two expert involvements.

$$from\ above\ one\ expert\ expense = 62.5\ birr\ per\ hour$$

$$Two\ experts\ expense\ for\ two\ hours = 62.5 \times 2 \times 2 = 250\ birr$$

Total Replacing cost of electrolyte

$$For\ 12V, 35AH\ battery = F = 1{,}058.35 + 10 + 250 = 1{,}318.35\ birr$$

$$For\ 12V, 100AH\ battery = 2{,}909.09 + 10 + 250 = 3169.09\ birr$$

4. De-sulfation Costs:

The cost of removing sulfation from lead plates in a lead-acid battery can vary depending on the size and type of the battery, the severity of sulfation, and the method or products used for de-sulfation (i.e., de-sulfation additives, pulse de-sulfation devices, or specialized de-sulfation chargers).

1. **Labor Costs**: These are calculated by breaking down the hourly salary of the laborers (experts) and considering the time required to adjust the de-sulfating device process. The time required includes connecting the de-sulfation device to the battery terminals, setting the device to the appropriate mode, turning on the de-sulfation device and allowing it to run for the recommended duration, disconnecting the device from the battery terminal after the de-sulfation process is complete, and fully charging the battery. To perform these activities takes approximately two and a half hours.

$Labor\ cost = 62.5 \times 5/2\ birr = 156.25 birr$, as the hourly labor cost is 62.5 birr

2. **Testing Equipment cost**: De-sulfation methods require testing equipment to monitor and assess progress. This includes safety equipment, a multimeter (digital voltmeter), a load tester, and a battery hydrometer (measures the specific gravity of the electrolyte in each cell). The cost of each piece of equipment is allocated across each battery, taking into consideration the purchase price and the estimated lifespan of the equipment. The purchase price and lifespan estimation were derived from expert interviews and are approximately **25 birr** per battery.

3. **De-sulfation cost:** To calculate the cost of the de-sulfation process, I have chosen to use the DK-GN50, a specialized device designed for charge and discharge testing, pulse de-sulfation, high-frequency activation, reconditioning, and capacity grading of lead-acid batteries.

Table 13. Technical Specifications of the Device (DK-GN50)

Production Capacity	10000 Pieces/Year
Applicable for	6V/8V/12V/16V Lead-acid batteries
Total Channel Number:	50 Channels
Pulse Repair Channels:	24 Channel
Capacity Test Channels:	24 Channels
HF Activating Repair Channels:	2 Channels
Power Supply:	AC 220V±10% 50 Hz
Power:	No-load 620 W, Full-loading 7 KW
Average life span	35,000 hours
purchasing price	450,800 birr

- The de-sulfation process for 12V,35AH battery took between 24 up to 36 hours
  - ✓ Average de-sulfation time is $= (24 + 36) \div 2 = 30\ hours$
  - ✓ The device Can load 24 batteries at time (i.e., it can de-sulfate 24 batteries in 30 hours)
  - ✓ It costs 450,000 birr for 35,000 hours
  - ✓ The device operational cost for 30 hours

$$= 30\ hour \times 4508000\ birr \div 350000\ hours$$

$$= 386.4\ birr$$

  - ✓ The device operational cost for one battery

$$= 386.4\ birr \div 24 = 16.1\ birr$$

  - ✓ Maintenance expense per battery (taken from experts' estimation) is 10% device operational cost $= 10\%\ of\ 16.1\ birr = 1.61\ birr$
  - ✓ Electric utility cost for device power consumption (Ethiopian Electric utility tariff is 0.4086 birr per kwh for industrial consumption); therefore, Electric utility power consumption expense per each battery

$$= 7kwh \times 30hour \times 0.4086birr/kwh \div 24\ batteries = 3.575\ birr$$

Total De-sulfation cost per battery (for 12V,35AH) is

$$= 156.25 + 25 + 16.1 + 1.61 + 3.575 = \mathbf{202.535\ birr}$$

- ✓ The de-sulfation process for **12V,100AH** battery took between 36 up to 48 hours
  - ✓ Average de-sulfation time is $= (36 + 48) \div 2 = 42\ hours$
  - ✓ The device operational cost for 42 hours

$$= 42\ hour \times 4508000\ birr \div 350000\ hours$$

$$= 540.96\ birr$$

  - ✓ The device operational cost for one battery

$$= 540.96\ birr \div 24 = 22.54\ birr$$

  - ✓ Maintenance expense per battery (taken from experts' estimation) is 10% device operational cost $= 10\%\ of\ 22.54\ birr = 2.254\ birr$
  - ✓ Electric utility power consumption expense per each battery

$$= 7kwh \times 42\ hour \times 0.4086birr/kwh \div 24\ batteries = 5.00535\ birr$$

Total De-sulfation cost per battery (for 12V, 100AH) is

$$= 156.25 + 25 + 22.54 + 2.254 + 5.00535 = \mathbf{211.05}\ \boldsymbol{birr}$$

5. **Operational Expenses**

Operational expenses are the costs that a business incurs on an ongoing basis to run its day-to-day operations. These expenses are typically deducted from revenue to calculate operating income, which is a measure of a company's profitability from its core business activities. These expenses include the cost of storage, transportation, marketing, and administrative costs. In this section, the following categories of expenses were taken into account:

Cost of storage: refers to the costs associated with storing inventory or goods. This includes: Rent or ownership of warehouse space, utilities (electricity, water, heating, cooling), insurance, security, and labor costs associated with storing and retrieving inventory.

Transportation costs: are the costs associated with moving goods from one place to another. This includes: Fuel costs, vehicle maintenance and repair costs, and labor costs associated with loading and unloading vehicles,

Marketing costs: are the costs associated with promoting and selling a company's products or services. This includes: Advertising costs, public relations costs, and sales commissions

Administrative costs: are the costs associated with running the general and administrative functions of a business. This includes: Salaries and benefits for administrative staff, office supplies and equipment, rent or ownership of office space, and accounting and legal fees.

I have utilized the following tariffs and scientific assumptions to estimate a portion of the operational expenses:

- Production workshop space: 150 square feet (≈14 m2) per employee
- Storage: 25% of the total square footage
- Shipping and receiving: 15% of the total square footage
- Office space: 10% of the total square footage
- Employee facilities: 10% of the total square footage

- Industrial lease: 7320 birr per square meter for 20 years
- Ethiopian Electric utility tariff for industrial consumption: 0.4086 birr per kwh

Finally, the monthly expense of each operational category is allocated, and the overall monthly expense is distributed to each product. These is done to determine the cost per unit of each product, which is essential for pricing and profitability analysis.

Table 14. Operational expense summary for 12V,35AH and12V,100AH LABs

Cost category	**Cost per kg birr**	**Cost per unit of battery birr**	
		12V,35AH	**12V,100AH**
Storage	12.9527	148.956	409.305
Transportation	16.191	186.195	511.631
Marketing	6.476	74.478	204.653
Administrative	29.144	335.151	920.937
Total		**744.78**	**2046.526**

6. Market Price for New Batteries

The price of a car lead-acid battery depends on several factors including the type and brand of the battery, its size and capacity, group size, technology, reserve capacity, cold cranking amps (CCA), warranty, and the retailer's location. Here's a market price range in Ethiopia as of July 2023 for my cost benefit analysis.

Table 15. Market Price for New Batteries in Ethiopia (July 2023)

Battery spec.	Average Price of different battery brands from different source						**Average Price**
	Brand-1	Brand-2	Brand-3	Brand-4	Brand-5	Brand-6	
12V, 35AH	6500	7890	8814	9860	10863	11,771	9283
12V, 40AH	7500	8400	10500	10867	12075	13282	10437.33
12V, 45AH	7500	8700	11080	12075	14490	15697	11590.33
12V, 50AH	8500	9080	11550	13285	15700	16905	12503.33
12V, 55AH	9800	10000	11055	13890	17270	18716	13455.17
12V, 60AH	10200	10200	16301	18113	19320	22880	16168.96
12V, 65AH	11560	16301	18113	19320	22943	24600	18806.04
12V, 70AH	12000	17000	18113	19924	23600	25773	19401.46
12V, 75AH	16301	18113	19320	20528	24150	26565	20829.38
12V, 80AH	18924	19131	20943	21150	23358	25565	21511.67
12V, 85AH	19735	20913	22150	24358	26565	27188	23484.58
12V, 90AH	21097	21116	23961	24773	26188	30810	24657.42
12V, 100AH	21735	23773	24980	26791	27603	31172	26008.92

Source: Local market and online market survey

Table 16. Cost benefit analysis summary

No.	Description	Average expense in birr	
		12V,35AH	**12V,100AH**
1	Buying price for scrap	797.8125	2,192.3
2	Replacing the Battery Vent Caps	740.384	740.384
3	Replacing electrolyte	1318.35	3264.47
4	Reconditioning lead plates (Cleaning and De-sulfation)	202.535	211.05
5	Operating Expenses	744.78	2046.5259
Total expense		3803.86	8454.68
Selling price (50% discount from new one)		4641.5	13004.46
Profit margin		837.6385	4549.7801
Profit as a percentage of total expenses		**22.02%**	**53.81%**

Conclusion: The cost-benefit analysis has shown that repairing and reselling lead-acid batteries can yield a significant profit margin. Even when offering them to customers at a 50% discount compared to the price of new batteries with a one-year warranty period, businesses can achieve a profit margin of 22% or higher. This suggests that investing in the repair and resale of lead-acid batteries can be a financially viable strategy for businesses in this industry.

4. ***Market Demand***: The interviews revealed that there is a growing market for used lead-acid batteries. These used batteries are considerably significantly less expensive compared to new ones, which makes them an appealing choice for businesses and consumers seeking cost-effective solutions. Additionally, these used batteries can typically serve their original purpose for 2-3 years, and providers can offer warranties, further enhancing their attractiveness to budget-conscious buyers.

5. ***Technological Compatibility:*** The interviews highlighted that there are numerous well-established technologies and processes available for the repair and reuse of lead-acid batteries. This technological compatibility provides businesses with effective and reliable methods for extending the life of these batteries within the circular economy framework.

6. ***Safety and Regulatory Compliance:*** The assessment results indicate that ensuring safety and regulatory compliance is of utmost importance when repairing lead-acid

batteries for reuse, as they are classified as hazardous waste by the Federal Democratic Republic of Ethiopia's Environmental Protection Agency (EPA). The EPA is responsible for managing and protecting the environment in Ethiopia. Within its regulatory framework (Industrial Chemical Registration and Administration Guideline June, 2023), the EPA provides general guidelines for industrial chemical registration and administration, including the storage and transportation of industrial chemicals, as well as general safety rules. It also formulates policies, regulations, and guidelines for environmental protection, monitors compliance with environmental standards, and offers technical assistance and capacity building to stakeholders. This comprehensive approach ensures that the repair of lead-acid batteries aligns with stringent safety and regulatory measures within the circular economy framework.

7. ***Resource Efficiency:*** The assessment results indicate that repair for reuse is a resource-efficient strategy as it significantly reduces the necessity for manufacturing new batteries, a process that is energy-intensive and environmentally polluting, while also minimizing waste by extending the battery's lifespan.

8. ***Ease of Implementation:*** The assessment results underscore the ease of implementing a repair circular strategy for lead-acid batteries, particularly when integrated within existing manufacturing and recycling facilities. This approach capitalizes on the infrastructure, expertise, and logistical advantages already in place within these facilities. By incorporating repair strategies into their operations, they can leverage existing resources and knowledge to effectively extend the lifespan of lead-acid batteries.

9. ***Long-Term Sustainability:*** The assessment results indicates that the repair-based circular strategy for lead-acid batteries is positioned for long-term sustainability. This is due to ongoing technological development, cost-effectiveness, a rising demand for repaired batteries, robust regulatory support, and alignment with the principles of the circular economy.

Summary: Based interview data analysis result and cost benefit analysis Repairing lead-acid batteries for reuse is a promising potential circular economy strategy as it can reduce environmental impact, generate economic benefits, growing demand for repaired lead-acid batteries, There are well-established technologies and processes available, can be aligned with stringent safety and regulatory measures, a resource-efficient strategy, Ease of implementation (can integrate within existing manufacturing and recycling facilities, Long-term sustainability and alignment with the circular economy principles.

To strengthen the robustness and credibility of my analysis, I have implemented the following measures:

Data Sources: The data employed for the Cost-Benefit Analysis (CBA) originates from reputable industry databases, online market and physical market.

Methodological Transparency: The methodology applied in the CBA is clearly outlined, offering transparency regarding the collection, processing, and analysis of data.

Peer-reviewed Literature: The literature reviewed for the CBA comprises studies and research that have undergone rigorous peer-review processes. This ensures that the data presented meets the highest standards of academic and industry scrutiny.

Expert Consultation: To enhance credibility, I have consulted with experts in the field of lead-acid batteries and circular economy practices. Their insights and feedback have played a crucial role in validating and cross-verifying my findings, contributing significantly to the overall credibility of the data used in the analysis.

Repurpose

Repurposing lead-acid batteries is the process of assigning for new applications after they have reached the end of their useful life in their original application. It is important to note that repurposing without prior repair or maintenance, as discussed in the reuse analysis, is often impractical. Examining repair for repurpose (new application) through expert interviews revealed responses aligned with those from the repair for reuse analysis in five key factors, including battery chemistry and characteristics, environmental impact, technological compatibility, resource efficiency, and ease of implementation. However, there are distinctive findings in the following four factors:

1. **Economic Feasibility:** The economic viability of repurposing lead-acid batteries depends on several factors, including the condition and cost of scrap batteries, expenses associated with repair and repurposing, the selling price of

repurposed batteries, and the existing market demand for such batteries. According to the interview responses, it is evident that repurposing can be a cost-effective approach to extending the lifespan of lead-acid batteries, particularly when the batteries are in good condition.

2. **Market Demand:** Repurposed vehicle lead-acid batteries offer versatile utility beyond their original automotive applications. While they may not be suitable for demanding automotive tasks after they've aged and lost some capacity, they can still serve effectively in other roles where the demands are less stringent. According to the interview responses, it is evident that there is a growing market for repurposed lead-acid batteries, as they can be used in a variety of applications, such as backup power, energy storage for off-grid systems, uninterruptible power supply (UPS) systems, and Education and Research activities.

3. **Safety and Regulatory Compliance:** Repurposing lead-acid batteries require specialized safety and regulatory compliance measures based on their application due to the presence of corrosive and hazardous sulfuric acid and the potential for hydrogen gas production during charging, which is both flammable and explosive.

4. **Long-Term Sustainability:** Repurposing lead-acid batteries aligns with circular economy principles, reducing the environmental impact of battery disposal, conserving natural resources, and achieving economic viability in certain cases, contingent on specific applications and market demand. This practice supports the sustainability of battery management within a circular economy framework.

Summary: Repurposing lead-acid batteries is a promising circular strategy. It extends battery life, is economically feasible (particularly when batteries are in good condition), aligns with circular economy principles, ensures safety compliance, and meets the growing market demand.

Remanufacturing

Based on interview data analysis Remanufacturing lead-acid batteries presents a complex challenge due to their battery chemistry and characteristics. The hazardous nature of lead and sulfuric acid raises safety concerns, including health hazards and the potential for flammable hydrogen gas production during charging. Additionally, the sealed nature of lead-acid batteries can make disassembly and reassembly difficult, hampering the inspection and replacement of damaged components. Remanufacturing, while environmentally friendlier than manufacturing new batteries, faces hurdles in economic feasibility. It becomes financially unviable when batteries are in poor condition, as the cost of replacing key components exceeds that of new battery production. The market for remanufactured lead-acid batteries is limited, largely due to their pricing proximity to new batteries and shorter lifespan. Remanufacturing also requires specialized facilities, equipment, and safety and regulatory compliance, making it a challenging strategy to implement. The long-term sustainability of remanufacturing depends on market demand and economic feasibility.

Summary: Remanufacturing lead-acid batteries presents significant challenges, including safety concerns related to lead and sulfuric acid, complex disassembly due to sealed units, economic feasibility issues, and limited market demand due to pricing proximity to new batteries. Remanufacturing demands specialized facilities, equipment, and strict safety and regulatory compliance, making it a challenging strategy to implement. The long-term sustainability of remanufacturing remains uncertain due to these obstacles.

Recycling

Recycling lead-acid batteries emerges as a more straightforward and sustainable approach, thanks to their characteristics. These batteries are straightforward to recycle, given their composition of common materials. The environmental impact of recycling is lower compared to manufacturing new batteries. From an economic perspective, recycling is feasible due to several factors. Lead-acid batteries contain valuable materials like lead, sulfuric acid, and plastics, which can be reclaimed and sold. Recycling is energy-efficient, with significantly reduced energy consumption compared to new battery production. Well-established recycling infrastructure and global demand for lead-acid batteries bolster economic viability. Safety, regulatory compliance, and resource efficiency are also strengths of recycling. Lead-acid battery recycling boasts a high recycling rate, valuable materials recovery, and closed-loop systems. The closed-loop nature of recycling contributes to resource efficiency, as it offers a sustainable resource beneficial to the environment. The effective separation of battery components enhances the recovery of valuable products. Recycling is relatively easy to implement, as numerous specialized companies provide this service. In terms of long-term sustainability, lead-acid battery recycling stands strong, possessing efficient recycling infrastructure, responsible resource management, compliance with stringent environmental regulations, technological innovation, stable market demand, and integration into circular economy principles. These attributes position recycling as a sustainable strategy for the foreseeable future.

Summary: Recycling lead-acid batteries is a highly promising strategy, backed by key advantages: their simple composition and well-established recycling processes ensure economic feasibility, strong safety and regulatory compliance, and contribute to resource efficiency. The ease of implementation and long-term sustainability further enhance the potential of recycling lead-acid batteries in the automotive industry.

Conclusion for potential circular strategies

The analysis of circular strategies for lead-acid batteries reveals that repairing, repurposing, and recycling are all promising circular strategies. These strategies provide substantial environmental and economic advantages, prolonged battery life, meet safety and regulatory standards, use resources efficiently, and promote long-term sustainability. Combining these strategies can maximize their positive impact and sustainability in lead-acid battery management.

To drive the adoption of these circular strategies, it is essential to:

- Raise awareness of their advantages
- Establish supportive policies and regulations
- Invest in research and development efforts

4.2.3. Analysis of expert opinions

Expert Opinions: This section presents and analyzes the expert's opinion data collected from 20 industry experts to examine the relevancy of 31 factors affecting adoption of circular business model for vehicle lead-acid batteries which is I summarized from literature review.

The data collection process consisted of two rounds: The first round of expert opinions involved 20 experts, each of whom was provided with 31 factors to evaluate. They were asked to rate each factor on a scale of 0 to 4, with 0 indicating irrelevance, 1 for very low relevance, 2 for low relevance, 3 for high relevance, and 4 for very high relevance. Based on the data obtained from the experts (Appendix A), a selection process was carried out to identify the relevant factors. The factors were selected by sorting the expert evaluations from largest to smallest, and any factors rated as less than or equal to one (indicating very low relevance or irrelevance) were omitted. As a result, 23 factors were determined to be relevant for further analysis.

Table 17. Relevant adoption factors based on expert evaluation (Recoded)

Category	**Adoption factors**
Organizational	Lack of Business model with take-back systems (OF1)
	Design limitation for disassembly capability (OF2)
	Capability of human resources (OF3)
	Lack of Industrial ecology and by-product synergy (OF4)
	Poor Company culture (OF5)
Technological	unavailability of efficient technologies (TF1)
	Limitation on Information digitalization (TF2)
	Lack of Proper status checking, diagnosing, and tracking technology (TF3)
Economical	High cost of handling, transporting, recovering process, and labor (EF1)
	Lack of incentives (EF2)
	Low economic value of EOL VBs (EF3)
	Low Market demand and customer preferences (EF4)
Supply-chain management	Uncertainty in supply (number and quality), price/value of VBs (SCM1)
	Lack of effective communication and coordination (SCM2)
	Lack of Competitiveness (SCM3)
Environmental	Stringent (Strict) regulations (ENF1)
	Lack of attention for Conservation and protection of natural resources (ENF2)
	Difficulties in disposing the wastes from recovered batteries (ENF3)
Political	Political instability (P1)
	Lack of Supportive government policies and regulations for circular economy adoption (P2)
	Lack of Collaboration between public and private sectors to promote circularity (P3)
Socio-cultural	Lack of Customer awareness (SF1)
	Perceived quality of the recycled products (SF2)

These 23 factors are considered to be of sufficient importance based on expert consensus, and they will serve as the focus of our analysis. This selection process helps ensure that the analysis is concentrated on the most meaningful aspects as determined by the experts' evaluations.

The second round of expert opinions aimed to evaluate the initial direct relationships between one factor and the other factors. This step is crucial as it forms the basis for Grey DEMATEL analysis. The experts were divided into six groups, with three groups allocated to each industry within three different departments (production, Supply Chain Management, and Marketing & Finance department). They were provided with 23×23 tables and asked to evaluate the influence of each factor on every other (grey pairwise influence relation comparison) based on their knowledge and experience within their respective groups. The rating scale used was as follows: 0 for no influence, 1 for very low influence, 2 for low influence, 3 for high influence, and 4 for very high influence. They generating 6 matrices with 529 comparisons for each expert group. It's important to note that the diagonal of the relation matrix was filled with 0, as factors were not considered to influence themselves.

In the subsequent step of the analysis, the evaluated scores from each group were converted into grey relation matrix using a predefined table that linked linguistic variables to grey number ranges. The table values used for this conversion are as follows:

Table 18. Grey linguistic scale

Linguistic variable	Influence score	Grey number
No influence	0	{0,0}
Very low influence	1	{0,0.25}
Low influence	2	{0.25,0.5}
High influence	3	{0.5,0.75}
Very high influence	4	{0.75,1}

This conversion process is important as it helps to quantify the influence of one factor on another in a more precise and standardized manner. The use of grey numbers allows for a degree of uncertainty and vagueness to be captured in the analysis, which can be particularly valuable when dealing with complex relationships.

In the next phase of the analysis, the converted grey relation matrix was aggregated to create an overall average as shown in Appendix B. The averages were calculated by summing the grey numbers for each pair of factors across the six expert groups and dividing by six to get the final, combined grey numbers.

After aggregating the grey relation matrix, the subsequent step in the analysis is the development of the crisp relation matrix. This involves a three-step

Step-1: Normalize lower and upper value; This ensures that all elements of the matrix are between 0 and 1, and done by the following formula.

$$\underline{\otimes}\tilde{x}_{ij}^{p} = (\underline{\otimes}x_{ij}^{p} - \min_{j} \underline{\otimes}x_{ij}^{p})/\Delta_{\min}^{\max}$$

$$\bar{\otimes}\tilde{x}_{ij}^{p} = (\bar{\otimes}x_{ij}^{p} - \min_{j} \bar{\otimes}x_{ij}^{p})/\Delta_{\min}^{\max}$$

where

$$\Delta_{\min}^{\max} = \max_{j} \bar{\otimes}x_{ij}^{p} - \min_{j} \underline{\otimes}x_{ij}^{p}$$

Step-2: Calculate the total normalized crisp value. This is done by the following formula

$$Y_{ij}^{p} = \frac{\left(\underline{\otimes}\tilde{x}_{ij}^{p}(1 - \underline{\otimes}\tilde{x}_{ij}^{p}) + (\bar{\otimes}\tilde{x}_{ij}^{p} \times \bar{\otimes}\tilde{x}_{ij}^{p})\right)}{\left(1 - \underline{\otimes}\tilde{x}_{ij}^{p} + \bar{\otimes}\tilde{x}_{ij}^{p}\right)}$$

Step-3: Compute final crisp values.

$$z_{ij}^{p} = \min_{j} \underline{\otimes}x_{ij}^{p} + Y_{ij}^{p}\Delta_{\min}^{\max}$$

- The subsequent step in the analysis involves the creation of the Normalized Direct-Relation Matrix, denoted as (N). in this process all elements within this matrix are constrained to values between 1 and 0.

$$N = S \times Z$$

$$S = \mathrm{Min}\left[\frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} Z_{ij}}, \frac{1}{\max\limits_{1 \le i \le n} \sum_{i=1}^{n} Z_{ij}}\right]$$

S is the normalization factor

- Determine the total relation matrix (T): To determine the total relation matrix, the following equation is employed.

$$T = N(I - N)^{-1} \text{ where (I) is denoted as an identity matrix}$$

- Determination of causal parameters: In the context of causal parameter determination, 'R_i' signifies the summation of rows, while 'C_j' represents the summation of columns within the total relation matrix, denoted as 'T'.

- Compute the Mean /Average/threshold value (α) of the Elements in T: Add up all the values in the Total Influence Matrix and Divide the sum by the total number of elements (N) in the matrix.

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} (T_{ij})}{N} = 0.14426$$

The GREY-DEMATEL analysis reveals a complex web of interconnected factors influencing the adoption of CBM. To identify the most significant influences, a threshold value (α) of 0.144263 was calculated. Factors exceeding this threshold are deemed to exert strong, significant influence on other elements within the system. Notably, every factor in the initial column exhibits a significant influence (either causally or effectively based on the net effect value $(R_i - C_j)$) on the corresponding factors in the row where the value surpasses the threshold value (highlighted in bold within Table 19).

- Identifying prominence and net effect group: In the process of identifying prominence and net effect groups, the overall prominence (P_i) and the net effect (E_j) can be derived using the following equations.

$$P_i = [R_i + C_j] \quad \forall i = j$$
$$E_i = [R_i - C_j] \quad \forall i = j$$

When the net effect ($E_j = R_i - C_j$) is positive, the corresponding factor acts as a cause, influencing the strength of other factors. Conversely, a negative net effect indicates that the factor is an effect, being influenced by other factors (Adegoke et al., 2022).

Table 19. Total relation matrix

i j	OF1	OF2	OF3	OF4	OF5	TF1	TF2	TF3	EF1	EF2	EF3	EF4	EF5	SCM1	SCM2	SCM3	ENF1	ENF2	EN3	PF1	PF2	SF1	SF2	R_i
OF1	**0.173**	**0.195**	0.123	**0.220**	0.144	**0.171**	**0.152**	**0.157**	**0.207**	**0.193**	**0.227**	**0.188**	**0.201**	**0.195**	**0.197**	**0.199**	**0.148**	**0.208**	**0.202**	0.113	**0.195**	**0.181**	**0.173**	4.162
OF2	**0.177**	0.116	0.111	**0.186**	0.115	**0.146**	0.112	0.143	**0.179**	**0.169**	**0.203**	**0.158**	**0.162**	**0.153**	**0.149**	**0.163**	0.133	**0.182**	**0.185**	0.088	**0.178**	0.135	**0.153**	3.496
OF3	**0.194**	0.142	0.085	**0.180**	**0.145**	0.139	0.124	0.137	**0.178**	**0.151**	**0.195**	**0.144**	**0.170**	**0.154**	**0.168**	**0.168**	0.125	**0.163**	**0.166**	0.080	**0.166**	**0.153**	**0.165**	3.492
OF4	**0.186**	**0.165**	0.115	0.141	0.117	0.144	0.117	0.137	**0.173**	**0.177**	**0.194**	0.143	**0.160**	**0.165**	**0.168**	**0.169**	**0.145**	**0.176**	**0.179**	0.092	**0.180**	0.137	**0.154**	3.533
OF5	**0.181**	**0.153**	0.129	**0.175**	0.085	0.133	0.108	0.127	**0.150**	**0.146**	**0.166**	0.133	**0.147**	0.142	0.143	**0.149**	0.116	**0.148**	**0.148**	0.080	**0.148**	0.125	0.142	3.175
TF1	**0.187**	**0.163**	0.111	**0.179**	0.116	0.112	0.141	**0.154**	**0.172**	**0.168**	**0.186**	0.141	**0.169**	**0.164**	**0.160**	**0.149**	0.125	**0.156**	**0.170**	0.091	**0.170**	0.136	**0.163**	3.483
TF2	0.128	0.106	0.084	0.123	0.090	0.123	0.068	0.125	0.117	0.114	0.127	0.107	0.116	0.129	0.109	0.114	0.097	0.119	0.116	0.070	0.116	0.103	0.111	2.513
TF3	**0.206**	**0.171**	0.119	**0.198**	**0.146**	**0.168**	**0.147**	0.119	**0.196**	**0.185**	**0.211**	**0.174**	**0.187**	**0.180**	**0.176**	**0.184**	**0.157**	**0.192**	**0.187**	0.120	**0.188**	**0.167**	**0.180**	3.957
EF1	**0.219**	**0.175**	0.139	**0.203**	**0.150**	**0.172**	0.132	**0.164**	**0.154**	**0.193**	**0.216**	**0.182**	**0.199**	**0.184**	**0.181**	**0.188**	**0.160**	**0.197**	**0.192**	0.129	**0.193**	**0.172**	**0.185**	4.079
EF2	**0.169**	0.132	0.088	0.133	0.091	0.115	0.092	0.102	0.131	0.106	**0.167**	0.127	**0.151**	0.120	0.121	0.127	0.103	**0.159**	**0.151**	0.075	**0.147**	0.134	0.143	2.880
EF3	**0.180**	0.123	0.095	**0.165**	0.099	0.120	0.106	0.117	**0.158**	**0.169**	0.130	**0.154**	0.139	**0.151**	0.126	**0.154**	0.114	**0.162**	**0.157**	0.091	**0.157**	0.120	**0.151**	3.140
EF4	**0.174**	0.119	0.092	**0.160**	0.099	0.120	0.100	0.110	**0.153**	**0.151**	**0.165**	0.103	0.131	**0.147**	0.122	**0.150**	0.107	**0.157**	**0.152**	0.085	**0.152**	0.116	**0.147**	3.012
EF5	**0.184**	0.127	0.098	**0.167**	0.106	0.128	0.107	0.122	**0.163**	**0.156**	**0.165**	0.141	0.123	**0.149**	0.143	**0.166**	0.119	**0.174**	**0.158**	0.094	**0.158**	**0.171**	**0.164**	3.283
SCM1	**0.194**	0.131	0.103	**0.186**	0.121	**0.149**	0.112	0.135	**0.177**	**0.164**	**0.197**	**0.165**	**0.165**	0.123	**0.149**	**0.174**	0.120	**0.181**	**0.176**	0.091	**0.166**	**0.148**	0.142	3.467
SCM2	**0.227**	**0.189**	0.123	**0.225**	**0.161**	**0.176**	**0.152**	**0.167**	**0.208**	**0.204**	**0.225**	**0.193**	**0.206**	**0.206**	**0.147**	**0.207**	**0.162**	**0.194**	**0.196**	0.126	**0.207**	**0.185**	**0.199**	4.285
SCM3	**0.151**	0.120	0.093	**0.169**	0.101	**0.147**	0.132	0.142	0.134	**0.159**	**0.146**	**0.150**	**0.162**	**0.157**	**0.152**	0.111	0.093	0.140	0.119	0.071	0.136	0.123	**0.157**	3.064
ENF1	**0.165**	0.123	0.090	0.144	0.100	0.123	0.093	0.103	0.138	0.121	0.138	0.113	0.125	0.121	0.118	0.120	0.081	0.136	0.137	0.080	**0.168**	0.108	0.119	2.767
ENF2	0.144	0.121	0.087	0.138	0.096	0.108	0.093	0.102	0.132	0.118	0.131	0.111	0.119	0.115	0.113	0.117	0.111	0.100	0.131	0.080	0.131	0.107	0.115	2.619
ENF3	**0.157**	0.120	0.085	0.137	0.081	0.106	0.078	0.101	0.131	0.117	**0.144**	0.110	0.118	0.114	0.112	0.117	0.110	0.133	0.096	0.065	0.130	0.109	0.114	2.585
PF1	**0.207**	**0.157**	0.119	**0.202**	**0.153**	**0.164**	0.128	0.142	**0.207**	**0.193**	**0.211**	**0.203**	**0.193**	**0.180**	**0.183**	**0.184**	**0.149**	**0.189**	**0.184**	0.085	**0.198**	**0.153**	**0.162**	3.944
PF2	**0.213**	**0.177**	0.117	**0.204**	0.127	**0.164**	0.127	0.141	**0.192**	**0.212**	**0.217**	**0.181**	**0.182**	**0.176**	**0.175**	**0.186**	**0.148**	**0.196**	**0.183**	0.133	**0.148**	**0.166**	**0.161**	3.929
SF1	0.134	0.110	0.072	0.131	0.079	0.108	0.094	0.103	0.122	0.119	**0.146**	0.112	**0.153**	0.116	0.138	0.119	0.101	0.143	0.121	0.081	0.121	0.087	0.143	2.654
SF2	**0.147**	0.114	0.093	0.137	0.097	0.116	0.098	0.111	0.128	0.124	**0.163**	0.121	**0.155**	0.121	0.119	0.128	0.108	0.130	0.129	0.087	0.130	0.141	0.099	2.795
C_i	4.095	3.250	2.371	3.900	2.617	3.152	2.611	2.963	3.698	3.608	4.072	3.356	3.632	3.460	3.369	3.541	2.834	3.735	3.635	2.108	3.683	3.180	3.443	

- Ranking and Interpretation: Rank the factors based on their Impact values, from highest to lowest. Interpret the results to identify the most influential factors in the system. Factors with higher Impact values have a greater influence on the system. This helped to identify the most important factors that need to be considered in the development of a circular business model.

Note: In the process of conducting Grey-DEMATEL analysis, Microsoft Excel served as the primary tool for executing intricate calculations. The software's robust functionality and formulaic capabilities were instrumental in ensuring accurate and efficient computation of the various parameters involved in the analysis.

Table 20. List of adoption factors by weight of influence

Factors	R_i	C_j	$R_i + C_j$	$R_i - C_j$	**Percentage** *for* $(R_i + C_j)$	**Cumulative percentage**
Lack Business model with take-back systems (OF1)	4.162	4.095	8.258	0.067	5.410	5.410
High cost of handling, transporting, recovering process, and labor (EF1)	4.079	3.698	7.777	0.380	5.095	10.506
Lack of effective communication and coordination (SCM2)	4.285	3.369	7.653	0.916	5.014	15.520
Lack of Supportive government policies and regulations for circular economy adoption (PF2)	3.929	3.683	7.612	0.246	4.987	20.507
Lack of Industrial ecology and by-product synergy (OF4)	3.533	3.900	7.434	-0.367	4.871	25.378
Low economic value of EOL VBs (EF3)	3.140	4.072	7.212	-0.932	4.725	30.103
Uncertainty in supply (number and quality), price/value of VBs (SCM1)	3.467	3.460	6.927	0.008	4.538	34.641
Limitation on Proper status checking, diagnosing, and tracking technology (TF3)	3.957	2.963	6.919	0.994	4.533	39.175
Low Market demand and customer preferences (EF5)	3.283	3.632	6.915	-0.349	4.531	43.706
Design limitations for disassembly capability (OF2)	3.496	3.250	6.746	0.246	4.420	48.125

Factors	R_i	C_j	$R_i + C_j$	$R_i - C_j$	Percentage *for* $(R_i + C_j)$	Cumulative percentage
Unavailability of efficient technologies (TF1)	3.483	3.152	6.635	0.332	4.347	52.472
Lack of Competitiveness (SCM3)	3.064	3.541	6.605	-0.477	4.328	56.800
Lack of incentives (EF2)	2.880	3.608	6.489	-0.728	4.251	61.051
Risk on investment (EF4)	3.012	3.356	6.369	-0.344	4.173	65.224
Lack of attention for conservation and protection of natural resources (ENF2)	2.619	3.735	6.355	-1.116	4.163	69.388
Perceived quality of the recycled products (SF2)	2.795	3.443	6.238	-0.648	4.087	73.475
Difficulties in disposing the wastes from recovered batteries (ENF3)	2.585	3.635	6.220	-1.050	4.075	77.550
Political instability (PF1)	3.944	2.108	6.052	1.836	3.965	81.515
Capability of human resources (OF3)	3.492	2.371	5.863	1.121	3.842	85.357
Lack of Customer awareness (SF1)	2.654	3.180	5.834	-0.525	3.822	89.179
Poor Company culture (OF5)	3.175	2.617	5.792	0.557	3.795	92.974
Stringent (Strict) regulations (ENF1)	2.767	2.834	5.600	-0.067	3.669	96.643
Limitation on Information digitalization technology (TF2)	2.513	2.611	5.124	-0.098	3.357	100.000
Total			152.630			
Average			6.636	0.000		
Maximum			8.258	1.836		
Minimum			5.124	-1.116		
Standard-Deviation			3.134	2.952		

In accordance with the Pareto principle, which states that roughly 80% of problems are created by 20% of critical causes, the analysis of factors influencing the adoption of the lead acid battery circular business model reveals that four out of the 23 factors stand out as the most influential. These factors are identified as the primary drivers behind the challenges and opportunities in adopting the circular business model for lead acid batteries. They are as follows:

1. **Lack Business Model with Take-Back Systems (OF1):** This factor plays a pivotal role in shaping the adoption landscape for circular business models. Its influence is substantial, indicating that addressing this issue can have a profound impact on the successful adoption of circular practices.

2. **High Cost of Handling, Transporting, Recovery Processes, and Labor (EF1):** The high costs associated with these operational aspects represent a significant barrier to the circular economy adoption. Strategies that aim to mitigate these costs can lead to improved adoption rates.

3. **Lack of Effective Communication and Coordination (SCM2):** Effective communication and coordination are essential components for the smooth integration of circular business models. The influence of this factor emphasizes the critical need for enhanced collaboration and information sharing among stakeholders.

4. **Lack of Supportive Government Policies and Regulations for Circular Economy Adoption (PF2):** Government policies and regulations have a substantial impact on the adoption of circular business models. The absence of supportive policies and regulations underscores the importance of advocacy and engagement with governmental bodies to foster an enabling environment for circular practices.

These four influential factors represent the 'vital few' in the context of lead acid battery circular business model adoption. Focusing on addressing these factors will likely result in significant improvements in the overall success and sustainability of circular business practices in the industry.

4.3. Model toward improvement of the problems

In a world facing pressing environmental challenges, it has become increasingly imperative to re-envision and restructure our approach to critical issues. The management and responsible handling of end-of-life vehicle lead-acid batteries have long posed environmental concerns, from improper disposal to the depletion of valuable resources. However, within this challenge lies an extraordinary opportunity a chance to steer the narrative towards sustainable practices and resource optimization.

In efforts to address the challenges faced by the Ethiopian lead-acid battery industry, this section introduces a circular business model (CBM) specifically designed for lead-acid batteries industry developed using the 11 building blocks of the circular business model canvas framework. This framework serves as a strategic guide, facilitating the design of a business model aligned with the principles of the circular economy. Grounded in the potential circular strategies of "Repair, Repurpose, and Recycle", this model aims to enhance value creation, resource efficiency, and environmental sustainability.

Building Block	Repair	Repurpose	Recycle
Value Propositions 	• Repaired LABs with a minimum price • Cost-effective and efficient battery repair services, • Extend the life of lead acid batteries, • Save customers money	• Sustainable energy storage for off-grid systems • Cost-effective repurposed batteries as an alternative to new energy storage products. • Reliable backup power	• Recovered valuable materials (lead, plastic, sulfuric acid and hardening agent such as antimony & calcium) • Convenient and affordable way to recycle lead acid batteries • New products from recycled LABs
	• Reduced waste and environmental impact		
Customer Segments 	• Vehicle owners (Individual consumers) • Auto repair shops. • Resellers and Retailers • Businesses that use lead acid batteries, such as construction companies, Government agencies and fleet managers (operators)	• Off-Grid Power Users • Emergency Services • Education and Research activities • Telecommunications companies • Data center operators • Uninterruptible power supply (UPS) companies • Businesses or Homes that need backup power	• Battery manufacturers, and recyclers, • Companies that use recycled lead, plastic and sulfuric acid in their products • Vehicle owners • Fleet managers
Customer Relationships 	• Offer with a satisfaction guarantee • Provide educational resources to customers about lead acid battery and maintenance, • Build trust and loyalty by providing high-quality repairs and excellent customer service • Timely repair services	• Offer with a satisfaction guarantee • Provide technical support to customers on how to install and use repurposed batteries • Build trust and loyalty by providing high-quality repurposed batteries and excellent customer service	• Provide excellent customer service to build trust and loyalty. • Educate customers on the benefits of circular strategies for lead acid batteries recycling. • Compliance with recycling regulations.

<table>
<tr><th>Building Block</th><th>Repair</th><th>Repurpose</th><th>Recycle</th></tr>
<tr><td>Channels
</td><td>• Direct sales to customers,
• Partnerships with vehicle manufacturers and battery retailers
• Online market platform</td><td>• Business-to-business (B2B) partnerships with renewable energy installers
• Workshops and Events
• Online and offline retail stores,</td><td>• Battery Collection centers
• Online platforms to reach customers and promote circular strategies.
• Partnerships with battery manufacturers and distributors to collect used batteries.</td></tr>
<tr><td rowspan="2">Key Resources
</td><td colspan="3">• Retired lead-acid Batteries
• Collection & transportation networks, infrastructure and facilities
• Skilled battery repair technicians</td></tr>
<tr><td colspan="2">• Repairing tools and equipment
• Battery replacement parts & materials</td><td>• Battery recycling facilities & technology</td></tr>
<tr><td>Key Activities
</td><td>• Collect retired lead acid batteries
• Diagnose and repair lead acid batteries
• Test and certify repaired batteries
• Deliver repaired batteries to customers</td><td>• Collect retired lead acid batteries
• Diagnose and repair
• Test and certify
• Repurpose lead acid batteries
• Deliver repurposed batteries to customers</td><td>• Collect retired lead acid batteries
• Diagnose and recover valuable materials
• Quality Control (Test and certify recovered materials)
• Deliver recovered materials</td></tr>
<tr><td rowspan="3">Key Partnerships
</td><td>• Battery manufacturers
• Battery repair businesses
• Local Automotive Repair Shops</td><td>• Solar Panel Manufacturers
• Renewable Energy Installation Companies</td><td rowspan="2">• Battery manufacturers
• Battery repair businesses
• Local Automotive Repair Shops</td></tr>
<tr><td colspan="2">▪ Vehicle manufacturers,
▪ Automotive parts suppliers</td></tr>
<tr><td colspan="3">▪ Battery retailers
▪ Battery recycling companies
▪ Logistics providers
▪ Waste management companies
▪ Environmental Organizations</td></tr>
</table>

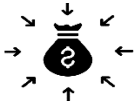
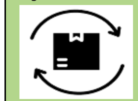
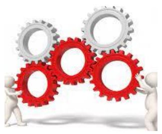
Building Block	Repair	Repurpose	Recycle
Cost Structure 	• Collection costs, and Labor costs • Operational costs (storage, transportation, marketing, and administrative activities)		
	• Cost of replacement battery parts and materials • Cost of tools and equipment		• Recycling costs
Revenue Streams 	• Repaired Battery sales • Battery repair fees, • Battery replacement fees	• Sale of repurposed batteries • Installation services • Battery maintenance and monitoring services	• Sale of recycled materials (lead, plastic, and sulfuric acid) • Sale of unretired battery parts
	• Funds from environmental organizations and agencies that support circular initiatives		
Take-back system 	• ***Develop partnership for stakeholders***: Establish partnership with automotive repair shops, battery manufacturers, battery repair businesses, and battery recycling companies to create a network of convenient collection point. • ***Offering a variety of return options***, (drop-off locations and mobile collection services) • ***Incentive Programs***: Offer customers the option to exchange their old batteries for either repaired or new ones at a discounted price		
Adoption factors 	**Organizational capabilities** ✓ Competent Human Resources with Team Motivation ✓ Robust Organizational Culture ✓ Effective Knowledge Management System ✓ Motivation and Training Initiatives	**External factors** **Technological Factors:** ✓Utilize advanced technologies and stay updated on the latest innovations. ✓Leverage digital information and data management technologies **Political Factors:** ✓Benefit from government policies and regulations that promote the circular economy. **Sociocultural Factors:** ✓Tap into the increasing consumer awareness of environmental issues and circular practices. **Economic Factors:** ✓Explore government-provided economic incentives and funding opportunities from environmental organizations and agencies supporting circular initiatives.	

Figure 6. Proposed Circular business model for vehicle LABs

The proposed circular business model (CBM) for lead-acid batteries (LABs) presents a comprehensive and innovative approach to addressing the challenges faced by the Ethiopian lead-acid battery industry. By adopting the three key strategies of Repair, Repurpose, and Recycle, the model encompasses the entire life cycle of LABs, promoting resource efficiency, environmental sustainability, and economic viability.

1. Value Propositions

The CBM offers a range of compelling value propositions for various customer segments:

- ✓ ***Vehicle Owners***: Reduced battery costs, extended battery life, and sustainable energy storage options.
- ✓ ***Businesses and Organizations***: Cost-effective repurposed batteries, reliable backup power, and improved sustainability credentials.
- ✓ ***Battery Manufacturers and Recyclers***: Access to valuable recovered materials and new revenue streams.

2. Customer Relationships

The model emphasizes building strong customer relationships through high-quality services, educational resources, and satisfaction guarantees, fostering trust and loyalty among its customer base.

3. Channels

The CBM utilizes a mix of direct sales, partnerships, and online platforms to reach its target customers, ensuring convenient access to its products and services.

4. Key Resources and Activities

The model's key resources include retired LABs, collection and transportation infrastructure, skilled technicians, repair tools and materials, and recycling facilities. Key activities involve collecting, diagnosing, repairing, testing, repurposing, and recycling LABs.

5. Key Partnerships

Strategic partnerships with battery manufacturers, repair businesses, automotive repair shops, renewable energy companies, and waste management organizations play a crucial role in implementing the CBM and creating a seamless circular economy for LABs.

6. Cost Structure and Revenue Streams

The model's cost structure includes collection, labor, operational, replacement parts, and recycling costs. Revenue streams are generated from repaired battery sales, repurposed battery sales, recycling materials sales, and service fees.

7. Take-back System

A robust take-back system is essential for the success of the CBM. The model proposes establishing partnerships with stakeholders to create a network of convenient collection points, offering diverse return options, and implementing incentive programs to encourage battery returns.

8. Adoption Factors

The successful adoption of the CBM hinges on various factors, including organizational capabilities, technological advancements, supportive government policies, consumer awareness, and robust take-back systems.

In summary, the Circular Business Model (CBM) for lead-acid batteries offers a transformative and holistic approach to the industry, paving the way for a more sustainable, resource-efficient, and economically viable future. The model, outlined within the Circular Business Model Canvas framework, addresses key adoption factors and encourages collaboration among stakeholders in the Ethiopian lead-acid battery industry. This comprehensive model encompasses eleven building blocks that intricately address every facet of the business, from value propositions and customer relationships to key resources and cost structures. By promoting a shift towards circular economy principles, the CBM not only prolongs the life of products but also introduces innovative revenue streams, aligning financial success with sustainable practices. As the industry adopts this model, supported by robust take-back systems and guided by key partnerships, it marks a crucial step towards a more eco-friendly and economically viable future. The success of this transition is contingent upon recognizing and embracing the both organizational and external adoption factors, that play pivotal roles in driving the circular business model forward.

Chapter five

5. Result and discussion

5.1. Overview of Industry Context

The secondary data analysis has revealed a concerning underutilization of both industrial capacity and end-of-life batteries within the lead-acid battery (LAB) industry in Ethiopia. Over the past five years, the average capacity utilization of the three active industries has been a mere 14.03%. Additionally, only 53.34% of the available end-of-life batteries are currently being utilized by these industries (Source: Manufacturing Technology and Engineering Industry Research and Development Center (2010-2014 E.C.), Ethiopian Customs Commission (2016-2022)).

In contrast, data from the Ministry of Transport and Logistics indicates a steadily growing demand for LABs in Ethiopia, with an annual average of 116,305 new vehicle registrations between 2010 and 2014 E.C. This suggests that the market for LABs is expanding at a rate outpacing the current capacity of the manufacturing and recycling industries.

This underutilization of industrial capacity and end-of-life batteries raises significant concerns about efficiency, resource management, and sustainability. Low-capacity utilization hinders economic growth and employment opportunities, while inefficient resource allocation lead to waste and missed opportunities. Furthermore, failing to utilize a significant portion of available end-of-life batteries raises concerns about environmental impact and the potential for increased waste. These findings underscore the need for further investigation and action to address these critical issues and promote sustainable circular practices.

5.2. Potential Circular Economy Strategies for LABs

This section presents the findings and discussion based on the thematic analysis of interview data from 20 industry experts regarding potential circular economy strategies for lead-acid batteries within the vehicle industry. The analysis identified repairing, repurposing, and recycling as the most relevant and potentially impactful circular economy strategies for vehicle lead-acid batteries. Combining these strategies maximizes their positive impact on lead-acid battery management, offering significant environmental and economic benefits. This integrated approach extends battery life, adheres to safety and regulatory standards, utilizes resources efficiently, and promotes long-term sustainability.

Repairing

Repairing lead-acid batteries emerges as a promising circular economy strategy due to its positive environmental impact and economic viability. The extension of battery life reduces the demand for new batteries, promoting resource conservation and waste reduction. Furthermore, a cost-benefit analysis underscores the financial feasibility, revealing profit margins exceeding 20%.

Repurposing

Repurposing lead-acid batteries offers an alternative use for batteries that are no longer suitable for automotive applications. This strategy extends battery life, aligns with circular economy principles, and meets the growing market demand for repurposed batteries in various applications, such as backup power systems and solar energy storage.

Recycling

Recycling lead-acid batteries is a highly promising circular strategy due to its established processes, economic feasibility, environmental benefits, and long-term sustainability. The simple composition of lead-acid batteries makes them easy to recycle, and the well-established recycling processes ensure resource recovery and waste reduction.

The proposed circular strategies move beyond simply recycling end-of-life lead-acid batteries. Instead, these strategies advocate for a combined approach that maximizes value extraction and promotes a more sustainable circular economy, as illustrated in (Figure 7).

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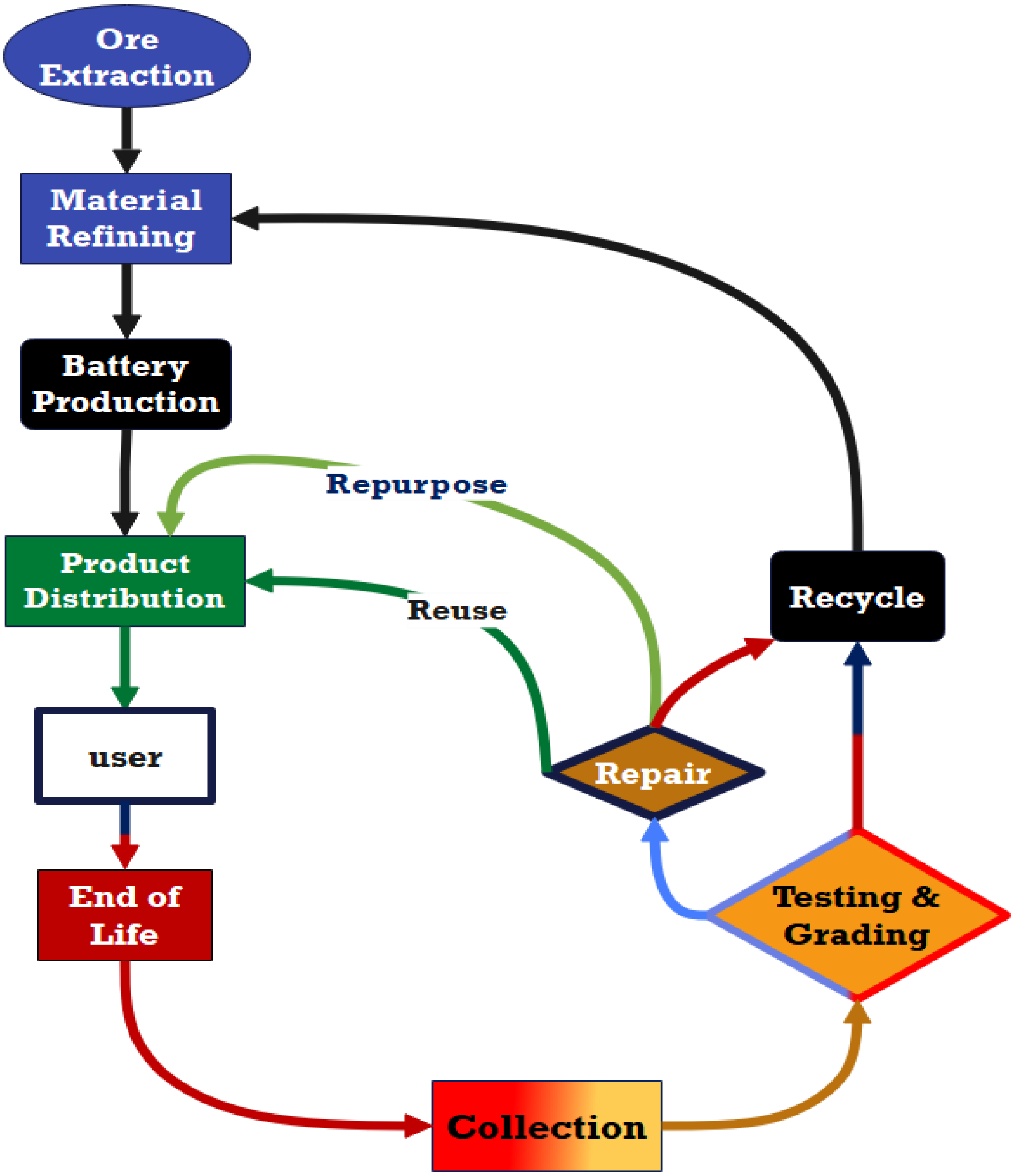

Figure 7. Circular economy illustration for lead acid battery (source author)

This multi-step approach addresses varying degrees of battery health, maximizing value extraction and promoting a sustainable circular economy. Here's how the three strategies work together:

Step-1. Sorting and Inspection: The initiation of the process involves a meticulous sorting of batteries based on type, size, and visible damage. This step is crucial for streamlined downstream processes.

Step-2. Testing and Grading: The utilization of specialized equipment for testing provides a quantitative basis for grading the batteries. This data-driven approach allows for precise categorization into B-Grade, C-Grade, or D-Grade, forming the foundation for subsequent decisions.

Step-3. Repair for Reuse: This step embraces a commitment to extending the life cycle of B-Grade batteries. By addressing their moderate issues and restoring them to near A-Grade condition, these batteries can be reborn for their original applications. This not only minimizes the need for virgin materials and reduces waste, but also extends the lifespan of existing batteries. This effectively slows the loop in the product life cycle, contributing significantly to a more sustainable approach.

Step-4. Repurposing: This step embodies the forward-thinking spirit of the circular economy by recognizing the potential utility of C-Grade batteries in less demanding applications, rather than discarding them. From providing stationary storage in off-grid systems to powering backup systems in homes and businesses, this strategic approach aligns with the principles of resource efficiency and versatility. It effectively extends the battery's lifespan beyond its original purpose, contributing significantly to waste reduction and minimizing resource extraction.

Step-5. Recycling: The final step, recycling D-Grade batteries and irreparable components from other grades ultimately reach the recycling stage. By extracting and separating lead, plastic, and acid through established processes, this step not only prevents environmental contamination but also harnesses these materials for the creation of new batteries or lead-based products. This closes the loop, ensuring that even heavily degraded batteries contribute to the circular economy.

Benefits of the Combined Approach

- ✓ *Reduced reliance on virgin resources*: Repairing and repurposing decrease the need for mining and refining.
- ✓ *Extended battery life:* Addressing degradation and finding new uses maximizes value and slowing the loop.

- ✓ *Less waste generation*: Avoiding direct recycling of all batteries minimizes waste and closing the loop promotes resource recovery.
- ✓ *Economic opportunities:* Repair, repurposing, and specialized recycling create new jobs and revenue stream

Therefore, the proposed circular strategies are not just alternatives to recycling, but rather a complementary and comprehensive approach to managing end-of-life lead-acid batteries. They offer environmental, economic, and resource-efficiency benefits, paving the way for a more sustainable and responsible future for this vital technology. To drive the adoption of these circular strategies, it is crucial to raise awareness of their benefits, establish supportive policies and regulations, and invest in research and development efforts.

5.3. Most Influential Factors affecting the Adoption of CBM

The GREY-DEMATEL and PARETO analysis of expert opinions from 20 industry experts regarding the most influential factors affecting circular business models for lead-acid batteries (LABs) identified four critical factors that play a pivotal role in shaping the adoption landscape:

1. *Lack of Business Model with Take-Back Systems (OF1)*: The absence of well-defined business models that incorporate take-back systems poses a significant barrier to circularity.
2. *High Cost of Handling, Transporting, Recovery Processes, and Labor (EF1):* The high costs associated with handling, transporting, recovering, and processing LABs represent a major hurdle to circularity.
3. *Lack of Effective Communication and Coordination (SCM2):* Effective communication and coordination among stakeholders, including manufacturers, recyclers, and consumers, are essential for the successful implementation of circular business models.
4. *Lack of Supportive Government Policies and Regulations for Circular Economy Adoption (PF2):* Supportive government policies and regulations can play a crucial role in incentivizing and enabling the adoption of circular business models for LABs.

Prioritizing these four critical factors holds strategic importance in the industry's quest to enhance sustainability and address approximately 80% of the challenges and opportunities associated with circular business practices. By focusing on these factors, stakeholders can effectively address the challenges and capitalize on the opportunities presented by circularity. This includes:

1. *Developing Robust Take-Back Systems*: Implementing robust take-back systems that efficiently collect and return end-of-life LABs for repair, repurposing, and recycling is essential for closing the loop and minimizing waste. Businesses can collaborate with recyclers to establish effective take-back mechanisms, incentivizing consumers to return their used batteries.
2. *Optimizing Logistics and Recovery Processes*: Streamlining logistics and adopting innovative recovery technologies can significantly reduce the costs associated with handling, transporting, and processing LABs. This can be achieved through route optimization, consolidation of collection points, and investment in advanced recycling technologies.
3. *Enhancing Communication and Collaboration*: Fostering effective communication and collaboration among stakeholders is crucial for the smooth integration of circular business models. This involves establishing clear communication channels, sharing information openly, and aligning incentives across the supply chain.
4. *Advocating for Supportive Policies*: Engaging with government bodies to advocate for supportive policies and regulations is essential to create an enabling environment for circular economy adoption. This includes promoting tax incentives for circular practices, funding research and development, and establishing clear guidelines for circular business models.

By addressing these critical factors and implementing effective strategies, stakeholders can drive the widespread adoption of circular business models for LABs, promoting resource efficiency, environmental sustainability, and economic growth.

5.4. Proposed Circular Business Model for Lead-Acid Batteries

The proposed Circular Business Model (CBM) for lead-acid batteries (Figure *6*), designed using the 11 building blocks of the Circular Business Model Canvas framework, offers a comprehensive and innovative approach to addressing the challenges faced by the Ethiopian lead-acid battery industry. By adopting the three key strategies of Repair, Repurpose, and Recycle, the model encompasses the entire life cycle of LABs, promoting resource efficiency, environmental sustainability, and economic viability.

Value propositions: The CBM offers a range of compelling value propositions for various customer segments:

- *Vehicle Owners*: Reduced battery costs, extended battery life, and sustainable energy storage options.
- *Businesses and Organizations*: Cost-effective repurposed batteries, reliable backup power, and improved sustainability credentials.
- *Battery Manufacturers and Recyclers*: Access to valuable recovered materials and new revenue streams.

Customer Relationships: The model emphasizes building strong customer relationships through high-quality services, educational resources, and satisfaction guarantees, fostering trust and loyalty among its customer base.

Channels: It utilizes a mix of direct sales, partnerships, and online platforms to reach its target customers, ensuring convenient access to its products and services.

Key Partnerships: Strategic partnerships with battery manufacturers, repair businesses, automotive repair shops, renewable energy companies, and waste management organizations play a crucial role in implementing the CBM and creating a seamless circular economy for LABs.

Cost Structure and Revenue Streams: The model's cost structure includes collection, labor, operational, replacement parts, and recycling costs. Revenue streams are generated from repaired battery sales, repurposed battery sales, recycling materials sales, and service fees.

Take-back System: A robust take-back system is essential for the success of the CBM. The model proposes establishing partnerships with stakeholders to create a network of convenient collection points, offering diverse return options, and implementing incentive programs to encourage battery returns.

Adoption Factors: The successful adoption of the CBM relies on organizational capabilities, technological advancements, supportive government policies, consumer awareness, and the establishment of robust take-back systems.

5.4.1. Advantages over traditional linear business models

The CBM offers several compelling advantages over traditional linear business models:

- *Resource Efficiency*: The model promotes resource efficiency by extending the life of LABs through repair and repurposing, reducing the demand for new batteries and minimizing the environmental impact associated with battery production.
- *Environmental Sustainability*: By recycling LABs, the model recovers valuable materials such as lead, plastic, and sulfuric acid, reducing the need for raw material extraction and minimizing waste generation.
- *Economic Viability*: The model creates new revenue streams through the sale of repaired, repurposed, and recycled batteries, offering financial incentives for businesses to adopt circular practices.
- *Consumer Benefits*: Consumers benefit from lower battery costs, access to sustainable energy storage solutions, and a reduced environmental footprint associated with battery disposal.

5.4.2. Key Factors for Successful Adoption

The successful adoption of the CBM for LABs hinges on several critical factors:

- Organizational Capabilities: Businesses need to develop the necessary competencies, including skilled human resources, robust organizational culture, effective knowledge management, and a commitment to training and motivation.

- Technological Advancements: Embracing technological advancements in battery repair, repurposing, and recycling is crucial for enhancing efficiency, reducing costs, and improving product quality.
- Supportive Policies: Favorable government policies and regulations that incentivize circular practices, such as tax breaks and subsidies, can significantly promote CBM adoption.
- Consumer Awareness: Raising consumer awareness about the environmental and economic benefits of circular practices can drive demand for sustainable battery solutions.
- Robust Take-back Systems: Implementing efficient and accessible take-back systems is essential for collecting end-of-life batteries for repair, repurposing, and recycling.
- Strategic Partnerships: Collaborations among stakeholders, including battery manufacturers, repair businesses, recyclers, and automotive repair shops, can facilitate the implementation of the CBM and create a seamless circular economy for LABs.

In conclusion the CBM for LABs presents a transformative approach to the industry, offering a path towards a more sustainable, resource-efficient, and economically viable future.

Chapter Six

6. Conclusion and Recommendation

6.1. Conclusion:

The Ethiopian lead-acid battery industry faces significant challenges in terms of resource utilization, waste management, and sustainability. Despite a growing demand for LABs in the market, the secondary data analysis revealed concerning underutilization of industrial capacity and inefficient management of end-of-life batteries. This inefficiency necessitates a shift towards circular economy practices to address environmental concerns, promote economic growth, and ensure efficient resource management.

Through thematic and cost-benefit analyses of data derived from expert interviews, this research identified and propose three promising circular economy strategies: repair for reuse, repurposing, and recycling. These strategies collectively address the unique challenges and opportunities associated with LABs and offer substantial environmental and economic benefits, including extended battery life, reduced resource consumption, and new revenue streams.

Furthermore, the study employed the Grey DEMATEL analysis to identify the most influential factors affecting the adoption of Circular Business Models (CBM) for Lead-Acid Batteries (LABs). The research analyzed the dynamic interplay of 23 factors across seven key dimensions: organizational, technological, economic, supply chain, environmental, political, and sociocultural, drawing insights from expert opinions. Applying the Pareto principle to the outcomes of the Grey DEMATEL analysis, four critical factors were identified: Lack of Business Model with Take-Back Systems, high cost of handling and processing, Lack of Effective Communication and Coordination, and Lack of Supportive Government Policies and Regulations. Addressing these vital few factors holds strategic importance for the industry's transition towards a circular economy and can contribute to tackling approximately 80% of the associated challenges and opportunities.

To facilitate the implementation of circular practices, the study concludes by offering a practical roadmap for implementing circular practices, integrating identified strategies within the Circular Business Model Canvas framework. The proposed model presents compelling value propositions for various customer segments, including vehicle owners, businesses, and battery manufacturers. The model:

- Emphasizes strong customer relationships through high-quality services, educational resources, and satisfaction guarantees,
- Utilizes diverse sales channels to reach its target customers, ensuring convenient access to its products and services, and
- Fosters strategic partnerships with stakeholders to ensure the creation of a seamless circular economy for LABs.
- Generate revenue streams from repaired battery sales, repurposed battery sales, recycling materials sales, and service fees sustain the CBM.

This research throws open the doors of opportunity for all invested in the future of LABs. By discovering innovative circular strategies and revealing their profound impact on the automotive landscape, this work sets the stage for a more sustainable future. Industry stakeholders, policymakers, and researchers alike can leverage these actionable insights to revolutionize LAB management, prioritizing environmental responsibility, resource efficiency, and economic viability. It's more than just research; it's a call to action for a greener future.

6.2. Recommendations

Collaborative Stakeholder Engagement: Foster collaboration and communication among key stakeholders in the LAB industry, including manufacturers, recyclers, policymakers, and researchers. Enhancing coordination can expedite the adoption of circular business models.

Advocacy for Regulatory Support: Work with governmental bodies to advocate for supportive policies and regulations that encourage circular economy practices. Regulatory backing can significantly influence the success of circular business models for LABs.

Investment in Advanced Technologies: Invest in research and development of advanced technologies for the repair, repurposing, and recycling of LABs. Technological innovations can improve the feasibility and efficiency of circular strategies.

Promote Consumer Awareness: Launch awareness campaigns to educate consumers about the benefits of repurposing LABs. Increased demand for repurposed LABs can stimulate the growth of this circular strategy.

Economic Viability Analysis: Conduct detailed economic viability assessments to identify the most cost-effective and financially sound circular strategy for LAB management in specific contexts.

Resource Efficiency Initiatives: Implement resource-efficient practices that focus on reusing and recycling materials, reducing waste, and conserving resources within the LAB industry.

Safety and Compliance Training: Provide specialized training to LAB industry workers to ensure the safe handling and processing of LABs while adhering to regulatory compliance.

Long-term Sustainability Planning: Develop long-term sustainability plans that consider market dynamics and economic feasibility for each circular strategy. A focus on sustainability will ensure continued benefits for the industry and the environment.

By implementing these recommendations, the LAB industry can transition towards circular business models that are not only environmentally responsible but also economically viable and sustainable. These efforts will contribute to a greener and more efficient automotive battery sector while aligning with the principles of the circular economy.

6.3. Future Research areas

1. Digital Technologies for Circular LAB Business Models:

    - Investigate the role of blockchain technology in facilitating secure and transparent tracking and tracing of LABs throughout their life cycle. This research could explore the implementation of blockchain platforms for recording ownership transfers, ensuring data integrity, and optimizing reverse logistics for LABs.

    - Analyze the potential of data analytics in optimizing resource utilization and predicting end-of-life for LABs. This research could investigate the development of predictive models based on historical data and sensor readings to optimize repair schedules, repurposing opportunities, and recycling processes for LABs.

2. Life Cycle Assessment (LCA) of Repurposed LABs:

- Conduct comprehensive LCAs of repurposed LABs under various application scenarios. This research could compare the environmental impact of repurposed LABs with virgin LABs and analyze the impact of different reuse scenarios (e.g., stationary energy storage, backup power, etc.).
- Analyze the trade-offs between environmental benefits and potential environmental risks associated with circular LAB practices. This research could identify potential hotspots for environmental impact and develop strategies to mitigate them.

3. Policy and Regulatory Frameworks for Circular LAB Economy:

Investigate and propose effective policy and regulatory frameworks for the circular economy of LABs. Examine how regulations can be tailored to incentivize sustainable practices, responsible recycling, and the adoption of circular business models in the LAB industry. Assess the impact of policy interventions on enhancing circularity and reducing environmental impact.

Appendix

Appendix A. Experts evaluated data for relevancy of adoption factors:

Category	Adoption factors	Average evaluation from experts
Organizational	Lack Business model with take-back systems (OF1)	3.83
	Perceived financial benefits (OF2)	0.94
	Design limitation for disassembly capability (OF3)	3.01
	Capability of human resources (OF4)	2.04
	Lack Industrial ecology and by-product synergy (OF5)	3.50
	Lack Top management support (OF6)	0.50
	Poor Company culture (OF7)	3.20
Technological	Battery modularization (TF1)	0.87
	Unavailability of efficient technologies (TF2)	3.60
	Limitation on Information digitalization (TF3)	3.10
	Proper status checking, diagnosing, and tracking technology (TF4)	2.20
Economical	High cost of handling, transporting, recovering process, and labor (EF1)	3.80
	Lack of incentives (EF2)	1.60
	Low economic value of EOL VBs (EF3)	3.02
	Risk on investment (EF4)	0.70
	Low Market demand and customer preferences (EF5)	3.90
Supply-chain management	Low rate of returned batteries (SCM1)	0.65
	Lack of information sharing of End-of-life process (SCM2)	0.56
	Uncertainty in supply (number and quality), price/value of VBs (SCM3)	2.85
	Lack of effective communication and coordination (SCM4)	2.02
	Lack of Competitiveness (SCM5)	3.66
Environmental	Stringent (Strict) regulations (ENF1)	3.88
	Lack of attention for Conservation and protection of natural resources (ENF2)	3.98
	Difficulties in disposing the wastes from recovered batteries (ENF3)	3.03
	Inadequate infrastructure (ENF4)	0.92
Political	Political instability (P1)	2.93
	Lack of Supportive government policies and regulations for circular economy adoption (P2)	3.68
	Lack of Collaboration between public and private sectors to promote circularity (P3)	3.05
	Absence of International agreements and commitments on sustainability and circularity (P4)	0.88
Socio-cultural	Lack of Customer awareness (SF1)	3.78
	Perceived quality of the recycled products (SF2)	3.14

Appendix B. Average grey relation matrix

i j	OF1	OF2	OF3	OF4	OF5	TF1	TF2	TF3	EF1	EF2	EF3	EF4	EF5	SCM1	SCM2	SCM3	ENF1	ENF2	EN3	PF1	PF2	SF1	SF2
OF1	0.000	0.625	0.208	0.583	0.333	0.375	0.417	0.292	0.542	0.417	0.583	0.500	0.500	0.500	0.583	0.500	0.250	0.500	0.500	0.250	0.417	0.500	0.250
	0.000	0.875	0.458	0.833	0.583	0.625	0.667	0.542	0.792	0.667	0.833	0.750	0.750	0.750	0.833	0.750	0.500	0.750	0.750	0.417	0.667	0.750	0.500
OF2	0.292	0.000	0.250	0.500	0.208	0.333	0.167	0.375	0.500	0.417	0.625	0.417	0.333	0.292	0.292	0.375	0.292	0.500	0.583	0.083	0.500	0.250	0.333
	0.542	0.000	0.500	0.750	0.458	0.583	0.417	0.625	0.750	0.667	0.875	0.667	0.583	0.542	0.542	0.625	0.542	0.750	0.833	0.333	0.750	0.417	0.500
OF3	0.500	0.250	0.000	0.417	0.542	0.250	0.292	0.292	0.500	0.250	0.542	0.250	0.417	0.292	0.500	0.417	0.208	0.292	0.375	0.000	0.375	0.417	0.417
	0.750	0.500	0.000	0.667	0.792	0.500	0.542	0.542	0.750	0.417	0.792	0.500	0.667	0.542	0.750	0.667	0.458	0.542	0.625	0.250	0.625	0.667	0.667
OF4	0.375	0.500	0.292	0.000	0.208	0.292	0.208	0.292	0.417	0.500	0.500	0.208	0.292	0.417	0.500	0.417	0.417	0.417	0.500	0.125	0.500	0.208	0.292
	0.625	0.750	0.542	0.000	0.458	0.542	0.458	0.542	0.667	0.750	0.750	0.458	0.542	0.667	0.750	0.667	0.667	0.667	0.750	0.375	0.750	0.458	0.542
OF5	0.500	0.500	0.542	0.500	0.000	0.292	0.208	0.292	0.292	0.292	0.333	0.250	0.292	0.292	0.333	0.333	0.208	0.250	0.292	0.083	0.292	0.208	0.292
	0.750	0.750	0.792	0.750	0.000	0.542	0.458	0.542	0.542	0.542	0.583	0.500	0.542	0.542	0.583	0.583	0.458	0.500	0.542	0.333	0.542	0.458	0.542
TF1	0.417	0.500	0.250	0.417	0.208	0.000	0.500	0.500	0.417	0.417	0.417	0.208	0.417	0.417	0.417	0.208	0.208	0.208	0.417	0.125	0.417	0.208	0.417
	0.667	0.750	0.500	0.667	0.458	0.000	0.750	0.750	0.667	0.667	0.667	0.458	0.667	0.667	0.667	0.458	0.458	0.458	0.667	0.375	0.667	0.458	0.667
TF2	0.208	0.208	0.208	0.208	0.208	0.417	0.000	0.500	0.208	0.208	0.208	0.208	0.208	0.417	0.208	0.208	0.208	0.208	0.208	0.125	0.208	0.208	0.208
	0.458	0.458	0.458	0.458	0.458	0.667	0.000	0.750	0.458	0.458	0.458	0.458	0.458	0.667	0.458	0.458	0.458	0.458	0.458	0.375	0.458	0.458	0.458
TF3	0.417	0.417	0.208	0.417	0.417	0.417	0.417	0.000	0.500	0.417	0.500	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.333	0.417	0.417	0.417
	0.667	0.667	0.458	0.667	0.667	0.667	0.667	0.000	0.750	0.667	0.750	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.583	0.667	0.667	0.667
EF1	0.500	0.417	0.417	0.417	0.417	0.417	0.208	0.417	0.000	0.458	0.500	0.458	0.500	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417
	0.750	0.667	0.667	0.667	0.667	0.667	0.458	0.667	0.000	0.708	0.750	0.708	0.750	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.667
EF2	0.500	0.375	0.167	0.167	0.125	0.208	0.125	0.125	0.208	0.000	0.500	0.292	0.458	0.167	0.208	0.208	0.167	0.500	0.458	0.083	0.417	0.417	0.417
	0.750	0.625	0.417	0.417	0.375	0.458	0.375	0.375	0.458	0.000	0.750	0.542	0.708	0.417	0.458	0.458	0.417	0.750	0.708	0.333	0.667	0.667	0.667
EF3	0.500	0.167	0.167	0.417	0.125	0.167	0.208	0.208	0.417	0.583	0.000	0.500	0.208	0.417	0.167	0.417	0.208	0.417	0.417	0.208	0.417	0.167	0.417
	0.750	0.417	0.417	0.667	0.375	0.417	0.458	0.458	0.667	0.833	0.000	0.750	0.458	0.667	0.417	0.667	0.458	0.667	0.667	0.458	0.667	0.417	0.667
EF4	0.500	0.167	0.167	0.417	0.167	0.208	0.167	0.167	0.417	0.417	0.417	0.000	0.167	0.417	0.167	0.417	0.167	0.417	0.417	0.167	0.417	0.167	0.417
	0.750	0.417	0.417	0.667	0.417	0.458	0.417	0.417	0.667	0.667	0.667	0.000	0.417	0.667	0.417	0.667	0.417	0.667	0.667	0.417	0.667	0.417	0.667
EF5	0.500	0.167	0.167	0.375	0.167	0.208	0.167	0.208	0.417	0.375	0.292	0.292	0.000	0.333	0.292	0.500	0.208	0.500	0.375	0.208	0.375	0.708	0.500
	0.750	0.417	0.417	0.625	0.417	0.458	0.417	0.458	0.667	0.625	0.542	0.542	0.000	0.583	0.542	0.750	0.458	0.750	0.625	0.458	0.625	0.958	0.750

i j	OF1	OF2	OF3	OF4	OF5	TF1	TF2	TF3	EF1	EF2	EF3	EF4	EF5	SCM1	SCM2	SCM3	ENF1	ENF2	EN3	PF1	PF2	SF1	SF2
SCM1	0.500	0.125	0.167	0.500	0.292	0.375	0.167	0.292	0.500	0.375	0.583	0.500	0.375	0.000	0.292	0.500	0.167	0.500	0.500	0.125	0.375	0.375	0.167
	0.750	0.375	0.417	0.750	0.542	0.625	0.417	0.542	0.750	0.625	0.833	0.750	0.625	0.000	0.542	0.750	0.417	0.750	0.750	0.375	0.625	0.625	0.417
SCM2	0.500	0.500	0.167	0.583	0.500	0.375	0.375	0.375	0.500	0.500	0.500	0.500	0.500	0.583	0.000	0.542	0.375	0.292	0.375	0.333	0.500	0.500	0.500
	0.750	0.750	0.417	0.833	0.750	0.625	0.625	0.625	0.750	0.750	0.750	0.750	0.750	0.833	0.000	0.792	0.625	0.542	0.625	0.583	0.750	0.750	0.750
SCM3	0.208	0.167	0.167	0.500	0.167	0.500	0.500	0.500	0.167	0.500	0.167	0.500	0.500	0.500	0.500	0.000	0.000	0.208	0.000	0.000	0.208	0.208	0.500
	0.458	0.417	0.417	0.750	0.417	0.750	0.750	0.750	0.417	0.750	0.417	0.750	0.750	0.750	0.750	0.000	0.250	0.458	0.250	0.250	0.458	0.458	0.750
ENF1	0.500	0.292	0.208	0.333	0.250	0.333	0.167	0.167	0.333	0.167	0.208	0.167	0.208	0.208	0.208	0.167	0.000	0.292	0.333	0.167	0.708	0.167	0.208
	0.750	0.542	0.458	0.583	0.500	0.583	0.417	0.417	0.583	0.417	0.458	0.417	0.458	0.458	0.458	0.417	0.000	0.542	0.583	0.417	0.958	0.417	0.458
ENF2	0.333	0.333	0.208	0.333	0.250	0.208	0.208	0.208	0.333	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.333	0.000	0.333	0.208	0.333	0.208	0.208
	0.583	0.583	0.458	0.583	0.500	0.458	0.458	0.458	0.583	0.458	0.458	0.458	0.458	0.458	0.458	0.458	0.583	0.000	0.583	0.458	0.583	0.458	0.458
ENF3	0.500	0.333	0.208	0.333	0.083	0.208	0.042	0.208	0.333	0.208	0.375	0.208	0.208	0.208	0.208	0.208	0.333	0.333	0.000	0.042	0.333	0.250	0.208
	0.750	0.583	0.458	0.583	0.333	0.458	0.292	0.458	0.583	0.458	0.625	0.458	0.458	0.458	0.458	0.458	0.583	0.583	0.000	0.292	0.583	0.500	0.458
PF1	0.417	0.250	0.208	0.458	0.500	0.375	0.208	0.208	0.625	0.500	0.500	0.750	0.500	0.417	0.500	0.417	0.333	0.375	0.375	0.000	0.542	0.250	0.208
	0.667	0.500	0.458	0.708	0.750	0.625	0.458	0.458	0.875	0.750	0.750	1.000	0.750	0.667	0.750	0.667	0.583	0.625	0.625	0.000	0.792	0.500	0.458
PF2	0.500	0.500	0.208	0.500	0.208	0.375	0.208	0.208	0.458	0.750	0.583	0.500	0.375	0.375	0.417	0.458	0.333	0.458	0.375	0.500	0.000	0.417	0.208
	0.750	0.750	0.458	0.750	0.458	0.625	0.458	0.458	0.708	1.000	0.833	0.750	0.625	0.625	0.667	0.708	0.583	0.708	0.625	0.750	0.000	0.667	0.458
SF1	0.208	0.208	0.042	0.250	0.042	0.208	0.208	0.208	0.208	0.208	0.375	0.208	0.583	0.208	0.500	0.208	0.208	0.417	0.208	0.208	0.208	0.000	0.500
	0.458	0.458	0.292	0.500	0.292	0.458	0.458	0.458	0.458	0.458	0.625	0.458	0.833	0.458	0.750	0.458	0.458	0.667	0.458	0.458	0.458	0.000	0.750
SF2	0.292	0.208	0.250	0.250	0.208	0.250	0.208	0.250	0.208	0.208	0.500	0.250	0.542	0.208	0.208	0.250	0.250	0.208	0.250	0.250	0.250	0.542	0.000
	0.542	0.458	0.500	0.500	0.458	0.500	0.458	0.500	0.458	0.458	0.750	0.500	0.792	0.458	0.458	0.500	0.500	0.458	0.500	0.500	0.500	0.792	0.000

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