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Electric vehicles lithium-ion batteries reverse logistics implementation barriers analysis: A TISM-MICMAC approach

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A R T I C L E I N F O

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A B S T R A C T

End of life (EoL) management of the electric vehicles lithium-ion batteries (EVs-LIBs) has become a vital part of circular economy practices, especially in the European Union (EU). Consequently, manufacturers must develop EoL management of EVs-LIBs through reverse logistics (RLs) activities, which are bounded with many implementation barriers. Although several studies have been accomplished for RLs barrier analysis in various industries, less attention has been devoted to identifying and systematically analysing barriers of EVs-LIBs RLs. The purpose of this study is to identify a comprehensive list of the main barriers to the successful implementation of EVs-LIBs RLs practices. Based on the inputs from European industrial experts, an integrated approach of Total Interpretive Structural Modelling (TISM) and Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) was applied to develop a hierarchical model based on the defined barrier categories. Finally, the most dominant barrier categories to the successful implementation of RLs activities for EVs-LIBs were prioritised to provide insights to industrial decision-makers and policymakers. Data were gathered using a questionnaire survey, which was distributed to various experts in EVs-LIBs manufacturing/recycling and EVs manufacturing companies. The findings revealed that 'market and social', and 'policy and regulations' categories are the two most influencing barriers to the implementation of EVs-LIBs RLs. This study lays the foundation for future research on the RLs activities for EVs-LIBs in a time that EU regulations on the circular economy are mandating all auto manufacturing companies to deal with their EoL wastes.

1. Introduction

The development of electric vehicles (EVs) has been accelerated given the growing concerns regarding climate change and the energy crisis (Alfaro-Algaba and Ramirez, 2020; Hua et al., 2020; Zeng et al., 2020). As the production cost of EVs is reducing, and their performance is improving, governments will seek to introduce regulations, tax incentives, and infrastructure support to augment their usage. For example, Norway's target is that by 2025 all their cars will be either electric or plug-in hybrid; Netherlands, Germany, France and Great Britain are looking to ban all gasoline vehicles by 2040 (Crabtree, 2019a; International Energy Agency, 2019). While Europe and the United States, each have just over 20% of the global EV stock, China has reached almost 50%. China's aggressive EV target was reflected since 2018 when 1.1 million units were sold in their country (Steer, 2018). One of the main factors that can affect the uptake of EVs is the battery technology, which represents its main downside compared to gasoline vehicles in terms of the purchase price, range, time to charge, durability, and safety (Andwari et al., 2017; Crabtree, 2019a; Rallo et al., 2020). These challenges are further exacerbated by the rapidly growing fleet of EVs worldwide and the need for managing lithium-ion batteries (LIBs) in the coming decades. It has been projected that by 2030, the sales for EVs will grow to over 11 million, as well as the demand for stationary electric storage facilities and consumer electronics (Pillot, 2019). This causes the use of LIBs to grow rapidly mainly for manufacturing the EVs (Gaines, 2019).

An important aspect to consider is the manufacturing process of EVs-LIBs and the raw materials required to sustain this level of demand. Given the scarcity and limited amount of raw materials, firms are promoting EVs-LIBs RLs activities which reduce the environmental impact and provide an important input source for the manufacturing process of EV-LIBs (Song and Chu, 2019). Meshram et al., (2014) highlighted that for the production of one tonne of lithium, it is necessary to mine two hundred and fifty tonnes of spodumene ore or seven hundred and fifty

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tonnes of mineral-rich brine. Moreover, the environmental impact of processing such large amounts of raw materials must be considered, as well as the waste which results from it. There are only a few countries in the world that have access to raw materials and minerals such as cobalt and lithium for manufacturing EVs-LIBs. Harper (2019) argued that EVs will become an important secondary resource for these critical materials. Although OEMs, such as BMW and Renault have developed EVs, the European manufacturers of EVs are highly dependent on their Asian counterparts for the supplies of components and manufacturing materials such as nickel, cobalt, lithium, etc. Asian manufacturers produce over 90% of the batteries worldwide, half of which are from China. European manufacturers dependency is not just related to the manufacture of batteries, but also throughout the value network in terms of extraction and processing of raw materials required for recycling. Therefore, European companies must enhance their manufacturing processes, invest in recycling infrastructure, and increase their LIBs supply chain resilience (Danino-Perraud, 2020).

In response to the abovementioned inequities and challenges associated with the EVs-LIBs supply chain, European Commission (EC) has recently established the European Battery Alliance (EBA). EVs-LIBs EoL management can have significant economic advantages resulting in reusing the mineral resources such as nickel and cobalt, which are not accessible in the EU lands (Harper et al., 2019). Hence, EoL management of the EVs-LIBs has become a vital part of circular economy activities, especially in the EU. Consequently, manufacturers must develop EoL management of EVs-LIBs through RLs activities such as collection, sorting, recycling, and remanufacturing processes (Ziemann et al., 2018). The used EVs-LIBs can be collected from consumers, then pushed into the recycling or remanufacturing processes through a reverse distribution chain (Song and Chu, 2019). Implementing these RLs activities will reduce the environmental burden by managing EoL product flows (Bouzon et al., 2018). However, managing EVs-LIBs EoL through RLs activities has many barriers and obstacles that need to be analysed and addressed. Previous studies have extensively researched the technical and development aspects (Alfaro-Algaba and Ramirez, 2020; Beaudet et al., 2020; Harper et al., 2019; Wu et al., 2020; Ziemann et al., 2018, 2018) of LIB design and production. However, defining and analysing the barriers to the successful implementation of RLs for EVs-LIBs has not been addressed yet. As shown in Table 1, during the past decade, researchers have strived to find and analyse RLs and closed-loop supply chain implementation barriers. These studies are categorised in Table 1 according to the involved industries, the considered methodology, and studied country.

Analysing the literature, it can be highlighted that there is a scarcity of studies related to the analysis of the EVs-LIBs RLs implementation barriers with a European context. Furthermore, based on the information provided in Table 1 related to RLs/CLSC barrier analysis, it can be perceived that there is a lack of studies in the literature that applied TISM-MICMAC in this context. This study aims to narrow this gap by identifying and analysing barriers to EVs-LIBs RLs implementation in the EU. The main contributions of the paper are twofold: firstly, it identifies and defines a comprehensive list of EVs-LIBs RLs implementation barriers; and secondly, it analyses the interrelations among the EVs-LIBs RLs barriers and constructs a hierarchy model of the barriers to provide recommendations for industrial practitioners and policymakers.

Initially, a set of barriers was extracted after performing a comprehensive literature review. After that, a Delphi analysis was performed to find the most relevant barriers for EVs-LIBs RLs implementation based on experts' opinion. Then, eight barrier categories were analysed using an integrated approach of TISM and MICMAC to find the causal relations and their interpretations given by experts for detailed systematic analysis. TISM-MICMAC analysis was performed based on the gathered inputs using a questionnaire-based survey. The main purpose of this paper is to identify the most influential and dominant barriers to the successful implementation of RLs for EVs-LIBs. Practical recommendations are provided to industrial decision-makers to make the adoption of RLs practices for EVs-LIBs easier while considering the most dominants barriers.

The rest of the paper is structured as follows. A literature review in the field of the current study is provided in Section 2. The proposed methodological approach of the study is provided in Section 3 followed by results and discussion in Section 4. Finally, the conclusions part is presented in Section 5.

Table 1
Recent publications related to barrier analysis for RLs/Closed-Loop Supply Chain (CLSC) implementation

Reference	Industry/ Product	Method	Country/ region
Abdulrahman et al. (2014)	Manufacturing	Descriptive statistics and Factor Analysis	China
Bouzon et al. (2015)	Manufacturing	ISM	Brazil
Chileshe et al. (2015)	Construction	Correlation analysis	Australia
Rameezdeen et al. (2016)	Construction	Descriptive statistics	Australia
Bouzon et al. (2016)	Electronic	Fuzzy Delphi- AHP	Brazil
Prakash and Barua (2016)	Electronic	FAHP	India
Prakash and Barua (2017)	Electronic	FAHP-IRP	India
Sirisawat and Kiatcharoenpol (2018)	Electronic	FAHP-TOPSIS	Thailand
Ali et al. (2018)	Computer	ISM	Bangladesh
Gardas et al. (2018)	Engine-Oil	ISM	India
Waqas et al. (2018)	Manufacturing	SEM	Pakistan
Abbas (2018)	Pharmaceutical	ISM	India
Bouzon et al. (2018)	Manufacturing	Grey-DEMATEL	Brazil
Chakraborty et al. (2019)	Automotive	Fuzzy ISM	India
Moktadir et al. (2019)	Leather	FAHP	Bangladesh
Bhatia et al. (2020)	Automotive	AHP-DEMATEL	India
Kaviani et al. (2020)	Automotive	Best-worst method	Iran
Kazancoglu et al. (2020)	Textile	Focus group and descriptive analysis	Turkey
Vieira et al. (2020)	E-waste	MCDA	Brazil
Phochanikorn et al. (2020)	Palm Oil	Fuzzy ANP and VIKOR	Thailand
Dutta et al. (2021)	Manufacturing	Grey-DEMATEL-Fuzzy Integral	India
Van Keulen and Kirchherr (2021)	Coffee industry	Business model experimentation	Netherlands
Urbinati et al. (2021)	Automotive	Correlation analysis	Italy
Current study	**EV-LIBs**	**TISM-MICMAC**	**Europe**

2. Literature foundation

2.1. Reverse logistics

With growing concern and recognition around the world for the environment, our natural resources, and climate change, RLs is considered to be the link in reducing waste and resource depletion through the implementation of a closed-loop supply chain and achieving a circular economy (Zarbakhshnia et al., 2020a). The concept of RLs was first introduced in the 1990s in the manufacturing and logistics industry by Rogers and Tibben-Lembke (1999), who defined RL as "*the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing or creating value for proper disposal*". Developing reverse logistics and supply chain systems has an important role in closing the supply chain loop and implementing circular economy principles but there remain many issues. Within this context, Turki et al. (2018) categorised such issues into four main aspects that deal with design (Tighazoui et al., 2019), planning (Pushpamali et al., 2021), management (Zarbakhshnia et al., 2020b), and carbon emission related constraints (Turki et al., 2020) of remanufacturing systems and returned products. Many researchers endeavoured to translate such issues into RLs implementation barriers for various industry sectors and products (see Table 1). However, such studies are still scarce for the EV batteries (EVBs) RLs implementation.

With the increased focus on climate change around the world, the quantity of produced EoL EVs-LIBs waste has prompted a significant amount of attention from policymakers to make changes. RLs for EVs-LIBs significantly reduces the quantity of such waste produced, thereby reducing the demand and requirement for environmentally unfriendly landfills. Care for the environment is a significant driver for the adaptation of RLs and great concern for the EU as the European Green Deal and potential legally binding European climate law will have requirements for the efficient use of resources by moving to a clean circular economy[1].

2.2. EV Batteries

Road transportation is responsible for around 27% of Europe's greenhouse gas emissions (GHG) (Andwari et al., 2017; Liu et al., 2015). The EC set out a vision for 2050 to be climate-neutral with net-zero greenhouse gases (GHG) emission in response to increasing concerns about climate change. One of the most important sectors that can help GHG emission reduction to achieve the EC's vision and objective is road transport. Therefore, there is a need for road transport vehicles, that are independent of oil and fuels with high carbon footprints (Andwari et al., 2017; Kosai et al., 2020; Sabri et al., 2016). The need can be met by EVs, as they utilise batteries for running their engines. Although EVs have several advantages such as low emission, good acceleration, and low cost of charging, the technological readiness of EV battery manufacturing and their EoL management is a critical concern in the production and marketing of EVs (Kumar and Revankar, 2017; Rallo et al., 2020). There are a few battery types in the market such as Lead-acid, Nickel Metal Hydride, Lithium-Ion, and Sodium Nickel Chloride that can be used in EVs. The different types of batteries are compared based on several factors such as lifetime, cost per kWh, energy and power density, and safety. As the LIBs have some advantages such as low self-discharge, good lifetime, and high energy density over the other types of batteries, they have been mostly used in EVs (Alfaro-Algaba and Ramirez, 2020; Hua et al., 2020). It has been reported in a McKinsey report that the price of a complete automotive LIBs pack could decrease to about $160 per kWh by 2025 compared to $500 to $600 per kWh in 2011 (Hensley et al., 2012). Given the abovementioned reason, LIBs related research and development have been at the centre of interest for academia and practitioners (Leon and Miller, 2020; Moore et al., 2020).

2.3. EVs-LIBs reverse logistics and EoL management

Innovative supply chain models are required to effectively manage the recovery of EoL products; handling the flow of materials and products between supplier and customers. In this context, RLs represents the solution based on circular economy principles, that enables the recovery and transfer of materials to original manufacturers or other external parties (Garrido-Hidalgo et al., 2019; Genovese et al., 2017). RLs activities require that all products at their EoL are collected from the customers and returned to original manufacturers to be recycled, reused, remanufactured, or properly discarded (Agrawal and Singh, 2019). This process creates new market opportunities, and at the same time enhances the reduction of waste and negative environmental impacts (Beiler et al., 2020; Julianelli et al., 2020). Therefore, RLs are an important instrument in the circular economy context, contributing significantly towards economic, environmental, and societal performance improvements (Julianelli et al., 2020).

[1] https://op.europa.eu/s/oTwN

The automotive industry is under pressure to change its approach to the management and discharge of EVs at EoL. Specifically, the decommissioning of LIBs represents a complex and challenging process (Danino-Perraud, 2020; Gaines, 2019; Harper et al., 2019). The rapid increase in sales of EVs is intensifying this issue and at the same time is creating a scarcity of the natural resources required for their production processes such as lithium, cobalt, manganese, nickel, and graphite. If RL processes are put in place, the production process will have enough raw materials to deal with increased demand. However, currently, LIBs have a recycling rate of less than 5%, in comparison with lead-acid batteries which have a recycling rate of 99.5% (Crabtree, 2019a). Hence, closing the LIBs supply chain loop and managing their EoL are needed to be fully taken under consideration by European countries. The implementation of effective RLs for EVs-LIBs is vital. The RLs processes such as reuse, remanufacturing, and recycling can have a significant impact on the recovery of EVs-LIBs at the end of their life cycle (Alamerew and Brissaud, 2020). A description of RLs activities (reuse, recycling, remanufacturing and repurposing) for EVs-LIBs are discussed in the following sub-sections. Fig. 1 depicts the circular processes for recovering EoL EVs-LIBs.

2.3.1. Reuse

In some cases, the EoL of EVs can occur (e.g., early crash or failure) while their EVs-LIBs still have more than 80% of their initial capacity. The EVs-LIBs can be reused in EVs of the same brand which has a battery problem, however, there are some concerns about the dependability and reliability of the used batteries (Alamerew and Brissaud, 2020; Rallo et al., 2020; Yang et al., 2020).

2.3.2. Repurposing

One of the growing strategies in the context of circular economy and RLs is repurposing where EoL recovered EVs-LIBs are used in a new product with a completely different function from the initial product (Alamerew and Brissaud, 2020; Rallo et al., 2020; Yang et al., 2020). For example, the recovered batteries can be used as a backup energy source in buildings, energy storage for solar panels, windmills, and the electric heater. It is worth mentioning that for repurposing the used batteries, there may be a need for additional design and modification for the new application (Alamerew and Brissaud, 2020).

2.3.3. Remanufacturing

Another RLs activity is remanufacturing that processes the recovered EoL products for delivering a new product with similar or improved functionality. Currently, as remanufacturing of LIBs needs several sophisticated processes, it is not an optimal solution for EoL management of the batteries (Alamerew and Brissaud, 2020; Kampker et al., 2016). Processes such as disassembly, replacement, and reassembly are included in the remanufacturing of LIBs (Foster et al., 2014).

2.3.4. Recycling

In recent years, recycling has become one of the most popular activities of the EVs-LIBs RLs in which valuable materials such as cobalt and lithium are recovered from the EoL EVs-LIBs (Sommerville et al., 2021; Winslow et al., 2018). The recovered LIBs can be recycled by different members of their supply chains such as battery manufacturers, automotive manufacturers, and third-party recyclers. There have recently been many efforts in the EU to establish proper recycling infrastructures (Alamerew and Brissaud, 2020). Pyrometallurgical, Hydrometallurgy and direct recycling are among the most used recycling techniques for LIBs. Each recycling technology has its advantages and disadvantages. For example, for the pyrometallurgical process, the poor quality of the recovered material, high energy usage, and high capital cost are the main disadvantages. Technology readiness and Low complexity are the main advantages of the pyrometallurgical process. Hydrometallurgy suffers from a lack of enough revenue because of the reduced cobalt content of the cathode materials. The ability to recover

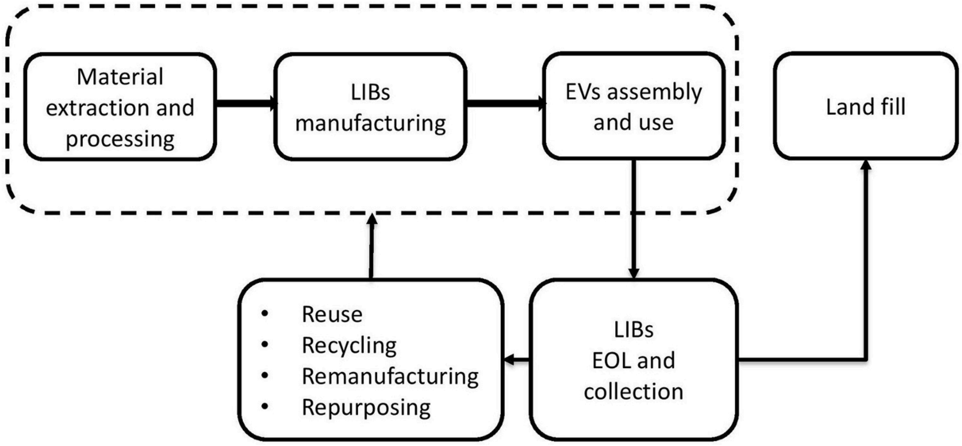

Fig. 1. LIBs RLs activities.

Aluminum is one of the advantages of Hydrometallurgy (Harper et al., 2019). High production cost and complexity of the processes are the main disadvantages of the direct recycling method, but the process can recover Lithium properly (Gaines, 2019).

To tackle the disadvantages, there is a need for supporting and carrying out research and development projects to develop efficient LIB recycling technologies (Crabtree, 2019b). In recent years, a few projects have been funded for recycling EVs-LIBs by several leading companies and organisations in the EU. For example, there is a joint project between Eramet, BASF, and SUEZ to develop an advanced closed-loop process for the recycling of LIBs. Also, Audi and Umicore have started to partner up for closing the supply chain loop of cobalt and nickel materials in EIBs[2].

2.4. EVs-LIBs RLs implementation barriers identification

Managing the EoL of EVs-LIBs RLs has its barriers and obstacles that need to be addressed. As it was discussed in the previous section, the existing studies in the literature have identified the technical barriers of EVs-LIBs. However, there is a lack of studies that define and analyse EVs-LIBs RLs implementation barriers. Therefore, to find the EVs-LIBs RLs implementation barriers, previous studies related to RLs barriers across various industries were reviewed. Based on a rigorous literature review, eight categories of barriers to RLs implementation have been identified. These eight barrier categories were extracted based on their frequency of occurrence in the related literature. Then, we mapped and defined these categories within the context of EVs-LIBs. Furthermore, these barriers have been validated based on experts' opinions using the Delphi method detailed in Section 3.1. Table 2 shows the list of identified RLs implementation barriers across various industries extracted from the related literature. A detailed description of each of the barriers within the context of EVs-LIBs is provided in the subsequent subsections. Identifying and defining this comprehensive list of EVs-LIBs RLs implementation barriers forms the first contribution of this study.

2.4.1. Financial and economic

There are several financial and economic barriers to the implementation of EVs-LIBs RLs. For EVs-LIBs RLs implementation, there is a need for establishing several infrastructures such as collection, sorting, dismantling, recycling, and remanufacturing centres (Danino-Perraud, 2020; Gaines, 2019; Kurdve et al., 2019). Establishing these centres requires high upfront investments as they need high-tech technologies, and highly skilled labours (Harper et al., 2019). So, in countries with high labour costs like EU countries, this can be a potential challenge.

Table 2
RLs barriers in various industries.

Barriers	Code	Reference
Financial and economic	B1	(Beaudet et al., 2020; Danino-Perraud, 2020; Gaines, 2019; Govindan and Bouzon, 2018; Harper et al., 2019; Kurdve et al., 2019; Leon and Miller, 2020; Prakash and Barua, 2016; Vermunt et al., 2019; Waqas et al., 2018)
Technology and infrastructure	B2	(Alamerew and Brissaud, 2020; Bouzon et al., 2018; Govindan and Bouzon, 2018; Harper et al., 2019; Hua et al., 2020; Kurdve et al., 2019; Leon and Miller, 2020; Salim et al., 2019a; Vieira et al., 2020; Waqas et al., 2018)
Governance and SC process	B3	(Ali et al., 2018; Beaudet et al., 2020; Gardas et al., 2018a; Govindan and Bouzon, 2018; Harper et al., 2019; Sasikumar and Haq, 2010; Vermunt et al., 2019)
Policy and regulation	B4	(Alamerew and Brissaud, 2020; Gaines, 2019; Govindan and Bouzon, 2018; Harper et al., 2019; Kurdve et al., 2019; Moore et al., 2020; Vermunt et al., 2019; Waqas et al., 2018)
Market and social	B5	(Govindan and Bouzon, 2018; Kurdve et al., 2019; Prakash and Barua, 2016; Salim et al., 2019a; Sasikumar and Haq, 2010; Vermunt et al., 2019)
Management and organisational	B6	(Abbas, 2018; Ali et al., 2018; Gardas et al., 2018b; Govindan and Bouzon, 2018; Waqas et al., 2018)
Environmental	B7	(Beaudet et al., 2020; Harper et al., 2019; Salim et al., 2019a; Waqas et al., 2018)
Knowledge and experiences	B8	(Abbas, 2018; Danino-Perraud, 2020; Govindan and Bouzon, 2018; Sari et al., 2018; Vermunt et al., 2019; Waqas et al., 2018)

Besides that, the current rate of returned LIBs is not sufficient and the cost of establishing the infrastructures is high, there is always a debate about financial feasibility, justification, and the economics of scale for implementing EVs-LIBs RLs (Beaudet et al., 2020; Kurdve et al., 2019; Sasikumar and Haq, 2010).

2.4.2. Technology and infrastructure

It has been discussed by many researchers that lack of proper technology and infrastructure is one of the crucial barriers for implementing closed-loop supply chains or RLs (Alamerew and Brissaud, 2020; Bouzon et al., 2018; Govindan and Bouzon, 2018; Harper et al., 2019; Kurdve et al., 2019). This can be highlighted for EoL management of EVs-LIBs as it is at its early stage. Lack of optimized and unified design for EoL of EVs-LIBs (design for recycling, disassembly) is one of the barriers in this category (Harper et al., 2019; Kurdve et al., 2019). EV designers have to make a trade-off between several factors such as

[2] https://www.eba250.com/accelerating-battery-recycling/

safety, space optimization, and serviceability when they design the cars (Andwari et al., 2017; Harper et al., 2019; Hua et al., 2020). Given these conflicting factors for designing the EVs, there may not be an optimized and unified design for EVs-LIBS s recyclability. This can be a big barrier for the RLs processes. Currently, there is a lack of unified and standardized design for different parts of EVS-LIBSs such as packs, modules, and cells. The EVs-LIBs are not designed optimally for being disassembled and recycled easily (Beaudet et al., 2020; Harper et al., 2019; Hua et al., 2020; Kurdve et al., 2019; Leon and Miller, 2020). All current commercial physical battery breaking processes use shredding or milling, followed by a sorting process that makes the RLs activities challenging (Harper et al., 2019; Leon and Miller, 2020). These barriers and challenges can be handled with the standardized design of EVS-LIBSs.

There is a low development of efficient infrastructure and technology for EVs-LIBs RLs (e.g. collection, sorting, disassembly, and recycling sites and technology) which makes the existing technologies more expensive and unattractive to companies. Each of the three main types of recycling has its issues such as cost and functionality (Gaines, 2019; Harper et al., 2019). Therefore, there is a need to develop new technologies for EVs-LIBs recycling. There is also limited efficient information sharing technology, tracking systems, and labelling standards for checking and possibly tracking of EVs-LIBs which are essential for efficient RLs implementation (Beaudet et al., 2020; Harper et al., 2019; Kurdve et al., 2019).

2.4.3. Governance and SC process

One of the main barrier categories is governance and supply chain process. There are several factors in supply chain process and governance categories for EVs-LIBs RLs implementation, such as lack of effective communication and coordination between the member of the EVs-LIBs supply chain, product quality reliability for returned EVs-LIBs the uncertainty of demand and return for EVs-LIBs, and lack of performance metrics system for EVs-LIBs RLs (Beaudet et al., 2020; Bouzon et al., 2018; Govindan and Bouzon, 2018; Mayyas et al., 2019; Sasikumar and Haq, 2010; Vieira et al., 2020). These barriers will have a high impact on the forecasting and planning functions of the EVs-LIBs RLs. As a result, there could be uncertainty about the quantity and quality of the used EVs-LIBs in the reverse flow of the supply chain (Beaudet et al., 2020; Harper et al., 2019).

2.4.4. Policy and regulation

This category encompasses policy and regulations barriers concerning the reverse flow of EVs-LIBs supply chain. Policy and regulation are crucial factors in the implementation of RLs for EVs-LIBs. It has been discussed by academia and practitioners that inappropriate and slow-changing legislation for EoL management of EVs-LIBs can negatively affect the RLs activities implementation (Alamerew and Brissaud, 2020; Gaines, 2019; Harper et al., 2019; Kurdve et al., 2019; Moore et al., 2020). Development of supportive policy and regulation for EVs-LIBs EoL management provides a better framework for the EVs-LIBs supply chain members for implementing EVs-LIBs RLs. For instance, it would be challenging to provide a warranty for the recovered EVs-LIBs due to the absence of a proper policy and regulation (Alamerew and Brissaud, 2020; Kurdve et al., 2019). Furthermore, extending producer responsibility across countries would be an issue as the supply chain of EVs-LIBs is global, and there are different policies and regulations in different countries (Govindan and Bouzon, 2018). Proper policy and regulations are required to support the implementation of practices and initiatives for enabling the second life of EVs-LIBs for stationary purposes (Moore et al., 2020; Neubauer et al., 2015). Consequently, precise and proper rules and regulations are needed for different life-cycle phases of LIBs.

2.4.5. Market and social

There are some market related and social factors that can affect the implementation of RL of EVs-LIBs. Several researchers have mentioned that the lack of customer interest in recycled or remanufactured EVs-LIBs is one of the main challenges for the second life of the batteries in the market (Govindan and Bouzon, 2018; Sasikumar and Haq, 2010; Vermunt et al., 2019). There is still a lack of community pressure to motivate governments and industries for the implementation of RL for EVs-LIBs (Waqas et al., 2018). It has been stressed by several researchers that factors such as lack of customer awareness about competitive advantage and urgency of EVs-LIBs RLs, lack of education training about RL, market competition and uncertainty, and undeveloped recovery marketplaces for EVs-LIBs are the other market and social related barriers for industries to implement of EVs-LIBs RLs (Bouzon et al., 2018; Kurdve et al., 2019, 2019; Vieira et al., 2020).

2.4.6. Management and organizational

This category is related to management and organizational barriers such as commitment from top management and governors, and lack of interest to invest in RLs practices (Abbas, 2018; Ali et al., 2018; Gardas et al., 2018a). This category of barriers exists due to a lack of obligation to adopt and implement RLs (Abbas, 2018; Govindan and Bouzon, 2018). Top management has to provide strategic plans with regards to the RLs programs as well as action plans to successfully implement their strategic plans, along with training staff and installing new systems (Gardas et al., 2018a).

2.4.7. Environmental

This category of barriers is about the environmental impact related to EVs-LIBs RLs activities. Although the literature in the field of EVs-LIBs suggests managing the EoL of the batteries can reduce the negative environmental impact, there is still a negative impact when RLs activities are implemented (Beaudet et al., 2020; Harper et al., 2019; Salim et al., 2019b). Recovery, sorting, disassembly, and recycling needs substantial amounts of energy, which could have a significant negative environmental impact. Although the total energy being used for LIBs recycling should be less than the scenario for production of the batteries from the very starting point in the supply chain, the recycling process still needs a considerable amount of energy (Salim et al., 2019b; Vieira et al., 2020). There is intensive chemical usage, thermal treatments, and machinery during the recovery and recycling process (Harper et al., 2019). Complexity in measuring and monitoring environmental practices is another challenge to be considered in this field (Waqas et al., 2018).

2.4.8. Knowledge and experiences

Lack of knowledge and experiences of EVs-LIBs EoL management is another category of barriers for implementation of EVs-LIBs RLs. As EoL management of the EVs-LIBs is still in its early stage, there is still a lack of knowledge and experiences in this area (Beaudet et al., 2020; Gaines, 2019; Harper et al., 2019). For example, the lack of knowledge about the RLs activities such as recycling and remanufacturing of LIBs is one of the main challenges that can lead to poor productivity of the activities (Danino-Perraud, 2020). This category includes some barriers such as lack of experience/knowledge of technology and management practice for EVs-LIBs reverse logistics, lack of awareness concerning RLs and its advantages for EVs-LIBs, lack of taxation on returned products, lack of knowledge and awareness of environmental impacts (Abbas, 2018; Danino-Perraud, 2020; Kurdve et al., 2019).

3. Research methodology and implementation

This research aims to identify and analyze the relationships between barriers for the implementation of EVs-LIBs RLs in the EU. Fig. 2 illustrates the proposed research methodology of this research study. The proposed methodology encompasses three main phases detailed in the following subsections. Phase 1 helps to identify EVs-LIBs RLs barriers. In phase 2, the TISM method is utilised for identifying and interpreting the interrelationship among the identified barriers. In phase 3, the identified

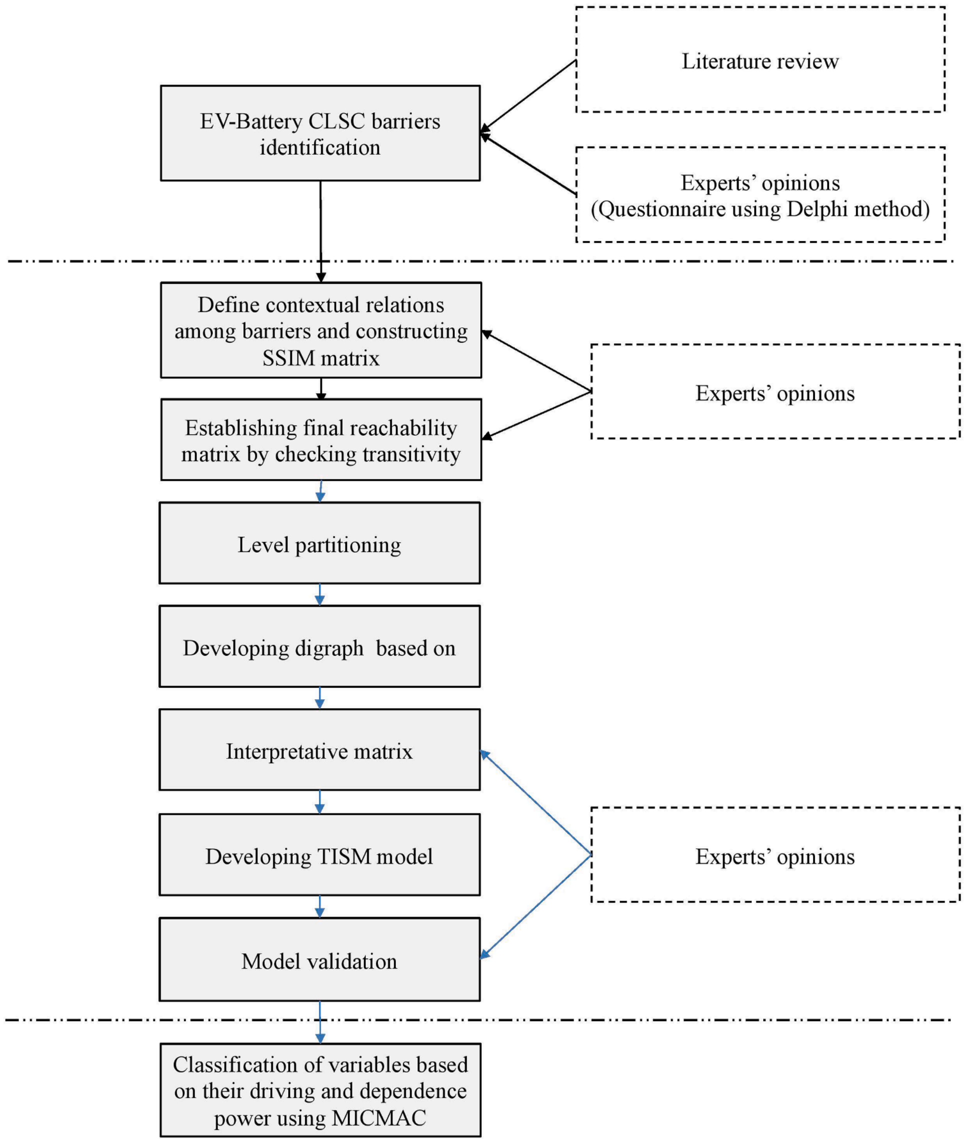

Fig. 2. The proposed methodology for EVs-LIBs RLs barriers analysis.

barriers are classified using the MICMAC technique. The following assumptions have been considered in this study:

- This study only considers the implementation barriers of RLs for EVs-LIBs as the most widely used battery type in EVs because of their cost and energy efficiency compared to the other batteries.
- This study is conducted for finding and analyzing EVs-LIBs RLs implementation barriers in the EU. EVs-LIBs EoL management can have significant economic advantages by extracting the mineral resources such as nickel and cobalt, which are not accessible in the EU lands.
- The experts were selected based on their experiences in the field of LIBs supply chains. EVBs manufacturing/recycling companies and EV manufacturing companies are the key stakeholders in the LIB supply chains. Therefore, most experts are selected from these types of organisations. Besides, some academics with more than 5 years of experience in the field of EVBs supply chain were invited to participate in the study and input gathering.
- The transitivity of the contextual relationships among the barriers is considered for developing the TISM model. It states that if barrier A is related to barrier B and barrier B is related to barrier C, then variable A necessarily is related to variable C.

3.1. EVs-LIBs RLs barriers identification

In this phase, the barriers to the successful implementation of EVs-LIBs RLs were identified. A list of barriers to implementing RLs was gathered from previous studies, categorised and sorted into eight groups as shown in Table 2. Afterwards, relevant experts were asked to identify the most relevant barriers using the Delphi method. In this study, a purposive sampling method has been used to select the experts. Hence, the experts were selected based on their expertise in the field of LIBs supply chain with at least five years of experience. A total of 20 experts participated, which include 10 experts from EVBs manufacturing/recycling companies, 6 experts from EV manufacturing companies, and 3 from academia with at least 5 years of experience in the field of study. To select the most relevant barriers, a Yes/No-based list of extracted barriers is provided as a questionnaire and sent to the experts to have their opinions. If 50% or more of the experts say Yes, then the barrier was selected. The experts were also asked to add any other possible barriers which were not on the list. Besides, they were asked to provide any comments/suggestion regarding the barriers. It is worth mentioning that based on the experts' opinions all the extracted barriers from Table 2 were selected. For the first round, the experts provided some minor changes regarding the names of the category. After that, the list of the selected barriers with modifications was sent back to the experts and they approved the list of barriers.

3.2. Identifying and interpreting interrelations between EVs-LIBs RLs barriers using TISM

After gathering the data, an integrated approach of TISM is used for developing the conceptual hierarchy model of barriers for implementing RLs for EVs-LIBs. ISM method generates suitable models by finding the relations between elements of a system by presenting the order and proper linkage and hierarchy of the interrelating elements of the system. The method is called interpretive as experts' opinions are used to find the relations of the system elements (Bhanot et al., 2017; Warfield, 1974). However, ISM suffers from lack of proper interpretations of the links. Therefore, TISM is developed to deal with this. TISM provides the interpretations of the significant links that are provided by experts (Choudhury et al., 2021; Dubey et al., 2015; Mathivathanan et al., 2021; Rajesh, 2017). TISM method generates suitable models by finding the relations between elements of a system by presenting the order and proper linkage and hierarchy of the interrelating elements of the system and providing interpretations of significant links. The method is called interpretive as experts' opinions are used to find the relations of the system elements (Bhanot et al., 2017). TISM method has been wildly applied by researchers during recent years in various contexts of research such as performance management (Patri and Suresh, 2017; Yadav, 2014) green/sustainable supply chain/logistics (Dubey et al., 2015; Mohanty and Shankar, 2017; Soda et al., 2018), humanitarian supply chain (Patil et al., 2020; Yadav and Barve, 2016), blockchain and digital supply chain (Choudhury et al., 2021; Mathivathanan et al., 2021; Prasad et al., 2018; Sharma and Joshi, 2021), service recovery (Baliga et al., 2021), supply chain resilience (Agrawal and Singh, 2019; Rajesh, 2017), control system (Jayalakshmi and Pramod, 2015), and lean manufacturing (Chaple et al., 2018; Vinodh, 2020). However, the TISM method has scarcely been applied in the context of RLs barrier analysis. In this research, the TISM methodology is employed to identify and analyse the interrelations between the EVs-LIBs RLs barriers. The results of the TISM analysis can be used as a guideline for industries to the successful implementation of EVs-LIBs RLs in Europe. In this research, Python coding was developed to process the collected data and implement the integrated approach of TISM and MICMAC techniques. The detailed steps of TISM are provided as follows:

Step 1. Establishing and interpreting contextual relation among barriers.

After finalising the barriers, an online questionnaire was created and sent to the experts for implementing TISM. After identifying the barriers that have been tabulated in Table 2, the initial relation matrix (IRM) that shows the relationship between the barriers is established. IRM is a binary matrix of 1s and 0s denoting if Variable *i* led to Variable *j* and vice versa. This can be done by asking questions such as, "Does the variable A influence the variable B?" If the answer is "yes,'' then $R_{ij} = 1$; otherwise, $R_{ij} = 0$ (Ghadimi et al., 2020). In this study, an online questionnaire survey was created and used to construct the IRM. EVs-LIBs experts were asked to answer the questions. A total number of 8 questions based on the defined barrier categories have been formulated in the questionnaire. For each barrier category, the experts were asked to decide if the barrier of interest, impacted or led to any of the other barriers, with "None" being a possible answer. During this step, the experts must decide about the pairwise relationship between the barriers. Afterwards, if more or equal than 50% of the experts agreed about a particular relation between two barriers, the value of '1' is assigned to that relationship. The threshold of 50% was obtained after performing a sensitivity analysis. Relationships of the barrier categories were analysed for various thresholds between 0% to 100% with increments of 5%. Consequently, IRM was derived using a threshold of 50% as a suitable one. This threshold value produced 14 significant influential links between barrier variables and 21 after applying significant transitivity links.

Table 3 shows the IRM for the barriers. Besides, to implement TISM, the experts' opinions were gathered regarding the interpretation of link among the barriers. If the contextual relationship between barrier A and B pertains yes, then they have been asked "In what way barrier A will impact barrier B". This interpretation for a relationship would assist to express in-depth knowledge about the management of these barriers. Table 4 show the excerpt of contextual relationships among the barriers.

Step 2. Establishing the final reachability matrix

Based on the results achieved in the previous step, the final reachability matrix (FRM) is constructed for considering transitivity. In the TISM technique transitivity says if the variable has a relationship with *j* and *j* is related to *k*, it can be concluded that i is related to k. If the cell (i, j) of the FRM is zero, it means there is not any relationship between *i* and *j*. While IRM cannot show the indirect relations between the variables, FRM will show the indirect relation (Malone, 1975). Table 5 shows the FRM. The Driving and Dependence Powers for the MICMAC analysis are also included in Table 5. To construct the final reachability matrix, experts' opinions have been captured to find the significant transitive links and provide knowledge. Their responses were used to transform the knowledge base into the final reachability matrix. In this step, to check the transitivity, if captured responses for transitive links were 50% or above, a transitive link was labelled as 'significant' transitive link otherwise transitive. This was done to only include the significant transitive links in the final digraph.

Step 3. Level partitioning of reachability matrix.

In this step, the level of each barrier in the model is determined. To do that, the reachability and antecedent set for each barrier are determined based on the FRM. The reachability set includes the barrier itself and the other barriers affected by the barrier. The antecedent set encompasses the barrier itself and the ones that affect the barrier. Afterwards, for each barrier, the intersection of the reachability and antecedent sets is found. The barriers that have the same member in the reachability and intersection sets are entitled as the top-level barrier in the TISM model hierarchy. After finding the top-level barriers, they are removed for finding the next level barriers. Again, a similar procedure is used to determine the next level barriers. This procedure is iterated till all the barriers are ranked (Tables 6-10). The rows that are highlighted in grey will be removed in the next iteration. Table 11 shows the final partition and hierarchy of the model.

Step 4. Developing digraph

In this step, barriers are assigned to their relative level based on the results from level-partitioning. To do this, digraphs are plotted to show the most significant relations. The constructed digraph is shown in Fig. 3. The relations are identified from the final reachability matrix and

Table 3
Initial reachability matrix of the barriers.

	B1	B2	B3	B4	B5	B6	B7	B8
B1- Financial and economic	0	1	0	0	0	0	0	1
B2- Technology and infrastructure	0	0	1	0	0	0	1	0
B3- Governance and SC process	0	0	0	0	0	0	0	0
B4- Policy and regulation	1	1	0	0	0	1	1	0
B5- Market and social	1	0	0	1	0	0	0	0
B6- Management and organisation	0	0	1	0	0	0	0	1
B7- Environmental	0	0	0	0	0	0	0	0
B8- Knowledge and experience	0	1	0	0	0	1	0	0

Table 4
Contextual relationships among the barriers with interpretation

No	Relation	Paired comparison of Barriers	Interpretation - In what way barriers will impact other barriers?
1	B1-B2	Financial and economic barriers impact technology and infrastructure barriers	EVs-LIBs RLs infrastructure are costly and needs funds. So, lack of financial sources and funds will impact establishing proper infrastructures.
2	B1-B8	Financial and economic barriers impact knowledge and experience	Lack of investment and financial sources for EVs-LIBs RLs activities will impact recruiting experienced people and less investment in R&D.
3	B2-B3	Technology and infrastructure barriers impact governance and SC process	Lack of proper tracking technology for EVs-LIBs creates uncertainty about the quantity and quality of the used EVs-LIBs in the reverse flow of the supply chain and improper forecasting
4	B2-B7	Technology and infrastructure barriers impact environmental	Lack of proper technologies for disassembly and recycling the EVs-LIBs will harm the environment. This can be happened by the amount of energy that is used for recycling and remanufacturing the EVs-LIBs.
5	B4-B1	Policy and regulation barriers impact financial and economic barriers	Lack of proper supportive law, regulation, and incentives for supporting the companies can lead to financial difficulties and barriers for companies
6	B4-B2	Policy and regulation barriers impact technology and infrastructure barriers	Lack of proper supportive regulation and law would lead to support R&D project for developing new technologies.
7	B4-B6	Policy and regulation barriers impact management and organisation	lack of proper regulation for managing EoL of EVs-LIBs will lead to a lack of interest and commitment of company managers to implement RLs activities.
8	B4-B7	Policy and regulation barriers impact environmental	Policy and regulation on hazardous material management and managing the environmental impact of EVs-LIBs RLs activities can also impact how the used EVs-LIBs pre-treatment processes are performed and affect the negative environmental impacts.
9	B5-B1	Market and social barriers can lead to financial and economic barriers	Undeveloped markets, uncertainty, and lack of awareness among customers will doubt the financial feasibility and lead to financial barriers
10	B5-B4	Market and social barrier impact policy and regulation	Lack of pressure from customers and society as the major stakeholders of government can lead to a lack of proper regulation regarding the EoL of EVs-LIBs
11	B6-B3	Management and organisation barriers impact governance and SC process	Lack of commitment and proper strategies for implementing RLs will lead to a lack of effective communication and coordination between the member of the EVs-LIBs supply chains.
12	B6-B8	Management and organisation barriers impact knowledge and experience	Lack of commitment, proper strategies, training programs will lead to a lack of knowledge and experience regarding EVs-LIBs RLs activities, taxation, and environmental impacts.
13	B8-B2	Knowledge and experience barriers impact technology and infrastructure	Lack of experience/ knowledge of technology and management practice for EVs-LIBs RLs can lead to inappropriate decisions about selecting the proper technologies and R&D decisions for new technologies for EVs-LIBs EOL management.
14	B8-B6	Knowledge and experience barriers impact management and organisation	Lack of knowledge and experience regarding EVs-LIBs RLs activities will impact companies commitment, strategies, and investment for managing EoL of the batteries

the interpretation of the relations. The significant transitive links are also recognized and represented in the digraphs. Table 4 shows the direct links used for developing the digraph and their relevant interpretation. Also, the most important transitive links for developing the digraph and the interpretations of the relations are shown in Table 12.

Step 5. Digraph validation

In this step, the constructed digraphs were validated using the experts' opinions. A Yes/No questionnaire was designed to select the significant relations in the digraph and validate the TISM model. If 50% or more of the experts say Yes, then the link was selected and kept in the digraphs and other links should be detached to construct the finalised digraph of the TISM model. The validated digraph can be interpreted rationally for a detailed understanding of the links in the constructed digraph as the input for the TISM model. Table 13 shows the digraph links validation.

Step 6. Developing final total interpretive structural model

The information from the links interpretations (Tables 4 and 12) and digraph are used to develop a finalised TISM-based model for EVs-LIBs

Table 5
FRM of barriers.

	B1	B2	B3	B4	B5	B6	B7	B8	Driving powers
B1- Financial and economic	1	1	1*	0	0	1**	1**	1	6
B2- Technology and infrastructure	0	1	1	0	0	0	1	0	3
B3- Governance and SC process	0	0	1	0	0	0	0	0	1
B4-Policy and regulation	1	1	1**	1	0	1	1	1*	7
B5-Market and social	1	1*	0	1	1	1**	1*	1*	7
B6-Management and organisation	0	1**	1	0	0	1	0	1	4
B7-Environmental	0	0	0	0	0	0	1	0	1
B8-Knowledge and experience	0	1	1**	0	0	1	1**	1	5
Dependence Powers	3	6	6	2	1	5	6	5	

* Transitive links
** Significant transitive links

Table 6
Level partitioning iteration 1.

Barrier	Reachability set	Antecedent set	Intersection set	Level
B1	1,2,3,6,7,8	1,4,5	1,7	
B2	2,3,7	1,2,4,5,6,8	2	
B3	3	1,2,3,4,6,8	3	I
B4	1,2,3,4,6,7,8	4,5	4,5	
B5	1,2,4,5,6,7,8	5	5	
B6	2,3,6,8	1,4,5,6,8	6,8	
B7	7	1,2,4,5,7,8	7	I
B8	2,3,6,7,8	1,4,5,6,8	6,8	

Table 7
Level partitioning iteration 2.

Barrier	Reachability set	Antecedent set	Intersection set	Level
B1	1,2,6,8	1,4,5	1	
B2	2	1,2,4,5,6,8	2	II
B4	1,2,4,6,8	4,5	4	
B5	1,2,4,5,6,8	5	5	
B6	2,6,8	1,4,5,6,8	6,8	
B8	2,6,8	1,4,5,6,8	6,8	

Table 8
Level partitioning iteration 3.

Barrier	Reachability set	Antecedent set	Intersection set	Level
B1	1,6,8	1,4,5	1	
B4	1,4,6,8	4,5	4	
B5	1,4,5,6,8	5	5	
B6	6,8	1,4,5,6,8	6,8	III
B8	6,8	1,4,5,6,8	6,8	III

Table 9
Level partitioning iteration 4.

Barrier	Reachability set	Antecedent set	Intersection set	Level
B1	1	1,4,5	1	IV
B4	1,4	4,5	4	
B5	1,4,5	5	5	

Table 10
Level partitioning iteration 5.

Barrier	Reachability set	Antecedent set	Intersection set	Level
B4	4	4,5	4	V
B5	4,5	5	5	VI

RLs barriers. A final TISM model for EVs-LIBs RLs barriers is presented in Fig. 4 that shows the barriers level, and their links with direction. Due to limited space, the interpretation of the transitivity links is shown by codes. These codes show the logic behind the significant transitive links. For instance, “B4-B6-B3” shows that B4 affects B6, B6 affects B3, consequently B4 influences B3, indirectly. Table 12 shows the logic behind the significant transitive links by presenting interpretations.

Table 11
Final iteration-level partition of barriers.

Barrier code	Barriers	Level
B1	Financial and economic	IV
B2	Technology and infrastructure	II
B3	Governance and SC process	I
B4	Policy and regulation	V
B5	Market and social	VI
B6	Management and organisation	III
B7	Environmental	I
B8	Knowledge and experience	III

3.3. Barriers classification using MICMAC analysis

The key barriers of EVs-LIBs RLs implementation in Europe are identified and categorized using the MICMAC analysis. The main objective of this step is to investigate the driving power and dependence power of the barriers using MICMAC analysis. Using the final reachability matrix, dependence powers were calculated for each barrier by summing the columns (X-axis), and driving powers were calculated by summing the rows (Y-axis) of each barrier. There could be four types of barriers based on the following categorization (Ghadimi et al., 2020):

- Autonomous variables: In this quadrant (Bottom-Left), the driving and dependence power of barriers are low as they don’t have enough relations with the other barriers.
- Dependent variables: In this quadrant (Bottom-Right), the driving powers of the barrier are low but the dependent powers are high. These types of barriers are influenced by other barriers.
- Independent variables: In this quadrant (Top-Left), the driving powers of the barriers are high but the dependent powers are low. These types of barriers are the most influential barriers of the system.
- Linkage variables: In this quadrant (Top-Right), the driving and dependent powers of the barriers are high. barriers have strong dependence and driving powers. These types of barriers have a big influence on the system. They are also influenced by the other barriers. This means that they have a high influence over the system, but also rely on other elements.

It is worth mentioning the barriers that are in the top half of the diagram can be labelled as the crucial barriers and play important role in the model. Fig. 5 shows the MICMAC analysis that was performed based on the driving and dependence power of the barriers. Based on Fig. 5, it can be concluded that most of the barriers are categorised as Dependent Barriers that are mainly influenced by other barriers and Independent/ driving barriers that have a high impact on the other barriers of the

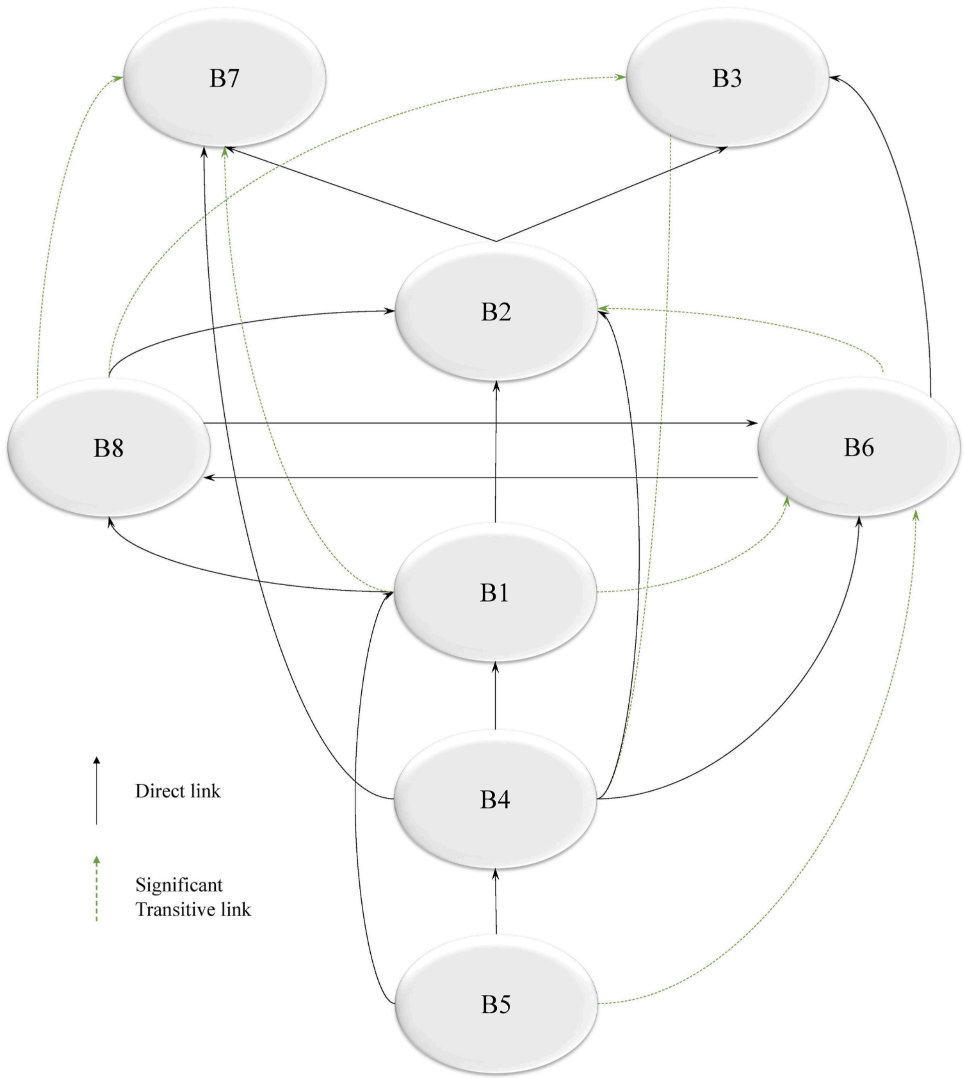

Fig. 3. Digraph with significant transitive links.

model. B8 is classified as a linkage barrier, any action taken on this barrier will affect other barriers. B6, although it is classified as a dependent barrier, can be considered as a linkage barrier as well since it sits in proximity to B8. The MICMAC analysis also shows strong connectivity between barriers in the model as most of the barriers categorized as independent and dependent barriers. According to the MICMAC analysis, the driving power of a barrier is measured based on the number of barriers affected by the barrier, and the dependence is measured based on the number of barriers that affect the barrier. Therefore, it can be perceived that barriers with more driving power (located in the independent barriers quadrant) have the chance to be at the bottom of the hierarchy and vice versa. So Level IV, V, and VI are the Independent Barriers that are strong drivers of the Dependent Variables. B8 (and to some degree B6) has a Linkage Barrier role as it interacts with B2, B1, and B6 (B6 interacts with B8, B4, B3).

4. Finding and Discussion

As was discussed in the previous section, there are several barriers to the implementation of EVs-LIBs RLs that needs to be taken into consideration. This paper identifies and analyses these barriers using an integrated approach of TISM and MICMAC techniques. Although there are several studies in the literature about CLSC/RLs implementation barriers, less attention has been devoted to finding and analyzing the EVs-LIBs RLs implementation barriers, especially in the EU. In this paper, firstly, the relevant barriers are identified and then a hierarchy model of the barriers has been developed. Then, a comprehensive analysis of the relations of these barriers is conducted using the TISM-MICMAC model. The TISM-MICMAC model obtained in this study depicts the relationships between barriers, their relevant categories, their level in the hierarchy. Below a detailed discussion of different important relations between the barriers obtained through the model is provided.

4.1. Market and Social Barrier (B5)

Market and Social Barrier (B5) which is located on level VI of the hierarchy model can be considered as the strongest barrier of EVs-LIBs RLs implementation, as it has the highest driving power and weak dependence power among the barriers. This barrier impacts policy and regulation (B4) and financial and economic (B1) barriers. The EVs market still being at its early stage creates further obstacles and uncertainties. The number of EVs is marginal, and most have not yet reached the EoL (Crabtree, 2019b; Harper et al., 2019). These factors can affect B1 and B4. Also, lack of customer awareness about competitive advantage and urgency of RLs of EVs-LIBs, lack of education training about RL, and undeveloped recovery marketplaces for EVs-LIBs are the other market and social related barriers for industries to implement the EVs-LIBs RL (Alamerew and Brissaud, 2020; Bouzon

Table 12
Interpretation of significant transitive links in the digraph

No	Transitive link	Interpretation
1	B5-B6 (B5-B4-B6)	Lack of pressure from customers and society as the major stakeholders of government can lead to a lack of proper regulation regarding the EoL of EVs-LIBs. Then, lack of proper regulation for managing EoL of EVs-LIBs will lead to a lack of interest and commitment of company managers to implement RLs activities.
2	B1-B6 (B1-B8-B6)	Lack of investment and financial sources for EVs-LIBs RLs activities will impact recruiting knowledgeable experienced people and less investment in R&D. Consequently, lack of experience and knowledge will affect the management of the organization.
3	B6-B2 (B6-B8-B2)	Lack of commitment, proper strategies, training programs will lead to a lack of knowledge and experience regarding EVs-LIBs RLs activities, taxation, and environmental impacts. Consequently, lack of knowledge and experience will impact the development of new technologies for managing EoL of EVs-LIBs
4	B4-B3 (B4-B6-B3)	lack of proper regulation for managing EoL of EVs-LIBs will lead to a lack of interest and commitment of companies' managers to implement RLs activities. Consequently, lack of commitment and proper strategies for implementing RLs will lead to a lack of effective communication and coordination between the member of the EVs-LIBs supply chains.
5	B1-B7 (B1-B2-B7)	EVs-LIBs RLs infrastructure is costly and needs funds. So, lack of financial sources and funds will impact establishing proper infrastructures. Consequently, the lack of proper technologies for disassembly and recycling the EVs-LIBs will harm the environment. This can happen by the amount of energy that is used for recycling and remanufacturing the EVs-LIBs.
6	B8-B3 (B8-B2-B3)	Lack of experience/knowledge of technology and management practice for EVs-LIBs RLs can lead to inappropriate decisions about selecting the proper technologies and R&D decisions for new technologies for EVs-LIBs EoL management (e.g., collection, sorting, and recycling). Consequently, lack of proper technologies will create uncertainty about the quantity and quality of the used EVs-LIBs in the reverse flow of the supply chain and improper forecasting.
7	B8-B7 (B8-B2-B7)	Lack of experience will lead to a lack of proper technologies for EVs-LIBs RLs. Consequently, the lack of proper technologies for disassembly and recycling the EVs-LIBs will harm the environment. This can happen by the amount of energy that is used for recycling and remanufacturing the EVs-LIBs.

et al., 2018; Govindan and Bouzon, 2018).

4.2. Policy and regulation (B4)

Policy and regulation (B4) is located on Level V of the hierarchy and is the only barrier on that level and classified as an independent barrier by the MICMAC model. Based on the TISM-MICMAC analysis, B4 is one of the important barriers to the implementation of EVs-LIBs RLs. B4 affects financial and economics (B1), technology and infrastructure (B2) environmental (B7), and management and organization (B6) barriers. Firstly, B4 can affect B1. With suitable regulations, proper incentive action plans, taxation, and legislation, manufacturers can be motivated for implementing EVs-LIBs RLs (Alamerew and Brissaud, 2020).

B4 also affects B6; there is a debate about considering extended producer responsibility regulation for the EVs-LIBs (or EV as a whole) (Beaudet et al., 2020). This means car manufacturers are responsible for the cost of RLs activities for EVs-LIBs while providing them incentives and supports for establishing an efficient reverse chain (Beaudet et al., 2020). Through the implementation of RLs, LIBs will be a valuable domestic source of raw materials as some raw materials like cobalt and nickel are depleting or difficult to import from outside the EU. There is a need to support manufacturing companies for their recycling process development providing them with subsidies and supportive packages

Table 13
Digraph validation

No	Relation link	Type	Explanation	Score	Accept/ reject
1	B1-B2	Direct	Financial and economic barriers impact technology and infrastructure	0.75	Accept
2	B1-B8	Direct	Financial and economic barriers impact knowledge and experience	0.65	Accept
3	B1-B6	Transitive	Financial and economic barriers impact management and organization	0.5	Accept
4	B1-B7	Transitive	Financial and economic barriers impact environmental	0.55	Accept
5	B2-B3	Direct	Technology and infrastructure barriers impact governance and SC process	0.7	Accept
6	B2-B7	Direct	Technology and infrastructure barriers impact environmental	0.75	Accept
7	B4-B1	Direct	Policy and regulation barriers impact financial and economic	0.8	Accept
8	B4-B3	Transitive	Policy and regulation barriers governance and SC process	0.5	Accept
9	B4-B6	Direct	Policy and regulation barriers impact management and organization	0.7	Accept
10	B4-B2	Direct	Policy and regulation barriers impact technology and infrastructure	0.7	Accept
11	B4-B7	Direct	Policy and regulation barriers impact environmental	0.75	Accept
12	B5-B4	Direct	Market and social impact policy and regulation	0.75	Accept
13	B5-B1	Direct	Market and social barriers impact financial and economic	0.7	Accept
14	B5-B6	Transitive	Market and social barriers impact management and organization	0.6	Accept
15	B6-B3	Direct	Management and organization barriers impact governance and SC process	0.65	Accept
16	B6-B2	Transitive	Management and organization barriers impact technology and infrastructure	0.55	Accept
17	B6-B8	Direct	Management and organization barriers impact knowledge and experience	0.6	Accept
18	B8-B2	Direct	Knowledge and experience barriers impact technology and infrastructure	0.65	Accept
19	B8-B6	Direct	Knowledge and experience barriers impact management and organization	0.7	Accept
20	B8-B7	Transitive	Knowledge and experience barriers impact environmental	0.6	Accept
21	B8-B3	Transitive	Knowledge and experience barriers impact governance and SC process	0.55	Accept

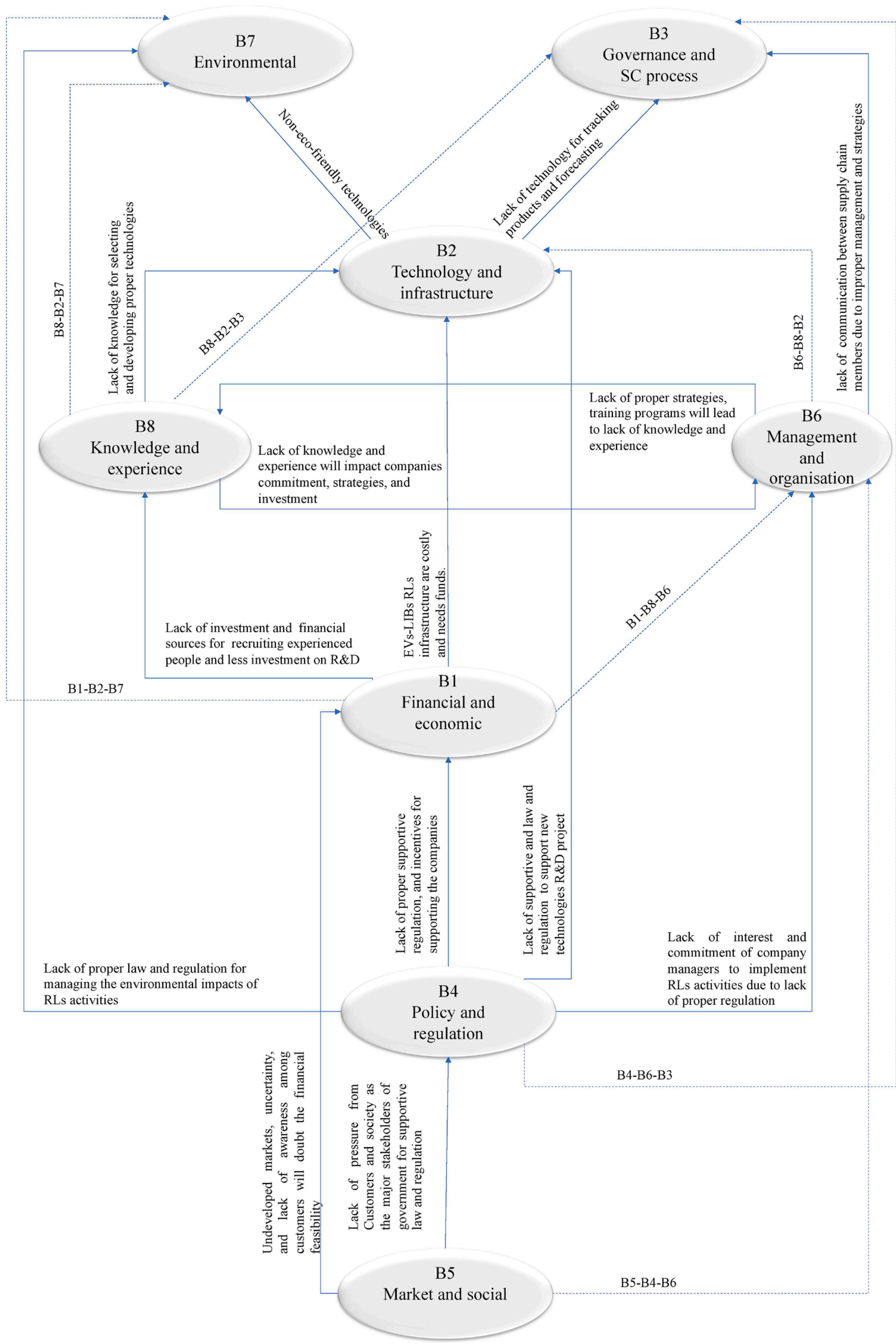

Fig. 4. Total interpretive structural model (TISM) for EVs-LIBs RLs barriers.

that can affect the financial status of the companies (Gaines, 2019). Hence, lack of proper policy and regulation can affect financial and economic, management, and organisation barriers for implementation of EVs-LIBs RLs. Current policies, most remarkably, the 2006 European Union (EU) Battery Directive, were developed mainly for portable electronics rather than EVs-LIBs (Leon and Miller, 2020; Mayyas et al., 2019). Research is required to develop the appropriate policy and regulation for EVs-LIBs packs, such as design for recycling, standard labelling, and tracking system (Gaines, 2019; Harper et al., 2019; Leon and Miller, 2020). Finally, B4 can affect B7; policy and regulation on hazardous material management can also impact how the used EVs-LIBs pre-treatment processes are performed (Leon and Miller, 2020).

4.3. Financial and economic (B1)

Financial and economic (B1) is another important category of barriers that affects the implementation of EVS RLs. B1 is located at level III of the hierarchy and can be considered as the weakest independent variable based on the TISM-MICMAC analysis. As shown in Fig. 4, B1 directly affects technology in infrastructure B2 and Knowledge and Experience (B8). For the implementation of EVs-LIBs RLs, several centres and facilities such as collection, disassembly, recycling centres

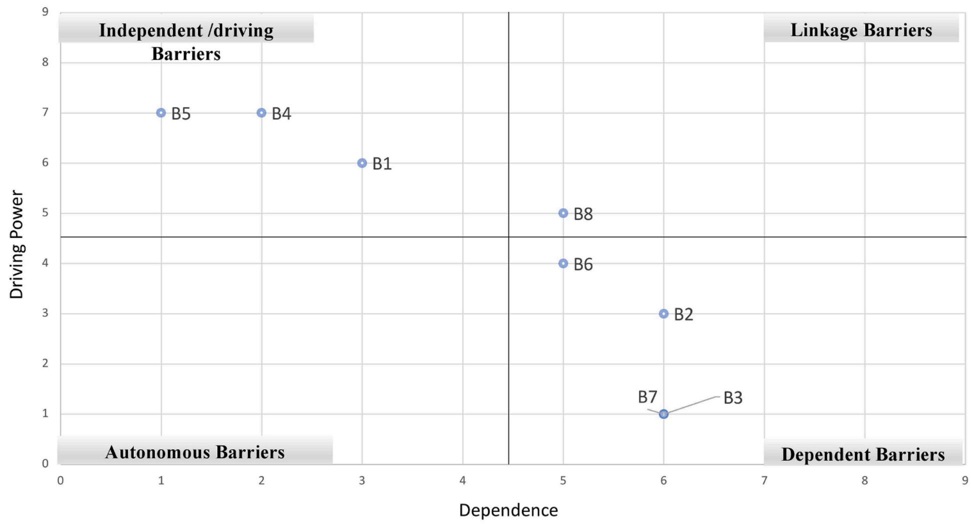

Fig. 5. MICMAC Analysis.

should be established which needs a high amount of investment (Beaudet et al., 2020; Harper et al., 2019; Kurdve et al., 2019). Also, effective EVs-LIBs RLs implementations need technologies like pyrometallurgical routes that suffer from high capital costs. So, financial barriers can directly affect the technological barriers as well. Also, regarding the link between B1 and B8, in some operations of the EVs-LIBs RLs, skilled and experienced labours are needed. For example, for battery disassembly, there is a need for experienced workers. This means in countries with high labour costs, it is costly to recruit experienced workers which may make the RLs adoption being not economically viable (Harper et al., 2019).

4.4. Knowledge and Experience (B8)

Knowledge and experience (B8) is the sole linkage barrier of the model and is located in level III of the hierarchy. These types of barriers are special as any action taken on them will impact other barriers (Kumar and Dixit, 2018). There is a mutual relation between B8 and management and organisation (B6). As mentioned earlier, the B8 category includes barriers such as lack of experience/knowledge of technology, management practice for EVs-LIBs RLs, lack of awareness concerning RLs and its benefits for EVs-LIBs, lack of taxation knowledge on returned products, lack of knowledge and awareness of environmental impacts (Abbas, 2018; Bouzon et al., 2018; Govindan and Bouzon, 2018). These factors can affect the barriers in the B6 category such as commitment from top management and governors, and lack of interest in investment in RLs practices and vice versa. B8 also affects technology and infrastructure barrier. Lack of experience/knowledge of technology and management practice for EVs-LIBs RLs can lead to inappropriate decisions about selecting the proper technologies and R&D decisions for new recycling technologies.

4.5. Management and organization (B6)

Based on the MICMAC analysis, B6 is located on Level III of the model and is categorised as a dependent barrier. This category of barriers exists due to a lack of commitment from top management and governors to adopt and implement RLs. Top management should show that their commitment is linear with long-term organizational goals. They must provide strategic plans with regards to the RLs programs as well as action plans to successfully implement their strategic plans. The management barriers include organisational strategy development, performance measurement, system development, and staff recruitment for implementing RLs (Abbas, 2018; Gardas et al., 2018a; Govindan and Bouzon, 2018). Based on the results, B6 directly influences knowledge and experience (B8) and governance and SC process (B3).

4.6. Technology and infrastructure (B2)

Based on the TISM-MICMAC analysis, technology and infrastructure (B2) is one of the dependent variables and is in level II of the hierarchy. B4, B1, and B8 barriers directly affect B2 which has been discussed in the previous sections. Based on the results, B2 affects governance and SC barriers (B3). Lack of proper tracking technology for EVs-LIBs creates uncertainty about the quantity and quality of the used EVs-LIBs in the reverse flow of the supply chain. Besides, B2 has a direct impact on environmental barriers (B7). For example, it has been discussed by several researchers that the lack of proper technologies for disassembly and recycling the EVs-LIBs will harm the environment. This can be happened by the amount of energy that is used for recycling and remanufacturing the EVs-LIBs. Moreover, disassembly of the LIBs has its hazards that need to be handled by sophisticated technologies (Alamerew and Brissaud, 2020; Harper et al., 2019; Leon and Miller, 2020).

4.7. Environmental (B7)

B7 as a dependent barrier is located in Level I of the model. Technology and infrastructure (B2) has a high impact on environmental barriers. Besides, policy and regulation barriers (B4) affect B7. Based on the location of B7 in the model, environmental barriers are seen to be one of the most influenced barriers for implementation of EVs-LIBs RLs, rather than a strong influencer of other barriers. This category of barriers shows the negative environmental consequences related to EVs-LIBs RLs activities. Although the literature in the field of EVs-LIBs shows managing the EoL of the batteries can reduce the negative environmental impact, there still negative impact associated with RLs activities such as disassembly, recycling, and remanufacturing (Beaudet et al., 2020; Salim et al., 2019a).

4.8. Governance and SC process (B3)

Similar to Environmental barriers (B7), governance and SC process barriers (B3) are ranked in level I of the hierarchy and categorised as dependent barriers. As discussed in the previous sections, technology and infrastructure (B2), management and organisation (B6) barriers affect B3. There are several barriers in this category of barriers such as lack of effective communication and coordination between the member of the EVs-LIBs supply chain, product quality reliability for returned

EVs-LIBs, the uncertainty of demand and return flows for EVs-LIBs, and lack of performance metrics system for EVs-LIBs RLs (Ali et al., 2018; Beaudet et al., 2020; Govindan and Bouzon, 2018; Vieira et al., 2020).

4.9. Theoretical and practical implications

This study provides an analysis of barriers associated with the successful implementation of EVs-LIBs RLs in Europe. Although there have been several research papers in the literature dealing with EVs-LIBs EoL management technically (Gaines, 2019; Harper et al., 2019; Kurdve et al., 2019; Leon and Miller, 2020; Mayyas et al., 2019), there is a lack of systematic approach that can identify and classify RLs barriers. The developed model assists industrial practitioners and policymakers develop business models and initiatives for effective EVs-LIBs EoL management.

The results of the current study have been shared with the EVBs experts to obtain their feedback and comments on practical and managerial issues. The experts were selected based on their expertise in the field of LIB supply chain with at least five years of experience. The constructed hierarchy model in Fig. 4 was shared with the experts to obtain their opinions. Their remarks are provided as follows:

(1) The constructed model provides a proper depiction of barriers to the implementation of EVs-LIBs RLs in Europe. The lower-level barriers such as B5 (market and social) and B4 (policy and regulations) as the independent/deriving barriers would have more long-term impact on the successful implementation of EVs-LIBs RLs and are very important. So, there is a need to focus on developing supportive rules and regulations, and customer awareness programs.
(2) A significant link from B6 (management and organization) to B2 (technology and infrastructure) would have been expected. It was discussed with the experts, as there is a mutual relation between B6 and B8 (knowledge and experience), the impact can be seen there.
(3) Most of the experts have mentioned the importance of EU countries' supports for R&D on EoL management of EVs-LIBs. It has been discussed that there is a need for radical change in RLs activities of EVs-LIBs.

The obtained results provide useful insights for practitioners and policymakers regarding the implementation barriers for EVs-LIBs RLs and their relations. Addressing the identified barriers based on the discussed strategies in Section 4 will help companies to successfully implement RLs for EV-LIBs reverse supply network. Implementing such reverse networks will lead to saving scarce natural resources such as lithium, cobalt, manganese, nickel, and graphite that are required for the production processes of EVs-LIBs. An important aspect to consider is the manufacturing process of EVs-LIBs and the raw materials required to sustain this level of demand. Given the scarcity and limited amount of raw materials in Europe, firms are promoting EVs-LIBs RLs activities which reduce the environmental impact and provide an important input source for the manufacturing process of EV-LIBs.

5. Conclusion

RLs activities require that all products at their EoL are collected from the customers and returned to original manufacturers to be recycled, reused, remanufactured, or properly discarded. EoL management of the EVs-LIBs has become a vital part of circular economy practices, especially in the EU. Consequently, manufacturers must develop EoL management of EVs-LIBs through RL activities. There have been publications related to the barriers of RLs in various industries, but none has considered such analysis for the EVs-LIBs manufacturing sector. In this study, a comprehensive list of main barrier categories of successful implementation of RLs activities for the EoL management of EVs-LIBs was identified using a Delphi method. Then, an integrated approach of TISM-MICMAC was applied to develop a hierarchical model based on the defined barrier categories and inputs from the experts. Finally, the most dominant barrier categories of RLs activities for EVs-LIBs were prioritised to help industrial decision-makers and policymakers.

The current study provides two key contributions. First, we identified the full set of barriers to EVs-LIBs RLs by examining the literature, and subsequently experts' opinions using a Delphi method. Furthermore, a detailed explanation of each barrier category to EVs-LIBs RLs was provided in order to enhance the understanding of the relevant barriers to EVs-LIBs. Second, the structured hierarchy model constructed by the TISM-MICMAC followed by an extensive analysis contributes to the theory and practice of RLs with a particular focus on EVs-LIBs. The results of the study provide a comprehensive insight to EU governments, policymakers, and industry practitioners regarding the existing barriers and their relations that help them to implement EVs-LIBs successfully.

There are always limitations and avenues for future works in all research activities. Firstly, the developed conceptual model can be further validated by performing a comprehensive statistical analysis to confirm the current links and relationships between various variables (barriers) and discuss and argue against some of the existing links or justify the neglection of some plausible links that are unaccounted for in the model. Given the limitation in the availability of the experts, a questionnaire survey was performed to obtain inputs for implementing the TISM-MICMAC approach. As a result, the required TISM-MICMAC threshold was obtained based on a sensitivity analysis study to minimise the subjectivity of the threshold. It would be advantageous to explore other mathematical methods such as Multi Mean De-Entropy assessment approach to minimise such subjectivity in threshold selection. Such a study requires a larger group of experts which will help in mitigating the risks of obtaining sensitive outputs. There could be a good opportunity to integrate fuzzy multi-criteria decision-making techniques with TISM to determine the final rank of each barrier category.

CRediT author statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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